5G Wireless Network Support

Using Unmanned Aerial Vehicles for Rural and Low-Income Areas.

Author: Hloniphani Maluleke

Supervisor: Prof. B.A. Bagula

Department of Computer Science
University of the Western Cape
Bellville, R.S.A.

Version II

November 2020

ABSTRACT

The fifth-generation mobile network (5G) is a new global wireless standard that enables state-of-the-art mobile networks with enhanced cellular broadband services that support a diversity of devices. Even with the current worldwide advanced state of broadband connectivity, most rural and low-income settings lack minimum Internet connectivity because there are no economic incentives from telecommunication providers to deploy wireless communication systems in these areas. Using a team of Unmanned Aerial Vehicles (UAVs) to extend or solely supply the 5G coverage is a great opportunity for these zones to benefit from the advantages promised by this new communication technology. However, the deployment and applications of innovative technology in rural locations need extensive research.

This thesis proposes and evaluates the performance of a 5G network architecture where a Low Altitude Platform (LAP) is used as a base station providing coverage to several UAVs carrying 5G devices in a prescribed area. Furthermore, an economic feasibility study was conducted to estimate the operational and capital expenditure of deploying the 5G network using UAVs. Both network evaluation and economic feasibility studies are conducted under rural settings of South Africa, specifically: i) the district municipalities of Mopani, Vhembe, Waterberg, Chris-Hani, and Frances Baard; ii) townships of Soweto, Duduza, Lulekani and Khayelitsha; iii) rural locations of Hlankomo, Mandileni, Gon'on'o; and iv) Zeerust town. In wireless communication, most of the energy is consumed during data transmission and packet control. A clustering approach has been adopted for the engineering feasibility of the team of UAVs topology, to ensure reliable and energy-efficient 5G network coverage. Additionally, two clustering models were proposed and evaluated in this work, which are: multi-sink airborne network with inter-cluster communication through the LAP (MSLBACK) and multi-sink airborne network with an inter-cluster communication through UAV gateways (MSGBACK).

The experimental results proved that, when the proposed models are benchmarked against several myopic approaches, they lead to better resource utilisation by ensuring that all the UAVs were actively involved in providing 5G connectivity to ground users; as against the myopic approaches with isolated UAVs and subsequent waste of network resources. The economic analyses reveal that implementing the proposed 5G network architecture in a rural area requires minimal investment yet yields a high internal rate of returns within a short period by having users pay as little as R0.20c per GB of data bundles.

Keywords – Clustering, Low Altitude Platform, Energy Efficiency, Unmanned Aerial Vehicles, Wireless Sensor Network, Fifth Generation Network, Economic Analysis.

PUBLICATIONS

As at the time of writing, one paper has been accepted for publication from this thesis, while a second is being finalised for submission.

i. H. Maluleke, A. Bagula and O. Ajayi, “Efficient Airborne Network Clustering for 5G Backhauling and Fronthauling,” 2020 16th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Thessaloniki, Greece, 2020, pp. 99-104, DOI: 10.1109/WiMob50308.2020.9253390.

ii. Maluleke, H., et al. “5G Drones as a Service to Rural and Low-Income Communities: An Economic Feasibility Study”, UWC Technical Report on 5G Drones. under journal submission.

DECLARATION

I, Hloniphani Maluleke, declare that this Masters by Research thesis has been composed solely by myself, under the supervision of Prof. B.A. Bagula, and that it has not been submitted, in whole or in part, in any previous application for a degree or professional qualification. Except where stated otherwise by reference or acknowledgement, the work presented is entirely my own.

I confirm that this dissertation presented for the degree of “MSc. Computer Science”, titled “5G Wireless Network Support: Using Unmanned Aerial Vehicles for Rural and Low-Income Areas”, has:

i. Been solely the result of my work.
ii. No more than 55,000 words in length, including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes.
iii. No more than 150 pages of the dissertation content.
iv. Introductory, review of the latest literature, system design, discussion, and conclusion chapters, respectively. Moreover, discussion chapters incorporate research design and results.

Student No.	3219279
e-Mail	kloniphani@gmail.com
Signature	
Date	Wednesday, 25 November 2020

CONTENTS

I. INTRODUCTION

The purpose of this study was to discover if the new Fifth-Generation (5G) cellular network can be effectively deployed in rural and low-income areas of the Republic of South Africa, using Unmanned Aerial Vehicles (UAVs); and doing this in a way that potential clients pay a reasonable monthly subscription fee for unlimited Internet connection, whilst being profitable to the Mobile Service Providers (MSPs). Heterogeneous networks have been considered as viable solutions to this issue. As discussed in the chapter on related works, some research has been done on UAVs aware projects aiming at providing wireless networks. The reason why remote areas lacked cheap and reliable Internet connection had remained largely unanswered before this study.

Arpanet experiments conducted by ARPA[1] half a century ago proved that four nodes could exchange simple messages (Luca, et al., 5G in Rural and Low-Income Areas: Are We Ready?, 2016). These experiments have led to the birth of the most powerful engine that is driving social and economic growth in the world today, and it is called the Internet. At the moment the Internet has evolved from the Arpanet into a common platform for all forms of modern communication that needs to be open, secure, trustworthy, and accessible to anyone and from anywhere (Dame, 2016). The high penetration of mobile technology and its ubiquity can be leveraged upon as a backbone for accelerating Internet access worldwide. However, there is still a massive portion of the world's population, especially in developing countries, that either lack access to or have inadequate Internet coverage. In affluent areas of the developing world, Internet coverage is provided using older generations of mobile telephone such as 2G and 3G. This is in sharp contrast to the rest of the world where 4G is the norm. The lack of adequate coverage can be attributed to the MSPs' view of these areas as expensive to deploy necessary infrastructure, with no or less Return on Investment (ROI). These issues lead to a considerable part of the world's population missing out on the opportunities provided by the Internet and emerging generations of mobile technologies.

According to Google, two-thirds of people on planet earth still live in areas that are outside the reach of reliable Internet connectivity (Katikala, 2014). This finding motivated the corporation to develop an innovative project called LOON, which is aimed at solving this global problem by beaming Internet access from giant balloons travelling on the edge of space to people living in rural and remote areas of the world. Different other projects from very well-known companies have emerged from similar initiatives. These projects include: i) Saving Lives project by Nokia, which is aimed at using UAVs to provide wireless connectivity to emergency response teams (Niemi, 2017); ii) a project initiated through a partnership between Ericsson and China Mobile that produced the first 5G-enabled drone prototype (Ericsson, 2016; Zeng, Lyu, & Zhang, Cellular-connected UAV: Potential, challenges, and promising technologies, 2018); iii) the SkyBender project that foresees thousands of high-altitude UAVs delivering Internet access around the world (Harris, 2016); iv) the AT&T and Qualcomm's LTE project which aims at connecting UAVs to the United States of America's commercial 4G LTE network and storing retrieved data that are fed directly to Qualcomm's systems (Dignan, 2016), and v) the experimental Aquila project by Facebook that aims to leverage High-Altitude

---

[1] Advanced Research Projects Agency (ARPA) of the United States Department of Defence.

Platform stations (HAPs) and solar-powered drones as atmospheric satellites for the delivery of wireless connectivity to users on the ground (Willems, 2016).

1.1 FIFTH GENERATION MOBILE NETWORK.

Figure 1 – Fifth Generation network use cases.

5G stands for the fifth generation and refers to the new mobile wireless technology based on the IEEE 802.11 AC standard of broadband technology. Though seemingly popular, a formal standard for 5G is yet to be finalised as at the time of writing. The most salient features of the 5G mobile technology include: i) A connection speed of approximately 10 Gb/s; ii) 90% less energy usage; iii) approximately 100% availability and coverage; iv) support for a significantly more significant number of simultaneous connections; v) network latency in the order of a millisecond or less; vi) the ability to support multi-tenants; and vii) modular programmability. The key enablers of 5G include: i) support for a complex set of services; ii) relatively cheaper manufacturing cost; iii) high transmission speed. A significant advantage of using UAVs for 5G network support is that they can offer wide coverage at a low cost. This coverage can be widened further with regulatory permission to allow drones to be used Beyond Visual Line-of-Sight (BVLoS). UAVs can fly in both the Stratosphere and Troposphere hovering at heights above 40 kilometres, beyond visual sight and without obstructing commercial flights.

Leveraging on this ability long-range UAV-Based 5G radio can, therefore, supply wireless coverage to a wide expanse of ground area.

Despite the apparent advantages of adapting 5G, there are some obstacles to its widespread adoption, prominent among which is the high cost of implementation, making accessibility to end-users a challenge. While the newest mobile phones and devices have 5G radios integrated into them, older phone handsets are not guaranteed to have such radios built-in, hence incompatibility could be an issue with these outdated phones. Furthermore, as a reliable wireless Internet connection can depend on the number of devices connected to one channel, the addition of 5G to the wireless spectrum could lead to the risk of overcrowding the frequency range. Though the network is still in the development stage, many companies have started developing 5G products and field testing them. Noteworthy advancements in 5G technologies have come from Nokia, Qualcomm, Samsung, Ericsson and British Telecom (BT), with growing numbers of companies forming 5G partnerships and pledging funds to support the continuous research into 5G and its application. As an example, Nokia, Huawei, and Ericson, for example, have designed 5G platforms aimed at mobile carriers rather than consumers. Ericsson announced the first 5G platform towards the end of 2019 that supply radio system, which was ready ever since 2015 (Ericsson, 2019). While in the same year, Huawei Technologies through both lab and field tests confirmed that sparse code multiple access is the best candidate for 5G non-orthogonal multiple access, that can triple the entire system throughput without compromising the link performance (Lu, et al., 2015).

Some of the main communication characteristics of the 5G are millimetre wave (mmWave) frequency usage and Massive-MIMO technology deployment. While spectrum is scarce at microwave frequency bands. However, it is abundant in the sphere of mmWave. Such a spectrum 'el Dorado' has led to a mmWave 'gold rush' where researchers from different backgrounds are studying various aspects of mmWave transmission. Although it is far from being fully understood, mmWave technologies have already been standardised for short-range services such as IEEE 802.11ad/ax. They have been deployed for niche applications such as micro-cell backhauls (Boccardi, Heath, Lozano, Marzetta, & Popovski, 2014). 5G proposals include the usage of an extremely high number of antennas to multiplex messages for several

Figure 2 – Fifth Generation Network possibilities (Rost, et al., 2015).

devices on each time-frequency resource, focusing the radiated energy towards the intended directions while minimising intra- and inter-cell interference (Boccardi, Heath, Lozano, Marzetta, & Popovski, 2014). Massive-MIMO may require significant architectural changes, in the design of macro base stations, and it may also lead to new types of deployments. As revealed in Figure 1 above, some of the key use cases that will be significantly enhanced by the 5G mobile network include: i) residential use, ii) Internet-of-things, iii) infrastructure connection, iv) vehicle connection, and v) augmented and virtual reality. These enhancements will come from: i) the increased basic connection coverage enabled by the high bandwidth and low latency provided by 5G ii) the integration of services such as emergency service, e-health, e-learning, entertainment, etc., and iii) the cross-integration of multiple networks including terrestrial networks (such as road traffic, data, education, health networks) and also aerial networks (such as satellite and flying eNB). These network capabilities are illustrated in Figure 2.

As revealed in Figure 2, 5G will provide a common platform for many industries, including information technology, automotive, entertainment, health, manufacturing, and many others. This platform will enable augmented and virtual reality technologies to transform professional procedures (e.g. a doctor can perform surgery remotely through the tactile Internet). A 5G architecture is presented in Figure 3 below, which reveals its various components, including: i) the radio resource management, ii), the mobility management, and iii) how the implementation of inter-vehicular communication will be implemented. The preliminary of the 5G Radio Access Network (RAN) architecture necessitates having a healthful equilibrium between evolution and revolution to fulfil the novel requirements and operation standards (Maeder, et al., 2016). The architecture design should feature: i) the integration of multiple radio access technologies to achieve better user experience and cost efficiency, ii) a framework for stringent integration of new 5G and the existing radio interfaces in the RAN, as well as Wi-Fi and LTE, iii) cloud RAN that provide on-demand operation and deployment of mobile networks capable of sharing physical hardware interfaces, and iv) efficient support of enhanced services and business models.

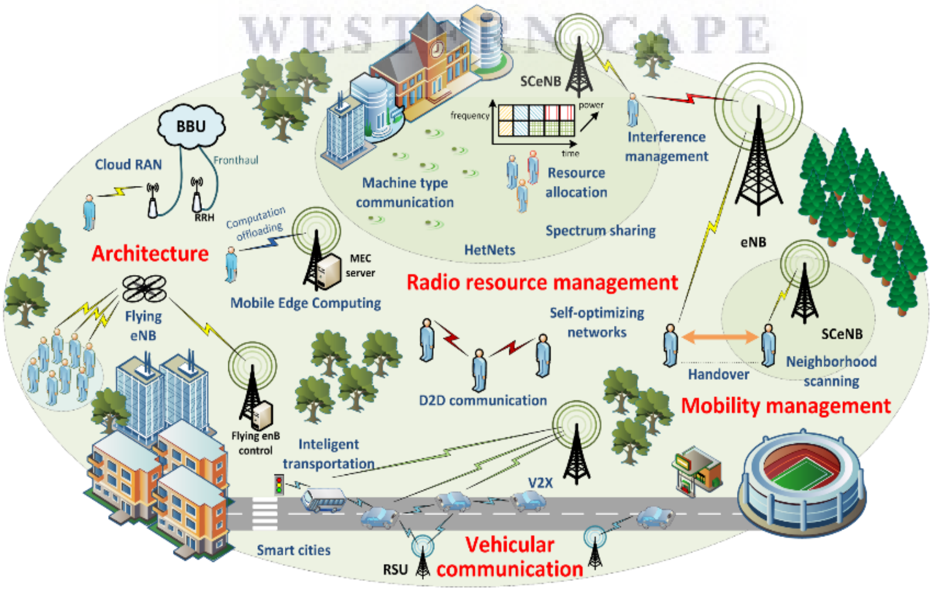


Figure 3 – Fifth generation network architecture © http://5gmobile.fel.cvut.cz/activities/

1.2 RESEARCH GAPS.

UAVs are often referred to as drones and have attracted substantial interest for various applications in the context of smart solutions and IoT (Hayajneh, Zaidi, Mclernon, & Ghogho, 2017). The NPD Group, in 2018, released a report that showed that retail sales of drones have tripled over the past couple of years (The NPD Group, 2018). The utilisation of UAVs is indeed a promising and efficient solution that led to a new hybrid networking paradigm sometimes called the "Internet-of-Things in motion" and more recently referred to as the "Internet-of-drones" as described in (Bagula, Abidoye, & Zodi, 2016; Tuyishimire, Bagula, & Ismail, Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion, 2018; Kalantari, Shakir, Yanikomeroglu, & Yongacoglu, 2017). This paradigm capitalises on the interaction between aerial and terrestrial networks to provide efficient ways of providing and/or complementing wireless network coverage (under challenging settings) and/or collecting data for different purposes. However, despite the growing interest in UAVs applications and emerging initiatives in the field, deploying UAVs to supply network cellular coverage in rural and low-income areas has not been extensively researched. It was shown in (Luca, et al., Bringing 5G in Rural and Low-Income Areas: Is it Feasible?, 2017) that 5G coverage could be provided to rural and isolated areas by leveraging the "Internet-of-things in motion" to mount 5G devices on UAVs to have these devices providing periodically or permanently wireless coverage from the air. When we look at some of the novel technological advances, clearly the UAVs with their easy on-demand deployment break new ground on how to carry out assigned tasks.

In the militaries, UAVs are used to perform reconnaissance missions, gathering battlefield intelligence or engage them in actual combat in high-risk missions. Recent advancements in energy technologies now allow harvesting of ambient energy (e.g. – the solar power, thermal, wind, and kinetic energy) to power an autonomous device, wearable electronics, and wireless sensor networks. These technologies have now been applied in UAVs as reported in (Katikala, 2014). With the ability to harvest energy, UAVs can recharge their batteries by exploiting solar energy, while hovering in the air and also acting as a 5G Internet access point. Furthermore, white papers from the 5G Infrastructure Public-Private Partnership (5G-PPP) present the 5G cellular network in detail (5G-PPP, 2017). Evidently, there is great potential for the application of UAVs in 5G networks, however, there are also drawbacks. In the quest to provide widespread Internet coverage (particularly in rural areas), attention needs to be paid to certain issues such as: i) how wide coverage networks can be developed and deployed profitably in rural communities, ii) what the capital and operational expenses for such network orchestration would be, and iii) how much levies should the subscribers pay monthly for the service provider to earn "healthy" Return on Investment (ROI)?

It is predicted that the "Internet-of-Things in motion" initiatives will result in a hybrid of air and ground wireless networks. The complexity of such a hybrid network will raise issues that can only be addressed by redesigning the existing techniques to manage these networks and/or the design of new techniques for handling such complex networks. These issues have been translated over the years into open problems revealing research gaps in the deployment of UAVs to provide wireless networks either or both data collection and distribution. Some of the issues are: i) the optimal placement in the 3D space, ii) energy limitation of UAVs, iii) UAV mobility, iv) interference during transmission, v) the issue of backhaul connectivity, and vi) deployment techniques for different applications and use cases. Also, the energy consumed by the onboard base station while powering the UAV platform can limit the flying time by 16%

(Alzenad, El-Keyi, Lagum, & Yanikomeroglu, 3D Placement of an Unmanned Aerial Vehicle Base Station (UAV-BS) for Energy-Efficient Maximal Coverage, 2017; Mozaffari, Saad, Bennis, Nam, & Debbah, A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems, 2018). Efficient wireless network development with UAVs requires addressing the backhaul-aware deployment of UAVs while using them as aerial base stations. The applications using UAVs wireless access network are drawn from various scenarios. These include use cases, such as for public safety scenarios, remote healthcare, e-learning, hotspot coverage, Internet-of-things, city surveillance, precision agriculture, and many others (Mozaffari, Saad, Bennis, Nam, & Debbah, A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems, 2018; Tuyishimire, Bagula, & Ismail, Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion, 2018). Some of these challenges associated with wireless network coverage by UAVs have been reported in (Stefano, Karol, Gregoire, Dario, & Bixio, Dynamic Routing for Flying Ad Hoc Networks, 2015).

1.3 PROBLEM STATEMENT.

There is an existing digital split between rural and urban communities in South Africa. It has been a massive challenge for government entities and private corporations to offer remote areas using cheap, yet efficient Internet access. In rural communities, there have been little or no changes in network infrastructure and service delivery for decades. Rapid development and urbanisation in cities have resulted in many young individuals relocating to the cities and thereby leaving the rural regions with substantial low population, mostly consisting of minors or elderlies. Furthermore, these rural areas are often extremely far from urban areas and with poor road infrastructure. These among other factors dissuade national private-sector operators and telecommunication industries from investing in these low-income areas, especially as they offer little return on investment.

As illustrated by the MTN scenario in Figure 4, the 4G network has not covered all countries and regions of Africa. The image on the left shows MTN’s network coverage by country, while the right one shows the MSP’s precise coverage in South Africa. Similarly, while promising effective communication opportunities, 5G deployment like previous generation mobile technologies might discount some of the regions of the world where mobile operators have not found financial incentives for its development. LTE, for example, has only been deployed in urban areas which are profitable to service providers. This is confirmed in the following statement by Jacqui O’Sullivan: a

> *“A challenge was the need to manage legacy technologies, while deploying modern technologies, in the spectrum-constrained environment within which we operate,” Jacqui O’Sullivan (MyBroadband, 2019).*

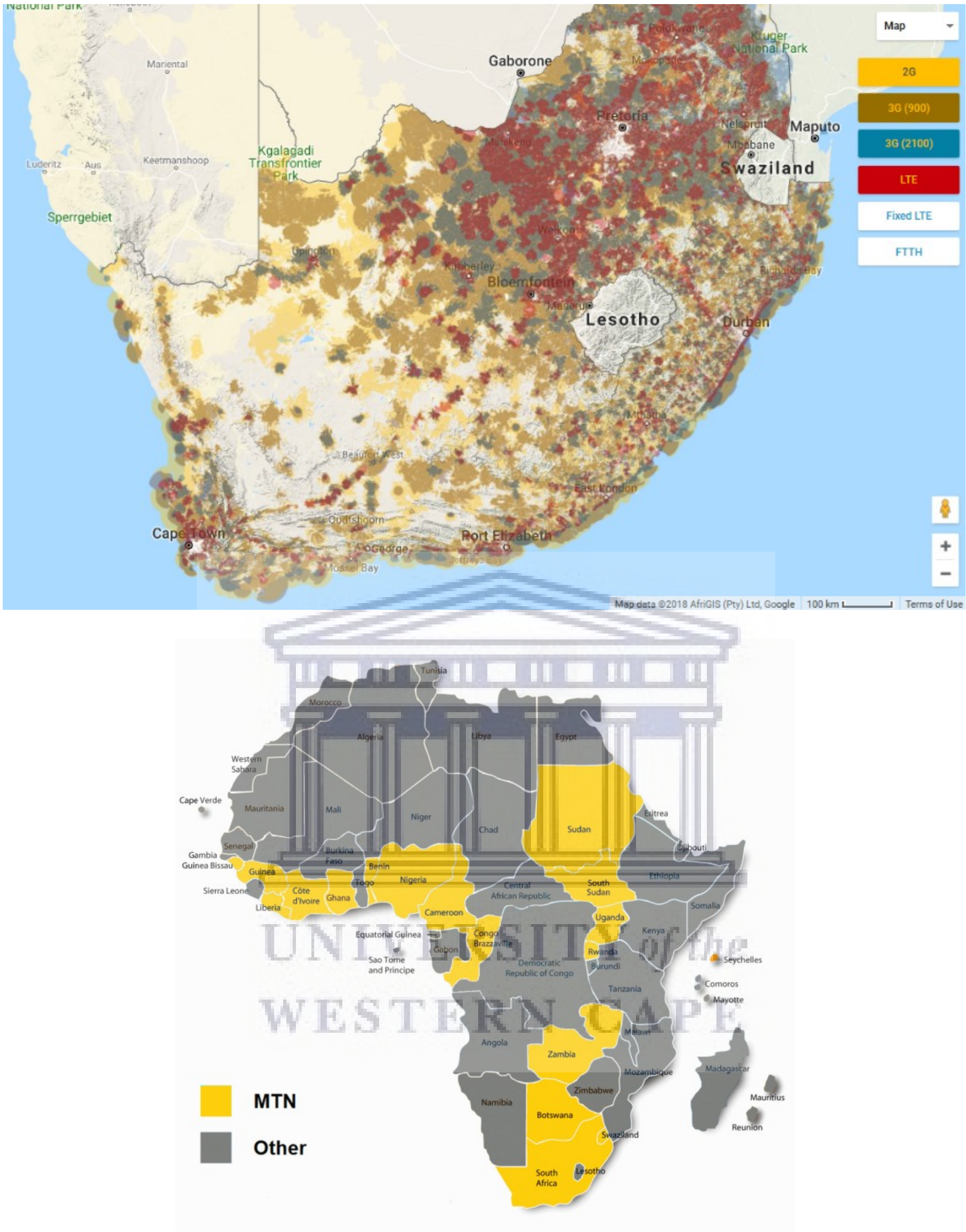


Figure 4 – MTN coverage map in Africa.
Top image – by country @ https://www.africanbusinesscentral.com/2015/05/08/mtn-group-an-interesting-way-to-gain-exposure-to-the-african-growth-story-infographic/
Bottom image – Coverage in the Republic of South Africa © https://www.mtn.co.za/Pages/Coverage_Map.aspx

This dissertation is aimed at a 5G implementation to connect the unconnected and assess the feasibility of using the Internet-of-things in motion for 5G coverage. The goal of this research work is to propose a novel model which uses cheap and easily accessible technology to efficiently deploy low-cost wireless network coverage in low-income, remote and rural locations.

1.4 RESEARCH OBJECTIVES.

The objectives of this dissertation are in twofold, which are:

i. To design a "heterogeneous air-to-ground network infrastructure" to provide services to terrestrial users in rural and low-income areas.
ii. To use unmanned aerial vehicles to provide 5G network coverage in a rural or low-income area to reduce capital and operational expenditure.

The goal and objectives of this research work are predicated on the fact that there are still many areas that do not have any form of network coverage globally. According to a McKinsey & Company's report of 2014, about 60% of the world's population are unconnected (McKinsey & Company, 2014). Undeniably, people who are deprived of Internet access are more likely to be poor and living in rural areas. Besides, network service providers, these locations are also overlooked by other utility companies. Oftentimes they are not connected to the nation's electricity grid, or portable water supply systems. These communities have sparse population density, produce less or no accounted Gross Domestic Product (GDP), and are located in areas that are not easily accessible. On the contrary, statistics show that almost everyone connected to the Internet is to an extent literate, whereas only about 28% of the disconnected population are literate regardless of which countries they live in (Bleiberg & West, 2014; Gandhi, 2019). Geographical and demographic features are also a limiting factor to network deployment and service orchestration. Hence, it makes financial sense for MSP to focus on areas that have better GDP and offering them better Quality of Service (QoS).

In modern economies, rural residents need faster and more affordable Internet. That will allow them to connect with the entire world to better their socio-economic and health status through the use of online services, educational tools, social media, news, information, and government data. When considering this lack of coverage in remote areas, it is imperative to consider the critical questions of whether this need can be met using the future 5G technologies and if it can be met in a sustainable and economically viable manner.

1.5 CHALLENGES.

Widespread deployment of 5G network is majorly being hampered as standards have yet to be approved by the ITU-R[2] (Shafi, et al., 2017). However, some of the potential challenges associated with the forthcoming 5G mobile network include:

1.5.1 Economic feasibility issues.

A mobile network service provider must pay the following costs during network deployment: i) spectrum licensing cost, ii) cost of physical hardware used in the 5G deployment, iii) cost of human resources (technicians and consultants) to install the necessary hardware, iv) cost for network tests and validations, and v) deployment fees demanded by regulatory bodies. The demand for general, reliable, and higher bandwidth wireless connectivity has been rising gradually (Basta, et al., 2017). In the forthcoming cellular networks, the coverage dilemma is

---

[2] The ITU Radiocommunication Sector (ITU-R) is one of the three sectors of the International Telecommunication Union (ITU) and handles radio communication.

likely to remain, therefore further broadening the rural-urban divide with regards the use and availability of Internet connection (Khalil, Qadir, Onireti, Imran, & Younis, 2017).

However, there are many gaps in both Ad Hoc and Ethernet networks where 5G deployment investments make financial sense. These include remote locations and less developed areas with huge attention of IoT interest and investment (Wang, et al., 2013). The 5G networks are costly to successfully deploy. With many operators only halfway to the final stages of their 4G rollout, investing in the infrastructure required to enable 5G connection is a costly commission.

Regarding the operational expenditure (OPEX), an automated operation can reduce human intervention. This, by extension, implies a reduction in employment costs and faulty-detection operations. Additionally, with regards to capital expenditure (CAPEX), a flexible, agile and nearly optimal provisioning of functions and services, will definitely reduce equipment costs and allows postponing investments (Panwar, Sharma, & Singh, 2016).

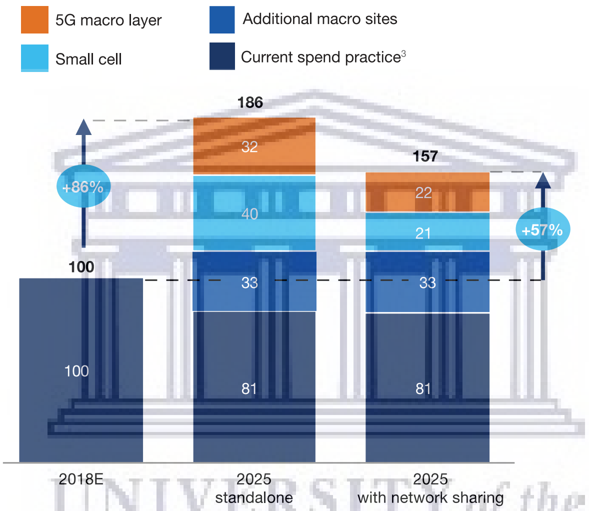


Figure 5 – Network slicing can reduce 5G CAPEX by 50% (Ferry, Alexandre, Halldor, & Nemanja, 2018).

Network slicing is one of the key features that 5G is bringing. However, the low cost of exploring network slicing does not compare to the opportunity it offers. To achieve a network slicing agreement is a complex and sensitive matter. If network service providers plan to meet expectations for 5G deployment before the end of 2020, they need to start acting now or before their competitors compel them into deployment. One of the strongest motivations for network slicing is cost savings and improved network quality. McKinsey & Company researchers believe that Greenfield[3] deployments of small-cells, where three operators can save up to half of the expenses each through sharing a sliced network infrastructure (Ferry, Alexandre, Halldor, & Nemanja, 2018). Through their report, one case showed that by sharing 5G small-cell deployment and building a common nationwide 5G IoT macro layer, operators could reduce 5G-related investments by more than 50%, as depicted in Figure 5. The stacked bar graph in the image compares the standalone and sliced network cost. At the same time, service providers could also condense the risk of their build-out plans by sharing access to capacity and sharing the costs accordingly (Grijpink, Ménard, Sigurdsson, & Vucevic, 2018).

---

[3] Greenfield deployment refers to the installation of an IT system where previously there was none.

1.5.2 Engineering feasibility issues.

A. *Frequency spectrum distribution.*

Frequency spectrum distribution is another potential impedance to 5G delivery. New mobile generations are assigned new frequency bands and wider spectral bandwidth per frequency channel, but there is little room for new frequency bands or larger channel bandwidths. There is already a shortage of spectrum available for the 4G network that can be distributed to MSPs. This foreshadows that base station designs must facilitate many different bands with different cell sites, where each site has multiple base stations (Rappaport, et al., 2013). The process of obtaining a new spectrum can take about a decade. The ICASA[4] needs to work closely with the government and stakeholders to ensure that similar shortages and allocation delays do not occur (Eckart, 2018). There is a lot of uncertainty with regards 5G spectrum allocation, this can invariably cause deployment delay and ultimately requiring consumers to pay high charges. This is because the spectrum has been and will continue to be a scarce resource for the mobile-communication industry.

Historically, up until now, the mobile industry has relied on the spectrum dedicated to mobile communication and licensed to a certain operator. However, in situations where a licensed spectrum is not available, other possibilities for increasing the spectrum availability are of interest. This could include the use of unlicensed spectrum, or secondary software-defined radio (SDR) benefits from today's high processing power to develop multi-band, multi-standard base stations and terminals. Although in future the terminals will adapt the air interface to the available radio access technology, at present this is done by the infrastructure. Several infrastructure gains are expected from SDR. For example, to increase network capacity at a specific time (e.g. during festivals or sports events), an operator will reconfigure its network, adding several modems at given base stations. SDR makes this reconfiguration easy. In the context of the expected 5G systems, SDR will become an enabler for terminal and network reconfigurability through a software download. For a manufacturer, this can be a powerful aid in providing multi-standard and multi-band equipment with reduced development effort and costs (Mousa, 2012).

Seamless interoperability among heterogeneous networks represents the cornerstone for the success of 5G systems with different evolving access technologies. A novel solution that ensures interoperability between several types of wireless access networks are given by the developing IEEE 802.21 standards. The IEEE 802.21 focuses on handover facilitation between different wireless networks in heterogeneous environments regardless of the type of medium. The standard names this type of vertical handover as media independent handover (MIH). The goal of IEEE 802.21 is to ease the mobile nodes' usage by providing uninterrupted handover in heterogeneous networks. The heart of the 802.21 frameworks is the media independent handover function (MIHF), responsible for communication with different terminals, networks and remote MIHFs. The function must be implemented in every IEEE 802.21 compatible device in either hardware or software. The interest that exists both in academia and industry shows that IEEE 802.21 may be the key enabler for seamless vertical handover and transparent roaming in heterogeneous networks. IEEE 802.21 standards are expected to make a significant contribution towards the reconfigurable interoperability aspect of 5G wireless and cellular communications systems. The reconfigurable interoperability offers network providers with a

---

[4] The Independent Communications Authority of South Africa (ICASA) is an independent telecommunication and broadcasting regulatory body of the South African government.

possibility to choose, with minimal investments, between alternative wireless access networks (Taniuchi, et al., 2009; Choudhary & Sharma, 2019; Siriwardhana, et al., 2018; Sharma, You, Andersson, Palmieri, & Rehmani, 2019).

B. *Resource consumption management.*

Low energy consumption for mobile terminals has been an important requirement since the emergence of hand-held terminals 25 years ago. The driving force has been a reduction in battery size and improved battery time. Today, reduced energy consumption also in the radio access network, is receiving increased attention. The cost of energy is a far from negligible part of the overall operational cost for the operator. With sufficiently low energy consumption, reasonably sized solar panels could be used as a power source, instead of the diesel generators commonly used today (Erik, Stefan, & Johan, 2014). Nevertheless, the future evolution of cellular systems should further strive for minimising transmission of signals not needed. (M Mousa, 2012). In the case of UAV, there are several issues to be addressed including: i) energy consumption, ii) topology optimisation when deploying a team of UAVs, iii) task allocation for the team of UAVs, as well as iv) legal and ethical issues to be addressed. For UAVs, the available energy is consumed in the onboard BS and in powering the UAV platform. It was shown that the power consumed in the BS could limit the flying time of the UAV-BS by 16% (Alzenad, El-Keyi, Lagum, & Yanikomeroglu, 3D Placement of an Unmanned Aerial Vehicle Base Station (UAV-BS) for Energy-Efficient Maximal Coverage, 2017; Mozaffari, Saad, Bennis, & Debbah, Drone small cells in the clouds: Design, deployment and performance analysis, 2015).

C. *Legal and ethical issues.*

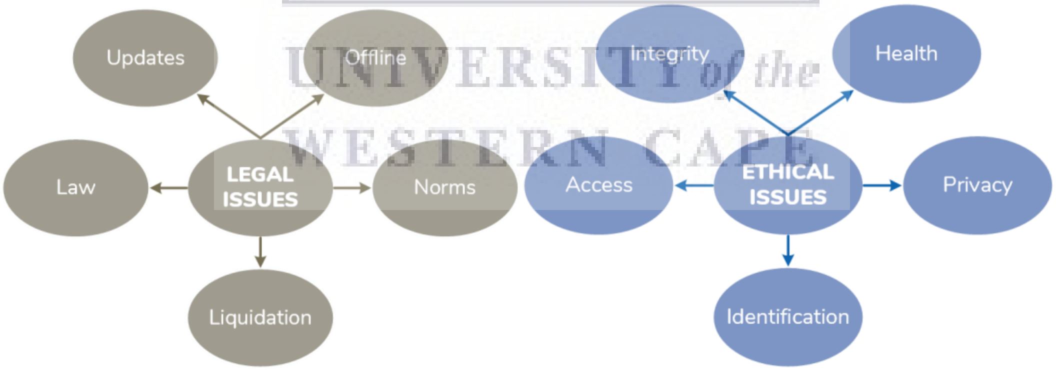


Figure 6 – Legal and Ethical issues in 5G network.

Where the benefits of the Internet are clear, the drawbacks are blatant as well. An entire underground market trading everything from drugs to slavery, to criminals stealing personal information for nefarious purposes or using technology destructively, all these are running through the Internet. Figure 6 above depicts legal and ethical issues which are still being addressed by governments all over the world. In some cases, human rights are ruthlessly trampled down by governmental bodies in the name of national security. The most significant issue is the willingness of people to give away their privacy to the growing "big data complex". These undoubted problems will grow, and new issues will arise (Tucker, Bulim, Koch, & North, 2018). The ethical issues might range from gender, religion, race, and even more significant aspect like nations. In other words, we can illustrate the problem between a wealthy and a poor family both wanting to buy a new technology device, and it will in some way “decrease the efficiency of higher socio-economical classes”, and cost the low-income family more to get it. This will cause the discrimination rate that we are trying to lower in our modern world (Tucker, Bulim, Koch, & North, 2018).

1.6 RESEARCH QUESTIONS.

There are three main questions associated with the design and implementation of a 5G network in rural and isolated areas of the developing countries. These research questions are:

i. How can heterogeneous network infrastructure be efficiently engineered?
ii. How can efficient traffic propagation be achieved of these heterogeneous network infrastructures?
iii. Will the proposed architecture be economically feasible and affordable?

The solution to these three questions and related implementations will require addressing the issue of network orchestration, which usually involves selecting the most appropriate backhauling techniques. In achieving this, some issues regarding backhauling techniques also need to be addressed. These are listed in the next subsection.

1.6.1 Backhauling techniques.

Some of the questions related to backhauling techniques include that also need to be addressed are as follows:

i. What is the current state-of-the-art regarding 5G?
ii. What are the main challenges currently being faced and those that might potentially be faced?
iii. Is it beneficial to utilise UAVs for multiple tiers communication network instead of a separate dedicated tier?
iv. If it is beneficial, then what ought to be an independent optimal altitude for UAV hovering at the different tiers?
v. How can spectrum bands be efficiently used to accommodate 5G services and standards?

1.6.2 Network operation.

Some of the questions related to network operation include:

i. Is it possible to deploy a holistic 5G architecture explicitly designed for low and sparsely populated areas?
ii. What would be the impact of infrastructure sharing?
iii. How many rollouts are needed for a complete infrastructure to take place and at what cost each?
iv. Can targeting different end-user bandwidth improve QoS and increased coverage?

v. What are governments, regulatory bodies and policymakers doing to ensure the swift rollout of 5G technologies?
vi. Finally, how are subscribers going to be billed?

1.7 RESEARCH CONTRIBUTION AND SCOPE.

Cost and demographic density are two of the significant reasons why rural Internet connection is inadequate. In urban communities, a kilometre-long Internet cable might pass through hundreds of homes and businesses. These are potential subscribers and possible revenue sources. On the contrary, in rural regions, this same length of cable might not only pass through a handful of buildings at most, hence not viable for the MSP (Sharon, 2018). Furthermore, these long stretches of unhindered cable frequently require signal-boosting equipment and longer wires – further incurring more cost for the MSP. The resolutions of this research will benefit operators, investors and government through its contribution.

The recent improvement of Low-cost micro-embedded computers and wireless radio interfaces has paved the way for Unmanned Aerial Vehicles to provide wireless network coverage to rural and low-income areas or during calamitous events, where ordinary infrastructure cannot provide services. The forthcoming 5G network can decrease installation and maintenance cost when appropriately designed. However, disruptive technologies could lead to both architectural and component design challenges, as stated in (Boccardi, Heath Jr, Lozano, Marzetta, & Popovski, 2013). Providing 5G networking in isolated and low-income areas will be a challenge because of the lack of incentives for MSPs to invest CAPEX into areas with little or no ROI. As it is, these areas are poised to miss another phase of mobile revolution if innovative methods and techniques are not taken to provide 5G connectivity at an affordable price. While one of these techniques was proposed in (Luca, et al., Bringing 5G in Rural and Low-Income Areas: Is it Feasible?, 2017), the provision of 5G to the least connected populations of the world is still in its infancy, especially when looking at 5G orchestration.

1.7.1 Research contribution.

The contribution of this thesis is to propose network and traffic engineering models that could be used to achieve 5G orchestration in a Software Defined Network (SDN) setting where these models can be computed and used to achieve fast and efficient 5G network provisioning in situations where UAVs or Low Altitude Platforms (LAPs) are used to provide 5G support to these areas. We present three networking engineering models for both LAP and UAV 5G aware networks. These include: i) a hybrid model where terrestrial nodes are structured into clusters and cluster heads are connected to 5G network either via UAVs or directly to LAP, ii) a hybrid model where the terrestrial nodes are organized into dominating sets using a backbone model where 5G support is provided through the backbone nodes by a LAP or UAVs, and iii) a hybrid model where the terrestrial nodes are organised in a multi-sink model, with each sink being used as a 5G access point for nodes which are clustered around the node or organised as a tree rooted at that node.

Recent literature has shown that clustering can be used as a network engineering approach in a dense aerial-terrestrial wireless network to minimise communication energy consumption (Tuyishimire, Bagula, & Ismail, Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion, 2018; Yang & Sikdar, 2007; Gu, Wu, & Rao, 2010; Chen, Nocetti, Gonzalez, & Stojmenovic, 2002; Wang, Wang, & Liu, 2009). In some UAV clustering scheme, the UAV nodes are divided into different virtual groups according to pre-defined rules (Yu & Chong, 2005). Clustered network architectures have the potential to improve basic performance in a dense aerial-terrestrial network. The main contribution of this research is to propose a network orchestration model for a 5G deployment that is built around clustering techniques with the expectation of achieving:

i. Rapid service conception.
ii. Cost reduction.
iii. Energy efficiency.
iv. Ease of deployment.
v. A geography-based service introduction.

A clustered wireless cellular network topology control will be proposed to provide the following essential benefits (Yu & Chong, 2005; Hayajneh, Zaidi, Mclernon, & Ghogho, 2017);

i. Reduce single point failure through virtual cluster failover functionality,
ii. Reuse of resources to increase the system capacity, such as coordinating transmission events with a cluster head to reduce transmission collisions and retransmitting,
iii. Routing traffic with cluster heads can form a virtual backbone for inter-clusters with restricted gateways,
iv. Improve coverage by grouping flexible nodes with a better line of sight communication link.
v. Improve coverage by grouping flexible nodes with a better line of sight into communication links.
vi. Enables data aggregation at CH to remove redundant and uncorrelated data, thus reducing the energy consumption of the network nodes.
vii. Conserves communication bandwidth, as the network nodes communicate with their CHs only. However, in the clustering approach, a CH bears some extra workload, i.e. receiving traffic data sent by cluster member nodes, data aggregation and data dissemination to the Base Station (BS).

1.7.2 Research scope.

This research extends the work done in “Bringing 5G into Rural and Low-Income Areas: Is it Feasible?” (Chiaraviglio, et al., Bringing 5G into rural and low-income areas: Is it feasible?, 2017), by focusing on underprivileged areas of South Africa. In this research, we introduce the hotspot based massive Multiple-Input and Multiple-Output (massive-MIMO) 5G Remote Radio Head (RRH). This is done while taking into consideration the fact that regulators typically auction spectrum blocks to the highest bidder. Ideal service and network orchestrations for low-income areas based on the 5G-PPP white papers (5G-PPP, 2017) are also considered in this work.

The cost or feasibility of operating virtual radios and slicing the network are considered outside the scope of this work. The rest of this thesis, the focus lies on the expenses related to the network and infrastructure as opposed to administration, billing, and marketing costs. This research discusses the source of energy for the proposed system and utilises sinusoidal functions to predict the system load over a twenty-four-hour period. The research also extends the economic framework proposed by Chiaraviglio to be able to compute the CAPEX and OPEX outcome for different South African scenarios. Concerning test environment, five category C district municipalities (Chris Hani, Mopani, Vhembe, Waterberg and Frances Baard), five low-income areas (Soweto, Khayelitsha, Lulekani, Zeerust and Duduza) and three rural areas (Hlankomo, Mandileni and Gon'on'o) in South Africa were considered for analysis. This work also takes cost implication into consideration, by showing that it is possible to connect remote locations with cheaper monthly fees compared to major service providers in the country. The minimum monthly subscription fees required to yield the best internal rate of returns over the considered scenarios are investigated. This work also considers cost implication, by showing that it is possible to connect remote location with cheaper monthly fees compared to major service providers in the country. The minimum monthly subscription fees required to yield the best internal rate of returns over the considered scenarios are investigated. Hence, the economic analysis is aimed at estimating the costs and revenue generated by the proposed 5G network architecture for the interested areas described in Chapter III. Furthermore, the ideal monthly subscription fee for users on each location is shown with at least 30% Internal Rate of Returns (IRR).

Numerous works in literature have focused on developing clustering schemes to extend coverage range, improve routing, or conserve energy. The clustering of UAVs to provide wireless communication in rural, low-income, and remote areas have, however, received less attention. Finally, to the knowledge of the authors, works on front and backhaul of 5G wireless clusters are still non-existent or in their infancy at best. This thesis revisits the use of 5G deployment for low-income areas by proposing a novel clustering scheme where UAVs are deployed to support a LAP used as RRH. The differences between our proposed techniques and some of the existing methods are summarised in Chapter V.

1.8 DISSERTATION OUTLINE.

The next sections discuss an overview of the related work, initiatives, network coverage, and deployment feasibility; subsequent chapters are arranged as follows:

i. Chapter II (Literature Review) discusses the state-of-the-art and related works on deployment and feasibility of the forthcoming cellular network architecture. It introduces the framework for the case study that includes the focus of the study described in this research.
ii. Chapter III (Network Orchestration) gives an overview of the proposed network orchestration and services. It introduces the framework for the case study, focuses on network orchestration, services, and presents the different plausible topologies for achieving energy-aware clusters.
iii. Chapter IV (Economic Feasibility), evaluates the feasibility of deploying the proposed network orchestration in rural areas of South Africa.
iv. Chapter V (The Network Engineering) proposes backhauling and backbone cluster selection model. These models are compared using Monte-Carlo simulations (with the signal-to-noise ratio as a metric), to measure the coverage of the proposed network over the terrain map and suggest some clustering techniques to improve the quality of service.

v. Lastly, Chapter **Error! Reference source not found.** (Discussion) gives a concise summary of the entire thesis with research deduction and the future work of this research.

Appendices, list of acronyms, figures, tables, equations, bibliography, and reference end the dissertation.

II. RELATED WORKS

This chapter provides an overview of previous research on the deployment and feasibility of the fifth generation (5G) cellular network architecture. It introduces the framework that describes the focus of the case study proposed in this research. A survey of projects implemented and a review of the literature on Aerial and Terrestrial cellular network architectures for rural areas are presented as critical components of this chapter. This chapter focuses on the state-of-the-art, including established, discredited, and accepted concepts; areas of controversy or conflict among different architectures; unsolved problems and challenges; emerging trends and new approaches. It then concludes with potential extensions introduced by this research work.

This chapter is structured around three main components:

i. Presentation and discussion of related projects that have been realised.
ii. A literature review of academic outputs on:
    a. Aerial and Terrestrial backbone technology.
    b. Clustering techniques used for topology optimisation.
    c. Economic analysis of hybrid models.
iii. A summary of the reviewed literature.

2.1 UAVS-AWARE PROJECTS.

Table 1 – Known related projects.

	PROVIDER	TYPE	ENABLERS	STATUS
Saving Lives	Nokia	LAP	UAV, 4G LTE, Rescue team, Data Centre	Non-profit initiative
5G Trial	Ericsson & China Mobile	LAP	UAV, 5G	Trials
Project Loon	Google	HAP	Weather Balloon, 4G LTE, Solar panel	Trials
SkyBender	Google	HAP	UAV, 5G, Solar panel	Trials
Extender	AT&T	LAP	UAV, 4G LTE	Trials
Project Aquila	Facebook	HAP	UAV, GPS, 4G LTE, Solar panel	Terminated

The philosophy behind any business is to make a profit by either being competitive or proactive. With the landscape of the future communication infrastructure not clearly defined, there have been efforts by a handful of corporations with the financial means to invest and shape the future of telecommunications. However, finding the right technology at minimal cost has been a challenging issue. Exciting new opportunities for using various types of Unmanned Aerial Vehicles (UAVs) for wireless networking purposes have spawned numerous recent research in the communication and networking area (Mozaffari, Saad, Bennis, Nam, & Debbah, A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems, 2018). However, despite the growing interest in UAVs applications, their deployment to supply network cellular coverage in rural and low-income areas has not been extensively researched. With 5G network, there is the potential to provide broadband connectivity through the sky, by mounting micro-cellular nodes on UAVs and having these UAVs periodically or permanently provide wireless network coverage to rural and low-income areas. As revealed in Table 1, different projects have emerged from such an objective. Some of these projects are discussed in subsequent subsections.

2.1.1 Saving Lives.

Saving Lives is a Nokia non-profit initiative venture that provides innovative communications technology that assists emergency response teams (Eder, 2017). The approach is the fastest method to bring required mobile broadband connectivity into the field whenever and wherever response teams are operating. This technology helps technical experts rapidly gain situational awareness so they can quickly supply adequate response by using drones and real-time applications like video streaming, gas sensing, mapping, and analytics. Data collection using drones is much more accurate, cost-efficient, and faster than using helicopters and other alternatives. Drone video feeds supply rescue teams a far better overview of the situation than is possible from the ground. The critical components of Nokia Saving Lives include:

i. **Network:** Mobile broadband connectivity ensures reliable and secure communication between equipment and rescue team members.
ii. **Drone:** A fleet of connected UAVs ensuring high accuracy and extensive reach with minimal human interaction. These drones can carry several types of sensors, speakers, or first aid kits.
iii. **Data Centre:** A high-performance computing and storage unit for local data analysis.
iv. **Team:** Nokia personnel to collaborate and ensures the fast setup and best operation of the technology.

2.1.2 Ericsson and China Mobile Project.

In 2016, Ericsson and China Mobile started a joint venture for China National Key 5G Project (The Ericsson Blog, 2016). The primary focus of this project was on the evolution of the network architecture in a user-centric manner as well as optimising latency for mission-critical use cases. The architecture requires dynamically deploying part of a network through a distributed cloud near the radio edge to reduce end-to-end latency and to serve a range of forthcoming network use cases at the same time.

2.1.3 Project Loon.

Google's project Loon is a network of giant balloons designed and manufactured to endure the harsh conditions in the stratosphere. It has taken the essential components of a cell tower and redesigned them to be light and durable enough to be carried by a balloon travelling on the edge of space. The aim is to provide broadband connectivity for free in rural and remote areas worldwide, as well as to improve communication during and after natural disasters or a humanitarian crisis (Katikala, 2014; Lardinois, 2013). The key components of Project Loon include:

i. The Balloon made from sheets of polythene built to last for well over 100 days before landing in a controlled descent back to Earth.
ii. All the flight equipment is highly energy-efficient and powered by renewable energy. Where,
    - **Antenna:** transmit connectivity from ground stations, across a balloon mesh network, and back down to a user's LTE enabled devices.
    - **Solar Panels:** Solar Panels power equipment during the day and charge an onboard battery to allow for night-time operation.
    - **Flight Capsule:** the flight capsule holds the electronics that control the Loon system.
    - **Parachute:** a parachute guides the balloon to land safely back on Earth.

2.1.4 SkyBender.

SkyBender is another project by Google which produced several prototypes of how to supply the next generation of network connectivity. These prototypes were tested in secret at the isolated spaceport according to documents obtained under public records laws at the United States of America (Harris, 2016). Google foresees thousands of high altitudes UAVs, delivering Internet access around the world. The SkyBender drone has at least 42 metres of wingspan, which is the width of a Boeing 737–900 ER through its carbon-fibre structure weighs only 400 kilograms.

2.1.5 AT&T and Qualcomm LTE Project.

> *"We're moving towards the future by pushing the envelope on what's technologically possible for drones. Look for more news from us at SHAPE, including a first-hand look at how drones are taking our network to new heights." – by John Donovan (Chief Strategy Officer and Group President – AT&T Technology and Operations)*

Qualcomm incorporated through one of its subsidiaries [Qualcomm Technologies, Inc.] and AT&T[5] tested a hybrid network which connected Unmanned Aerial Vehicles (UAVs) to the United States' commercial 4G LTE network and stored fed data directly on their systems. The trials analyse how UAVs can operate safely and securely on current commercial and future networks, including the fifth-generation network (5G). Their research studies elements that can affect future drone operations. Such as coverage, signal, strength, and mobility across network cells and how they function in flight. The drone's capability to fly beyond an operator's visual range could enable successful delivery, remote inspection, and exploration. Wireless technology can bring many advantages to drones such as ubiquitous coverage, 5G mobile support, and quality of service (QoS).

2.1.6 Aquila.

Aquila is an experimental high-altitude platform station (HAPS) connectivity system and solar-powered drone developed by Facebook as an atmospheric satellite. This initiative, by the social media giant, intends to use a specialised drone that runs on solar power. The main design of the drone is to hover above areas as a communication station, bringing Internet access to remote areas. With a significant effort by the Internet.org campaign, Aquila drone is already a reality with complete construction of a single full-sized drone. Aquila completed the first successful flight on Thursday 28th of June 2016, in Arizona. Initially, the proposal was to fly Aquila for at most thirty minutes. Because it performed so well, then Aquila flew for ninety-six minutes straight.

2.2 SUMMARY OF THE PROJECTS.

The projects discussed thus far reveal that supplying broadband connectivity to remote areas of the Republic of South Africa is quite possible with the aid of Remote Radio Heads (RRHs) mounted on UAVs. Project Loon, Aquila and SkyBender with their different approaches prove how supplying Internet connectivity to low-income, and rural areas can realise the proposed solution in this literature. However, these projects were designed without any consideration of the economic feasibility related to the implementation and supply of wireless connectivity for a certain duration. This oversight is one of the primary reasons Facebook terminated the Aquila project. The Ericson and China Mobile project, on the other hand, focused on a user-centric architecture for the 5G mobile network. For this reason, the Ericson and China Mobile's venture like many network providers' models (aimed at providing services in ultra-dense populations for a better return on investment) do not address the key issue of connectivity in remote areas. By focusing on a user-centric model, the project automatically disregards those who are living in rural and isolated areas with low population density.

2.3 LITERATURE REVIEW.

The current telecommunication network models are commercial and revenue-oriented. This suggests that even the forthcoming 5G networks will be mainly deployed in urban areas for

---

[5] AT&T – American Telephone and Telegraph

healthier revenues generation from subscribers (Chiaraviglio, et al., Bringing 5G into rural and low-income areas: Is it feasible?, 2017). It has been recently forecasted that 5G architectures will become more heterogeneous with cellular Base Stations (BS) cells ranging from Macro, Micro, Pico to Femto sizes. In this manner, the radio module can be mounted in Unmanned Aerial Vehicle to provide wireless coverage (Nikolikj & Janevski, 2014; Khaturia, Jha, & Karandikar, 2019; Mozaffari, Kasgari, Saad, Bennis, & Debbah, 2018). Although 5G is still in its initial deployment stages, governments and industries are already searching for evidence for supporting the Fourth Industrial Revolution (4IR) services by building around 5G features. However, with significant technical and economic hurdles associated with the deployment of the technology; combined with the historical evidence of how policies affect the rollout of the new networks, especially in terms of allocation of additional spectrum band (Oughton & Frias, 2018), some potential investors might shy away. The recent improvement of Low-cost micro-embedded computers and wireless radio interfaces has paved the way for Unmanned Aerial Vehicles to provide wireless network coverage to rural and low-income areas, where ordinary infrastructure cannot provide services (Luca, et al., Bringing 5G in Rural and Low-Income Areas: Is it Feasible?, 2017; Stefano, Karol, Gregoire, Dario, & Bixio, Dynamic Routing for Flying Ad Hoc Networks, 2015). The applications of UAVs for wireless coverage are not without their challenges as discussed, some of which have been discussed by Stefano, *et al.* (2015).

In addressing the application of UAVs in providing wireless cellular coverage, Luca, *et al.* (2017) demonstrate that providing connectivity with a low subscription fee in Rural and Low-Income areas is feasible by using a proposed 5G architecture. Their approach was to mount remote radio heads (RRHs) on top of UAVs, as well as large cells (LCs) to increase coverage range. The 5G nodes are powered with solar energy and batteries. The use of a renewable energy source can make UAVs operate for the entire 24 hours of a day even in bad weather condition. The UAV can also land temporarily when it does not have enough energy and recharge the batteries. Stefano, *et al.* (2015) proposed a model that used multi-hop communication to extend the operative area on a partially connected mesh ad-hoc network on a UAV. The authors use two fixed-wing UAVs (eBees) to carry an embedded computer module and 802.11n radios, thereby setting up an ad-hoc network. They then compared the Optimised Link-State Routing (OLSR) and Predictive – Optimized Link-State Routing (P-OLSR) for the ad-hoc network in a flying vehicle. In work done by Vishal *et al.*, (2016), authors propose an intelligent deployment of UAVs in a 5G heterogeneous communication environment to improve coverage. The solution intelligently positions the UAVs in areas that need to increase network coverage. In their model, a Macro Base Station (MBS) decides where to place the UAVs, and the nodes operate in layers such that each UAV get a coverage range and mapped based on service demand. The downside of this solution is that UAVs are at high speeds, which can cause a poor transfer of data and reduced services. (Mohammad, Walid, Bennis, & Merouane, 2016) and (Yaliniz, El-Keyi, & Halim, 2016) Mohammad, *et al.* (2016) and Yaliniz, *et al.* (2016) attempted to deploy multiple UAVs for best wireless coverage. Their work revealed that: i) a 3D deployment of multiple UAVs can minimise the transmitting power, ii) adjusting the UAV's altitude based on the elevation angle can better the Line-of-Sight (LoS) links to ground users and iii) using the received Signal-to-Noise Ratio (SNR) threshold to measure Quality of Service (QoS), the number of users on the drone cell affects both the coverage region and the air-to-ground link.

2.3.1 A glance at the Fifth Generation Network.

In this section, we discuss our view on the current and forthcoming generation of cellular broadband networks. The section starts with a background of 5G dependent services, followed by a brief discussion on the telecommunication industry of South Africa. Thereafter, the feasibility of the forthcoming 5G mobile network is discussed by looking at its proposed standards, spectrum licensing and cost issues.

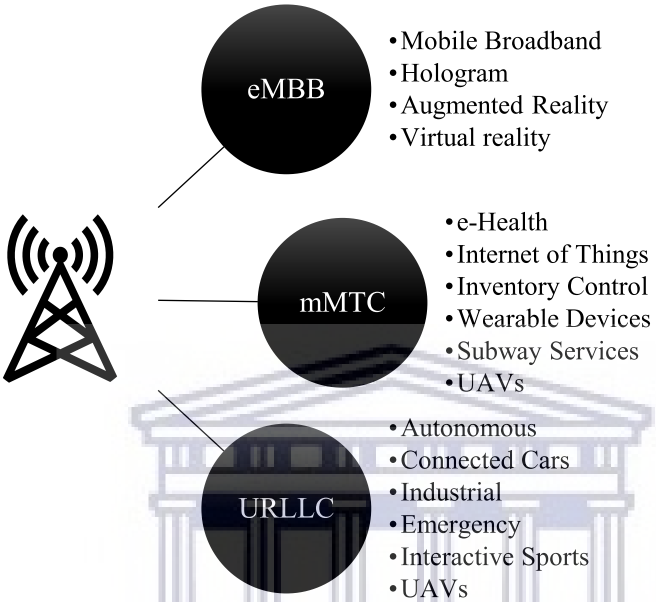


Figure 7 – Fifth-generation dependent services.

A. 5G Dependent Services.

It is planned that the specifications of 5G New Radio (NR) in standalone operation must extend to those of the 5G core network exceeding non-standalone standards. Through collaboration, we can have a high-frequency radio system complementing a low-frequency radio (Parkvall, Dahlman, Furuskar, & Frenne, 2017; Ateya, Muthanna, Makolkina, & Koucheryavy, 2018). The preliminary phase of 5G dependent deployments focused on enhancing the current network by supplying high broadband Internet services with improved latency and bandwidth on both 5G and 4G LTE radios. This will also help to develop today’s tactile applications and improve existing use cases. Figure 7 depicts classified services that are dependent on 5G systems (Shafi, et al., 2017; Tripathi & Prasad, 2018; Ateya, Muthanna, Makolkina, & Koucheryavy, 2018; Nekovee, 2018). These services include:

i. **Enhanced Mobile Broadband** (eMBB): this communication scenario covers various cases, such as mobile wide-area and hotspots coverage. Hence, the application is universal. eMBB can reach 10 to 20 Gbps speed, which is 10,000 times more bandwidth compared to 4G LTE. eMBB also supports macro and Micro Cells (MiC). For terrestrial coverage, the network must include seamless handover, support an enormous number of connected users, and provide wide bandwidth for each user. Same inclusion for hotspots with the ones in terrestrial requirements, focusing only at pedestrian mobility speeds. However, with the emphasis on much higher bandwidth than that of extensive area coverage.

ii. **Ultra-Reliable and Low Latency Communications** (URLLC): in this scenario, there are rigorous requirements for short-latency, reliability, and availability. URLLC has to offer at most one-millisecond air interface latency and five-millisecond latency between end-to-end User Equipment (UE) and 5G access point. The coverage must be reliable all the time, providing 10 Mbps for high-speed mobility.

iii. **Massive machine-type communications** (mMTC): a communication paradigm for things directly connected to the Internet. It is also called a massive Internet-of-Things (mIoT). These things/devices form many families of applications where they communicate autonomously. As a result, the network must cover a higher density of devices about 2 x 10^2 in 10^6 per Km^2. Hence, it supports long-range communication with low data rate around 100 Kbps. It influences assistance for ridiculously cheap things with a long battery life that can provide energy for ten years. Furthermore, the applications must support asynchronous access.

B. Telecommunication in South Africa.

Table 2 – 2019 Mobile telecommunication trading update.

	SUBSCRIBERS (IN MILLIONS)	MARKET SHARE (IN %)	JSE STOCK VOLUME (IN THOUSANDS)	REVENUE (IN RANDS)
Cell C	17.2	16.88		R 1.3Bn
MTN	30	29.44	903.11	R 134.6Bn
Telkom	9.7	9.52	468.99	R 41.8Bn
Vodacom	43.2	42.39	426.02	R 90.1Bn
Others	1.8	1.77		

The South African telecommunications industry was reported to be worth R148.8bn as of 2016, and with a yearly increase of 1% (ICASA, 2019). This sector contributes approximately 2.7% to the Gross Domestic Product (GDP) and employs over 26,000 people, according to the Independent Communications Authority of South Africa (ICASA). Furthermore, studies confirm that countries have more connected mobile devices than citizens based on the ratio of active Smart-card Inside Mobile (SIM) to the number of permanent residents (Schoentgen & Gille, 2017). Recent technologies such as the Internet of Things, social media, virtual reality, and other cloud-based applications have created a necessity for fast and reliable data communication systems. These have resulted in a competitive and viable market for mobile telecommunications operators in developed countries (Schoentgen & Gille, 2017). This is Unlike in South Africa (ZA), where the wireless and Ethernet communication industry is monopolised, resulting in expensive subscription prices for end-users. RIA African Mobile Pricing (RAMP) revealed that ZA is ranked 10th on the cheapest voice/Short Message Service (SMS) and 35th on cheapest 1 GB prepaid mobile data bundle out of 49 African countries in the first quarter of 2019 (Mothobi, Gillwald, & Rademan, 2018). Despite numerous complains about the cost of data, both ICASA and the Government still do not have any regulation in place to address this issue. There are only a few mobile telecommunications providers in ZA, with Mobile Telephone Network (MTN) being the largest and providing coverage for most of Africa and the Middle East. Market share values for mobile telecommunications providers in ZA are shown in Table 2. The table shows that MTN though having the second-largest subscriber base has by far the highest revenue as for 2019 (Business Tech, 2019).

The commercial network typically is driven by colossal customer appetite for a low cost of Internet data bundles and continuous updates to connection standards. Over half of the Internet-enabled smartphone belong to teenagers aged fourteen years and older with no source of income (Amanda, Rich, Scott, & Kristen, 2010). This fact is one of the driving forces being non-profit initiatives such as Project TshWi-Fi in Tshwane (Tshwane Capital, 2018). With respect to Internet coverage, in the City of Cape Town, there are hotspots installed at taxi ranks, e.g. Khayelitsha (Site C) and the city's Wi-Fi project which shows even more innovative ways of providing the Internet by installing free Wi-Fi hotspots in civic centres (BMIT, 2019). Similar projects have been kick-started in Johannesburg and Ekurhuleni, with eThekwini scheduled to follow suit. Telkom overshadows the competitors in ZA with the number of exceptional Wi-Fi hotspot locations. Where a single spot such as a hospital may have up to 500 Access Points (AP). Huawei (information and technology solutions provider) has partnered with Rain (a Mobile data-only network operator) to launch 5G mobile cellular networks across ZA (Sibanda, 2019). Vodacom also recently announced the rollout of its commercial 5G network in ZA and across the African continent at large (Andy, 2019).

C. *Forthcoming 5G Mobile Network.*

The last decade has been characterised by the hype of gigabyte speed networks capable of downloading high-definition movies within minutes. The next-generation wireless network will offer around ten times that speed (10Gbit/s) with greater reliability than ever before. Undoubtedly, this will be possible by merging pioneering network technologies with some of the best and latest technologies and techniques. Then, 5G should offer connections that are multitudes faster than current connections by likely introducing multiple frequency bands (Shafi, et al., 2017). With different deployment tests throughout the world, 5G commercial networks are projected to be launched by 2020. Moreover, they will work alongside existing wireless communication systems and in the unlicensed 2.4 GHz and 5 GHz bands for private use to provide swifter connections regardless of the location (Shafi, et al., 2017). In this manner, networks can empower the fast-growing Internet of Things (IoT) by providing the communication infrastructure required to convey a large volume of data. It is predicted that by 2022, there will be over 1.5 billion devices connected to the 5G network, according to Ericsson (Ericsson, 2020). To attain the connection milestone, goals must be clearly defined, and the technologies to achieve these goals must be determined. The "where", "how" and "who" this forthcoming network would serve must also be logically specified. For this purpose, countries with adequate resources have instituted organisations that will oversee the development of 5G. The successful deployment of 5G will depend on: i) network standards ii) radio frequency licensing and iii) costs and feasibility issues. These are elaborated as follows:

(i) *Network Standards.*

The Institute of Electrical and Electronics (IEEE) started a 5G project to supervise the roadmap of developments for several current and new technologies such as: i) Wireless Local Area Network (WLAN) codenamed 802.11ax (WLAN), ii) short-range technologies codenamed 802.15, iii) fixed wireless broadband codenamed 802.22, iv) fronthaul solutions to support cloud radio access network (Cloud-RAN) codenamed P1914.3, v) tactile and haptic Internet codenamed P1918.1 (Shafi, et al., 2017). Furthermore, the Third Generation Partnership Project (3GPP) is tasked with articulating the 5G technical specifications. Also, 3GPP has completed standard operational service requirements to support network slicing. The tasks were system orchestration, architecture aspects and related management capabilities (Ferrus, Sallent, Perez-Romero, & Agusti, 2018). On the other hand, the Internet Engineering Task

Force (IETF) has been studying specifications for virtualisation functions. Meanwhile, the International Telecommunication Union (ITU) focused on information and communication technologies to manage the global distribution of radio spectrum. The next generation must support legacy networks and implement new approaches to guarantee interoperability among the current RAN (Parkvall, Dahlman, Furuskar, & Frenne, 2017) and the IEEE 802.21, Media Independent Handover (MIH) developed as seamless communication assistance among various systems in different conditions. The objective of IEEE 802.21 is to enable a smooth and continuous handover in the heterogeneous network while using a mobile device. However, the core function oversees correspondence with various access point terminals. Hence, IEEE 802.21 standard is relied upon to contribute towards the reconfigurable interoperability part of 5G RAN (Taniuchi, et al., 2009; Choudhary & Sharma, 2019; Siriwardhana, et al., 2018; Sharma, You, Andersson, Palmieri, & Rehmani, 2019).

(ii) *Radio Spectrum Licensing.*

The wireless communication system uses radio spectrum to relay messages. Currently, spectrums are one of the most valuable and limited natural resources today (Chandramouli, Liebhart, & Pirskanen, 2019) since any basic wireless network implementation requires equipment that uses certain frequency bands to carry traffic generated by user's devices. Therefore, the spectrum needs to be globally available. South Africa is one of the many countries that are utilising this finite resource by licensing spectrum blocks for different purposes such as radio and television broadcasting. Also, standardisation is one of the most critical topics worldwide that still need to be regulated (Matinmikko-Blue, et al., 2018; Au, 2018). Latest mobile devices can use new frequency bands and wider spectral bandwidth per frequency channel. On the contrary, there is already a shortage of spectrum available for Long-Term Evolution (LTE) network service providers (Rappaport, et al., 2013).

- Regulator decides who can use the spectrum. Aims at creating rules that minimise harmful interference and protect existing users.
- Spectrum sharing is possible but not encouraged.

- Regulator defines spectrum property rights that are awarded using market mechanism (e.g. Auctions).
- Encourage sprectrum sharing through secondary markets.

- Allows spectrum access to many under regulator defined rules and regulations.
- Entirely based on spectrum sharing through technical criteria for sharing.

Figure 8 – Spectrum Management Approaches.

Despite the endless demand for spectrum blocks for private and commercial usage, regulatory bodies have not found a perfect way of distributing these blocks efficiently. In the past Global System for Mobile commutations (GSM) and Universal Mobile Telecommunication Systems (UMTS), and now Long-Term Evolution (LTE) has managed to provide mobile broadband and voice services by using the lowest spectrum band (Chandramouli, Liebhart, & Pirskanen, 2019). Vodacom claims that there is a tremendous amount of spectrum not utilised in the 2.6 GHz and 3.5 GHz bands (de Villiers, 2019). Figure 9 reveals some of the spectrum management approaches that are currently in use. Regulatory bodies auction earlier generations of communication bands to the highest bidder under specific terms. ICASA has used the Market-Based approach regardless of its shortfalls. An accredited block permits a private use, (and in some cases public) use of an unlicensed specific block in individual sites are beneficial (Au, 2018; Marcus, 2018). The radio spectrum is a prime factor in driving the growth of mobile services. The success of 5G network is based on the unrestricted availability of the spectrum (Tripathi & Prasad, 2018) to meet most if not all of the Quality of Service (QoS) requirements in coexistence use cases and new radio protocol mechanisms.

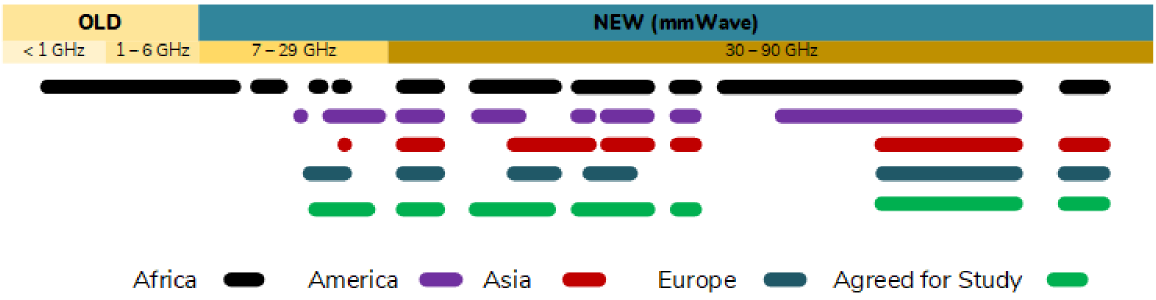


Figure 9 – Frequencies proposed by regions for study.

The World Radio Communication Conference in 2019 (WRC-19) focused on the study of new Millimetre Waves (mmWave) between 24.25 and 86 GHz for International Mobile Telecommunications (IMT)/5G, as illustrated in Figure 9. The study concluded that the following need to be considered: i) technical and operational characteristics of terrestrial network systems, ii) deployment scenarios, and iii) and the ideal timeline where spectrum bands are needed for both public and private use.

Mobile wireless communication relies on a specific spectrum block licensed to a service provider. This has been a common practice ever since the first generation (1G) of mobile wireless telecommunication, whereas spectrum blocks have been an increasingly valuable and scarce natural resource for the wireless communication industry. However, there is an interest in providing coverage in circumstances where a network operator with accredited spectrum block is not available. One of the best approaches could be, to integrate the utilisation of unlicensed frequency blocks, or to implement multi-band on the physical radio through software. The 5G cellular network is expected to make Software Defined Radio (SDR) reconfiguration easy. SDR will turn into an empowering agent for terminal and system reconfigurability by allowing downloads and installation of programming instructions. With this technology, organisations and service providers can remotely reconfigure the multiple-band radio equipment, which will reduce development effort and expenses.

Unfortunately, On the other hand, Software Defined Network (SDN) is not without its challenges. The core network can have heterogeneous resources such as legacy radio support systems, which need their network design, management, and orchestration. Hence, effective distribution and implementation of heterogeneous resources to maintain low latency with high bandwidth is an emerging research area (Parvez, Rahmati, Guvenc, Sarwat, & Dai, 2018). The unified interoperability among heterogeneous SDN signifies the essential success of the 5G cellular network.

(iii) *Cost and Feasibility Issues.*

Telkom South Africa claims that, the forthcoming cellular 5G will cost much more than current used 4G LTE in South Africa. Hence, the service operator has no plans to launch the next-generation network technology (de Villiers, 2019) since the high demand for rudimentary networks with reliable, low latency, and higher bandwidth wireless connectivity has rapidly risen (Basta, et al., 2017). Even with the forthcoming cellular systems, the coverage predicament is probably going to remain the same. Therefore, service providers will look over the low-income and rural areas, further widening the urban-rural digital use through broadband connection availability (Khalil, Qadir, Onireti, Imran, & Younis, 2017). Despite coverage convenience, both Ethernet and Ad Hoc connections have investment prospects (Wang, et al., 2013), the deemed non-lucrative areas have a vast Internet-of-Things (IoT) interest. However, the 5G networks are anticipated as costly to deploy compared to the traditional communication systems. Several service providers are still rolling out LTE-Advanced. Thus, capitalising on the infrastructure to enable 5G connection is not of importance. Hence, an automated process might reduce Operational Expenditure (OPEX) and human intervention. Whereas, offering the forthcoming cellular network as agile, flexible, and optimal services might drastically reduce Capital Expenditure (CAPEX), which will invite more investors even in remote areas (Panwar, Sharma, & Singh, 2016). Nevertheless, network sharing or slicing can offer rewarding opportunities with less CAPEX. As a result, a network-slicing agreement can be a complex and sensitive issue.

From a revenue standpoint, network service providers who plan to meet some of the expectations for 5G deployments beforehand must act now before competitors do so. One of the sound motivations for network slicing is to reduce expenses and improved Quality of Service. Greenfield[6] small-cell (SC) deployments can halve expenses of three service providers each over network slicing, as McKinsey research team's belief. Furthermore, service providers currently work with a model whereby operators build a common 5G macro layer nationwide through sharing small-cell deployment. With this collective network, operators could condense 5G-related investments by more than forty percent as against the standalone and sliced network cost. Simultaneously, service providers could also reduce the risk of their development strategies by sharing the expenses accordingly (Grijpink, Ménard, Sigurdsson, & Vucevic, 2018).

2.3.2 Aerial and Terrestrial Backhauling Technology.

Intelligent UAV scheduling and mobile routing are some of the critical problems in air-to-ground network coverage. Mozaffari, *et al.* (2018) proposed a framework that includes a Three-Dimensional (3D) placement of UAV-BSs. The authors in (Cheng, et al., 2018) however argued that the Three-Dimensional (3D) mobility feature of UAVs increase the complexity of traffic routing topology. The time-variant features of wireless links and geometric-based stochastic channel modelling technology can be implemented in system recognition and coefficient estimation of various communication such as only aerial links (e.g., UAV-to-UAV node), Aerial-Terrestrial Network (ATN), device-to-device channels (Cheng, et al., 2018).

The ATN has a two-layer networking architecture, wherein multiple UAVs carrying communication radio form aerial network, and with the aid of link budget calculation ground

---

[6] Greenfield deployment refers to the installation of an IT system where previously there was none.

RAN cells are positioned efficiently. Mobile users, vehicles, and IoT infrastructure create the ground network. With these in mind, we consider a tiered wireless communication network involving a core network and multiple access networks as in Khaturia, et al. (2019) and Alzenad, et al. (2018). The novel concept of micro-operator enables a versatile set of stakeholders to operate 5G networks within their premises with a guaranteed QoS to complement services provided by the traditional network operator. The authors in (Siriwardhana, et al., 2018) analysed the feasibility and performance advantage of using micro-operator instead of traditional network coverage in a smart factory environment which supports 4IR standards. The research revealed that a local 5G coverage established by the micro-operator within the factory premises could accommodate tactical service such as augmented and virtual reality.

2.3.3 Topology Optimisation using Clustering Techniques.

Clustering is a task of distributing a collected population or data points into several assemblies such that the population or data points in the same gathering are very similar. In a cluster-based Cellular Network (CN), the network nodes are organised into distinct clusters. Each collection has a leader, called Cluster Head (CH), and each network node belongs to one and only one group but can also be shared by several groups when it is a border/gateway node. Recent literature has shown that clustering nodes in a dense aerial-terrestrial wireless network can minimise communication energy consumption (Tuyishimire, Bagula, & Ismail, Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion, 2018; Yang & Sikdar, 2007; Gu, Wu, & Rao, 2010; Chen, Nocetti, Gonzalez, & Stojmenovic, 2002; Wang, Wang, & Liu, 2009). In some UAV clustering schemes, nodes are divided into different virtual groups according to pre-defined rules (Yu & Chong, 2005). Cluster network architectures have a potential basic performance in a dense aerial-terrestrial network. The ability of unmanned aerial vehicles to self-organise or remotely organise in an on-demand manner makes the fifth-generation aerial to terrestrial cellular coverage a resilient communication network. A clustered wireless cellular network topology provides the following basic benefits:

i. Eradication of single points of failure through virtual cluster failover functionality.
ii. Traffic routing can be easily managed because only Cluster Heads (CHs) need to keep the local route setup to other CHs. Therefore, the network requires small routing information. This can improve the scalability of the network by routing traffic through cluster heads which form a virtual backbone for inter-clusters with restricted gateways.
iii. Improving coverage by grouping flexible nodes with a better line of sight into communication links.
iv. Enables data aggregation at CH to remove redundant and uncorrelated data, thus reducing the energy consumption of the network nodes.
v. Conserves communication bandwidth, as the network nodes communicate with their CHs only. However, in the clustering approach, a CH bears some extra workload, i.e., receiving traffic data sent by cluster member nodes, data aggregation and data dissemination to the Base Station (BS).
vi. Reusing of resources to increase the system capacity, such as coordinating transmission events with a cluster head to reduce transmission collisions and retransmitting.

The usage of UAVs to provide wireless network coverage is not without its challenges (Stefano, Karol, Gregoire, Dario, & Bixio, Dynamic Routing for Flying Ad Hoc Networks, 2015). Some of these open challenges are: i) optimal 3D placement, ii) energy limitation, iii) node mobility, iv) transmission interference management, v) and Backhaul connectivity.

A typical cellular network forms a connected graph consisting of links between nodes and user equipment. Dominating set in a network graph is the subset of nodes such that each node not in a subgroup of the graph has only one direct neighbour from the subset of nodes. Nodes in the Connected Dominating Set (CDS) are known as the dominator or backbone node, while other nodes are dominated (non-backbone nodes). Figure 10 depicts a classic example of the connected dominating set graph.

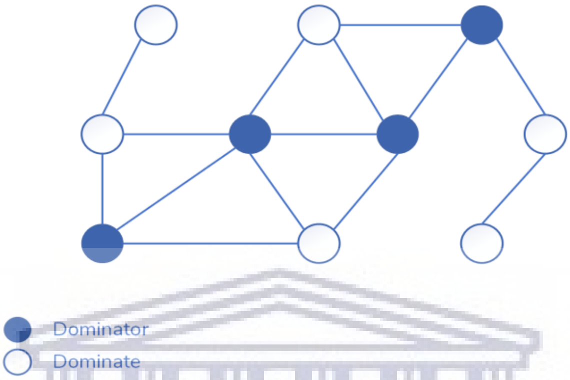


Figure 10 – Dominating Set an example.

Communication is the primary purpose of the cellular network. In the aerial vehicle cellular network, all nodes rely on batteries as their primary energy source. To attain longer operation time and lower latency, the network nodes should be energy efficient in packet transmission (Nimisha & Ramalakshmi, 2015). Hence, Vehicular Ad hoc Networks (VANETs) are designed to make communication between a set of vehicles possible using ad hoc wireless devices. However, one of the main issues for VANETs protocols is ensuring topology stability which encourages the need for an efficient clustering protocol (Hadded, Zagrouba, Laouiti, Muhlethaler, & Saidane, 2015). Furthermore, the development of cognitive radio encourages new communication paradigm, where a group of unlicensed users are equipped with cognitive radio networks in the same area (Yu, et al., 2016) to enable communication.

With respect to energy, attaching an onboard base station to the UAV and powering it with the UAV's battery can reduce flight time by about 16% (Mozaffari, Saad, Bennis, Nam, & Debbah, A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems, 2018; Hayajneh, Zaidi, Mclernon, & Ghogho, 2017; Mozaffari, Saad, Bennis, & Debbah, Drone small cells in the clouds: Design, deployment and performance analysis, 2015). To have an efficient wireless network development using UAVs as aerial base stations, the backhaul connection must also be well addressed. These challenges notwithstanding, UAVs wireless access network has been applied in various scenarios including but not limited to public safety, remote healthcare, e-learning, hotspot coverage and Internet-of-Things (IoT) (Tuyishimire, Bagula, & Ismail, Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion, 2018; Tuyishimire E. , Bagula, Rekhis, & Boudriga, 2016; Hayajneh, Zaidi, Mclernon, & Ghogho, 2017).

There have been numerous clustering schemes intending to address terrestrial mobile ad-hoc networks by discussing the network design and management challenges. To our knowledge, literature that address UAV clustering techniques for aerial to the terrestrial networks are still very limited, especially in the case where a base station provides access to the LAP and/or UAVs when they are playing the role of cellular access nodes providing access to terrestrial users. In (Yu & Chong, 2005), the authors discuss common clustering schemes for mobile ad-hoc networks. The paper further explains more about a number of proposed clustering techniques by classifying them based on their objectives. Their work describes mechanisms, evaluations of the clustering schemes performance and costs while detailing their weakness and strengths. In (Chandrasekharan, et al., 2013), they propose a clustering mechanism aiming at improving energy efficiency in aerial-based access systems focused on disaster recovery events. The paper considers a LAP that provides access to ground nodes in a prescribed area, where the terrestrial nodes are battery operated with restricted access to the LAP rather than a base station. The authors in (Kalantari, Shakir, Yanikomeroglu, & Yongacoglu, 2017) investigated the UAV 3D placement in 5G wireless networks where the UAVs are aware of the backhaul connection links. Their approaches were user and network-centric to optimally place the UAVs.

Both in (Tuyishimire, Bagula, & Ismail, Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion, 2018) and (Tazibt, Bekhti, Djamah, Achir, & Boussetta, 2017), authors investigate how to apply UAVs in a clustered wireless sensor network for data gathering. They attempted to improve energy efficiency by grouping the ground nodes and have UAVs visit the different clusters via computed optimal paths. In (Tuyishimire, Bagula, & Ismail, Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion, 2018), the authors design the clustering algorithm using three policies: i) density-aware selection policy, where children nodes are assigned to their head based on their node density degree, ii) distance-aware selection policy where nodes are selected based on their distance to the UAV base station, iii) and hybrid selection policy that combines both distance and density-aware properties. In (Tazibt, Bekhti, Djamah, Achir, & Boussetta, 2017), the clustering scheme includes the distance where each sensor can hop several CHs to reach the cluster head. The above-mentioned literature considers the coverage range by each node. The authors in (Hayajneh, Zaidi, Mclernon, & Ghogho, 2017) analysed the performance of UAV disaster recovery networks with an extended Matern and Thomas clustering mechanism where UAVs carry a microcellular network to provide coverage in the event of natural or manufactured disasters that will destruct the coverage.

In recent past, researchers have used meta-heuristic approaches such as particle swarm optimisation (PSO) in a wireless sensor network to cluster the nodes. The particle swarm algorithm commences by creating the initial particles and assigning them with initial velocities. PSO evaluates an objective function of each particle by using its location to determine the best function value and the best location. Then it updates the particle locations iteratively by choosing the current best velocity and location of their neighbours over the previous ones. Iterations advance until the algorithm reaches a stopping criterion (Kuila & Jana, 2014; Vimalarani, Subramanian, & Sivanandam, 2016; Jana, 2016; Elhabyan & Yagoub, 2015). (Elhabyan & Yagoub, 2015) proposed a practical two-tier PSO by developing the algorithm with a novel particle encoding scheme and a fitness function to determine optimal routing tree that connects the cluster heads with the base station. In (Jana, 2016) and (Kuila & Jana, 2014), the authors attempted to improve energy efficiency through PSO load balancing in the routing phase. Vimalarani, *et al.* (2016) considered maximising the lifetime of the sensor nodes by enhancing a basic PSO with energy optimisation techniques. In their proposed algorithm, the base station must be in the centre of the clusters. They also assumed that the network has symmetric links, with all nodes are considered static after deployment and each node can use its transmitting power to communicate.

In search of an energy-efficient network, (Nimisha & Ramalakshmi, 2015) proposed an Ant Colony Optimisation (ACO) method inspired by the behaviour of ants to construct an energy-efficient connected dominating-set. They compared its performance against the genetic algorithm based CDS. The proposed technique revealed that CDS with energy richness took longer computation time compared to ACO and showed that the internal lifetime of the network can suddenly drop due to adding of external nodes whose lifetimes are shorter. Thus, the lifetime of the whole network also decreased (Yu, et al., 2016). (Yassen, Aljawaerneh, & Abdulraziq, 2016; Khediri, Nasri, Wei, & Kachouri, 2014; Leu, Chiang, Yu, & Su, 2015; Jia, Zhu, Zou, & Hu, 2016; Zhang, Zhang, & Bu, 2014; Nayak & Devulapalli, 2016; Bandyopadhyay & Coyle, 2003) attempted to improve the popular Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol in WSNs, where the whole network is divided into several clusters with a single node in every cluster being assigned to be a cluster head (CH). This CH is tasked with communicating with the base station (BS). The protocol works in separate phases, which are: i) the setup phase, which concentrates on constructing the cluster and selecting the cluster heads, ii) and steady phase, which builds on the previous phase by defining how data is transmitted (Khediri, Nasri, Wei, & Kachouri, 2014; Yassen, Aljawaerneh, & Abdulraziq, 2016). The basic LEACH can enable the WSN to extend the regular life of the nodes. In the basic LEACH, the location of each node in the topology does not matter even if there is a probability of the node becoming a cluster head periodically. In (Leu, Chiang, Yu, & Su, 2015), the authors proposed an extension to the LEACH protocol by also considering the isolated nodes. In (Nayak & Devulapalli, 2016), the authors' target was to extend the lifetime of nodes by adding a Super-Cluster Head (SCH) selected among the CHs that will only communicate with the BS. The model elects the SCH by using fuzzy descriptors such as residual energy, centrality, and mobility of the BS. The authors in (Nayak & Devulapalli, 2016) adopted Fuzzy Logic (FL) in LEACH technique to handle uncertainties in electing the SCH. They assumed that the BS was mobile, all other sensor nodes were static, and the network was homogeneous. (Gu, Wu, & Rao, 2010) in their work, optimised CH to improve energy efficiency by considering the location of the crowding neighbours. The authors in (Sabet & Naji, 2015) proposed a new decentralised hierarchical clustering scheme by hopping traffic in inter-clusters.

2.3.4 Network Operational Analysis.

As stated earlier, the primary objective of any business is to make a profit. Customarily, service providers, before deploying any kind of network coverage must be sure of healthy ROI. Considering these questions, there are only a few kinds of literature that tried to address economic issues related to the modelling of 5G deployment in rural communities. Nonetheless, Table 3 briefly discusses the literature that analysed the financial aspect of various telecommunication networks. (Chiaraviglio, et al., Bringing 5G into rural and low-income areas: Is it feasible?, 2017) and (Chiaraviglio, et al., 2018) perform an economic analysis to estimate expenses and revenues generated by their proposed network architecture in rural and low-income areas. Furthermore, they discussed the CAPEX required to acquire and deploy the 5G network as well as the OPEX needed to operate and maintain the network architecture. The work done in (Chiaraviglio, et al., Bringing 5G into rural and low-income areas: Is it feasible?,

2017) proves that it is feasible to provide essential network connectivity in low-income areas while maintaining the end-user monthly subscription charges sufficiently low. Nikolikj & Janevski in (Nikolikj & Janevski, 2014) also studied the CAPEX and OPEX for LTE and Wi-Fi by considering Base Station (BS), backhaul transmission and radio network controller equipment, as well as the costs of electric power, operation and maintenance, and site accusation, while the backhaul transmission was considered as a leased OPEX. By enabling aggregation of the carriers in the band of 700 MHz and of 2.6 GHz on the current sites, they introduced cost-efficient deployment for sensible bandwidth demand. Furthermore, using macro-cell deployment scenarios, they demonstrated a linear increase which is proportional to the demand. As a result, rather than investing in additional spectrum bands or deploying a denser network, mobile network operators could leverage on the indoor coverage of Wi-Fi hotspot. In (Wang & Ran, 2016), it was attested that cell planning often ignored heterogeneous networks as compared to conventional cellular networks. However, it is still an effective and efficient method to improve system QoS. Given, the organised cells, from an implementation standpoint, one of the main challenges would be to sustain a decent network QoS in areas that feed traffic through a single gateway base station installed at developing areas while comprising of successive relay points within the network path (Khalil, Qadir, Onireti, Imran, & Younis, 2017). Additionally, traffic interference management among various cells becomes harder to address, which introduces complex signal processing and cell collaboration techniques that drastically increase CAPEX and OPEX of the cellular system (Wang & Ran, 2016).

The economic challenge of providing a flat rate to subscribers for wireless access at the same cost as fixed Internet access is undoubtedly tricky. Conventional wireless cellular networks concept are not capable of offering related QoS to match bandwidth speeds economically (Giles, et al., 2004). Studying the current LTE network signal behaviour in the atmosphere for the ground users, (Xilouris, et al., 2018) prove from real-life scenarios of an urban area that the signal strength is still adequate for reaching a reliable link between the ground BS and the airborne node. However, the UAV must be in Line-of-Sight (LoS). The authors in (Khaturia, Jha, & Karandikar, 2019) proposed a novel concept of combining wireless technologies under a unified framework to realise advantages such as: i) rapid service conception, ii) cost reduction, iii) energy efficiency, iv) ease of deployment, and v) the geography-based service introduction. Thereby addressing the rural areas broadband communication needs effectiveness.

For Internet coverage to reach the final 10% of the world's population without essential wireless connection is a daunting task due to exponentially increasing CAPEX and OPEX (Oughton & Frias, 2018). Moreover, three-dimensional node mobility, time-varying channel condition, air-ground link interactions, and dynamic topology, are issues which altogether lead to relatively network analysis and optimisation complications (Cheng, et al., 2018). Service providers claim to be ready to deploy network equipment ready for 5G standards as soon as regulating bodies release new spectrum for operation. Nevertheless, there are only a few kinds of literature addressing some of the significant issues in providing affordable and reliable broadband in disadvantaged areas. Furthermore, there is still no standardised heterogeneous 5G network architecture for these areas. The broadband service billing systems are currently conceptualised for the fortunate individuals who earn above average while segregating those staying in rural areas. For this reason, a new billing method built on 5G and its services for these areas must be implemented. Works that tried to propose network architectures have blind spots, which leaves people travelling between rural areas devoid of broadband services coverage.

2.4 5G ENABLING TECHNOLOGIES.

It is currently widely recognised that enriched networking capabilities resulting from the fourth industrial revolution (4IR) technologies, such as cloud computing, software-defined networking (SDN), Network function virtualisation (NFV) and network programmability (NP) will underpin digital transformation initiatives. While SDN provides the advantage of shaking off the constraints of hardware-based networks to provide management flexibility and speed up the access to market and revenue, NFV is a software-based technology that relies on traditional server-virtualisation techniques to provide greater management flexibility by using IT virtualisation to virtualise entire classes of network node functions into building blocks that may connect, or chain together, to create communication services. These techniques will transform the forthcoming network coverage development, from planning, design, and construction through deployment by making network connectivity available anywhere and anytime by using them to move away from the usual features where services are supplied based on federations in single network nodes. Fulfilling some of the flexibility objectives requires the actual resources in the infrastructure to be adjustable dynamically without manual involvement by the service provider. To realise these requirements, it needs a control architecture with a prominent level of programmability. This architecture should enable a network operator to package customised algorithms into the control plane for optimisation of Radio Access Network (RAN), edge cloud resources, and core transport network (Rostami, et al., 2017). Furthermore, the control plane must not be bound to any particular use case or scenario. The following core functions are fundamental to the success of 5G. Hence, this subsection briefly describes these functions.

2.4.1 Network Programmability.

Network Programmability (NP) has been a popular subject in networking research for the last two decade and a half (Rostami, et al., 2017). Throughout the years, several approaches have brought out techniques to light ranging from active networks to multiprotocol label switching. The SDN concept could bring required programmability in the transport layer of mobile networks (Rostami, et al., 2017). Technologies like SDN and VFN are enabling a radical change in network architecture where traditional network structures get split into programmable functions to supply the satisfactory connectivity on typical architecture. The worth of SDN in the forthcoming wireless networks is precisely in its ability to supply virtualisation, automating, and multi-tenancy services on top of the virtualised. Also, SDN enables the bifurcation of the control logic from service operator-specific hardware and software controllers. Consequently, it allows the implementation of routing and data processing functions into software packages in the wireless infrastructure (Rostami, et al., 2017; Hakiri & Berthou, 2015). The interfaces and architectural building blocks should also support infrastructural stacking, to enable 5G network deployments tailored to specific scenarios. Control of resources in each of the domains is a complex task, as it usually requires dealing with a significant number of network elements as well as that of control parameters and procedures. With the proposed architecture requirements, it is suitable to adopt SDN principles in the design of service management and orchestration.

2.4.2 Cloud and Virtual Technology.

According to Ericsson, "The greater elasticity brought about by network slicing will help to address the cost, efficiency, and flexibility requirements imposed by future."

Collaborative or centralised radio access network is a cloud computing-based architecture for RAN that enables extensive network deployment. Network slicing is one of the critical capabilities that allows the flexibility of multiple logical systems to function on the shared physical infrastructure. Slices distributed to different clients can be higher-level controllers or service functions and applications. Dedicated slices should be inaccessible by others on the shared resource for both security and performance reasons. Moreover, Cloud-RAN uses new radio interfaces to support real-time virtualisation capabilities to distribute shared resources in the BBU dynamically.

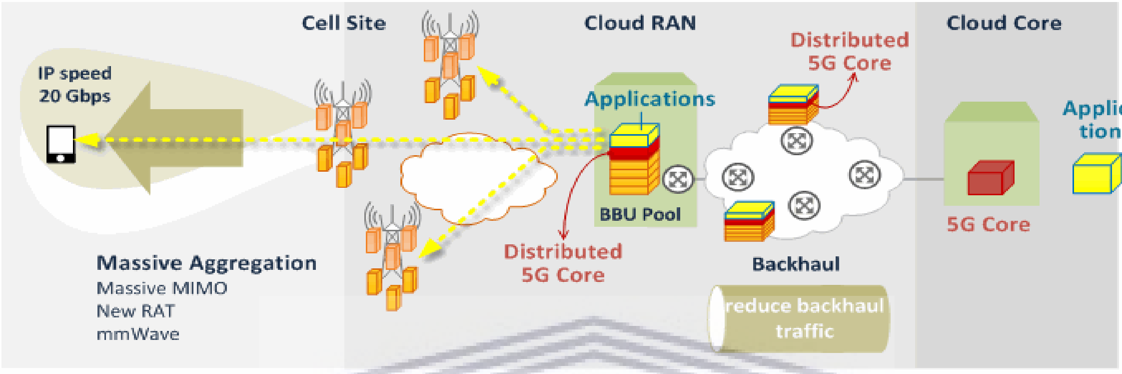


Figure 11 – Mobile Network Architecture (Harrison & Do, 2015).

The Base Band Unit (BBU) pool is a centralised site where individual units can be stacked together to function as a processing centre without interconnected, as shown in Figure 11. A Remote Radio Unit (RRU) network is customarily used to connect wireless devices to access points. While the fronthaul connection (between a baseband unit and a set of RRUs) uses physical optical fibre cables or wireless communication links. Also, the interface produces a higher spectrum efficiency that enables a massive number of mobile users and wireless standards support. Cloud-RAN creates a more simplified, scalable, and flexible network that allows for more efficient network upgrades, enhancements, testing, monitoring, and maintenance.

2.4.3 Service Orchestration and Management.

Network Orchestration (NO) is aimed at boosting operational efficiency and business outcomes by further increasing the automation of network service deployments and configurations and enabling the monitoring of how those services perform to address performance issues with the least amount of disruption to users and customers. While SDN can be run in conjunction with network function virtualisation (NFV) to digitise and automate the network management process by spinning virtual servers up and down manually, NO provides a cleaner and faster path to that process by speeding up and making easier the deployment of the network management functionality which is needed, thus introducing innovations to customers, and resolving problems without taking critical systems offline for hours or days.

Some of the advantages of NO includes:

i. **Faster provisioning** which cuts processing time required to deploy new services or application through orchestration from months to days.

ii. **Remote deployment** enabling services to be up and run quickly on appliances which are already on site. NO allows these appliances to be accessed remotely to make all required connections, implement a managed services console and potentially provider's billing systems.
iii. **Performance assurance** providing means of fine-tuning service and network performance to help maintain business continuity.
iv. **Business benefits** such as enabling the redeployment of IT and network management staff to less-routine tasks by using automation and artificial intelligence (AI) to reallocate staff to those areas for planning and programming. Other benefits of network orchestration include: i) improved customer experience ii) enhanced network management through automation and fast remediation iii) accelerated time to market for services and innovations and iv) operational improvements.
v. **Better budget management** in terms of security, for example, by enabling processes to be automated and monitored, and DevOps, where multiple tasks can be automated and streamlined for faster development.
vi. **Network connectivity** by allowing efficient planning and execution to enable organisations to successfully implement their digital transformation strategies and become the kind of company others will want to emulate.

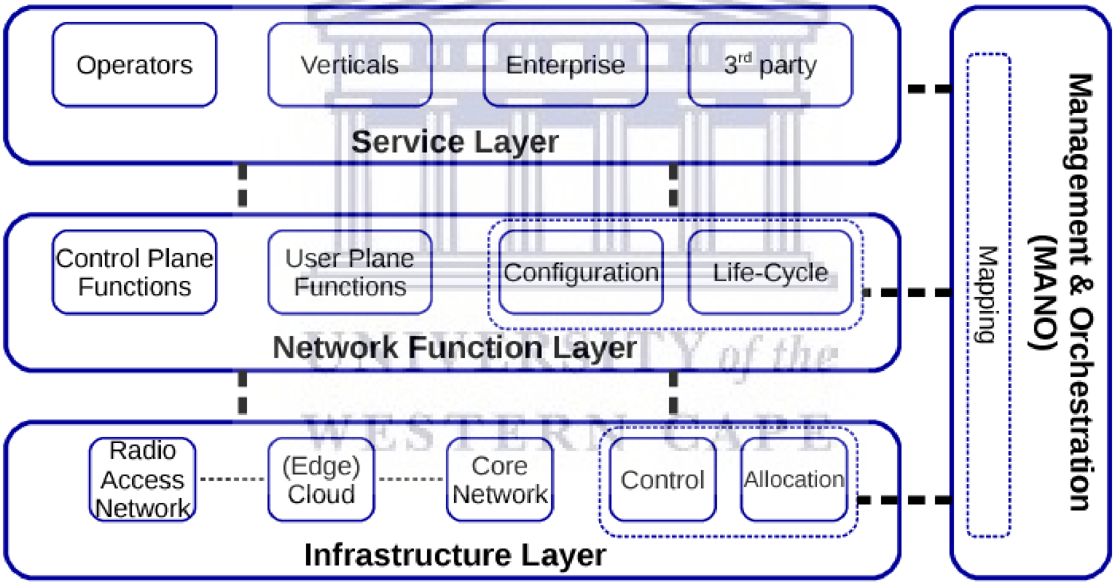


Figure 12 – Generic framework representing various 5G architectural proposals (Foukas, Patounas, Elmokashfi, & Marina, 2017).

Figure 12 illustrates a generic 5G architectural framework with network management and orchestration mapping various layers. Service orchestration is the execution of the operational and functional processes involved in designing, creating, and delivering an end-to-end service, whereas, network management is the process of administering and managing computer networks. 5G embraces service assurance, network monitoring, the embedding of virtual functions, multi-operators on shared infrastructure, and lifecycle management. Customarily, domain-specific functions handled network processes and services. Also, some operational support systems do not interact with other core systems and tools made for static environments. With the introduction of NFV and SDN, service management and orchestration must take a novel approach in serving the requirements of current more dynamic and sophisticated service provider environments.

2.4.4 Guaranteed Service and Network Monitoring.

Since network slicing appeared in 5G deployment, many tailored services have been derived from a network slice instance and multi-tenancy applications. Hence, the 5G deployment envisions that several inter-operating virtualisation environments could be useful (5G-PPP, 2017). Network Management System (NMS) is one of the three key technologies that ensure service in network slicing. NMS contributes to the entire system architecture by providing a slice design template to the network capabilities and Service-Level Agreement (SLA). Also, include slice instantiation, configuration, and activation. Additionally, NMS observes the running status of virtual instances and ensures SLA adherence. This system provides swiftly decommissioning of virtual instances when their services are not required anymore. The other crucial enabling technology is Cyber Security. From Figure 12, verticals are to operate with infrastructure and network layers. Each of these layers must consider security risk and protection measures in a holistic framework to provide overall security. Moreover, critical technology must empower services with a guaranteed performance that relies on enabling technologies from all end-to-end functional, operation, and management.

2.4.5 Multi-tenancy Support.

> *According to 5G Americas, a clear benefit of 5G network slicing for network operators will be the ability to deploy only the functions necessary to support particular customers and particular market segments.*

Multi-tenancy is an architecture where an instance of a single software application serves multiple tenants (clients or customers). Tenants may be empowered to customise individual sections of the app on their sides, such as the colour of the user interface or business rules to meet their needs. However, a tenant cannot change the core of the code. Figure 14 depicts an end-to-end network slicing with different tenant use-case scenarios over shared physical infrastructure. For example, eMBB slice might be used for high-definition video streaming and virtual reality with 5G, LTE, and Wi-Fi, whereas, uRLLC slice could use only 5G and LTE radios with an edge cloud cache server in the central office. By introducing virtual networks

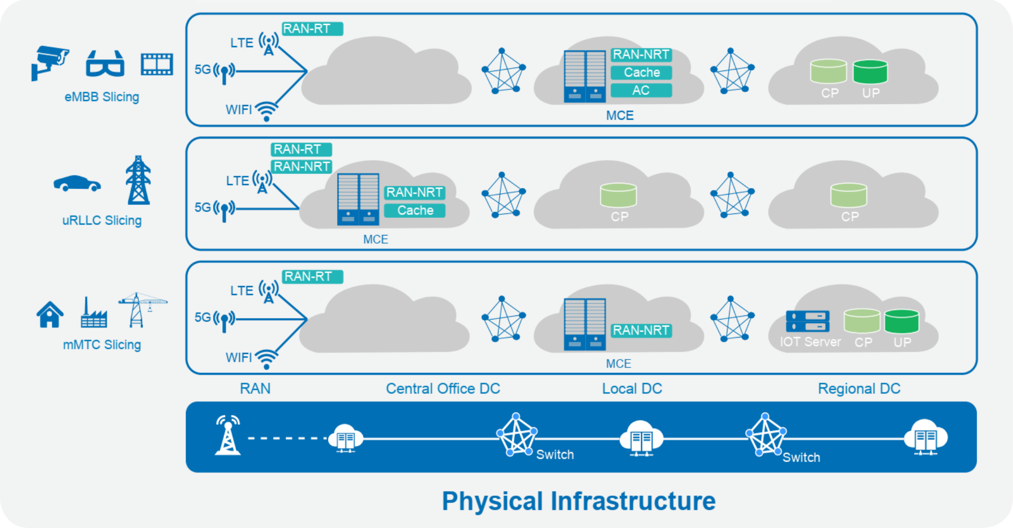


Figure 13 – End-to-End Network Slicing for Multiple Industries Based on One Physical Infrastructure ©5G Network Architecture Whitepaper.

(VNs), service providers can share physical equipment and the CAPEX. They can further have tenants on their respective VNs. For example, one VN can have IoT, Specific Industry, or Government slices while still supplying coverage to the public, as shown in Figure 13. The distinction between the customers would be achieved during application design. Hence, tenants do not have permission to share or see data belonging to a fellow tenant. In virtualisation infrastructure enable each application to appear to run on a separate physical machine. While in multi-tenancy, tenants share the same software application.

2.4.6 Embedding of Virtual Functions.

Embedding virtual network architecture that forms service is one of the trends and most significant aspects of 5G. The placement of the Virtual Network Functions (VNF) and their interconnections in an efficient manner contribute into dynamic network slicing that maximises network resources effectively. The heuristic mapping algorithm for embedding VNF must unite these functions and services. A fixed lifecycle management approach should allow unique algorithms to be used for each VNF separately. Moreover, the embedding algorithm needs to deal with resource conflicts and arbitrates. The metric information and user data could be hidden because of isolating the algorithms.

2.4.7 Multi-Operators.

> *"will ease the process of mixing and matching these different options, and sourcing from multiple vendors, while allowing for future 5G technologies to be inserted into the existing framework rather than forcing a rip-and-replace." by ReTHINK.*

Multi-Operators is a critical part of 5G that will incorporate verticals into the telecommunication evolution. The 5G New Radio is going to enable new splitting options between a centralised and distributed unit as a VNF that can make either unit realised as a conventional Physical Network Function (PNF). However, industrial and automotive companies have different telecommunication requirement. For example, an automotive company might require a considerable coverage area, while a small manufacturing company only need a few square metres. The condition can also be radio frequencies. Furthermore, the focused services for the verticals could require practical skills not available at a single operator. For successful joint services, tenants could work together to serve their end-users. Hence, multi-operators could establish a multi-vendor split to enable a mutual DU/PNF to be shared between multiple operators but are individually accountable for their own separate CU/VNFs.

2.4.8 Lifecycle Management.

The forthcoming 5G will be based upon virtualisation technologies for the core network and software-driven network cores and functionalities. The 5GPPP determination has developed complete management of SDN and NFV applications (5G-PPP, 2017). The prototype supplies a fully automated lifecycle management of NFV and SDN applications, from Apps encapsulation, onboarding, and instantiation to deployment, configuration, update/modification, and termination. It enables one to click automated Apps onboarding. New Apps are made accessible in the framework with a single action from the GUI. Furthermore, it supplies common lifecycle mechanisms and procedures for various kinds of applications such as VNFs, SDN, and PNF for backward compatibility. Also, cloud computing, Multi-access Edge Computing (MEC), and Service Function Chaining (SFC). Therefore, the creation and deployment period for infrastructures and their services can be reduced to minutes from several days. Hence automating infrastructure and service deployment can improve the network lifecycle management. The Cognitive Smart Engine (CSE) handles autonomic network management through a machine-learning algorithm to aid with self-organising of the network.

2.5 SUMMARY OF RELATED LITERATURE.

Table 3 summarises the literature reviewed thus far and categorising the works into four different families, namely: i) Network Architecture, ii) Economic Analysis, iii) Network Deployment, and iv) Dominating/Governing Set. Where "*Ref.*" stands for Reference, which relates to the bibliography of the publication, the lead author, and published year. The "*Approach*" briefly discusses the abstract, objectives, and strengths of the literature under review; while the identified shortcomings/gaps are highlighted under "Limitation".

Table 3 – Related Literature.

FAMILY	REF.	TITLE	APPROACH	ASPECT	LIMITATION
Architecture	(Alzenad, Shakir, Yanikomeroglu, & Alouini, 2018)	FSO-based vertical backhaul/fronthaul framework for 5G+ wireless networks.	Examines the viability of a novel vertical backhaul/fronthaul framework, where the UAV network nodes transport traffic between the access point and core networks via point-to-point Free-Space Optic (FSO) links. Moreover, it investigates the impact of weather conditions on bandwidth accessible with vertical FSO link.	2D UAV Location, 5G	
Architecture	(Cheng, et al., 2018)	Air-ground integrated mobile edge networks: Architecture, challenges, and opportunities.	Recommends a novel air-ground amalgamated mobile edge network that utilises UAVs to flexibly deploy and schedule assistance communication, caching and computing on the edge network.	2D UAV Location.	Only mobile edge and aerial network
Architecture	(Khaturia, Jha, & Karandikar, 2019)	Connecting the Unconnected: Towards Frugal 5G Network Architecture and Standardisation.	Suggests a novel holistic wireless network architecture called the "*Frugal 5G Network*" for poor broadband connectivity in rural areas. The architecture is a heterogeneous access network, where Wireless Local Area Networks (WLANs) provide additional capacity to serve the village clusters backhauled with fibre-optic links.	Heterogeneous Network, 5G, Wi-Fi, Fibre-Optic links.	There will be a poor connection on the edge of villages It will need more Wi-Fi APs
Architecture	(Mozaffari, Kasgari, Saad, Bennis, & Debbah, 2018)	3D cellular network architecture with drones for beyond 5G.	Proposes a concept of three-dimensional cellular networks, which introduces UAV base stations and end-user access points. Furthermore, the novel framework proposes the deployment of UAV base stations by tractable octahedra shape method and latency-minimal cell association for access point nodes.	3D UAV Location.	No fibre connection No terrestrial towers

FAMILY	REF.	TITLE	APPROACH	ASPECT	LIMITATION
Architecture	(Sekander, Tabassum, & Hossain, 2018)	Multi-tier drone architecture for 5G/B5G cellular networks: Challenges, trends, and prospects.	The article focuses on investigating the feasibility of multi-tier over traditional single-tier network architecture carried by UAV and identifying possible scenarios in which aerial networks can potentially harmonise with traditional terrestrial networks.		
Architecture	(Siriwardhana, et al., 2018)	Micro-operator driven local 5G network architecture for industrial Internet.	Proposes a descriptive architecture for emerging 5G micro operators which provides user and location-specific services in a restricted environment. The proposal expresses the architecture in terms of network functions and operational units that denotes the radio access and core networks for a 4IR standards-compliant factory environment.	5G.	Focus on spatial confined environment
Architecture	(Xilouris, et al., 2018)	UAV-Assisted 5G Network Architecture with Slicing and Virtualization.	The literature put forth the architecture and possible applications of airborne 5G nodes supporting network slicing and lightweight virtualisation. While supporting the feasibility of using UAVs in capacity enhancement and increasing network coverage scenarios by measuring LTE aerial performance.		The UAVs are network relays It needs an existing Network
Deployment	(Chandrasekharan, et al., 2013)	Clustering approach for aerial base-station access with terrestrial co-operation.	Propose a clustering mechanism for improved energy efficiency in aerial-based access systems suitable for disaster recovery scenarios and large-scale public events. The aerial base station is a low altitude platform (LAP) station that provides access to several terrestrial nodes on the ground over a prescribed coverage area. The presented clustering algorithm is compared with HEED for energy efficiency.	Low-Altitude Platform, Terrestrial Network.	
Deployment	(Elham, Halim, & Abbas, On the Number and 3D Placement of Drone Base Stations in Wireless Cellular Network)	On the Number and 3D Placement of Drone Base Stations in Wireless Cellular Network.	Uses a heuristic algorithm to find the minimum number of UAV-BSs position in various user densities. The UAV-BS might follow users if needed and form a coalition to maximise the network coverage.	3D UAV Location, UAV Coalition, Optimisation.	Analysis limited to downlink transmission
Deployment	(Mohammad, Walid, Bennis, &	Efficient Deployment of Multiple Unmanned Aerial Vehicles	Propose an optimal 3D deployment of multiple UAVs to maximise coverage time while using minimal transmitting power. The deployment considers LoS and none-LoS links		Focuses on the UAV altitude Does not map UAVs concerning the demand

FAMILY	REF.	TITLE	APPROACH	ASPECT	LIMITATION
	Merouane, 2016)	for Optimal Wireless Coverage.	between the UAV and user's equipment. Flexible deployment of UAVs makes it easier to adjust the altitude based on the elevation angle based on the ground users.		Poor D2D[7] communication when relaying through the UAVs UAVs do not overlap to form layered network Stationary low-altitude UAVs
Deployment	(Stefano, Karol, Gregoire, Dario, & Bixio, Dynamic Routing for Flying Ad Hoc Networks, 2015)	Dynamic Routing for Flying Ad Hoc Networks.	Uses two fixed wing (*eBees*) to carry an embedded computer module and 802.11n radio. To compare OLSR and P-OLSR for ad-hoc' network in a flying vehicle. It uses multi-hop communication to extend the operative area on a partially connected mesh ad-hoc network on a UAV.		
Deployment	(Tuyishimire E. , Bagula, Rekhis, & Boudriga, 2016)	Co-operative Data Mulling from Ground Sensors to Base Station Using UAVs.	Present a heuristic algorithm to plan a path and task where a set of UAVs will collect sensor reading from various nodes and convey these readings to the nearest BS.	Data Collection, 2D UAV Location.	
Deployment	(Vishal, Kathirava, Han-Chieh, Kai-Lung, & Wen-Huang, 2016)	Intelligent deployment of UAVs in 5G heterogeneous communication environment for improved coverage.	Introduce an intelligent resolution for accurate and efficient placement of the UAVs concerning the demand areas to increase network coverage. The Micro Base Stations decide where to place the UAVs to handle network services and load balancing. UAVs are mapped based on service demand. Where a set of UAVs handling group of users. Furthermore, UAVs operate in layers such that each UAV get a coverage range.		UAVs are in high speed which causes a poor transfer of services MBS controls UAVs
Deployment	(Vishal, Roberto, & Subramanian, UAVs Assisted Delay Optimization in Heterogeneous Wireless	UAVs Assisted Delay Optimisation in Heterogeneous Wireless Networks.	Propose a technique to efficiently position UAVs to facilitate end-user equipment usage in macro areas. Uses the heterogeneous network to optimise the overall network delays. An optimal placement algorithm improves coverage, also lower the delay transmission, and prevents extra-hop relaying, which reduces the delays.	3D UAV Location, Heterogeneous Network.	

FAMILY	REF.	TITLE	APPROACH	ASPECT	LIMITATION
	Networks, 2016)				
Deployment	(Yaliniz, El-Keyi, & Halim, 2016)	Efficient 3D Placement of an Aerial Base Station in Next Generation Cellular Networks.	A low-altitude quasi-stationary UAV assists terrestrial base stations. A drone cell is positioned as a 3D placement to maximise the revenue of the network. The Air-to-Ground channel differs from the ground's channel due to its high chance of LoS connectivity. The received SNR threshold measures QoS.	3D UAV Location, 5G, Optimisation.	When there is congestion within the cell or malfunction of the infrastructure, the ground base station may not be able to serve all users. Drone cell has a fixed power transmission The number of users on the drone cell affects both the coverage region and air-to-ground link
Economic Analysis	(Chiaraviglio, et al., Bringing 5G into rural and low-income areas: Is it feasible?, 2017)	Bringing 5G into rural and low-income areas: Is it feasible?	Study the possibility of extending the coverage range of the solar and battery-powered UAV 5G nodes and Large Cells with holistic network architecture.	5G, Heterogeneous Network, Economic Analysis.	Considered an already service provider No propagation models Does not include Slicing Pricing Price model based on a monthly subscription only
Economic Analysis	(Giles, et al., 2004)	Cost drivers and deployment scenarios for future broadband wireless networks – key research problems and directions for research.	Analyse various network infrastructure for initial CAPEX to demonstration that, deployment-related costs and maintenance costs are extremely higher than radio equipment itself.		Focuses on terrestrial tower cells Only analysis of other literature Focused in developed areas No 5G Services
Economic Analysis	(Khalil, Qadir, Onireti, Imran, & Younis, 2017)	Feasibility, architecture and cost considerations of using TVWS for rural Internet access in 5G.	Show that a merge of TV band white space with 5G infrastructure for rural coverage can yield cost efficiency from a service provider's viewpoint.		No maintenance cost in OPEX
Economic Analysis	(Li, Hua, & Zheng, 2016)	CAPEX advantages of multi-core fibre networks.	Investigate CAPEX advantages of multi-core fibre networks by modelling expenses as an integer linear problem.		Only investigate fibre CAPEX and OPEX
Economic Analysis	(Nikolikj & Janevski, 2014)	A cost modelling of high-capacity LTE-advanced and IEEE 802.11 AC based heterogeneous networks, deployed in the 700 MHz, 2.6	Develop CAPEX model of the heterogeneous wireless networks to determine the most cost-effective radio network deployment, by performing an analysis of extreme data demand per month with consideration of LTE Advanced and IEEE 802.11 AC Wi-Fi technologies as end-user access points.	The heterogenous Network, 4G, Wi-Fi, Economic Analysis.	No 5G Services Developed area

FAMILY	REF.	TITLE	APPROACH	ASPECT	LIMITATION
		GHz and 5 GHz Bands.			
Economic Analysis	(Oughton & Frias, 2018)	The cost, coverage and rollout implications of 5G infrastructure in Britain.	Focus on testing the impact of 50 Mbps ubiquitous broadband annual capital intensity, infrastructure sharing, and dropping the end-user speed in rural areas to approximately 30 Mbps.	4G, Economic Analysis.	Uses the LTE only
Economic Analysis	(Smail & Weijia, 2017)	Techno-economic analysis and prediction for the deployment of 5G mobile network.	Propose a techno-economic analysis and mathematical modelling to compare CAPEX and OPEX with the revenue expected within the deployment period.		They focused on areas already have a connection No monthly subscription models
Economic Analysis	(Wang & Ran, 2016)	Rethinking cellular network planning and optimisation.	Develop a dynamic cellular network forecasting framework that can significantly reduce the CAPEX and OPEX of the system. Furthermore, the QoS for users get improved while shifting away from commissioning complex and expensive signal processing techniques.		Focus on reducing CAPEX and OPEX on existing network No 5G Services
Governing Set	(Hadded, Zagrouba, Laouiti, Muhlethaler, & Saidane, 2015)	A multi-objective genetic algorithm-based adaptive weighted clustering protocol in VANET.	Present an Adaptive Weighted Clustering Protocol that is designed for vehicular networks. The proposed protocol takes highway identification, the direction of vehicles, position, speed, and the number of neighbouring vehicles into account to enhance the stability of the network topology. They address this multi-objective problem with the Nondominated Sorted Genetic Algorithm version 2 and Multi-objective Particle Swarm Optimisation.		
Governing Set	(Nimisha & Ramalakshmi, 2015)	Energy efficient connected dominating set construction using ant colony optimisation technique in wireless sensor network.	Construct an energy-efficient connected dominating set using the Ant Colony Optimisation technique and compare it with the Genetic Algorithm based Connected Dominating Set for energy efficiency.		
Governing Set	(Yu, et al., 2016)	Connected dominating set construction in cognitive radio networks.	Introduce a mechanism that is inspired by a connected dominating set as a virtual backbone in traditional wireless networks to prolong the lifetime of the network.	Heterogeneous Network.	

2.6 CONCISE RELATED WORKS.

In summary, this chapter (Related Works) discusses some of the implemented solution that are on initial stages or testing such as Saving Lives by Nokia and Project Loon from Alphabet company which owns Google. It is important to note that recent literature revealed that most energy consumption occurs during data transmission and packets control. Hence, clustering protocols must ensure reliability and connectivity in wireless 5G network coverage. Using UAVs to provide the forthcoming network generation has many research areas such as: i) UAV coalition to seamlessly handover packet, ii) find the optimal placement of the UAV, iii) energy management and many more. South African government and ICASA have not started issuing spectrum licensing for the forthcoming network. Service providers claim that the total cost of deploying and supporting a network is prohibitive while they are worth more in the Johannesburg Stock Exchange (JSE).

III. NETWORK ORCHESTRATION

This chapter presents an overview of the proposed network orchestration and services. It introduces the theoretical framework for the hybrid network case study, considers different topologies for achieving energy-aware clustering and presents the main building blocks for building these topologies. The chapter begins with a discussion of the fundamental technical views of the fifth generation of mobile network, then presents hybrid topologies derived from a combination of a team of UAVs and a Low-Altitude Platform (LAP). The primary purpose of the network orchestration proposed in this dissertation is to present a hybrid network and discuss the processes associated with the deployment of such a network in a mixed Aerial/Terrestrial cellular network infrastructure for rural areas. This chapter discusses the proposed solution for this research by providing answers to the following questions:

i. Which architectures are acceptable for such a hybrid network?
ii. What are the best emerging trends and approaches for its design?
iii. What is the proposed architecture?
iv. What are potential business models suitable for the proposed solution?

As proposed in this chapter, the key features of the hybrid model are presented as follows:

i. Introduction of the prospective networking technologies.
ii. Presentation of the conceptual model.
iii. Definition of the ideal network topology by discussing:
    a. Envisioned network coverage model for rural areas.
    b. The energy model for the communication radio.
    c. A geometric model for the active network node.
    d. The physical infrastructure and network coverage deployment.
iv. Finally, a foundation is laid for actualising the proposed model as well as presenting deployment scenario parameters and business models.

3.1 NETWORKING TECHNOLOGIES.

Table 4 – Comparison of Different Ad Hoc Networks (Gupta, Jain, & Vaszkun, 2016).

	MANET	VANET	FANET
Description	Mobile wireless nodes connect with other nodes that are within the respective communication range in an Ad Hoc means.	Vehicles Ad Hoc enabled wireless nodes to communicate with other vehicles and roadside units.	The Ad Hoc infrastructure is based on airborne nodes that communicate among UAVs and with the base stations.
Mobility	Inconsistent movement and slow speeds ~2 m/sec. Higher density in popular places.	Up to 30 m/sec on highways and 6–10 m/sec in urban areas restricted by road regulations and traffic.	Predetermined route with typically speeds up to 100 m/sec. The movement could be in 2 or 3 Dimensions.
Topology	Nodes are dynamic where they join and leave the network unpredictably.	Star topology with roadside supplementary infrastructure. Linear movement is more dynamic than MANETs.	The hierarchal star or mesh topology among controlled UAVs.
Energy	Battery-powered with energy-efficient protocols.	Devices maybe car battery-powered or own battery powered.	UAVs are energy-constrained where batteries affect the flying duration.
Propagation	Poor LoS due to close to manufactured infrastructure.	Poor LoS, same as MANETs.	Above ground level with mostly free-space loss in LoS.
Localisation	GPS	GPS, AGPS, DGPS	GPS, AGPS, DGPS, IMU
Use Cases	Information distribution (emergencies, advertising, shopping, and events notification), and Internet Hotspots.	Traffic & weather info, Emergency warnings, Location-based services, and Infotainment.	Rescue operations, Agriculture: crop survey, Wildlife search, and Oil-Rig surveillance.

The Military has been using Unmanned Aerial Vehicles (UAVs) for more than 25 years, mostly for surveillance, investigation, and conducting strikes (Gupta, Jain, & Vaszkun, 2016). The public and private corporation also took an interest in utilising these UAVs for different applications such as delivering consumer products from the warehouse to clients' door using UAVs. From these public utilisation scenarios UAVs, it can easily be deduced that the wireless connectivity is an essential requirement for intercommunication between these vehicles and with the control centre. Furthermore, clients need to be wirelessly connected with the online shop to be able to view contents and place orders.

Table 4 concisely compares three main Ad hoc networks and reveal the key connectivity requirements for these networks. From the table, it can be observed that the Flying Ad Hoc Network (FANET) is suitable for the fifth-generation (5G) network, yet the architecture remained understudied until recently. In 2018, Ericsson and China Mobile partnered to conduct the world's first 5G-enabled drone prototype field trial on the operator's network. Many other companies have also taken interest in developing their FANETs. Nokia and AT&T[8] are one such example. However, their approach is based on the Fourth Generation (4G) network which might soon be outdated. The applications of multiple UAVs in coalitions or co-operative manner are now receiving widespread attention. This has raised the interest of this dissertation in studying how to apply UAVs in supplying basic 5G mobile wireless network to reduce Operational Expenditure (OPEX) and increase Capital Expenditure (CAPEX) in rural areas

---

[8] American Telephone & Telegraph

where mobile operators are reluctant to invest in less populated areas because of lower Return on Investment (ROI).

Though a few countries such as Australia, Argentina, Finland, and Germany have started committing to deploying 5G ready equipment, it does not negate the fact that 5G network is still experimental and operational standards are yet to be confirmed. Several challenges still need to be addressed before the full-scale deployment of the next generation of mobile cellular systems and networks (Liang & Yu, 2015). However, despite the lack of uniform standards for the forthcoming network, the essential technology must be known to realise the conceptual model swiftly. The 5G New Radio (NR) features are the core variables when analysing the economic and deployment feasibility. Hence, the following subsections will start by describing the prospective 5G NR as currently know. Lastly, it will discuss the network topology.

3.2 KEY FEATURES OF 5G TECHNOLOGY.

The next-generation core of networks will run in a business environment that is significantly different from that of today. The primary technological function is to support shared-infrastructure model that can still run the traditional operator model to accomplish a vertical integration. While the model can dedicate both hardware and software utilisation for specific use cases, more of these functions will be enabled by a software-defined network. Since virtualisation can run various models or network functions in a single dedicated hardware, operators can supply services through shared network equipment. This forthcoming network could be an answer to many of Africa's current wireless and local area network connectivity concerns, especially in remote and low-income areas where service providers are not keen to invest in cellular network connectivity.

The current quality of service levels being promised by 5G communication service providers is only available to premium users and organisations who can afford to pay for fibre connections. It can, therefore, be concluded that developed areas and districts with better communication infrastructure will have access to these services. Nevertheless, 5G mobile connectivity can enable users in rural areas to use online software applications and previously inaccessible access sites. Many data bundle consumers of major network providers in the Republic of South Africa have often confirmed through different media that data bundle prices have a reputation of being unnecessarily expensive compared to the rest of the world. Thus, end service pricing of 5G to fully cater to everyone everywhere will need careful evaluation. From a holistic perspective, a significant difference between the current generation mobile technology and the forthcoming 5G consists of communication networks discounting the following requirements (M Mousa, 2012; Sunitha, G Krishnan, & Dhanya, 2017):

i. Lower energy consumption.
ii. Multiple simultaneous data transfer paths.
iii. 1Gbps Ad Hoc data rates.
iv. Better cognitive radio security.
v. Better and broader network coverage.
vi. High data rates are available at the cell edge.
vii. Higher system-level spectral efficiency.
viii. Easy access to typical web applications wirelessly.
ix. Not harmful to human health.

x. Cheaper data bundles fees due to low infrastructure deployment expenses.

The explosive growth of Internet traffic is as a result of Internet-of-Things (IoT) and Smart devices, immersive environments and the tactile Internet. This explosive growth would only continue and can overwhelm the current network infrastructure. The millimetre-Wave (mmWave) band in the 30–300 GHz frequency range on which the emerging 5G wireless communication network runs may mitigate the issue of communication latency between devices (Bae, Choi, Kim, & Chung, 2014)In the forthcoming years, an increase of over a thousand magnitude is expected for data traffic volume for devices connected to the Internet. The 5G systems can handle this capacity when configured with the following functions:

i. Beamforming technology on patch antenna array can resolve propagation limitations of mmWave communication systems.
ii. Massive Multiple-Input Multiple-Output (MIMO) antenna arrays at Base Stations (BSs) and at the User Equipment (UE) to minimise errors and optimise data speed.
iii. Increased spectrum bandwidth and use of wideband at the BS communication systems can connect more devices and offer faster speeds.
iv. Above 100 MHz channels, multi-user, and Three-Dimensional (3D) MIMO will aid in distinguishing different users and steering the array's beam to the desired direction, which optimises the ideal performance metric of the network.
v. Network densification employing a smaller cell to increase in traffic within mobile broadband systems and UE.
vi. New modulation waveforms will pave the way for better IoT and Machine-to-Machine communication.

Table 5 – Fifth Generation network Specifications and Services

The 5G NR speed in sub-6 GHz bands can be slightly higher than the current Fourth-Generation Cellular Network (4G) with a similar amount of spectrum and antennas. Furthermore, the "air latency" target is expected from 1 up to 4 milliseconds. The incomplete 5G standards have not stopped manufacturers from releasing new 5G enabled devices to the market. Spectrum limitation can lead to expensive service to the intended users because network operators will be trying to get profit from the already deployed 5G infrastructure. Some of the key 5G network specifications derived from the functions described are reported in Table 5.

	PARAMETER	DESCRIPTION	U. LINK	D. LINK	DEPLOYMENT	SERVICE
Latency	User plane	The delay before a transfer of data begins following an instruction for its transfer. The contribution by the radio network to the time from when the source sends a packet to when the destination receives it (in ms)	4 ms for eMBB 1 ms for URLLC			eMBB URLLC
	Control plane		10 – 20 ms			

	PARAMETER	DESCRIPTION	U. LINK	D. LINK	DEPLOYMENT	SERVICE
Traffic	Area capacity	Total traffic throughput served per geographic area (in Mbit/s/m2)	10 Mbit/s/m^2		Indoor Hotspot	
	Connection density	Total number of connected and/or accessible devices per unit area (per km2)	1,000,000 devices per km^2			mMTC
Spectrum	Average efficiency	Average data throughput per unit of spectrum resource and per cell (bit/s/Hz)	6.75 bps/Hz/TRxp	9 bps/Hz/TRxp	Indoor Hotspot	
			5.4 bps/Hz/TRxp	7.8 bps/Hz/TRxp	Dense Urban	
			1.6 bps/Hz/TRxp	3.3 bps/Hz/TRxp	Rural	
	5% User experience		0.3 bps/Hz	0.3 bps/Hz	Indoor Hotspot	
			0.225 bps/Hz	0.15 bps/Hz	Dense Urban	
			0.12 bps/Hz	0.045 bps/Hz	Rural	
Data rate	Peak	Maximum achievable data rate under ideal conditions per user/device (in Gbit/s)	10 Gbps	20 Gbps		eMBB
	Spectral efficiency		15 bps/Hz	30 bps/Hz		
	User experience	Achievable data rate available ubiquitously across the coverage area to a mobile user/device (in Mbit/s or Gbit/s)	50 Mbps	100 Mbps		
Bandwidth	Up to 1 GHz for operation in higher frequency bands		100 Mhz			
Energy	Energy efficiency on the network side, quantity of information bits transmitted to/received from users per unit of energy consumption of the RAN (in bit/Joule) and on the device side, the quantity of information bits per unit of energy consumption of the communication module (in bit/Joule)		Able to support higher sleeping ratio and long deep sleeping duration			

	PARAMETER	DESCRIPTION	U. LINK	D. LINK	DEPLOYMENT	SERVICE
Reliability			1 - 10^{-5} success probability of transmitting a layer 2 protocol data unit of 32 bytes within 1 ms in channel quality of coverage edge			URLLC
Mobility	Interruption time	Maximum speed at which a defined QoS and seamless transfer between radio nodes (in km/h)	0 ms			eMBB, URLLC
	Classes supported		Stationary: 0 km/h Pedestrian: up to 10 km/h		Indoor Hotspot	eMBB
			Stationary: 0 km/h Pedestrian: up to 10 km/h Vehicular: up to 30 km/h		Dense Urban	
			Stationary: 0 km/h Pedestrian: up to 10 km/h Vehicular: up to 500 km/h		Rural	

3.3 CONCEPTUAL MODEL.

Building upon the work done by Luca, *et al.* (2017) this work proposes a heterogeneous 5G architecture comprising of micro-cells, macro-cells, relays, and femtocells in a Cloud Radio Access Network (Cloud-RAN). This architecture supports wireless technologies such as massive MIMO which will trigger an increase in the downlink and uplink data rate achievable by end-users, Device-to-Device (D2D) and Delay Tolerant Network (DTN).

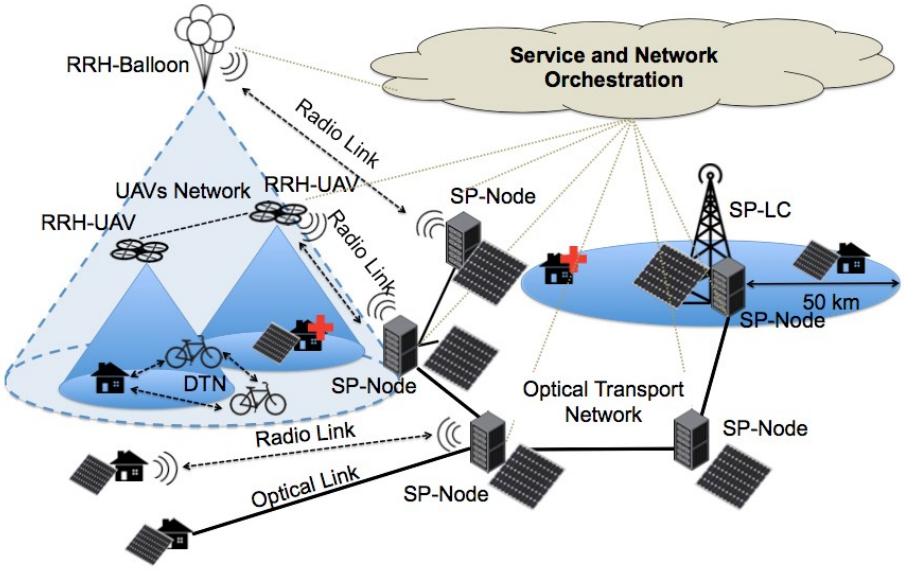


Figure 14 – A conceptual model for 5G deployment in Rural and Low-Income Areas. Chiaraviglio, et al.in (Luca, et al., Bringing 5G in Rural and Low-Income Areas: Is it Feasible?, 2017)

In line with the white paper on forthcoming network architecture and application trends (5G-PPP, 2017), Figure 14 illustrates our conceptual network coverage model. This model adheres with the design goals of the IEEE P2061. The architecture comprises of a mix of terrestrial and airborne cells interconnected with both fibre optics and radio connection. The micro-cells are mounted on battery-powered UAVs with energy harvesting systems for extended flight time. The terrestrial cells also have energy harvesting technology to supplement grid electricity. The design considers the following network engineering challenges:

i. Communication links interference (both terrestrial and aerial).
ii. Spatial modulation and mmWave communication.
iii. UAV and network radio energy consumption.
iv. Operation altitude of the UAV.
v. Backhauling cellular connection.
vi. Drone trajectory planning and mobility control.
vii. Terrestrial cell planning.

Note that it would be overly ambitious to consider the implementation of all 5G standards and services in low-income areas. The major problem this dissertation identifies and seeks to tackle is the lack of broadband connectivity in rural areas. Hence, proposing an architecture that can be deployed in phases with a tailored billing system targeted at these low-income areas. Cognisant of the fact that our proposed model has both aerial and terrestrial network nodes, Table 6 compares the characteristics of both types of network elements (base station and access) when deployed as aerial and terrestrial nodes.

Table 6 – Network Nodes Comparison (Mozaffari, Saad, Bennis, Nam, & Debbah, A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems, 2018).

	AERIAL	TERRESTRIAL
Base Station	*Deployment is naturally three-dimensional.*	Deployment is typically two-dimensional.
	Mobile and dynamic.	It is fixed and static.
	Mostly unrestricted locations.	Few, selected locations.
	Short-term, frequently changing deployments.	Mostly long-term, permanent deployments
Access Node	Spectrum is scarce.	
	Hover and flight time constraints.	No timing constraints, BS always there.
	Elaborate and stringent energy constraints and models.	Well-defined energy constraints and models.
	Varying cell association.	Static association.

3.4 DEFINING THE NETWORK TOPOLOGY.

A network topology depicts the logical or physical layout of a communication network consisting of links and nodes. A topology is an application of graph theory that defines the way different nodes are found and interconnected respectively among themselves. Network topology could also give insights into how nodes convey data among themselves. The network topology consists of the logical and physical components. The logical topology depicts signal properties within a network (e.g., data flows, distances between nodes, physical interlinks, transmission rates, or signal types), while the physical topology portrays the assignment of various components of a network (e.g., device location, network interface, routers, and cable installation). Nodes can be physically connected by optical wires or wireless to form the geometric layout of the communication network. These nodes can be arranged in several ways, including: bus, star, ring, mesh, and tree topological layout (Sukesh, 2018). Some of these topologies are briefly described below:

i. **Bus Network:** the main cable (called the bus) connects every node in the network, hence all nodes are directly linked to each other.
ii. **Star Network:** All nodes are directly connected to a central server. Where every node is indirectly connected to other nodes through the central server.
iii. **Ring Network:** adjacent pairs of nodes are directly linked, which makes all nodes connected in a closed-loop formation. Other pairs of nodes communicate indirectly, using the next intermediate pair to forward data.
iv. **Mesh Network:** when each node is linked directly to each of the other nodes in the network, the topology is called a full-mesh scheme. In the partial mesh topology, some nodes are linked to all the other nodes, and some are linked to at least one node which they use to communicate with other nodes.
v. **Tree Network:** in this topology no less than two Star-networks are linked to form the network. The central nodes of the star networks are linked to the main bus. Thus, a tree network is synonymous to a bus network of star networks.

This section discusses all the core components of the proposed network topology by firstly introducing the envisioned coverage model. Secondly, it illuminates functional organisation, system configuration and framework types of the ideal architectural design. Furthermore, the section will briefly discuss the energy model and geometric models for the FANET. Lastly, the foreseeable 5G network orchestration is explained.

3.4.1 Envisioned Network Coverage Model.

Developing a hybrid network has its pros and cons (Ji, et al., 2016; Gu, Zhang, Ji, Bai, & Sun, 2018). In this human-centred tech-driven world, the Internet plays a crucial part in daily activities. To connect all different devices from various users to the Internet with their specific tasks, network engineers must follow some particular models or guidelines that will make connecting to the web effortlessly. The models considered must improve the overall functionality of the network; as well as reduce the initial capital, operational expenditure, and maintenance costs of the service provider after deployment. A network topology is a factor in determining the media type to be used, error or fault detection, practical application of resources and networking components.

With UAV FANET infrastructure, we envision that the management of services and network will be in a collected way that shadows the emerging trends recommended by the 5G network architecture (Narang M. , et al., 2017). In brief, the forthcoming 5G network allows the adaptation of a virtual function (VF). Through VF, it will be possible to run network functionalities in software that are running in hardware on current network generation (Chiaraviglio, et al., Optimal Pricing Strategy for 5G in Rural Areas with Unmanned Aerial Vehicles and Large Cells Optimal Pricing Strategy for 5G in Rural Areas with Unmanned Aerial Vehicles and Large Cells, 2017). Moreover, 5G is going to revolutionaries how the design and management of mobile networks. By bringing Multi-User, Multiple-Input Multiple-Output technology (MU-MIMO) will trigger an increase in downlink and uplink data rates achievable by end-users.

UAVs are easily deployable to carry out their respective tasks on command and can easily set up a wireless network topology virtually everywhere on earth and space. As a practical example when considering rural areas in Kwa-Zulu Natal (in ZA), which are mostly mountainous areas, installing a wireless network using traditional means would not be economically viable. Hence, exploiting UAVs to provide wireless network connectivity in such an area might be profitable to investors yet with minimal maintenance. An added advantage is the ability of UAVs to fly in formation, which is beneficial in designing the topology layout.

In the proposed topology, 5G wireless network modules are mounted on UAVs to provide the air-to-ground communication links with users on the one hand and the Low Altitude Platform (LAP) on the other. One of the drawbacks of utilising UAVs is energy consumption. UAVs have limited energy supply, and mounting network modules on them would drain their batteries faster. Clearly, energy consumption makes this method not practicable to solely provide wireless communication. Fitting solar panels on the UAVs to complement the batteries might be a viable solution to the energy problem.

Figure 15 depicts our envisioned optical 5G network coverage model for rural and low-income areas. The system consists of $N_c \in \mathbb{N}$ 5G dedicated hardware indexed by i or j, where $i \neq j$ and $i, j \in 1,2,3, \ldots, N_c$. Index $i, j = 0$ represent the LAP. To calculate the number of 5G remote radio heads (RRHs) N_c we use the expression as below, *Equation 1 – Total number of radio heads*

$$N_c = max\left(\frac{2 \cdot A}{3\sqrt{3} \cdot R_c^2}, \frac{N_u \cdot \alpha \cdot T}{\gamma}\right)$$

Where, Where, N_c is the total number of required remote radio heads, R_c is the radius of the hexagonal cell coverage, A is the prescribed area of size, N_U is the total number of users, α is the ratio of active users in the network, T is the Average throughput per subscribed user, γ is the peak capacity of the remote radio head. Our proposed network architecture has terrestrial and airborne nodes for easy deployment and increased coverage. The complete architecture is presented in the following subsections: Commodity and Dedicated Hardware, where essential components are discussed, and Communication Links. sub-section which discusses the physical and wireless network connection.

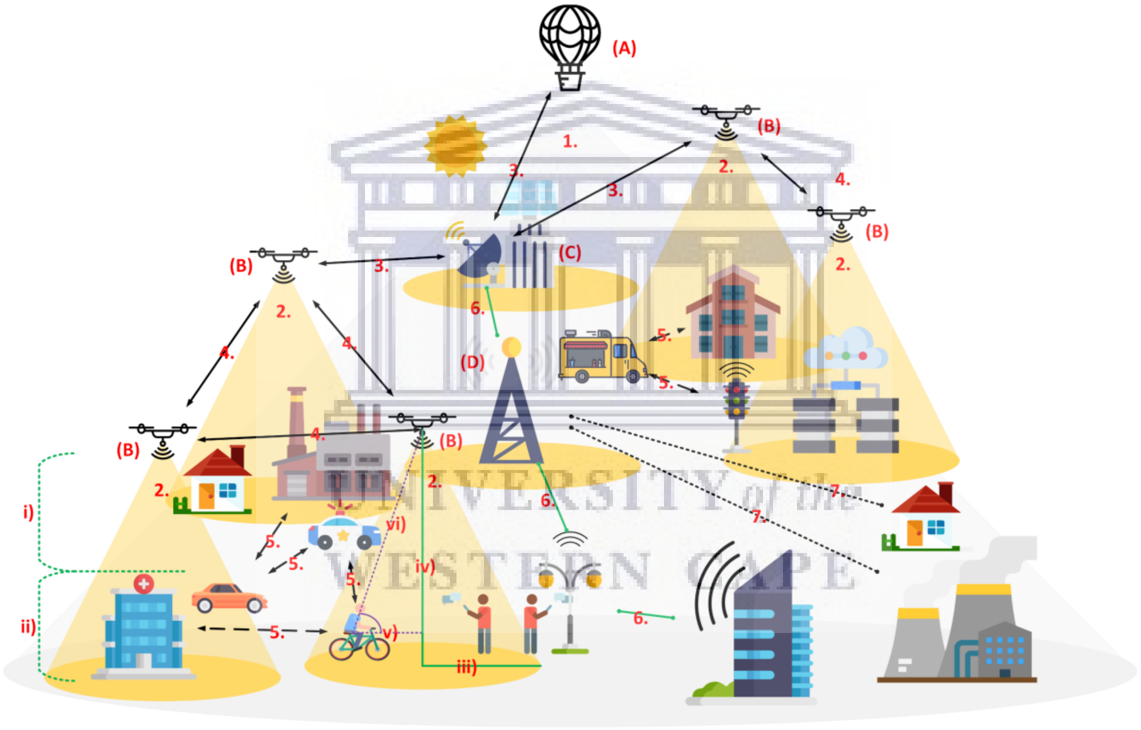


Figure 15 – Coverage Model with logical connection lines.
(A) RRH – Balloon, (B) RRH – UAV, (C) Base Station, (D) Large Cell Radio, 1. Balloon Coverage Area, 2. UAV Coverage Area, 3. Backhaul Radio Link, 4. Fronthaul Radio Link, 5. DTN, 6. Optical Link, 7. Radio Link, i) Free Space Path loss, ii) Excessive Path loss, iii. UAV Coverage Radius, iv) UAV Height, v) UE Radius, vi) UE distance to Access Point.

3.4.2 Commodity and Dedicated Hardware.

Fifth-generation network module provides support for up to 800 MHz of bandwidth from 26.5 to 29.5 GHz, 27.5-28.35 GHz, and 37–40 GHz millimetre wave (mmWave) spectrum bands (Qualcomm, 2020). The Qualcomm 5G module (QTM052) is designed to support up to 2x2 MIMO with dual-layer polarisation in both the downlink and the uplink, also supports beamforming, beam tracking, and beam steering for bi-directional mobile mmWave communication. The spectrum figure above depicts the frequency range support by the LAP, terrestrial cell, UAV and the base station cell.

3.4.3 Balloon Remote Radio Head.

The LAP act as an aerial base station to UAVs. This base station can communicate with all the nodes (aerial and terrestrial cells) and is located at least ten kilometres above the ground. It has a processing unit, where Software-Defined Networking (SDN) and Network Function Virtualisation (NFV) with multiple network slicing are utilised. The LAP processes the low-

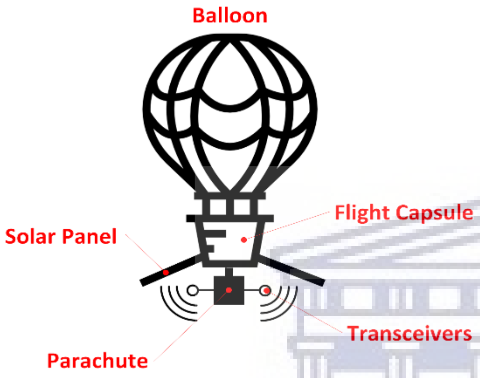


Figure 16 – Low altitude platform design.

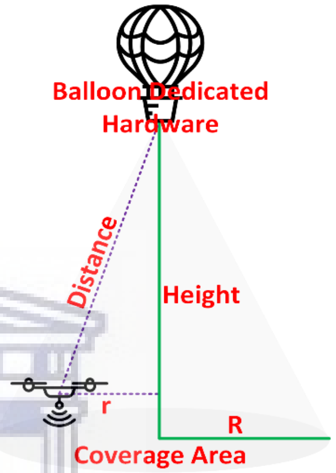
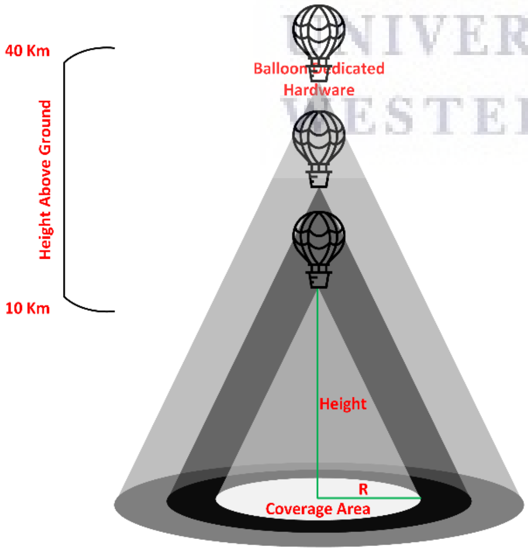


Figure 17 – Low altitude platform coverage model.



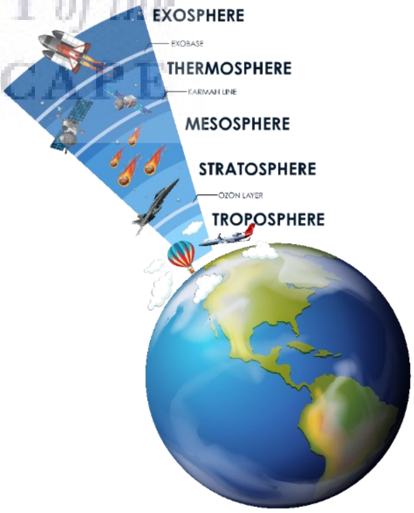


Figure 18 – Low altitude platform coverage model with full-duplex and height control.

Figure 19 – Atmosphere.

level network slices which are allocated to other network service providers, fog-computing, and industries. The RRH performs functions such as basic radio operations such as signal processing (digital to analogue conversion, analogue to digital transformation), power amplification and signal filtering. Figure 16 shows that the balloon is equipped with a parachute to land safely. Furthermore, it has a flight capsule where the control units are stored. In Figure 17, R represents a coverage radius of the LAP, r represents a coverage radius of the UAV cellular node. Radio heads will take advantage of full-duplex technology to increase coverage. Communication frequency between the UAVs and LAP can be as high as 40 GHz to reduce latency and improve bandwidth significantly. UAVs have 3D positioning systems and hover mostly in high altitude where there is free space path loss (labelled i in Figure 15) to accommodate the communication with the LAP. Commercial aeroplanes mostly fly just above the cumulonimbus clouds in the Troposphere. The ideal location of the LAP can be between 10 and 40 Km above ground as shown in Figure 18. Moreover, Figure 19 shows layers in their atmosphere. Since the air in the Stratosphere moves in different directions, the balloon carrying the 5G dedicated hardware will have to move up and down to remain in the proximity with drone cellular networks.

3.4.4 Unmanned Aerial Vehicle Remote Radio Head.

A UAV usually has an onboard controller that can self-propel the drone or execute commands via remote access. The ideal UAV to provide a variable wireless network is a quadcopter with a solar panel(s) roof. Apart from the onboard controller which is housed in the flight capsule, the capsule also holds the 5G dedicated hardware (as shown in Figure 20 and Figure 21). A quadcopter has four rotors to keep it balanced while flying, hence, it can hover in a single spot for a long time. Unlike high-altitude balloon or wing drone, a quadcopter can change direction fast and reach speeds of up to 180 km/h.

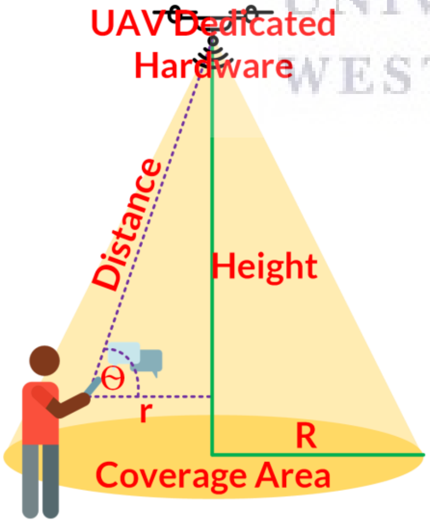


Figure 20 – Unmanned Aerial Vehicle coverage model.

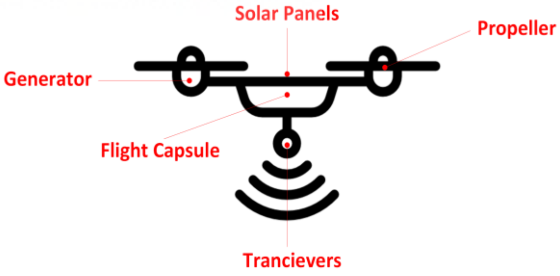


Figure 21 – Unmanned aerial vehicle design.

In Figure 20, R represents the UAV remote radio head (RRH) coverage radius, $Height$ is the altitude above ground level. Furthermore, the figure shows the User Equipment (UE) at radius r from a point corresponding to the direct projection of UAV-RRH onto the ground. The

$Distance$ between the UAV-RRH and UE receiver is $d = \sqrt{r^2 + h^2}$. Whereas, $\theta = \tan^{-1}\left(\frac{h}{r}\right)$ indicates the angle of elevation (in radian) with UE respect to the UAV-RRH. The efficiency nature of energy consumption by small cells takes full advantage of multi-input-multi-output (MIMO), Beamforming and Full-duplex technologies (M Mousa, 2012). Assuming a drone providing coverage to a convenience store with potential users. Logically, these users will connect their equipment to the network. Therefore, the UAV will apply network data to the neural network and spatial clustering algorithms to predict the best position to hover at.

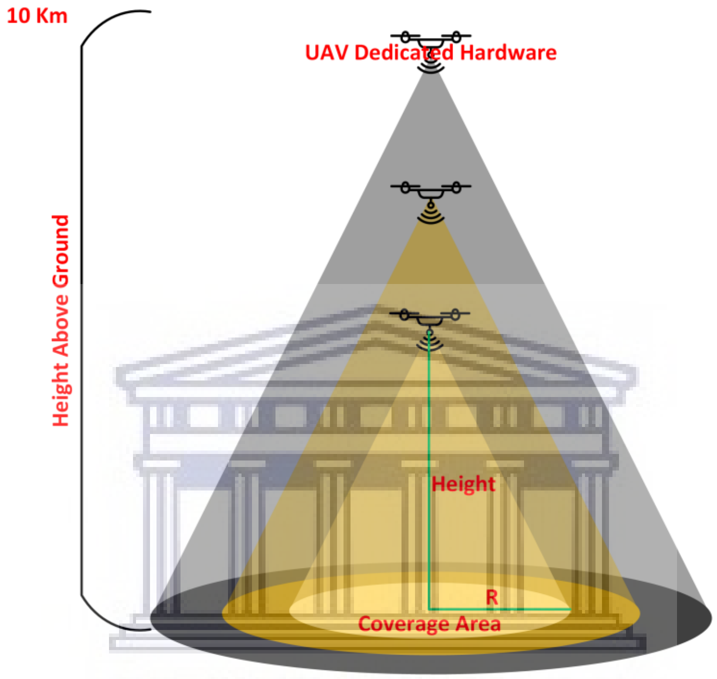


Figure 22 – Unmanned aerial vehicle coverage model with full duplex and height control

Figure 22 depicts three UAVs with different heights and coverage area, respectively. The UAVs will fly in the troposphere, which is up to ten kilometres above the ground. UAV-RRH can reduce the rated transmission power to conserve energy after using the spatial algorithm to check the required energy based on the connected users.

3.4.5 Cellular Tower Network Coverage.

A cell tower is usually tall and has one or more antennas attached which emit radio frequencies to create a coverage area. The UE in the coverage area connects wirelessly to the base station (BS), allowing uninterrupted data commutation. Multiple cellular providers often save money by mounting their antennas on a typically shared tower, since separate systems can use different frequencies. This is called co-location, where antennas can be found close together without interfering with each other. There are four various types of cell towers (Whatsag, 2019):

i. **Lattice Towers**: these typically have three or four sides with similar shaped bases. They have excellent flexibility and often used in heavy loading conditions. They are also known as a self-supporting tower.

ii. **Monopole Tower**: is single steel or concrete cylinder tower that does not exceed 50 metres. The exterior of the tower houses the antennas.
iii. **Guyed Tower**: It is a thin and tall structure that depends on the guy line for stability and the cheapest tower to construct, but it requires a significant amount of land. It can reach heights of 100 metres or higher. It is the most used radio and television stations.
iv. **Stealth Tower**: These towers are aesthetically modified to conceal their appearance. They may be shaped like palm trees or artistic structures. This is usually done in compliance with councils' regulations. They are more expensive than other types of towers because they need to add material to hide their appearance.

The main task of the tower is to elevate the antenna. Series of wires connect an antenna with BS equipment on the ground. Components of the include BS include transceivers, signal amplifiers, combiners, multiplexers, and system controllers. For best and reliable wireless network coverage, the tower is usually at a height of at least fifteen metres and depend on:

i. The frequency of the signal in use.
ii. The manoeuvring features of the site antenna array.
iii. Rated power on the transceiver.
iv. The rated uplink or downlink data rate of the subscriber's mobile device.
v. Ambient weather conditions around the cell tower.
vi. Reflection or absorption of radio energy from nearby buildings.

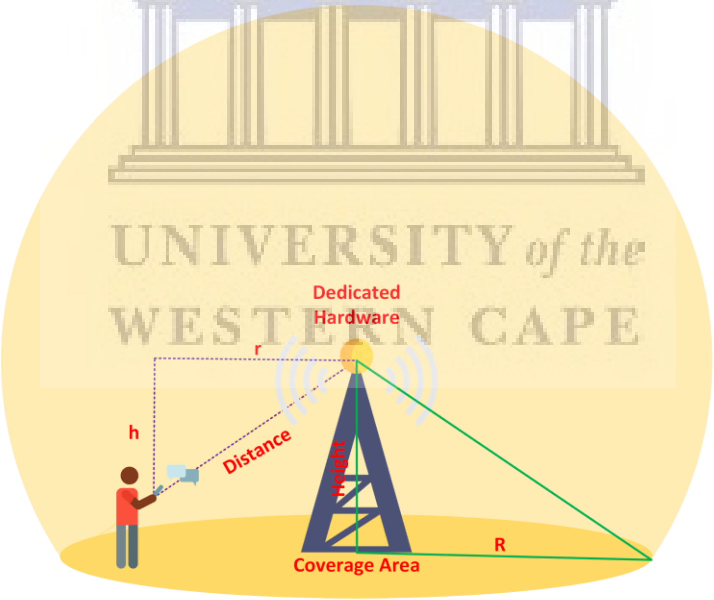


Figure 23 – Cell tower coverage model.

The fifth-generation network promises a faster and reliable connection. This service is achievable with massive multiple users (MIMO), which could require a cell tower in every street (Bill, 2016). Since 5G towers need less energy, they can be relatively small and installed on a traffic light, light poles, and public buildings. Figure 23 depicts a 5G cell tower coverage, where the $Distance$ between the Tower-RRH and UE receiver is $d = \sqrt{r^2 + h^2}$. Whereas, $\theta = \tan^{-1}\left(\frac{h}{r}\right)$ indicates the angle of elevation (in radian) with UE respect to the Tower-RRH. Lattice towers will have 5G Large cell that supplies coverage for long-distance. They will also have to be a base station for UAVs. During dangerous weather where the drones cannot fly, be able to recharge batteries, or due to maintenance. They will have to land in these base stations. The terrestrial cell can operate with the low spectrum to cover a wide area while the base station cell operates with high spectrum because it provides high bandwidth communication links to the LAP, UAV, and terrestrial cell nodes.

3.4.6 Fibre Optical Network.

A fibre-optic cable is composed of thin strands of glass or plastic known as optical fibres. The cable can have at least two strands or as many as several hundred strands of optical fibres. Each strand though less than a tenth of a human hair in thickness can transmit signals for more than twenty thousand telephone calls simultaneously. Hence, the entire fibre-optic cable effortlessly takes several million calls. Fibre-optic communication is a way of conveying information from one place to another by sending pulses of light through optic cables. Fibre-optic cables are now the *de-facto* channel of transmitting information across the globe. This is possible because the following advantages which Fibre-optics have against copper cables:

i. Less signal attenuation: data travels ten times further before requiring amplification.
ii. No interference: they communicate data more reliably with better signal quality.
iii. Higher bandwidth: fibre-optic cables can send more data than copper cables with the same diameter.

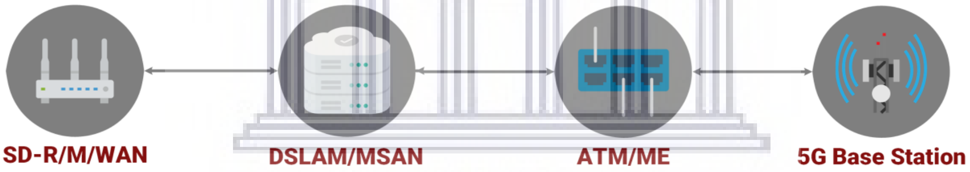


Figure 24 – Fibre optical network.

Fibre-optic networks have been in service for decades to send large volumes of traffic across and within countries. The economics of fibre networks have only recently allowed for the connection of fibres directly to the home, creating a Fibre-to-the-Home (FTTH) network. Traditionally fibre architecture was for fibre remote access and was a high-speed fibre trunk (Synchronous optical networking or Ethernet) that terminated in electro-optical multiplexers. In recent times, “Deep fibre” has emerged and is one in which fibre connections are brought as close to the customers as possible. An example is fibre-to-home. Figure 24 shows the 5G deep fibre layout from the base station to the client’s 5G hotspot. It comprises of the following components:

A. SD-R/M/WAN.

i. Router (R) and Modem (M), which are installed near the clients such as in offices, homes, and shopping centres. The user will be able to connect wirelessly or use fibre-optic cables. The SDN will help to create virtual topologies on demand and also extend the wireless coverage.
ii. SD-WAN – Software-Defined Wide Area Network is a novel approach to network connectivity that reduces operational costs and improves resource usage for various site

deployment. With SD-WAN managers can throttle bandwidth more efficiently and ensure the highest level of performance for critical applications without sacrificing security or data privacy (CISCO, 2019).

B. DSLAM/MSAN.

i. DSLAM – Digital Subscriber Line Access Multiplexer, swiftly establish a connection between various locations. They include three essential functions as a multiplexer, data switch and modems. Multiplexers encode both phone and data signals from phone exchange to an Internet service provider (ISP). While data switches establish Internet connections to numerous clients at once (Tech Terms, 2020).
ii. MSAN – Multi-Service Access Node/Gateway, connect a telephone line to the central network in a telephone exchange. MSANs are essential for supplying a host of services such as integrated services digital network (ISDN), broadband and the telephone (Dealna, 2019).

C. ATM/ME.

i. ATM – Asynchronous Transfer Mode, is a dedicated-connection switching technology that organises digital data into 53-byte cell units and conveys them over a physical medium using digital signal technology (Margaret, ATM (asynchronous transfer mode), 2007).
ii. ME – Metro Ethernet, is the use of carrier ethernet technology in metropolitan area networks (MANs). Since it is a collective endeavour with numerous financial contributors, it offers cost-effectiveness, reliability, scalability, and bandwidth management superior to most proprietary networks (Margaret, Metro Ethernet, 2009).

The fibre optical network will help to create an end-to-end 5G wireless network connection. As depicted in Figure 24, software-defined hotspots from client's proximity will connect to the local gateway or multiplexer. Then a fibre-optic bus will convey data to the local base station. Since millimetre waves are sensitive to interference, it is ideal that clients have hotspot coverage in their proximity (Buzzi & D'Andrea, 2017).

3.4.7 Communication Links.

A telecommunication link is a communication channel that requires two or more access devices to convey data through a medium (Gummalla & Limb, 2000). Where a medium might be a wireless radio such as LTE, Bluetooth, GPS, or Wi-Fi; or ethernet cable connecting the interfaces at both ends. These mediums may link physically or logically to each other, forming a point-to-point, multipoint, or broadcast communication. On this research, we consider Multipoint connection, where the LAP and the terrestrial tower will act as base stations for a logical drone network. Uplink is the transmission path from the UAV-RRH to the LAP, equally be the path from Tower-RRH to UAV-RRH. Conversely, the path from the LAP to UAV-RRH and UAV-RRH to tower-RRH are downlink transmission. Forward and reverse links are transmission paths between the user equipment and a gateway, respectively.

A. *Backhaul Radio Link.*

The up/down communication links between Tower/UAV and the LAP has properties represented as $\ell_b = \{\wp_{i0}, \varphi_{i0}, \delta_{i0}, \delta_{\xi_{i0}}\}$, where parameters are given by $\wp_{i0}$, the distance in metres between i^{th} RRH and the LAP and equal to $\sqrt{r_{i0}^2 + h_{i0}^2}$, r_{i0} is the radius from the cell to the coverage centre of the LAP, h_{i0} is the difference in altitude of Tower/UAV-RRH and LAP), φ_{i0} is the slow fading random wireless channel envelope between i^{th} RRH and the LAP, δ_{i0} is the path loss between i^{th} RRH and the LAP, $\delta_{\xi_{i0}}$ is the mean path loss between i^{th} RRH and the LAP.

B. *Fronthaul Radio Link.*

The up/down logical communication link between i^{th} and j^{th} RRHs with properties represented as $\ell_c = \{\wp_{ij}, \varphi_{ij}, \delta_{ij}, \delta_{\xi_{ij}}\}$, where parameters are given by precisely the same as the backhaul link with the focus among the nodes. Whereas the distance between radios is $\wp_{ij} = \sqrt{r_{ij}^2 + h_{ij}^2}$.

C. *User Equipment Radio Link.*

The communication link between k^{th} user equipment and a respective gateway i^{th} represented as $\ell_u = \{\wp_{ik}, \varphi_{ik}, \delta_{ik}, \delta_{\xi_{ik}}\}$, will be a point-to-point communication. The environment dictates the random fading rate φ_{ik} in a connection, if the subscriber's device does not have good line-of-sight (LoS), then the link will be weak. Some waves might diffract from the path or get soaked up by different media such as trees and animals. Section 3.6 gives an elaborative discussion of radio propagation model.

3.4.8 Delay Tolerant Network.

DTN try to address the lack of continuous connectivity in disjoint heterogeneous networks. It operates effectively over long distances where latency might be measured in hours or even days (Margaret, delay-tolerant network, 2007). DTN requires devices that can permanently store a large amount of data until all the data are successfully forwarded to the next device(s). The data must be accessible at once. Thus, traffic can be classified in the following ways:

i. **Expedited Traffic**: reassembles packets to obtain the original data before they are redirected to their destination.
ii. **Regular Traffic**: sent when all expedited traffic is defragmented successfully in their intended destination.
iii. **Bulk Traffic**: sent only when all packets of other classes from the same source and bound for the same destination have been successfully transmitted and reassembled.

To reduce the workload in the Base Band Unit (BBU) connection with RRH, DTN may develop to further spread the information using the user equipment. The communication link between k^{th} and l^{th} user equipment and a respective gateway i^{th} is represented as $\ell_u =$

$\{\wp_{kl}, \varphi_{kl}, \delta_{kl}, \delta_{\xi_{kl}}, \tau_{kl}\}$. The terms of accessibility in a link ℓ_u constituted by τ_{kl}, where it can be a private or public link.

3.5 ENERGY MODEL.

Deployment of the proposed 5G network architecture in low-income and rural areas will be very challenging due to the absence of reliable energy sources. According to (Stats SA, 2020), more than 20% of South African dwellings are informal. These informal settlements are mostly found in low-income areas and rural areas. Hence, it will be very challenging to install a perfect or an ideal 5G wireless connection network without batteries and solar systems. To supply a reliable network, the system must use renewable energy to lower the electricity cost.

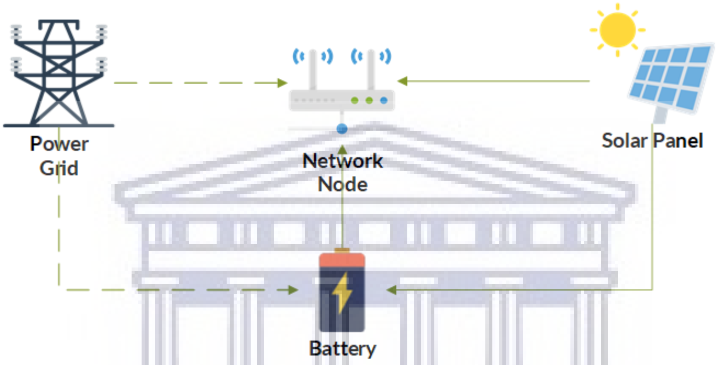


Figure 25 – Energy Source for the Network Node.

Figure 26 depicts three energy sources to supply electricity to the Network Node (NN). Solar panels will be the primary source of energy and it will supply power to the UAVs and the site where the Large Cells (LC) are located. The solar panel will be able to solely provide energy to the NN and be capable of charging the battery. For the periods when the solar panel is unable to provide enough energy to the NN (such as during cloudy days or at night), the battery will

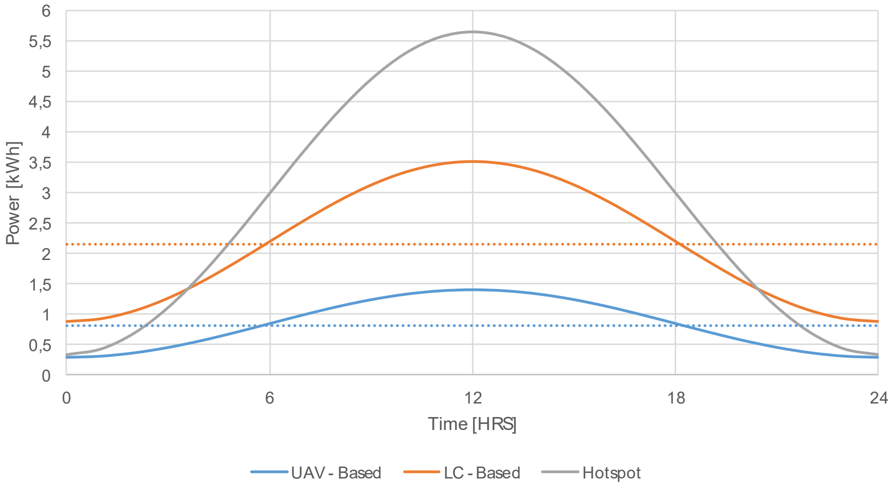


Figure 26 – Power required per hour over a 24-hour period.

provide the needed power to augment the solar panels or directly power the NN. The power grid will be utilised optionally, in cases where the battery is depleted or when there is no sunshine for extended periods.

The sinusoidal graph in Figure 25 illustrates the ideal power load required by the two systems to operate for the entire day. The minimum point shows the power required by the system to function without supporting any user. Power peak values for both UAV-Based and LC-based cells are detailed in Figure 25. South Africa's climatic conditions usually range from the Mediterranean in the south-western areas to temperate in the interior plateau, and subtropical in the northeast. Most of the country has warm, sunny days and cold nights (SA Venues, 2019). Since South Africa has sunny days, solar panels can operate from 6 a.m. until 6 p.m. while the batteries provide power at night. The grid electricity will only be required in cases where the batteries and solar panels are unable to power on the node cells. Equation 3 produces a generic sinusoidal function of energy consumption for both UAV-Based and LC-based nodes.

Equation 2 – Mid-power between the power required to run the node with minimum users of 20% and the maximum power with the full

$$m = \frac{P^{MAX} - P^{MIN}}{2}$$

Equation 3 – Kilowatt-hour required by the node.

$$\varphi_h = (P^{MIN} + m) - \left(m \cdot COS\left(\frac{2\pi}{24} \cdot h\right)\right)$$

Where, m is the mid-power between the power required to run the node with minimum users of 20% and the maximum power with the full capacity, P^{MAX} is a maximum power consumed when the available capacity to users is maximum, while P^{MIN} is a minimum power consumed when the node does not serve any user, and φ_h is the amount of energy in kilowatts required for a specific hour by the node. Kilowatt-hour $\varphi_h$required by the node is given by Equation 3.

3.6 RADIO COVERAGE MODEL.

The continuously increasing demand for mobile communications influences the rapid improvement for better coverage and higher transmission quality. As a result, more efficient ways to use the radio spectrum is required (Krzysztofik, 2018). Traditional topology uses terrestrial nodes to provide coverage. Besides, rural areas have a sparse population and mountainous surface. In these cases, deploying UAVs as base stations is very useful in providing an improved QoS for ground users. UAVs deployment, however, it faces numerous challenges, such as power consumption, coverage optimisation, and interference management (Mozaffari, Saad, Bennis, & Debbah, Drone small cells in the clouds: Design, deployment and performance analysis, 2015). Signal-to-Noise Ratio (SNR) aid to determine the signal strength between transmitter and receiver. Hence, this section discusses the network propagation model and node locality planning.

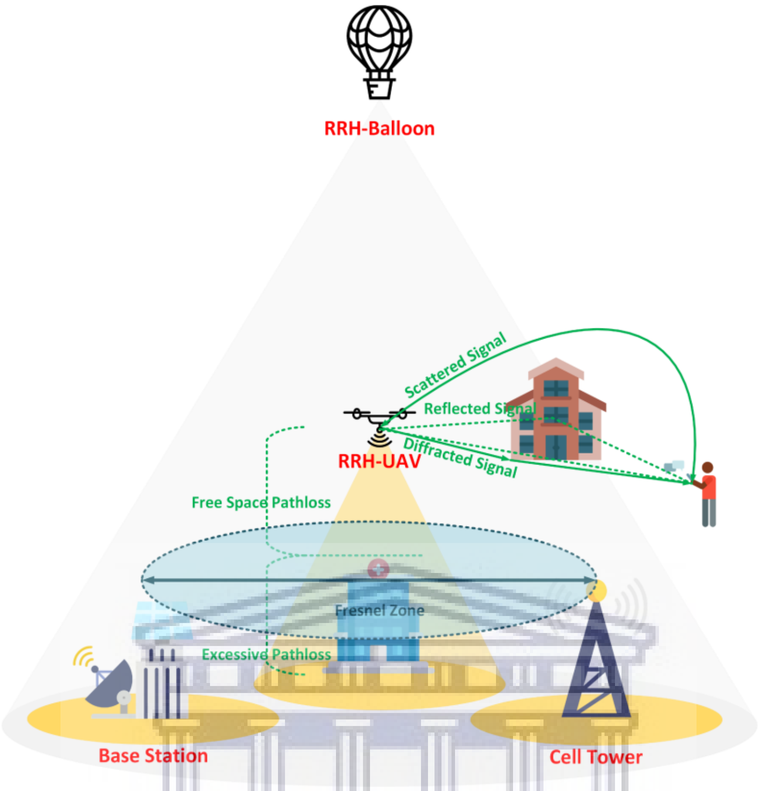


Figure 27 – Low Altitude Platform Air-to-Ground Propagation Model.

3.6.1 Radio Propagation Model.

Radio propagation is how radio waves are affected by the medium in which they travel around the Earth from the transmitter(s) to the receiver(s) in various atmospheric conditions. Also, various objects along the path may result in reflection, refraction, absorption, and diffraction of the propagated waves. These objects govern the level and quality of the received or lost signal. Figure 27 depicts an air-to-ground propagation model and the Fresnel zone between the cell tower and base station. For LAP, UAV-Based, and Terrestrial-Based up/down communication links, we consider a generic wireless link binary phase-shift keying modulation. As depicted in Figure 15 front/backhaul corresponding signal can be generalised as,

Equation 4 – Corresponding Received Signals

$$\Gamma(t) = \frac{1}{\sqrt{\delta_\xi}} \cdot \varphi_{ij}(t) \cdot \Gamma_{tx}(t) + v(t)$$

Where, δ_ξ is the path loss over a certain distance, $\varphi_{ij}(t)$ is Rice and Log-normal models, $\Gamma_{tx}(t)$ is the transmitted signal, and $v(t)$ is the corresponding additive Gaussian noise at the receiver.

The proposed infrastructure considers a double-sided power spectral $^{N_0}/_2$ with $N_0 = 2x10^{-15}\,{}^{W}/_{HZ}$. The expression below compute the mean received signal $\bar{\Gamma}$, where $P_{tx_{ij}}$ is the base station or cluster head transmission power to other cluster members (CMs), conversely $P_{tx_{ji}}$ from CMs to CH and from CH to the LAP. Furthermore, ω represent factors which justify geometrical considerations.

Equation 5 – Mean Received Signal.

$$\bar{\Gamma}(\wp_{\mathrm{ij}}) = \frac{P_{tx_{ij}} \cdot \omega}{\wp_{\mathrm{ij}}^{\delta}}$$

In most cases, the LAP will be hovering in approximately ten kilometres above sea level. In these altitudes, signals emitted by the balloon base station will propagate through free space until they reach low height, where they will experience excessive strength loss caused by manufactured infrastructure as shown in the coverage model, Figure 15 and Figure 27. In this case, we have two different path loss expressed as:

Equation 6 – Path loss.

$$\delta_{\xi} = \psi + \eta_{\xi}$$

Where, ψ is a Free-space path loss, η_{ξ} Excessive path loss, and η is the mean value of the experienced excessive path loss in decibels and ξ signifies the dominant propagation such as line-of-sight (LoS) or non-line-of-sight (NLoS).

Equation 7 – Free-space path loss in terms of frequency at a reference distance.

$$\psi(\overline{\wp}) = \left(\frac{4\pi \cdot f \cdot \overline{\wp}}{c}\right)^2$$

Equation 8 – Free-space path loss in terms of wavelength at a reference distance.

$$\Psi(\overline{\wp}) = \left(\frac{4\,\pi \cdot \overline{\wp}}{\lambda}\right)^2$$

Where, $\overline{\wp}$ is a reference distance, f is a signal frequency in hertz (Hz), c is the speed of light in metres per second (3 x 10^8 m/s), and λ is the signal wavelengths in metres. Furthermore, f represent the 5G communication frequency defined by a carrier based on the legal range allocated by the government. For UE, some factors affect the probability of LoS, such as the height of buildings, occupied land, and the mean building per unit of the area.

3.6.2 Free-Space Path Loss.

In telecommunication, the free-space path loss (Ψ) is the attenuation of radio energy from the transmitter to the receiver while propagating through LoS and NLoS space. This loss can be expressed in decibels which are calculated by disregarding some hindrances, even reflections that might occur in its path. Moreover, IEEE defines Ψ as "The loss between two isotropic radiators in free space, expressed as a power ratio" (IEEE Standard Definitions of Terms for Radio Wave Propagation, 1998). As Figure 27 discusses, the UE receives five different groups of signals, including LoS, NLoS, reflected, diffracted, and scattered the signal, which causes multipath fading. Hence, these groups can be measured separately with different probabilities of occurrence. Each group has a specific chance of existence that is determined by the environment, density and height of buildings and elevation angle. However, the probability of receiving LoS and reliable NLoS signals are considerably higher than fading (Mozaffari, Saad, Bennis, & Debbah, Drone small cells in the clouds: Design, deployment and performance analysis, 2015; Feng, McGeehan, Tameh, & Nix, 2006). Below expression determines the signal losses that can occur:

Equation 9 – Line-of-Sight path loss.

$$\zeta_{LoS} = 20\log\left(\frac{4\pi \not{f}_c d}{c}\right) + \eta_{LoS}$$

Equation 10 – Non-Line-of-Sight path loss

$$\zeta_{NLoS} = 20\, log\left(\frac{4\pi \not{f}_c d}{c}\right) + \eta_{NLoS}$$

Where, $\not{f}_c$ is the carrier frequency, d is the distance between a transmitter and a receiver, c is the speed of light in metres per second (3 x 10^8 m/s), η_{LoS} is an average additional loss of the Line-of-Sight in the free-space propagation that depends on the environment, and η_{NLoS} is the average additional loss of the None-Line-of-Sight in the free-space propagation that depends on the environment. The probability $\rho(\xi, \Theta)$ on the occurrence of NLoS related to an angle of elevation can be expressed as $\rho(NLoS, \Theta) = 1 - \rho(LoS, \Theta)$. The expression below computes the probability of LoS:

Equation 11 – Probability of Line-of-Sight.

$$\rho(\mathrm{LoS}) = \prod_{i=1}^{m} 1 - e^{-\frac{2\gamma^2 \cdot [\wp_{ij} \cdot (n + {}^{1}/_{2}) \cdot (\wp_j - \wp_i)]^2}{(m+1)}}$$

Where $m = \lfloor r\sqrt{\alpha - 1} \rfloor$, r is the ground distance between UE and RRH-UAV, γ describe the building elevation distribution, while $\wp_{ij}$ represents the altitude of two devices communicating. One can understand that once UAVs are above ground, there is less to no building distribution that contributes to fading of signals. Therefore, there is always a high probability of LoS from the UAV to the LAP. However, fronthaul communication links among UAVs may have weak LoS due to manufactured structures and mountains if located in low altitude. $\Lambda = \sum_{\xi} \delta_{\xi} \cdot \rho(\xi, \Theta)$ expresses the typical angle of elevation created by 3d location (longitude, latitude, and altitude) of UE, UAV and LAP. The International Telecommunication Union (ITU) in its recommendation document (R, 2003) recommends using a unique method to get the probability of geometry-based LoS between a terrestrial transmitter at an elevation h_{tx} and a receiver at an elevation h_{rx} in urban environments. The cell coverage radius of the coverage zone can be expressed as $R = r|\Lambda = \delta_{max}$. The maximum path loss exponent δ_{max} can be figured from the expression below:

Equation 12 – Maximum path loss.

$$\delta_{max} = \frac{\eta_{LoS} - \eta_{NLoS}}{1 + \alpha \cdot e^{-\mathscr{b} \cdot tan^{-1}\left(\frac{h}{R}\right) - \alpha}} + 10\left(\log \wp_{ij}^{2} \cdot 2\left(\log f + \log \frac{4\pi}{c}\right)\right) + \eta_{NLoS}$$

Equation 13 – Rayleigh probability density function.

$$F(H) = \frac{H}{2\gamma^2} e^{\frac{-H^2}{2\gamma^2}}$$

Where, α is the ratio of built-up land area to the total land area, $\mathscr{b}$ is an environmental variable, f is the signal frequency in hertz (Hz), γ describes the height of buildings distribution according to the Rayleigh probability density function, H is the building height in metres, d is the distance between a transmitter and a receiver, c is a speed of light in metres per second (3 x 10^8 m/s), η_{LoS} is an average additional loss of the Line-of-Sight in the free-space propagation that depends on the environment, η_{NLoS} is the average additional loss of the None-Line-of-Sight in the free-space propagation that depends on the environment, h is the altitude of the access point, R is a cell coverage radius in the coverage zone, and $\wp_{ij}$ is the height between two devices communicating. Rayleigh probability density function is suitable to predict cases in which there NLoS between transmitters and receivers. Furthermore, the Rayleigh function can model channels in communicating devices. Where modelling for multipath fading in power P_{rx} that will be received, because of phase differences between multipath signals arriving the receiver (MUTLU, 2014). Rayleigh probability density function is expressed in Equation 13.

A. *Signal-to-Noise Ratio.*

The SNR is a measure used in engineering and science which compares the level of signal to the level of background noise. Clearly, SNR may be defined as a ratio of signal power to the noise power, frequently expressed in decibels (dB). A ratio higher than 1:1 (greater than 0 dB) indicates more signal than noise. It can be expressed in its purest form using the S/N ratio formula below:

Equation 14 – Signal-to-Noise Ratio for a fixed static power.

$$\Gamma_{SNR}(R, h) = \frac{P_{rx}}{v}$$

Where, Γ_{SNR} is Signal-to-Noise Ratio (SNR), R is the cell coverage radius of the coverage zone, h is an optimal height of the network node, P_{rx} is a signal power at the receiver, and v is the Background noise power. Though the RRH (mounted on the UAV) often have good LoS to the LAP, the signals can arrive with noise at the receiver. The average received signal-to-noise ratio (SNR), and bit energy for the considered link is expressed as:

Equation 15 – The mean received signal-to-noise ratio for the considered link.

$$\Gamma_{SNR} \triangleq \frac{E_b \cdot \gamma}{N_0}$$

Equation 16 – The received bit energy.

$$E_b = \frac{\Gamma_{tx} \cdot G_{tx} \cdot G_{rx}}{\Delta\delta_{\xi}}$$

Where G_{tx} and G_{rx} are respectively the transmitter and receiver antenna gains, Γ_{tx} is the transmitter signal, and Δ represents data in $bits/s$. We consider Decode-and-Forward (DoF) co-operative communication model from (Chandrasekharan, et al., 2013), that is given by $\rho_e = \rho_A(1-\rho_B) + \rho_B(1-\rho_A)$. Figure 26 depicts three energy sources to provide current to the Network Node. The primary source of energy will be a solar panel that is mounted on a UAV. The solar panel will be able to solely provide power to the node and be capable of charging.

3.6.3 Topology Locality.

UAVs have become an ideal aerial base station, relays, or access points to provide network coverage (Luca, et al., Bringing 5G in Rural and Low-Income Areas: Is it Feasible?, 2017; Mozaffari, Saad, Bennis, & Debbah, Drone small cells in the clouds: Design, deployment and performance analysis, 2015). However, there are challenges which still need addressing, such as the optimal placement of the UAV (Feng, McGeehan, Tameh, & Nix, 2006). It is crucial to locate the UAV in 3D space (longitude, latitude and altitude) for better QoS when proving coverage to ground UE. For the proposed coverage model, it starts by finding the optimal longitude and latitude, then find the optimal altitude by evaluating the SNR among the considered UEs.

3.6.4 Optimum Horizontal Placement.

The coverage region of a UAV-Based cell is considered to be a disc-like. Hence, by formulating and placing a circle on the horizontal plane is equivalent to deploying the UAV in 2D horizontally. Figure 28 thus depicts a UAV providing coverage to ground UE. The yellow cone represents the coverage area. Clearly, in Figure 28 not every UE is on the coverage region. The use-case above raises issues on how to optimally provide wireless services to as many UEs as possible. Hence, the UAV coverage region C should be approached as a circle placement problem, which will optimally maximise the number of UEs covered. By considering the number of UEs within the UAV's coverage will aid with its placement.

Figure 28 – Unmanned Aerial Vehicle serving users in a targeted area.

The conditional expression below identifies if a UE_i is within the targeted coverage zone for a specific UAV:

Equation 17 – Check if the user is in the coverage area.

$$u_i\left(\left(x_i - x_{D_i}\right)^2 + \left(y_i - y_{D_i}\right)^2\right) \leq R^2$$

The UE_i is considered to be covered if it is located within a distance of at most R from the centre of the coverage region C. By permitting $u_i \in \{0,1\}$ to be the binary decision variable such that $u_i = 1$ when the UE_i is inside the coverage region C, and $u_i = 0$ when is not inside. Alzenad, *et al.* (2017), in their work, took a step further and enforced the requirement that constraint Equation 17 be satisfied when $u_i = 0$. With this, the Equation 17 can be re-expressed as:

Equation 18 – Constraint method for checking if users are inside the coverage zone.

$$\left(x_i - x_{D_i}\right)^2 + \left(y_i - y_{D_i}\right)^2 \leq R^2 + M(1 - u_i)$$

Where M is the constant which satisfies the constraint in Equation 17 when $u_i = 0$. When $u_i = 1$, the equation reduces to the constraint Equation 17. Conversely, when $u_i = 0$, any preference for $\left(x_{D_i}, y_{D_i}\right)$ within the allowable deployment region will satisfy the constraint Equation 18. This problem is a Mixed Integer Non-Linear Problem, which is expressed as:

$$maximise\left(x_{D_i}, y_{D_i}, u_i\right), \sum_{i \in \mathcal{u}} u_i$$

Subjected to:

$$\left(x_i - x_{D_i}\right)^2 + \left(y_i - y_{D_i}\right)^2 \leq R^2 +, \forall i \in \mathcal{u}$$

Equation 19 – The horizontal dimension placement.

$$u_i \in \{0,1\}, \forall i \in \mathcal{u}$$

Where, x_i is a latitude position for a specific user considered, x_{D_i} is the latitude position for the UAV providing coverage, y_i is the longitude position for a specific user considered, y_{D_i} is the longitude position for the UAV providing coverage, R is a cell coverage radius of the coverage zone, M is a constant variable, and u_i is a binary decision variable to check if the user is covered. Let $\left(x_{D_i}, y_{D_i}\right)$ and $\mathcal{u}^{cov} \subseteq \mathcal{u}$ signify the optimal 2D horizontal location of UAV and the set of the covered users obtained by Equation 19, separately.

3.6.5 Optimum Altitude for Unmanned Aerial Vehicle.

Figure 29 – Unmanned Aerial Vehicle adjusting altitude to serve ground users.

After finding the optimum horizontal placement, the next step is to find the optimal altitude for the best QoS. Figure 29 illustrates a UAV adjusting the altitude to cover targeted UE. The UAV transmits a signal at a specific power of P_{tx}, and in return receive the power of P_{rx} from UE, which is express as (Mozaffari, Saad, Bennis, & Debbah, Drone small cells in the clouds: Design, deployment and performance analysis, 2015):

Equation 20 – Received Power.

$$P_{rx} = P_{tx} - \eta(R, h)$$

Equation 21 – Signal-to-Noise must be equal to, or greater than the threshold.

$$\Gamma_{SNR}(R,h) = \frac{P_{rx}}{v} \geq \Gamma_{SNR_{thr}}$$

Where, P_{rx} is a signal power at the receiver, P_{tx} is a signal power at the transmitter, $\eta(R,h)$ is the average additional loss between the transmitter and receiver during radio wave propagation depending on the environment, h is the altitude of the access point, R is the cell coverage radius of the coverage zone, and v background noise power, and $\Gamma_{SNR_{thr}}$ is Signal-to-Noise Ratio threshold. The moment Equation 21 is satisfied at the UAV height h, the altitude is optimal. To find the maximum possible coverage radius, $\Gamma_{SNR}(R,h) = \Gamma_{SNR_{thr}}$ should be satisfied. Assuming the UAV is covering the maximum possible UEs with a fixed transmission power of P_{tx}. Then by solving Equation 22 will yield the optimal altitude, which is expressed as (Feng, McGeehan, Tameh, & Nix, 2006; Mozaffari, Saad, Bennis, & Debbah, Drone small cells in the clouds: Design, deployment and performance analysis, 2015):

Equation 22 – Optimal Altitude based on maximum coverage.

$$\frac{180(\eta_{NLoS} - \eta_{LoS})\beta Z}{\pi(\mathrm{Z}+1)^2} = \frac{20\mu}{\log(10)}$$

Where, η_{LoS} is an average additional loss of the Line-of-Sight in the free-space propagation that depends on the environment, η_{NLoS} is the average additional loss of the None-Line-of-Sight in the free-space propagation that depends on the environment, and β describes the mean number of buildings per unit area $\left({}^{Buildings}/_{km^2}\right)$. And $Z = \alpha^{-\beta\left[\frac{180}{\pi}\tan^{-1}(\mu)-\alpha\right]}$, furthermore $\mu = \frac{h}{R}$. Through solving Equation 22, $\mu_{Optimal} = \frac{h_{Optimal}}{R_{max}}$ is computed.

3.6.6 Network Topology Overview.

The forthcoming 5G network is anticipated to be the foundation for various use cases (Foukas, Patounas, Elmokashfi, & Marina, 2017). 5G-PPP[9] in architectural vision article provides convolutional characteristics among related parts of 5G (Cosmas, Jawad, Salih, Redana, & Bulakci, 2019). Additionally, both ITU[10] and 5G-PPP have recognised the following use-case families:

i. Enhanced mobile broadband.
ii. Massive machine-type communications.
iii. Critical communications.

---

[9] The 5G Infrastructure Public Private Partnership.
[10] The International Telecommunication Union.

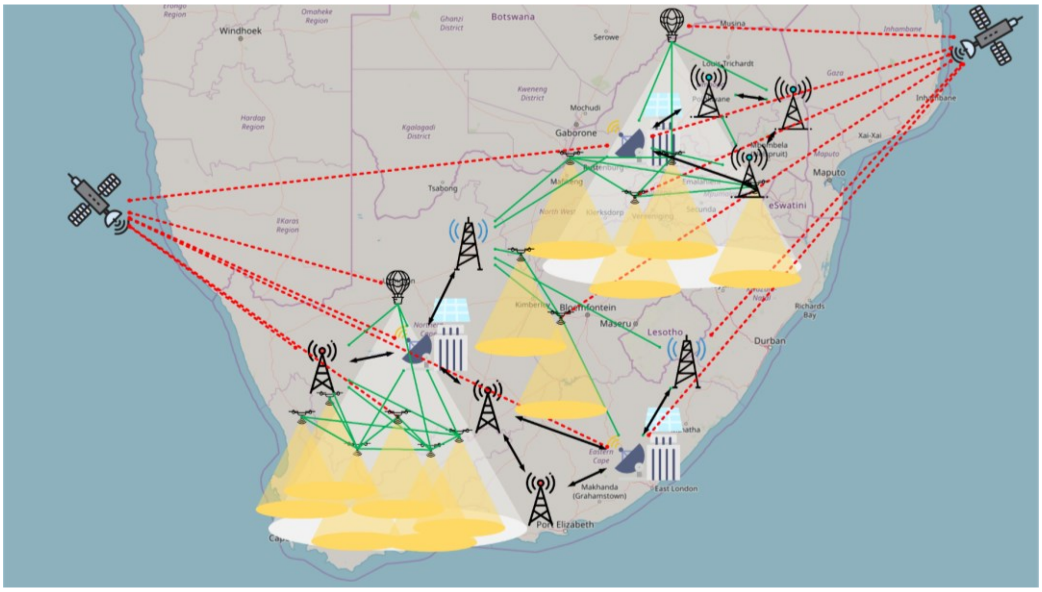


Figure 30 – Envisioned forthcoming network connecting South Africa

NGMN[11] in architectural vision article endorses SDN implementation (Alliance, 2015). Network management and orchestration must map in service, network, and infrastructure layers to deposit an excellent foundation of virtual networking. Figure 30 depicts the ideal infrastructure orchestration with red lines representing logical connection from terrestrial network nodes and LAP (Air Balloon), while green lines are also the logical connection among UAV based nodes and terrestrial-based nodes. Moreover, black arrow lines are the physical connection among terrestrial nodes over optic cables.

3.6.7 Physical Infrastructure and Deployment.

The architecture of the new 5G network will be different from those of the older generations. Current systems are in a race to effectively utilize and get the most out of the existing technologies before they become obsolete. Service providers are also upgrading their systems or adding on 5G infrastructure to enable much faster networks capable of delivering the richer content such as HD-4K (High Definition) multimedia/video streaming, Hi-Res (High Resolution) images and the data flood produced from mobile phones and social media apps. The 5G mobile network needs to deal with some of the challenges facing the 4G network nowadays such as high energy consumption, spectrum crisis, bad interconnectivity, inadequate coverage, flexibility, and poor Quality of Service (QoS) (Al-Namari, Mansoor, & Idris, 2017).

One potential solution could be the use of a SDN architecture. In SDN, terminals and network components can be dynamically reconfigured (adapted) to a new situation. Network operators use the reconfigurability to introduce value-added services more efficiently. Reconfigurability is based on cognitive radio, which is a technology that enables devices to determine their location, sense spectrum used by neighbouring devices, change frequency, adjust the output power, and alter transmission parameters and characteristics. Cognitive radio is a transceiver

---

[11] The Next Generation Mobile Networks.

that can understand and react to its operating environment. Thus, cognitive radio concerns mobile devices and networks which are computationally intelligent about radio resources and related communications to detect user communication needs and provide wireless services appropriate to those needs. Hence, the radio is aware and cognitive about changes in its environment and responds to these changes by adapting operating characteristics in some way to improve its performance (M Mousa, 2012).

LAP are seemingly-stationary aerial platforms such as quadcopters, balloons, and helicopters, usually characterised by an altitude laying within the troposphere (Al-Hourani, Kandeepan, & Lardner, 2014). This section discusses two kinds of networks that are considered ideal for LAP with ground BSs. The first recognised type is FANET, and the second type is the Hybrid network composed of UAVs and terrestrial towers.

3.6.8 FANET Configuration.

In our architecture, we envision two separate FANET configurations, where on one network the services are provided with only UAVs and on the other one services are provided with a hybrid of a network as discussed below.

A. Unmanned Aerial Vehicle Network without Base Station.

In this framework, all airborne nodes act as the access point and connect directly to the gateway base station. FANET consist of airborne nodes in motion, location, and image sensors. Table 4 discusses four distinct types of networks, including FANET. The airborne nodes flying in the

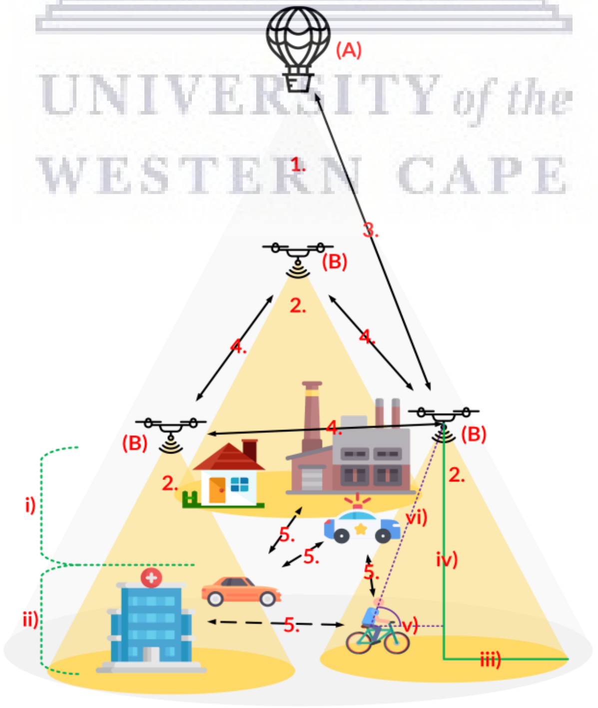


Figure 31 – UAV aware coverage model, connection lines are logical.
(A) RRH – Balloon, (B) RRH – UAV, 1. Balloon Coverage Area, 2. UAV Coverage Area, 3. Backhaul Radio Link, 4. Fronthaul Radio Link, 5. DTN, i) Free Space Path loss, ii) Excessive Path loss, iii. UAV Coverage Radius, iv) UAV Height, v) UE Radius, vi) UE distance to Access Point.

sky, communicate with each other using an Ad Hoc network. The above illustration (Figure 31) depicts a LAP network coverage provided by a balloon [labelled A in the figure] and UAVs. Additionally, the picture shows another way where DTN might reduce the stress on the network. However, the illustration does not depict the terrestrial network (To see the entire proposed system see Figure 15). A hot-air balloon (labelled 'A') is a gateway base station allowing public and local commutations to the airborne nodes. UAVs are hovering to their designated location providing a wireless network, fronthaul link (labelled '4') making it possible for the drone to communicate with each other, while the backhaul link connecting the UAVs with the balloon.

The mobile user equipment can reduce the network load using delay tolerant network. This method can also improve the way IoT devices convey information. Instead of a device having to query the database for precise information, it can directly get it from the neighbouring devices. For example, in a motor vehicle accident, it might be necessary for the police personnel and emergency assistant to synchronise records. In this way, they can share information faster. UAVs, hot-air balloons, and terrestrial-BSs form the ideal flying Ad Hoc network. All the airborne cells will have to convey their information to the gateway, which may be a hot-air balloon or terrestrial base station. Conveniently, the base station will connect with the satellite to send and receive public messages. Table 7 discusses the technology of the framework.

Table 7 – Flying Ad Hoc System configuration.

COMPONENTS	TYPE	TECHNOLOGY
UAV	Access point	Wi-Fi, 5G
	Base Station	4G, WiMax, 5G
Balloon	Gateway	5G

B. *Unmanned Aerial Vehicle Network with Base Station.*

The hybrid network is composed of flying and mobile terrestrial Ad Hoc networks. Figure 15 and Figure 32 show the mobile and flying Ad Hoc network with fibre optical network. Since the hybrid network is a combination of MANET, FANET, and Cable network, by default it inherits all the properties of the FANET described in the section above. Fibre-optic network [labelled '6'] connects the nearby residences, co-operation, towers, streetlight cells. The terrestrial base station [labelled 'C'] also acts as a landing area for the airborne nodes. Fortunately, maintenance and updates will be carried out in these base stations. The drones can land at the base station in case emergencies or severe weather. Conceptually, towers are the best fit for large cells can cover a long-range than small cells. Radio link '7' from Figure 32 connects isolated subscribers such as those in the farms, even in mines, with 5G wireless network through large cells. Furthermore, UAVs can be specially tasked with hovering around co-operates during the time that they require high bandwidth to update their data centres. Users with fibre-optic [labelled '6'] can increase 5G coverage by using software define network devices just like the way public traffic lights will be extending the coverage with MU-MIMO. Table 8 discusses the technology of the framework.

Table 8 – Hybrid Ad Hoc System configuration.

COMPONENTS	TYPE	TECHNOLOGY
UAV	Access point	Wi-Fi, 5G
	Base Station	4G, WiMax, 5G
Street Pole/Light	Access point	WiMax, 5G
Traffic light	Access point	WiMax, 5G
HUB/Router/Modem	Access point	4G, WiMax, 5G
User Equipment	Subscriber	Wi-Fi, 4G, WiMax, 5G
Fibre optic	Cable/Ethernet	CATe5, CAT 6
Tower	Access point	3G, 4G, WiMax, 5G
	Base Station	3G, 4G, WiMax, 5G
Balloon	Gateway	5G

Figure 32 – Hybrid network coverage, connection lines are logical. (A) RRH – Balloon, (B) RRH – UAV, (C) Base Station, (D) Large Cell Radio, 1. Balloon Coverage Area, 2. UAV Coverage Area, 3. Backhaul Radio Link, 4. Fronthaul Radio Link, 5. DTN, 6. Optical Link. 7. Radio Link

3.7 NETWORK PROVISION.

An Air-to-Ground link is established from the LAP to the UAVs and terrestrial base stations. UAVs has autopilot feature, with all cellular nodes assumed to have similar characteristics; and each UAV can communicate telemetric information within the network. We propose the network service delivery for our ideal architecture, depicted in Figure 33. The model takes into consideration user spatial and weather forecast data to create backhauling links. The UAV can periodically change position to support particular tasks, such as providing a hospital with unthrottled bandwidth to perform remote surgery or backup their entire database, including large data of ultra-definition recorded scans and surgery.

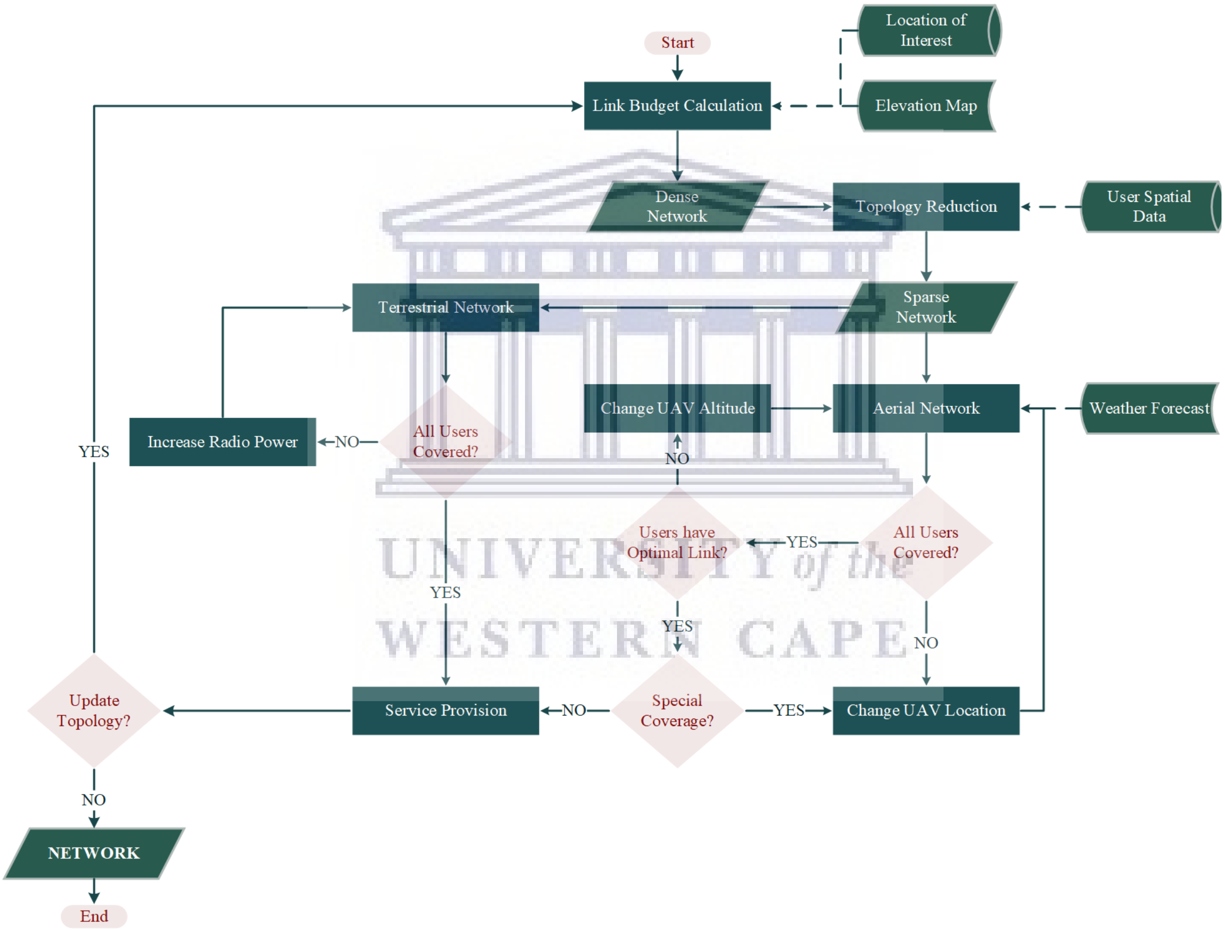


Figure 33 – 5G network provision in rural and low-income areas model.

3.8 COVERAGE TASK ALLOCATION.

Many studies have been done on task allocation in a wireless network with positive results (Yin, Dai, Li, Chang, & Li, 2017). Most of these task allocation approaches focused on optimising the network performance by distributing various subtasks to access nodes. The approaches were mainly developed as a multi-objective constrained optimisation problem and have been proven to be non-deterministic polynomial-time problem (Yang, Qiu, Meng, & Long, 2014). For commercial 5G network, the service can be offered as the user or area centric. In user-centric, the network is developed to meet the client's expectations, while the other prioritizes the coverage area.

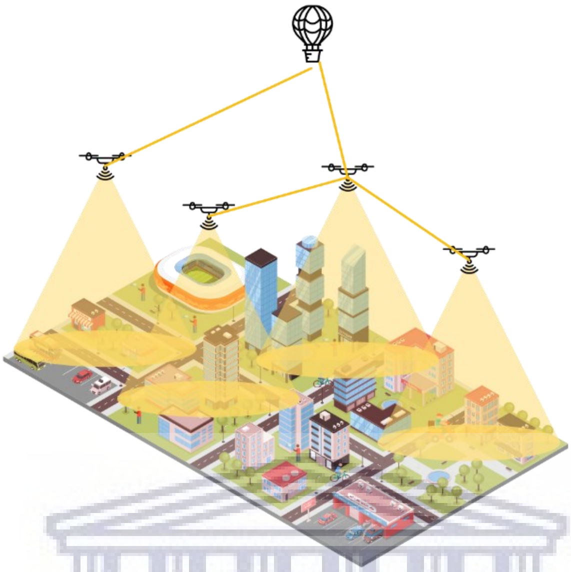


Figure 34 – Unmanned Aerial Vehicle Task Allocation Scenario.

Our proposed architecture requires that tasks get allocated among users and nodes. From Figure 34, we have Flying Ad-Hoc Networks (FANET), where UAVs are communicating through the LAP as their gateway node. The yellow cone represents the coverage range per each UAV. Considering a coverage scenario where servers within a hospital are connected to one UAV-based node, which also serves other clients in the local area. In the case of an emergency, the doctor might want to perform a remote surgery through tactile Internet, which requires high bandwidth. This scenario brings up the questions of how best to distribute services to all users and to which node they should be connected to. Furthermore, the best access point needs to be selected for users in an overlapping coverage zone. This issue is addressed in Chapter V, where two algorithms (Stable Roommate and Gamma Random) are considered proposes for assigning users the best access point without compromising coverage on the considered area.

3.9 SUMMARY.

This chapter (Network Orchestration) start by introducing the key features of 5G technologies and concept model by (Luca, et al., Bringing 5G in Rural and Low-Income Areas: Is it Feasible?, 2017). In our envisioned model, we introduce 5G hotspots that can be mounted on streetlights and residential complexes. The 5G architecture enables: i) network programming, ii) cloud computing, iii) virtual technology, and iv) multi-tenancy. Also, its service orchestration and management guarantee service all the time. Also lays the foundation for the folliwing chapter by discusing the energy and coverage models.

IV. ECONOMIC FEASIBILITY

This chapter evaluates the economic feasibility of deploying the network orchestration models proposed in chapter 3 for setting up a hybrid network in rural areas of South Africa. The evaluation reveals that such a network can be engineering at low monthly subscription fees to the end-users. In summary, the chapter starts by defining the foundation to the economic model and then computes the Capital and Operational Expenditure. It also sets the context of the evaluation of the service provision in rural areas by providing: i) an explanation of the specific purpose for this research, and ii) the scope of the work presented in this chapter.

The primary purpose of the economic analysis is to determine whether or not it is economically feasible to provide a profitable network in rural areas using cellular nodes (mounted on Unmanned Aerial Vehicle) to play the role of a backbone network for a terrestrial cellular network. This chapter presents and discusses the economic parameters calculations from five district municipalities, four townships, three rural residential areas, and one low-income town with the expectation of:

i. Revealing ways by which clients can be billed.
ii. Determining the number of rollouts required for a complete infrastructural deployment.
iii. Comparing the terrestrial network to the aerial network in terms of expenses.
iv. Studying the shared network cost on the terrestrial nodes.

The discussion on the economic feasibility of the proposed network in this chapter is organised in the following manner:

i. Introduction to the chapter and its contextual direction.
ii. Computational methodologies
iii. Analysis of expenditures, including:
    a. Computation of Capital expenditure on:
        i. Remote access network.
        ii. Virtualised network.
    b. Computation of Operational Expenditure on the remotely accessed network.
iv. Recommendation on appropriate monthly subscription index to yield maximum Internal Rate of Returns.

4.1 INTRODUCTION.

The rapid proliferation of mobile devices and the corresponding growth in the volume of multimedia data traffic have necessitated the push to re-architect the current generation of mobile cellular communication and move into the fifth generation cellular technology. This fifth-generation (5G) is characterised by three unique features, viz.: ubiquitous connectivity, extremely low latency and ultra-high-speed data transfer (Panwar, Sharma, & Singh, 2016). To achieve this goal, Mobile Service Providers (MSPs) will be obliged to purchase and operate new physical infrastructure, hire engineers with high qualifications (to operate this equipment) and deploy dense terminating network equipment such as Base Stations (BSs). All these will lead to high Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) for TSPs. Therefore, it is important to reduce the factors affecting the Total Cost of Ownership (TCO) for mobile network operator or MSP, especially as there might be a mismatch between the requirements of the market and capabilities provided by network equipment, as well as the demand for resource sharing.

Table 9 – Spectrum Cost Matrix (Loni, 2018).

FEATURE	PRICES
Individual Application	R500 000 (as in 2014 ITA)
Class Application	R12 187
Renewal	R6 094
Amendment	R60 940
Uni Price per MHz	R2 344
Price per Block	Auctioned
Auction Investment	R25Bn
Satellite Hub Station	R58 596

The cost and process of obtaining a BS is often expensive and cumbersome. In South Africa (ZA), this cost is well over R100,000 on average. Beyond the cost element, it also takes months for the approval of the necessary license(s). Currently, there are only 20 fully licensed commercial operators in South Africa as of January 2018 (African Drone, 2018). Table 9 summarises the primary cost estimation for acquiring a spectrum license. However, the cost of spectrum blocks are not shown because these are often auctioned to the highest bidder. Spectrum management approaches have been briefly discussed in Chapter III.

4.2 RESEARCH QUESTIONS.

This chapter contains the results of the grounded theory methodology study conducted to answer the following research questions from Chapter I:

i. *Is it possible to deploy a holistic 5G architecture explicitly designed for low and sparsely populated areas?*
ii. *What would be the impact of infrastructure sharing?*
iii. *How many rollouts are needed for a complete infrastructure to take place and at what cost each?*
iv. *Can targeting different end-user bandwidth improve QoS and increased coverage?*
v. *What are governments, regulatory bodies and policymakers doing to ensure the swift rollout of 5G technologies?*

vi. *Finally, how are subscribers going to be billed?*

4.3 ECONOMIC MODEL FOUNDATION.

The modern telecommunication society has recently witnessed the convergence of cloud networking, fast connectivity and high processing power taking place over the existing Internet model (Bouras, Ntarzanos, & Papazois, 2016). However, despite the gap between market requirements and network capabilities, there is still a significant absence of literature that caters for the rolling out of heterogeneous telecommunication technologies (Bouras, Ntarzanos, & Papazois, 2016). Frequently, researchers either concentrate solely on modelling the spatial viability aspect, as evidenced in the fixed broadband literature by Oughton & Frias (2018) and/or on cost-effective radio network deployment as done in the work of Nikolikj & Janevski (2014). It has been predicted that, with the emerging heterogeneous 5G wireless network infrastructure, the administration of services and network will be in an assembled way (Narang M. , et al., 2017). Hence, this chapter studies the Total Cost of Ownership, CAPEX, OPEX, Return on Investment (ROI), Internal Rate of Return (IRR) and the Economic Value Added (EVA) for deploying 5G wireless connections into rural and low-income areas of South Africa.

4.3.1 Assumptions and Scope.

For this work, the following assumptions are made: i.) in computing the CAPEX, the costs of obtaining both the spectrum-operating license(s) and the Remote Operator’s Certificate (ROC) for operating UAVs are neglected. This is due to the cumbersome process (es) involved which cannot be directly modelled. ii.) for the aerial network, all UAVs are assumed to have autopilot functions, allowing them to hover over an area to supply coverage. Furthermore, they are equipped with energy-saving protocols, for prolonged flight times. iii.) There are three types of nodes in the system, Table 12 presented and discussed these nodes and their features based on the modelling functions and network architecture given by Luca, *et al.,* (2017)

It is also assumed that all cellular nodes (user equipment) have poor and limited connections to the public gateway BS. The economic framework considered in this thesis includes the cost of equipment and deployment scenarios that will enable the computation of CAPEX, OPEX and the best monthly subscription fee. These financial and economic analyses are performed on five category C district municipalities, four different townships, three rural residential areas, and a low-income town in ZA. For this work, we define a community as a cluster of individuals in the form of families living together for a long time in a neighbourhood while having mutual goals, interest, ways of life, and cultural norms. A rural community is thus an area under development and characterised as follows:

i. A community living in a region that is sparsely populated. This sparse population can mainly be attributed to mass migrations to the cities and other urban areas.
ii. Residents live a communal lifestyle with lower average income compared to the cities. For example, the average monthly income of a rural household in ZA is R2 542 (Werner, 2017),versus R21 966 in urban areas (Trading Economics, 2020).
iii. Rural communities experience slower development compared to urban areas due to numerous factors. For instance, the Internet and telecommunications, if present are typically slower than those in the cities.

iv. Poor roads network and mountainous landscape, which pose a serious challenge to the installation and maintenance of cell towers.

v. Intermittent electricity supply from the grid, hence difficult to guarantee QoS if the network equipment is solely dependent on an electric grid. To provide reliable broadband connectivity, it is crucial to focus on the development of technologies capable of harnessing renewable energy sources.

4.3.2 Deployment scenarios and sites.

The economic analysis carried in this chapter is performed to estimate the costs and revenue generated by the proposed 5G network architecture for the areas of interest described in Table 10. Furthermore, the ideal monthly subscription fee for users on each location is shown with at least a 30% internal rate of returns.

Table 10 – District Municipalities of South Africa (Stats SA).

	EASTERN CAPE	LIMPOPO			NORTHERN CAPE
District	Chris-Hani	Mopani	Vhembe	Waterberg	Frances Baard
Area Size	36,407 km²	20,011 km²	25,596 km²	44,913 km²	12,836 km²
Main Economic Sectors	Community Services (52%) Trade (15%) Finance (14%) Transport (6%) Agriculture (4%) Manufacturing (4%) Electricity (2%)	Mining (30.1%) Community Services (22.6%) Trade (14.6%) Finance (14.6%) Transport (8.2%) Agriculture (3.2%) Electricity (2.8%) Construction (2%)	Mining Community services Finance	Mining Agriculture Tourism	Community services (28%) Finance (22%) Trade (15%) Transport (12%) Mining (10%) Agriculture (4%) Manufacturing (4%) Construction (3%) Electricity (2%)
Population	840,055	1,159,185	1,393,949	745,758	387,741
Unemployment rate (Aged 15–34)	~ 60%	51.4%	~50.6% (Year 2011)		43.9% (Year 2011)
Higher Education (Aged 20+)	6.5%	8.1%	9.6%	9%	8.4%
Water	41,822%	47,313%	33,557%	-	-
Piped water inside dwelling	22.3%	12.8%	7.4%	24.4%	48.4%
Electricity	89.9%	94.5%	94.6%	86.1%	90.2%
Sewerage and Sanitation	32.8%	20.5%	20.9%	-	-
Flush toilet connected to sewerage	31.6%	14.1%	16%	43.8%	78.4%
Solid Waste Services	No	No	No	No	No

Figure 35 – Frances Baard District Municipality © Google Maps.

Figure 36 – Vhembe District Municipality © Google Maps.

Figure 37 – Mopani District Municipality © Google Maps.

Figure 38 – Waterberg District Municipality © Google Maps

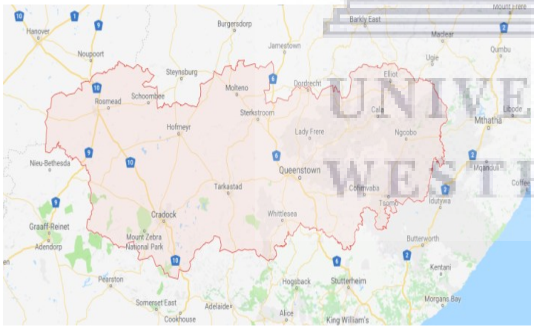


Figure 39 – Chis-Hani District Municipality © Google Maps.

The 5G network architecture proposed in this thesis is to be deployed in rural areas and low-income regions. Hence, the regions of interest as described in Table 10, and are district municipalities with a large percentage of the able citizens working in mining and agricultural industries. The 5G network can improve production in industries while also providing residents with access to a basic wireless connection.

A. Climate History.

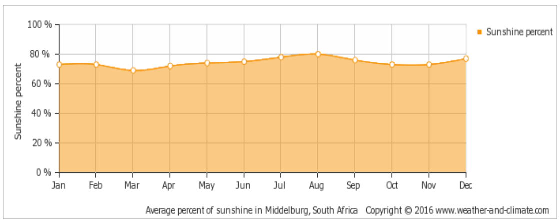


Figure 40 – Average percentage of Sunshine in Middleburg

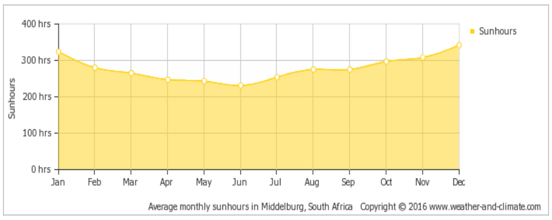


Figure 41 – Average monthly Sun hours in Petersburg © Weather-and-Climate.com

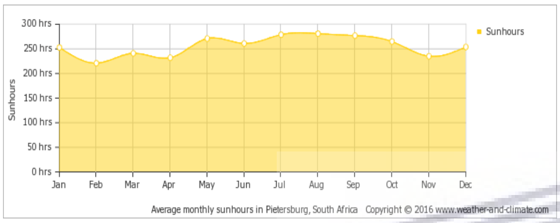


Figure 42 – Sun hours in Middelburg © Weather-and-Climate.com

Without loss of generality, the climate conditions of Frances Baard and Chris-Hani district municipalities would be considered similar to those of Middelburg, while those of Mopani, Vhembe, and Waterberg district municipalities (all in Limpopo province) are considered similar to that of Petersburg. Middleburg and Petersburg both get about 70% of sunshine throughout the year, as shown in Figure 41. This makes them absolutely ideal locations for implementing the proposed 5G network architecture. Figure 40 and 42 respectively depict the average hours of sun throughout the year for these two districts.

B. Deployment Parameters.

This economic analysis would help determine the optimal monthly subscription fee for users within these designated areas that will yield profitable revenues. The low-income / rural areas considered in this work are briefly described below.

(i) Townships/Low-Income Areas.

Figure 43 – Khayelitsha in Cape Town © http://purposefultravel.net/

Figure 44 – Soweto in Johannesburg © https://csolsqs.com/

Soweto and Khayelitsha are low-income areas selected that do not belong to any Category C district municipality because of their high population. Soweto is a township in Gauteng under the Johannesburg Metropolitan Municipality with approximately 1,271,628 inhabitants, and an average population density (user density) of 6,400 people per square kilometre (users/km^2) (Adrianfrith, 2011). The digital population statistics in South Africa as of January 2019 show 31.18 million Internet users, of which 28.99 million are mobile Internet users (Clement, 2019). For our study, we assume that 80% of the population in Soweto are active users of the Internet. Khayelitsha, on the other hand, is an area under the City of Cape Town municipality, with a population of 391,749 inhabitants and an average of 10,000 people per square kilometre [users/km^2]. Since these two townships are neighbours to the two major cities that drive the South African economy (Johannesburg and Cape Town), it would be ideal for each user to get an average downlink throughput of at least a hundred megabytes per second (100 Mbps/user).

Figure 45 – Zeerust Town in North West Province
© http://www.bluegnu.co.za/

Zeerust is a small commercial town in the North West Province with approximately 9,093 inhabitants. The main economical trades are cattle, wheat, maize, tobacco, and citrus fruit farms as well as fluorite and chromite mines. It has an average user density of 160 per square kilometre [users/km^2] and 75% of its inhabitants are active on the Internet and use wireless communications. Both Zeerust and Lulekani require fifty megabytes per second on average for each user [50 Mbps/user]. Other township considered are Lulekani, a township outside Phalaborwa in Limpopo province; Duduza – a township in East Rand, Gauteng. Most areas within these towns do not have electricity, the deployed network will have to rely solely on solar power and batteries.

(ii) ***Rural Areas.***

Figure 46 – Mandileni Village in Eastern Cape © http://www.tripmondo.com

Figure 47 – Old Telkom Line in Chris-Hani Municipality © http://www.tripmondo.com

Figure 48 – Clinic in Hlankomo Rural Area © http://www.tripmondo.com

Hlankomo is a rural area with 199 households with a population of about 1,111 people, and none of the households has electricity supply (Stats SA, 2019). The two other rural areas considered are Mandileni – a village next to Mthatha in the Eastern Cape and Gon'on'o – a village next to Giyani Town in Mopani District municipal. Each of these villages only requires fewer than five UAV-based cells or at most two LC-based wireless connection. These three villages are not connected to the national electricity grids, hence deployed cells have to use solar power and batteries as energy sources. Figure 48 is a picture of a clinic in Hlankomo that already uses solar power for lighting and powering required machinery.

C. Parameters set over the different scenarios.

Table 11 describes a detailed set of parameters for the different deployment scenarios. Lack of power grids in rural areas contributes to fewer people having device(s) that can access the wireless network. Hlankomo and Mandileni have 30% of active user ratio due to lack of electricity, while in sharp contrast Duduza in Gauteng (an area with mostly illegal electricity connections) has a higher active user ratio of 80%.

Table 11 – Parameters set over the different scenarios.

PARAMETER		SYMBOL	SCENARIO												
			Mopani	**Vhembe**	**Waterberg**	**Chris-Hani**	**Frances Baard**	**Soweto**	**Khayelitsha**	**Lulekani**	**Zeerust**	**Duduza**	**Hlankomo**	**Mandileni**	**Gon'o'o**
Type		-	District	District	District	District	District	Township	Township	Township	Low-Income	Township	Rural Residential	Rural Residential	Rural Residential
Area Description		-	Category C Municipality located in Limpopo	Category C Municipality located in Limpopo	Category C Municipality located in Limpopo	Category C Municipality located in Eastern Cape	Category C Municipality located in Northern Cape	Next to Johannesburg	Next to Cape Town	Outside Phalaborwa in Limpopo	Commercial town situated in North West	A township west of Nigel on the East Rand	A village next to Qumbu and Mthatha in Eastern Cape	A village next to Mthatha in Eastern Cape	A village next to Giyani in Limpopo
Area Size		A	20,011 [km^2]	25,596 [km^2]	44,913 [km^2]	36,407 [km^2]	12,836 [km^2]	200.03 [km^2]	38.71 [km^2]	6.61 [km^2]	57.09 [km^2]	11.23 [km^2]	- [km^2]	- [km^2]	- [km^2]
Average Density		δ	55 [users/km^2]	51 [users/km^2]	15 [users/km^2]	22 [users/km^2]	30 [users/km^2]	6,400 [users/km^2]	10,000 [users/km^2]	2,200 [users/km^2]	160 [users/km^2]	6,500 [users/km^2]	- [users/km^2]	- [users/km^2]	- [users/km^2]
Average Downlink Throughput		T	50 [Mbps/user]					100 [Mbps/user]		50 [Mbps/user]		100 [Mbps/user]	10 [Mbps/user]		
Number of Inhabitants		N_U	1,092,507	1,294,722	679,336	795,461	382,086	1,271,628	391,749	14,464	9,093	73,295	1,111	~3,500	~5,000
Active Users Ratio		α	0.5					0.8		0.75		0.8	0.3		0.4
Probability of Usage		β	0.3					0.6		04		0.6	0.1		0.2
Electricity Grid Cost		C_E	R 2.89 [/kWh]									No legal connection	No connection	No connection	No connection
Solar Panel Power	UAV – Based	P_{SP}	4.5 [kWp/site]	3.5 [kWp/site]	4.1 [kWp/site]	3.8 [kWp/site]	3.1 [kWp/site]	4.8 [kWp/site]	4.6 [kWp/site]	2.6 [kWp/site]	3.2 [kWp/site]	3.4 [kWp/site]	1.8 [kWp/site]	1.9 [kWp/site]	2.1 [kWp/site]
	LC – Based		12.7 [kWp/site]	12.6 [kWp/site]	11.5 [kWp/site]	10.7 [kWp/site]	12 [kWp/site]	12.8 [kWp/site]	12.5 [kWp/site]	10.7 [kWp/site]	10.8 [kWp/site]	10.2 [kWp/site]	10.2 [kWp/site]	10.5 [kWp/site]	10.2 [kWp/site]
	Hotspot – Based		7.5 [kWp/site]	7.6 [kWp/site]	7.5 [kWp/site]	7.5 [kWp/site]	6.9 [kWp/site]	9 [kWp/site]	8.1 [kWp/site]	6.5 [kWp/site]	6.3 [kWp/site]	6.8 [kWp/site]	6.4 [kWp/site]	6.5 [kWp/site]	6.9 [kWp/site]
Number of Batteries	UAV – Based	N_B	15 [units/site]	13 [units/site]	12 [units/site]	20 [units/site]	15 [units/site]		6 [units/site]	5 [units/site]		5 [units/site]	3 [units/site]	10 [units/site]	7 [units/site]
	LC – Based		26 [units/site]	27 [units/site]	18 [units/site]	32 [units/site]	24 [units/site]	5 [units/site]	13 [units/site]	10 [units/site]	2 [units/site]	10 [units/site]	7 [units/site]	17 [units/site]	11 [units/site]
	Hotspot – Based		18 [units/site]	18 [units/site]	18 [units/site]	18 [units/site]	18 [units/site]	20 [units/site]	20 [units/site]	15 [units/site]	15 [units/site]	9 [units/site]	7 [units/site]	7 [units/site]	7 [units/site]
Number of Deployed 5^{G-}Nodes	UAV – Based	N_{C-}Max	30,809	39,408	69,149	56,053	19,763	23,654	7,287	127	88	1,364	3	3	5
	LC – Based		2,117	2,509	1,317	1,542	741	7,885	2,429	43	29	455	1	1	2
	Hotspot – Based		30,809	39,408	69,149	56,053	19,763	1,514	467	11	88	88	1	1	1
	UAV – Based	N_{C-}User	6,351	7,527	3,949	4,624	2,222	23,654	7,287	127	85	1,364	3	3	5
	LC – Based		2,117	2,509	1,317	1,542	741	7,885	2,429	43	29	455	1	1	2

<table>
<tr><th colspan="2" rowspan="2">PARAMETER</th><th rowspan="2">SYMBOL</th><th colspan="13">SCENARIO</th></tr>
<tr><th>Mopani</th><th>Vhembe</th><th>Waterberg</th><th>Chris-Hani</th><th>Frances Baard</th><th>Soweto</th><th>Khayelitsha</th><th>Lulekani</th><th>Zeerust</th><th>Duduza</th><th>Hlankomo</th><th>Mandileni</th><th>Gon’on’o</th></tr>
<tr><td rowspan="4"></td><td>Hotspot – Based</td><td rowspan="4">N_{C-}Area</td><td>407</td><td>482</td><td>253</td><td>296</td><td>143</td><td>1,514</td><td>467</td><td>9</td><td>6</td><td>88</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>UAV – Based</td><td>30,809</td><td>39,408</td><td>69,149</td><td>56,053</td><td>19,763</td><td>308</td><td>60</td><td>11</td><td>88</td><td>18</td><td></td><td></td><td></td></tr>
<tr><td>LC – Based</td><td>78</td><td>99</td><td>173</td><td>141</td><td>50</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td></td><td></td><td></td></tr>
<tr><td>Hotspot – Based</td><td>30,809</td><td>39,408</td><td>69,149</td><td>56,053</td><td>1.9763</td><td>308</td><td>60</td><td>11</td><td>88</td><td>18</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Site Acquisition Costs</td><td>UAV – Based</td><td rowspan="3">C_{SA}</td><td colspan="5">R577.3 [k/site]</td><td colspan="2">R173.3 [k/site]</td><td colspan="3">R120 [k/site]</td><td colspan="3">R120 [k/site]</td></tr>
<tr><td>LC – Based</td><td colspan="5">R1732 [k/site]</td><td colspan="2">R519.6 [k/site]</td><td colspan="3">R480.8 [k/site]</td><td colspan="3">R480.8 [k/site]</td></tr>
<tr><td>Hotspot – Based</td><td colspan="5">R812 [k/site]</td><td colspan="2">R240 [k/site]</td><td colspan="3">R160 [k/site]</td><td colspan="3">R160 [k/site]</td></tr>
<tr><td colspan="2">Monthly Subscription Fee</td><td>F</td><td colspan="7">R400</td><td colspan="3">R300</td><td colspan="3">R20</td></tr>
</table>

4.3.3 Commercial Feasibility Objectives.

The commercial feasibility analysis consists of determining: i) the financial investments required for the implementation of the proposed network architecture in rural areas; ii) if a sufficient internal rate of returns can be obtained in the shortest period of time. The economic framework will be implemented within the following context in order to meet the primary goal of this thesis:

i. Consideration of five district municipalities (Chris-Hani, Mopani, Vhembe, Waterberg, and Frances Baard), five low-income areas (Soweto, Khayelitsha, Lulekani, Zeerust, and Duduza) and three rural areas (Hlankomo, Mandileni and Gon'on'o) in South Africa are considered as areas of interest for the study leading to different deployment scenarios.
ii. The economic framework is designed to be able to compute the CAPEX and OPEX outcome for different deployment scenarios.
iii. Furthermore, the feasibility study will compute the minimum monthly subscription fees that will yield a better internal rate of returns over the considered deployment scenarios.
iv. The CAPEX and OPEX for all scenarios are computed using a mixture of Microsoft Excel and Python programming language.

4.4 PROSPECTIVE BUSINESS MODEL.

4.4.1 Service Provision Plan.

Rapid urbanisation has brought about revolutionary concepts, such as uninterrupted Internet access even in public places. With the use of Wi-Fi hotspots, Internet can be made available in public spaces such as malls, bus stations and local hangout spots. However, these developments have been limited to urban areas, while rural areas remain with limited or not no Internet coverage. This section focuses on potential business models for our proposed 5G network architecture, which aims at using UAVs and terrestrial nodes to provide swiftly and on-demand network access. Therefore, it will enable higher bandwidth network coverage in remote areas previously considered economically non-viable at lower subscription costs. This section discusses business vision, process, and structural views.

A. Business Vision View.

The quote below is a business vision view for the proposed architecture.

> *"Agility, inclusivity, and growth of economic, social, and health aspects for impoverished communities through connectivity, communication, and collaboration solutions by providing the 5G coverage with UAVs"*

B. *Business Process View.*

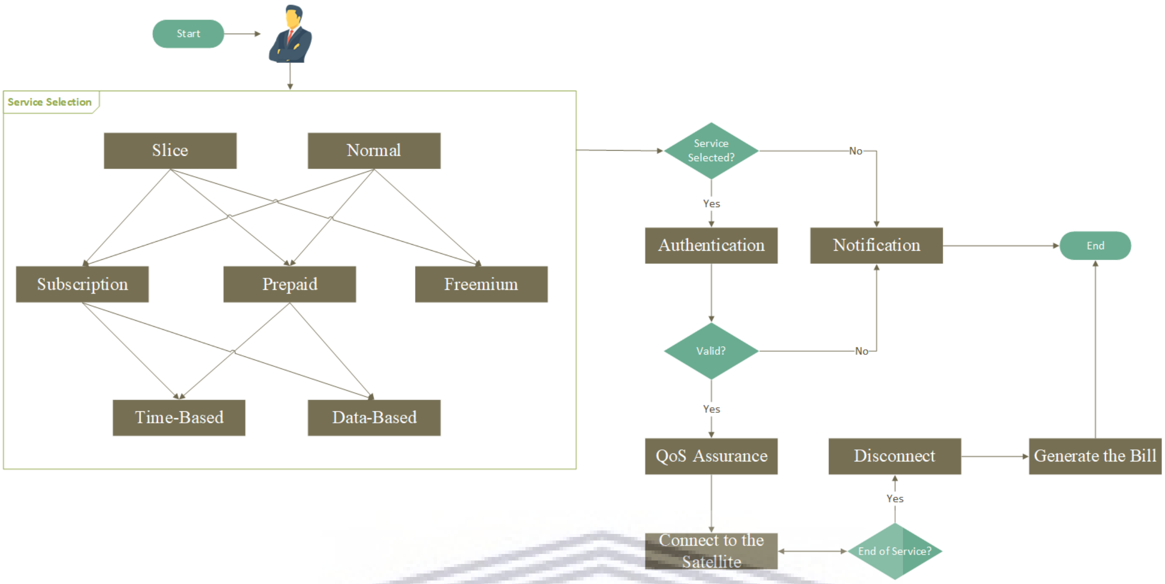


Figure 49 – Client relationship business process.

Figure 49 visualises the business process for client relations in our proposed architecture. Firstly, a client initialises the connection by registering for the required network service. Ideally, corporations and government would require a slice on the network with an unlimited connection. The normal service consists of voice, SMS, data, and fax choices that can be combined as the client wishes. Revenue can be generated on time commitment subscriptions, and for example, a government can make yearly subscriptions while an individual client commits to a monthly subscription model. Prepaid service is designed for subscribers to pay for service before they use them while in freemium, coverage is provided in communities that cannot afford to pay for services with the help of the government and donations. The revenue can also be generated from third-parties that would like to advertise, for example, before a freemium subscriber can make a call, they will have to listen to an advert. The adverts can also be integrated into each website a client visit. The subscription commitment can further be selected as time or data-based service, wherein time-based usage is measured in minutes and in data-based it is measured per GB data bundles until the expiration date, or the services are depleted. The following sections discuss operation management in detail.

C. *Business Structural View.*

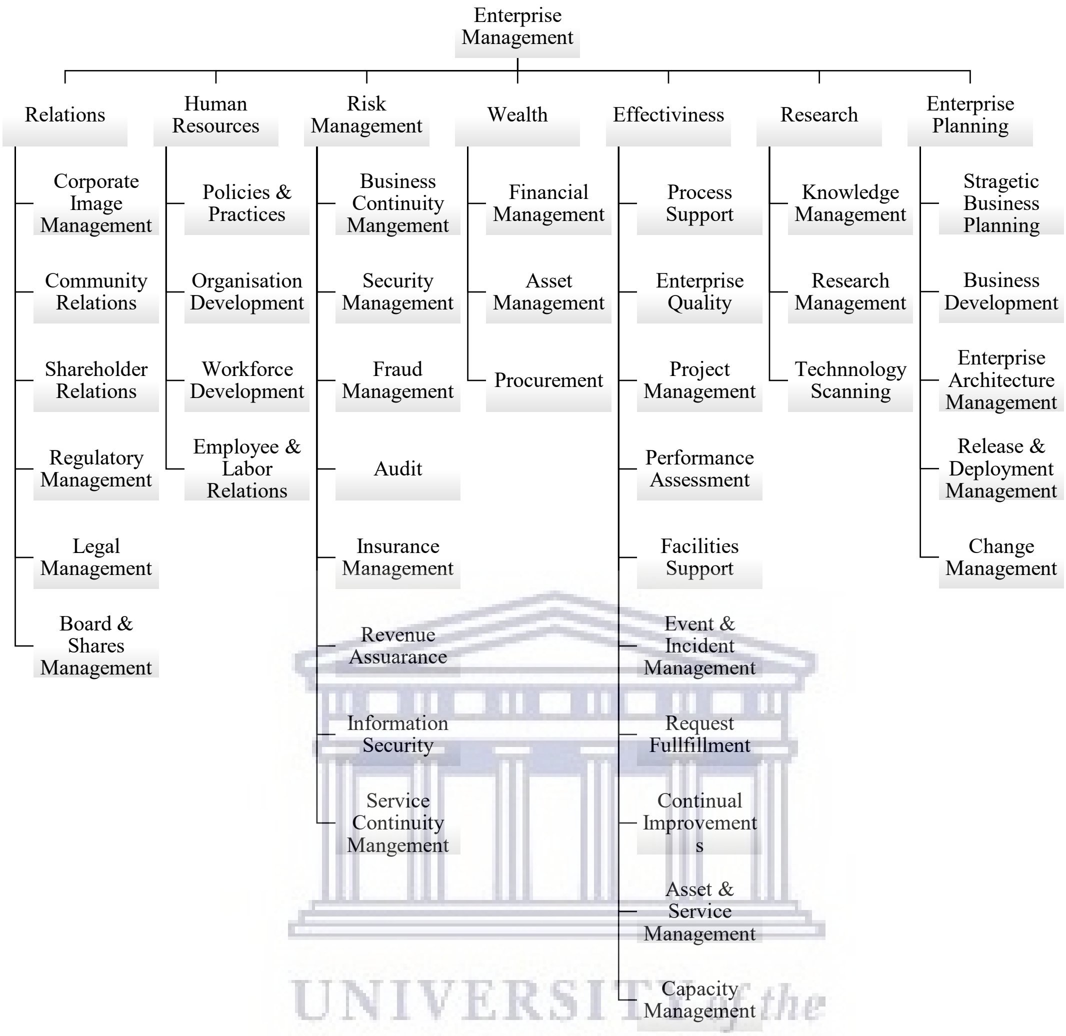


Figure 50 – Business structure.

We foresee that the proposed architecture will be implemented under limited liability corporation with the business structure shown in Figure 50. The network coverage operational activities are:

i. Strategic Planning, in which the vision will be modified to suit every targeted scenario.
ii. Operation Design creates processes in an organisation that understands its structure to prioritise tasks and connect the business efficiently.
iii. Initiative Execution, it is a project-level activity which ensures that the team is in the right place, and the roles are evident in each project. Furthermore, it sets up the overall strategy with the business's vision. The network can be deployed as the phases below to minimise the rate of vision failing:
    a. The initial phase, the 5G Network infrastructure will be solely to provide services to a governmental institution.
    b. On the second phase, services will be extended to the private sectors.
    c. The third phase introduces network hotspots in public areas and some facilities where users will pay to use this equipment.

d. Final phase opens the network to everyone who has the device to connect.

iv. Business Intelligence, the activity measures the overall health of the organisation by understanding how each strategic initiative to provide transparency.

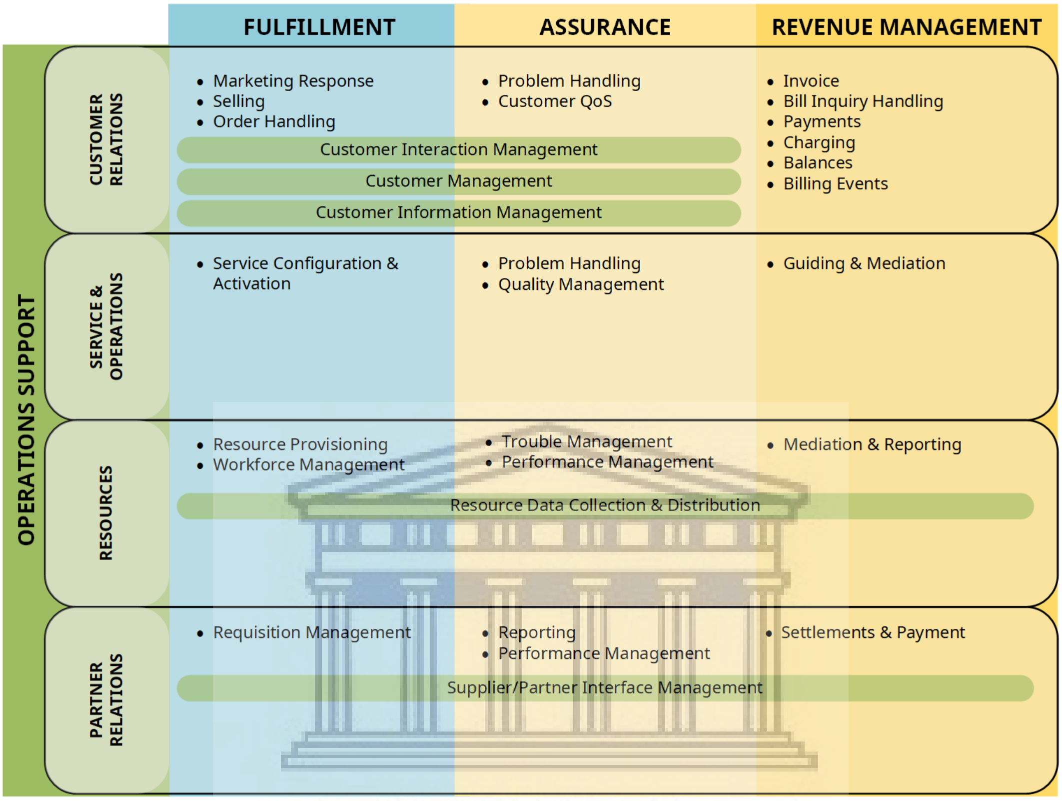


Figure 51 – Business Operations.

D. *Business Operation Management.*

Four departments handle the day-to-day operations, namely: i) Partner Relation, ii) Resources, iii) Service and Operations, and iv) Customer Relations that have fulfilment, assurance, assurance, and revenue management respectively, as illustrated in Figure 51.

4.4.2 Business Models.

Three business models are recommended that can successfully generate revenue in the proposed 5G network for rural and low-income areas. These models and how they will suit the 5G architecture are briefly described below.

A. *Business-to-Client.*

Business-to-Consumer/Client (B2C) refers to the process whereby business sell products or services directly to consumers who are the end-users (Will, 2019). The term B2C became popular during the dotcom boom of the late 1990s when it was used to refer to online retailers who sold products and services to consumers through the Internet. However, all Internet service providers use this model as the heart and soul of their business revenue, for example, Cell C, MTN, and Telkom they have retail stores that sell mobile phones to individual consumers. These operators also supply wireless network coverage directly to end-users and bill these clients for services rendered. This model will be applied in our network after the final stage of deployment because the coverage will be accessible by individual consumers.

B. *Business-to-Business.*

Business-to-Business (B2B) refers to business between companies, rather than between a company and individual consumers. (Chen J. , 2019). B2B is a form of transaction between businesses, such as one involving a manufacturer and wholesaler, or a wholesaler and a retailer. Cell C and MTN have extended the roaming deal they will cause 4G coverage of Cell C to reach 95% of the South African population (Mudiwa, 2019). With this agreement, MTN becomes a network infrastructure supplier to Cell C, and by using the infrastructure Cell C will reduce CAPEX costs of building its network across South Africa. Telkom and Vodacom had a similar deal of sharing the 4G network (IoL, 2018). Since some part of South Africa has no network coverage, this makes a business opportunity for our proposed network to supply 5G infrastructure to network operators. The network operators would provide the primary Internet while an organisation running our model extends it to rural/low-income areas.

C. *Business-to-Government.*

Business-to-Government (B2G) refers to the business relationship a company and a public institution to provide services or products (Market Business News, 2020). One of the major telecommunications service providers in South Africa, Vodacom has an annual B2G subscription model with the Gauteng Department of Education to provide feature-rich mobile application for the administration and management of Gauteng schools (Vodacom, 2016). This business relationship elaborates one of our main points of this research, which is that the government and corporates overlook rural and low-income areas.

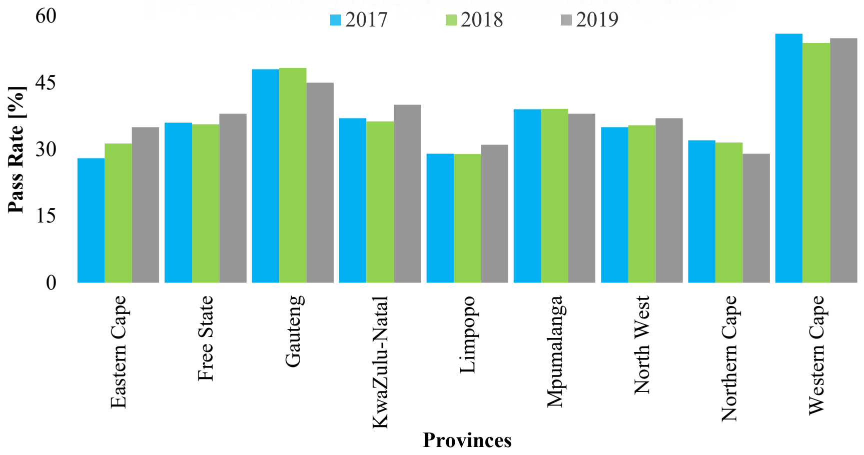


Figure 52 – Matric pass rate of South Africa
© https://www.thesouthafrican.com/da-real-matric-pass-rate-37/; https://www.thesouthafrican.com/news/matric-2018-south-africas-real-pass-rate-revealed-and-its-a-shocker/

Figure 52 illustrates the real pass rate of grade 12 students from 2017 to 2019 in the entire South African high schools per province. The Eastern Cape province, which has most underprivileged high schools, has been improving ever since 2017 without any online application to help with the management of the schools. In our proposed services, we can slice the network to focus on a governmental connection which will supply e-Learning, remote healthcare, traffic management, and smart grids. These use cases are discussed in detail the section of 5G enabled use cases below. Government has increasingly relied on the private sector to reach public goods and services. Such dependency has the potential to improve performance in the public sector while generating better profit to the private sector.

4.4.3 5G Enabled Applications and Use Cases.

New services, as well as use cases, are envisioned for 5G, and they will be a driver for the Fourth Industrial Revolution (4IR). This section provides different possible use cases that can be enhanced by the new 5G network and its services. Each use case has an ideal location and proposes ways by which the ISP can generate revenue.

Figure 53 – Robot Restaurant use case.

SERVICE ROBOT

Location	Urban Area
Business Model	B2B
Billing Method	Yearly Subscription
User Mobility	Pedestrian
Service Type	mMTC
Target Users	Disabled People; Businesses; Chefs; Cleaners
Opportunity	Hotels; Restaurants; Homes; Companies; Hospitals; Warehouses; Airports; and Retail outlet
5G Rewards	Real-time; Intelligent and Autonomous decision; Consistency; Reliability; Sustainability on food; Always open store
Enablers	99.9% accessibility and retain ability: 1 ms round trip latency

Robots have moved from science fiction to the world. Robots can be deployed in kitchens to flip burgers to specific preferences, pouring the perfect cup of coffee, or even preparing fast meals. Moreover, they can

Figure 54 – Smart Grids use case.

SMART ENERGY GRIDS

Location	Low-Income; Rural; and Urban areas
Business Model	B2G in Governmental Slice
Billing Method	Decennial Subscription
User Mobility	Machines
Service Type	URLLC; mMTC
Target Users	Municipalities; General Public; Electricity Distributors; and Companies
Opportunity	Farms; Homes; Smart Cities; Industries; and Universities
5G Rewards	Efficient and sustainable energy; Ecosystem friendly; Real-time management and automation
Enablers	QoS functions and network slices

5G capabilities are best suited for the technology in the energy and utilities sector. The smart electricity solutions are intended to optimise operations and maintenance by quickly detecting and responding to faults along the grid. Energy stations can be decentralised producing electricity to supply a city

Figure 56 – Remote Health Care use case.

SMART HEALTHCARE

Location	Low-Income; Rural; and Urban areas
Business Model	B2G in Governmental Slice; B2B in IoT Slice, B2C
Billing Method	Decennial; Yearly; and Pay-as-You-Use Subscriptions
User Mobility	Pedestrian; Machines
Service Type	mMTC
Target Users	Patients; Athletes; Health Fanatics
Opportunity	Olympics; Gymnastics; Sporting Events; Clinics; Mines; and Pharmacies
5G Rewards	Remote surgery and diagnosis; Real-time vital monitoring; Healthcare; and Fitness
Enablers	High service availability at least 99,999% node availability

Wearables, trackers, and sensors will provide great market for the Massive-IoT aspect of 5G in health sector which has many applications that can receive help from the network. The new 5G enables telemedicine, which

Figure 55 – e-Logistic use case.

LOGISTIC, TRACKING AND INVENTORY

Location	Low-Income; Rural; and Urban areas
Business Model	B2B
Billing Method	Yearly Subscription
User Mobility	Pedestrian; Vehicular; Machines
Service Type	URLLC; mMTC
Target Users	Drivers; Consumers; Securities
Opportunity	Government; Transport and Shipping Companies; Warehouses; Automotive industry
5G Rewards	Real-time package security and monitoring; Business intelligence; Autonomous shipping
Enablers	Broad network coverage; Cloud platform for data storage and analysis

Logistics and freight tracking are important use cases for 5G. The network can enable tracking of inventory and packages wherever they are through using location-based information systems. Moreover, drivers can know exactly which route to use when delivering in remote areas. This improves

Figure 57 – Automated Manufacturing use case.

AUTOMATED MANUFACTURING

Location	Low-Income areas
Business Model	B2B
Billing Method	Yearly Subscription
User Mobility	Pedestrian; Machines
Service Type	mMTC
Target Users	Miners; Assemblers; Engineers
Opportunity	Manufacturing; Oil Plant; Mines; Automotive industries
5G Rewards	Real-time process; Remote control of heavy machinery; Increased efficiency and reduced operational cost; and Low risks in hazardous environments
Enablers	Extremely low latency; Best use of licensed and unlicensed technologies

Main advantages of 5G in industry automation are wireless flexibility, reduced costs and feasibility of applications that are not possible with current

Figure 59 – Traffic Safety use case.

TRAFFIC SAFETY

Location	Low-Income, Rural, and Urban areas
Business Model	B2G in Governmental Slice, B2B and B2C in IoT Slice
Billing Method	Decennial, Yearly, and Monthly Subscriptions
User Mobility	Pedestrian, Vehicular
Service Type	URLLC
Target Users	Drivers; Pedestrians; Commuters; Police; Emergency teams
Opportunity	Governments; Shipping companies;
5G Rewards	Connected cars and trucks; Public safety; Navigation and augmented reality; Ecosystem scale and diversity
Enablers	Always available and basic service

Biggest impact that 5G is expected to have in the automotive and technology sector is to enable the sharing of real-time information about traffic and road conditions among cars and other road users. These new co-operative mobility

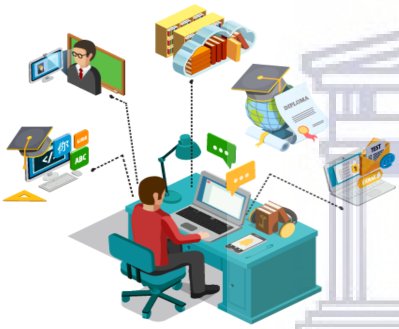


Figure 58 – e-Learning use case.

e-LEARNING

Location	Low-Income, Rural, and Urban areas
Business Model	B2G in Governmental Slice
Billing Method	Freemium
User Mobility	Pedestrian
Service Type	eMBB
Target Users	Professors; Students; Researchers; Educators
Opportunity	University and Research; Libraries
5G Rewards	Ai language translation; HD class videos; online study content; Real-time HD video and text communication; Online degrees
Enablers	Orchestration of a large amount of data and input interfaces

5G network will help the public schools to educate relevant and competitive content. e-Learning can solve some of the currently faced issues (e.g., lack of enough textbooks, stationary or classrooms).

Figure 60 – Tactile Manufacturing use case.

TACTILE MANUFACTURING

Location	Urban areas
Business Model	B2B
Billing Method	Yearly and Monthly Subscription
User Mobility	Pedestrian; Machines
Service Type	eMBB
Target Users	Engineers; Researchers
Opportunity	Manufactures;
5G Rewards	Tactile, reliable, and precise production; Real-time, intelligent, and autonomous decision
Enablers	Fast response time for diagnostics; Meets real-time constraints

The new 5G will enable tactile manufacturing where engineers will tune their product in real-time while watching its performance. This will elevate the simulation tasks.

Figure 63 – Virtual Reality use case.

VIRTUAL REALITY

Location	Urban areas
Business Model	B2C
Billing Method	Pay-as-You-Use Subscription
User Mobility	Pedestrian
Service Type	eMBB
Target Users	Consumers; Learners; Patients
Opportunity	Health; Gaming; Universities
5G Rewards	Immersive augmented and virtual reality; Remote check-up; Privacy; Non-intrusiveness
Enablers	Reduce load on transport links and central processing units; Congestion handling per subscriber/service or based on usage

Sporting events and experiences will be some of the top applications for 5G in the consumer space. Anytime you need to react quickly to a stimulus, such as in a sports training application, it must happen with minimal latency.

Figure 62 – Smart Home use case.

SMART HOME

Location	Urban areas
Business Model	B2C
Billing Method	Monthly Subscription
User Mobility	Pedestrian; Machines
Service Type	URLLC; mMTC; eMBB
Target Users	Consumers; Securities
Opportunity	Homes; Companies; Water and electricity distributors; Hotels
5G Rewards	Public safety; Live TV; On-demand home monitoring
Enablers	Cloud based flexible deployment of media services

Smart homes will gain popularity with 5G enabling the IoT device to communicate with extreme low latency and be capable of using cloud data on-demand. This will also allow homeowners to interact with the devices anywhere in the world.

Figure 61 – Office Surveillance use case.

OFFICE SURVEILLANCE

Location	Urban areas
Business Model	B2B
Billing Method	Yearly Subscription
User Mobility	Pedestrian
Service Type	mMTC
Target Users	Employees; Securities; Doctors; Police
Opportunity	Offices; Airports; Malls; Events; Smart houses
5G Rewards	Surveillance; Healthcare; Public safety; Privacy
Enablers	Significantly reduced signalling overhead on device energy consumption

Due to the increasing threats to public safety in recent years, many governments and private sectors around the world are investing in public surveillance and security systems. The system can use infrared sensors to detect if a person is sick or not, avoiding disease outbreaks in offices.

4.5 STUDYING BUSINESS EXPENDITURE.

Starting a new business can be extremely costly (Palmer, 2019); hence, it is crucial to have a business plan that analyses the CAPEX needed to get necessities and implement the services to be offered. Likewise, to determine the IRR, the daily operational cost must be known. This section estimates both CAPEX and OPEX for deploying a proposed network in the considered scenarios. Furthermore, Table 12 discusses the essential tangible and intangible requirements that form the basis of this business analysis. The analysis excludes marketing and brand awareness expenses. However, this section's goal is mainly providing information on the benefits that the initial expenditure will bring and proves to the service providers that investing in a rural area can be beneficial.

Table 12 – Fifth Generation Network Node features (Luca, et al., Bringing 5G in Rural and Low-Income Areas: Is it Feasible?, 2017).

FEATURE	SYMBOL	DESCRIPTION	UAV-BASED	LC-BASED	HOTSPOT-BASED
Lifetime	L	Average time before disposal.	5 years	10 years	5 years
Cell Radius	R	Maximum cell range.	0.5 km	10 km	0.5 km
Peak Capacity	γ	Maximum available capacity available to users, obtained by multiplying the maximum number of users from the reverse link constraint of 9 for a maximum user downlink throughput of T^{MAX} = 100 Mbps.	4.2 Gbps	12.6 Gbps	67.2 Gbps
Max. Power	P^{MAX}	Maximum power consumed when the available capacity to users is maximum (the power scales with the amount of available capacity).	1.4 kW	3.5 kW	5.6 kW
Min. Power	P^{MIN}	Minimum power consumed when the node does not serve any user (20% of the maximum node power).	0.28 kW	0.88 kW	0.28 kW
Battery Cost	C_B	Cost of a lead-acid battery with 12 V and 200 Ah generating 2.4 kWh.	R2.2 k/battery		
Solar Panel Cost	C_{SP}	Cost for a standard module type, size 1 kWp, system losses 14%, tilt 20, azimuth 180, DC to AC size ratio 1.1, inverter efficiency 96%, ground coverage ratio 0.4.	R11.55 k/battery		
Commodity HW Cost	C_{CHW}	Cost of the HW hosting high-level computing and networking virtual functionalities.	R144.4 k	R433 k	R 144.4 k
Dedicated HW Cost	C_{DHW}	Cost of the HW deploying the RRH and the connection of the node with the optical network.	R144.4 k	R938.2 k	R 39.5 k
UAV Cost	C_{UAV}	Cost for a rotary-wing quadcopter, four-engine, and maximum load weight equal to 5 kg.	R62.1 k	-	-
Site Acquisition Cost	C_{SA}	The total site acquisition cost mainly depends on the cell type, the cost to connect the site to the electricity network (if available) and the cost to build an access road up to the cell location. This cost is related to the considered scenario.			
Spectrum License Cost	C_{SL}	Cost for spectrum licensing.			

FEATURE	SYMBOL	DESCRIPTION	UAV-BASED	LC-BASED	HOTSPOT-BASED
Node Maintenance Cost	C_M	The yearly cost of the inspection, solar panel cleaning, and software updates.	R5.1 k/year	R7.65 k/year	R 2.55 k/year

Table 12 depicts the key features and their description of the 5G nodes being considered. Commodity Hardware (HW) is used to perform high-level functionalities performed by virtualisation of the network to reduce expenses. Dedicated HW can perform low-level tasks such as the Remote Radio Head (RRH) functionalities and the interconnection with the optical fibre. Clearly, in the UAV-based solution, the RRH are mounted on UAVs. Finally, each node requires a yearly maintenance cost to perform essential functions such as inspection, cleaning of the solar panels, and Software (SW) updates (Luca, et al., Bringing 5G in Rural and Low-Income Areas: Is it Feasible?, 2017).

4.5.1 Capital Expenditure.

The Capital Expenditure (CAPEX) is the foundational business cost that creates future benefits. This section examines the cost of tangible assets concerning remote cell commodity hardware, site acquisition, and UAVs. Additionally, analysis of the number of 5G nodes required for various deployment scenarios are considered. The network costs are calculated in two parts, the traditional Radio Access Networks (RAN) and the virtual-RAN. The possible number of BS can be obtained using Equation 23 below:

Equation 23 – Number of possible Base Station.

$$N_{BS} = \frac{(1+m) * T^{MAX}}{c}$$

Where T^{MAX} is the total peak throughput capacity per node, C is the average capacity supplied by Microcell, and m is the ratio of connected margin to c. To calculate the number of 5G RRH-UAVs N_c, the equation X below is used:

Equation 24 – Maximum number of Fifth Generation Remote Radio Heads required.

$$N_C = max\left(N_{C_{area}}, N_{C_{users}}\right)$$

Where,

Equation 25 – Number of Fifth Generation Remote Radio Heads required based on the area size of the targeted scenario.

$$N_{C_{area}} = \frac{2 \cdot A}{3\sqrt{3} \cdot R_c^2}$$

is an expression that is based on the size of the area A of interest and

Equation 26 – Number of Fifth Generation Remote Radio Heads required based on the active users on the network.

$$N_{C_{users}} = \frac{N_u \cdot \alpha \cdot T}{\gamma}$$

is an expression which is based on the active users N_u . R_c is the radius of the hexagonal cell coverage area, A is the size of the prescribed area, N_U is the total number of users, α is the ratio of active users in the network, T is the average throughput per subscribed user, and γ is the peak capacity of the RRH network cell. Note that in future considerations, we will refer to "based on area" or "based on active users" in our results when the higher value in Equation 24 is given by the first or second term respectively.

Virtual Radio Access Networks (V-RAN) are less efficient than real machines because they access the hardware indirectly (Rost, et al., 2015). The virtual system running on a host Operating System (OS) must repeatedly request access to the underlying hardware every time from the host. This makes V-RAN operate slower in comparison to the physical (non-virtualised) RAN. Furthermore, running multiple virtual machines on a single host may result in performance dips and higher power consumption. Hence, this research proposes that virtualisation of RAN be done on terrestrial cellular nodes that are connected to the power grid.

A. Nodes Comparison.

This section compares the number of nodes required in the considered scenarios based on several types of network. The equations to determine the total number of nodes discussed earlier, their results are represented as follows:

i. Equation 24, is "Based on Max"
ii. Equation 25, is "Based on Active Users"
iii. Equation 26, is "Based on Area"

Where the legend structure is constructed as "*Type of the Network – Equation used*".

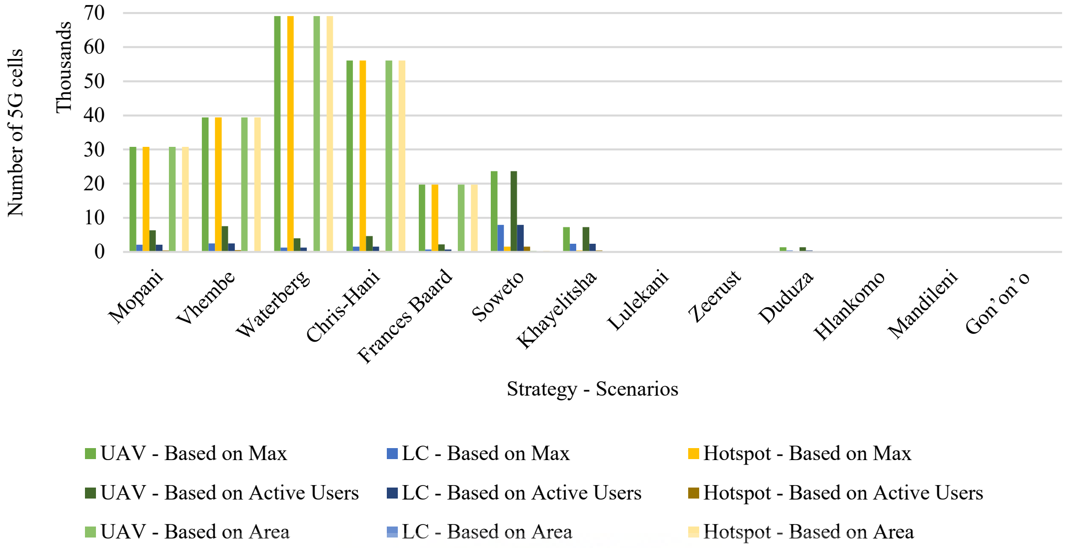


Figure 64 – Number of Cells Over Selected Scenarios.

The number of cellular networks forms the basis of the entire CAPEX analysis. It also influences the OPEX because the cost of operation grows in proportion to the number of service stations. Comparing nodes yield expense estimates over the selected scenarios in Figure 64. Certain areas require more nodes to provide network coverage for everyone within them. Such areas will result in higher OPEX. In Figure 64, a comparison of the various deployment scenarios is shown. The figure shows the possible number of 5G nodes required for UAV-based, LC-based, and Hotspot-based cells for a varied number of active users, area sizes (in square metres) and highest values. It can be seen from the figure that covering each of the municipalities (Mopani, Vhembe, Waterberg, Chris-ani, and France Baard) requires a higher number of nodes compared to the rural areas. The total number of nodes is based on area size and the highest between the area and active users (Equation 24) requires the same number of cells, because of their area size. However, townships such as Soweto and Khayelitsha have a dense population which causes the number of cells based on active users to be high. Furthermore, the townships have a slightly higher number of literates which have heard about cellular phones and/or have used one for social communications.

B. Expense Analysis for Remote Access Network.

This subsection discusses the CAPEX of three different nodes types (UAV, LC and Hotspot) over the same scenarios in Table 11. For an objective CAPEX analysis, a required total number of cell nodes is found based on the possible active end-users or the size of the targeted area. Equation X below yield the total CAPEX needed to deploy a certain RAN with one of the node types over selected scenarios:

Equation 27 – Capital Expenditure for Remote Radio Head Network.

$$CAPEX = N_C(C_B N_B + C_{SP} P_{SP} + C_{CHW} + C_{DHW} + C_{UAV} + C_{SA})$$

Where C_B is the cost of a single battery, N_B is the number of batteries per site, C_{SP} is the cost for one [kWp] of solar panels, P_{SP} is the power of the solar panels per site, C_{CHW} is the cost of commodity hardware, C_{DHW} is the dedicated hardware cost, C_{UAV} is the UAV cost and C_{SA} is the site acquisition cost (Luca, et al., Bringing 5G in Rural and Low-Income Areas: Is it Feasible?, 2017).

(i) *Based on the Number of Possible End-Users.*

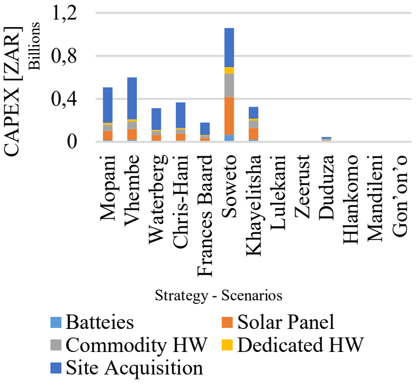


Figure 65 – Large Cell capital expenditure breakdown over selected scenarios based on the possible number of active end users.

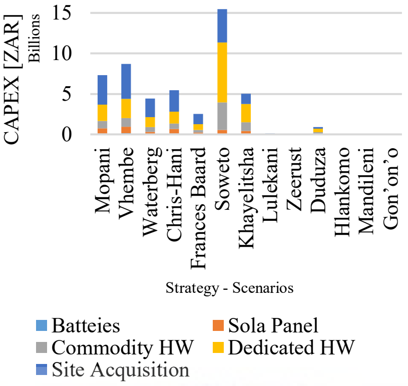


Figure 66 – Hotspot capital expenditure breakdown over selected scenarios based on the possible number of active end users.

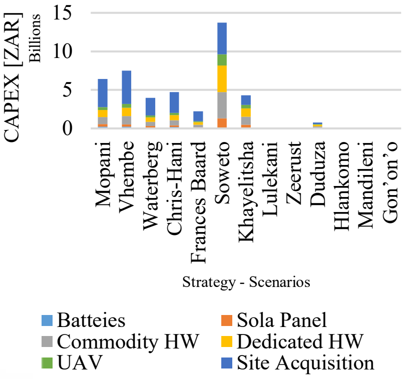


Figure 67 – Unmanned Aerial Vehicle capital expenditure breakdown over selected scenarios based on the possible number of active end users.

In this section, the CAPEX is broken down using bar graphs. Figures M, N, O depict the total CAPEX computed using Equation 27 to scenario parameters for the thirteen considered strategy cases. Each graph shows the cost of each parameter needed to deploy a network in South African Rands over a targeted zone that forms their total expenditure. Moreover, by examining the possible clients in the area and serving ability of a single cell unit yields the required cells N_c for every case. Interestingly, in each scenario, the UAV-based and Hotspot-based solutions require consistently far more significant CAPEX than the LC-based solution. Though Soweto and Khayelitsha are significantly smaller areas when compared to entire districts, they are densely populated areas hence, the massive CAPEX observed. The most substantial contributions to the costs are due to site acquisition and commodity/dedicated Hardware (HW) HW expenses, while the UAVs, solar panels and the batteries have a lower impact on the CAPEXs.

(ii) *Based on the Size of a Targeted Area.*

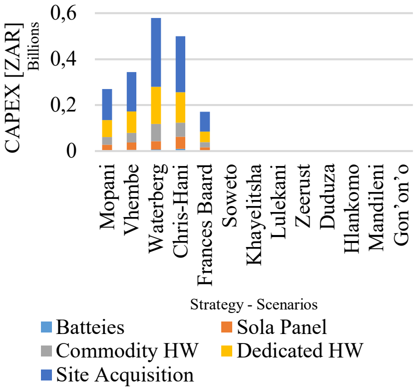


Figure 68 – Large Cell capital expenditure breakdown over selected scenarios based on the size of the targeted aera.

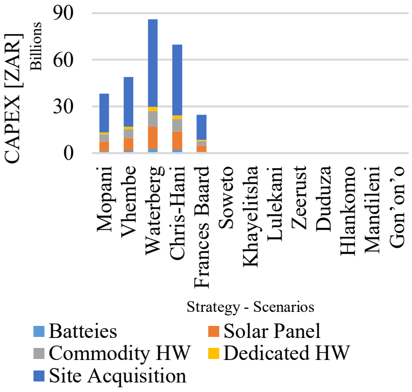


Figure 69 – Hotspot capital expenditure breakdown over selected scenarios based on the size of the targeted aera.

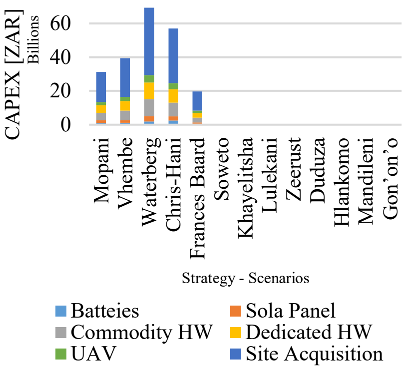


Figure 70 – Unmanned Aerial Vehicle capital expenditure breakdown over selected scenarios based on the size of the targeted aera.

The CAPEX breakdown bar graph in Figure 68, Figure 69, and Figure 70 depict the entire expenses of each scenario by following the same conditions in the analysis of RAN based on the possible number of clients. Costs are directly proportional to the size of the targeted areas hence, the five districts have preposterous expense compared to the other locations. The UAV-based and Hotspot-based solutions need greater CAPEX than the LC-based solution because of the small coverage range. This implies that only a few (possibly only one) LC network cell(s) is/are required. Thus, site acquisition contributes more than half of the entire CAPEX because the required cells are based on the size of the scenario.

(iii) *Based on the Number of Highest Cells.*

The CAPEX breakdown bar graph in Figure 71, Figure 72, and Figure 73, and discuss the expenditures of each scenario by showing the analysis for RAN based on the possible number of users and the size of the targeted area. Equation 24 determines the highest possible number of required cells by considering both the number of users and the size of the areas. This analysis is thus a combination of the first and second cases for RAN expense analysis. Similar to the first two cases, the UAV-based and Hotspot-based solutions need greater CAPEX compared to the LC-based. However, in this analysis, the size of the scenario has a greater impact on the CAPEX, with the expenditure being significantly higher for the district municipalities.

For the rural areas, a single LC-Based solution can supply basic network services over the considered areas. Looking closer at these rural residential zones, Gon'on'o requires five UAV, two LC, or a single Hotspot based cellular node to provide full coverage to the village. While Mandileni and Hlankomo require three UAV, one LC or one Hotspot based cell, Table 11 discusses these values in detail. Though Gon'on'o is a small residential area, it needs more nodes than the other rural residential areas because more people live there. In LC-Based solution, Soweto township has the highest CAPEX over all other scenarios because of its vast population density. Conversely, Mopani, Vhembe, Waterberg, and Frances Baard municipalities have the highest CAPEX in the UAV-Based and Hotspot-Based solutions due to the immense area size. Despite the dense population of the townships, the UAV-Based or

Hotspot-Based solution costs less. Commodity and dedicated *HW* slightly cost more in the LC-Based solution because the targeted scenarios have a vast area that requires many cells to have full coverage. Contrarily, they cost less in UAV-Based and Hotspot-Based Solution due to the coverage range of a single cellular unit. A considerably large area requires more cells which in return contributes extensively to site acquisition expenses.

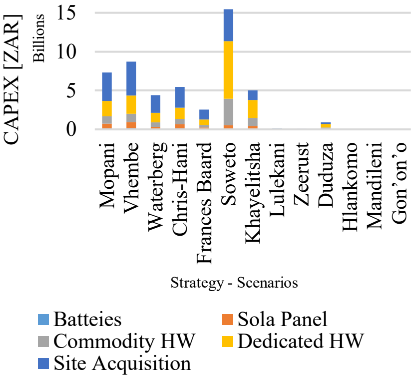


Figure 71 – Large Cell capital expenditure breakdown over selected scenarios based on the highest number of cells required.

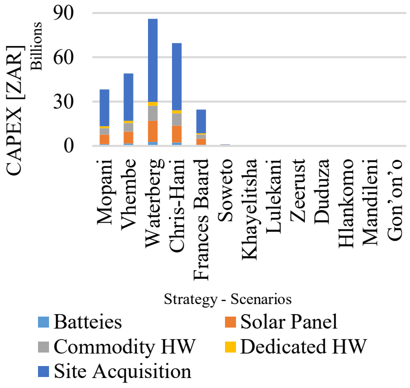


Figure 72 – Hotspot capital expenditure breakdown over selected scenarios based on the highest number of cells required.

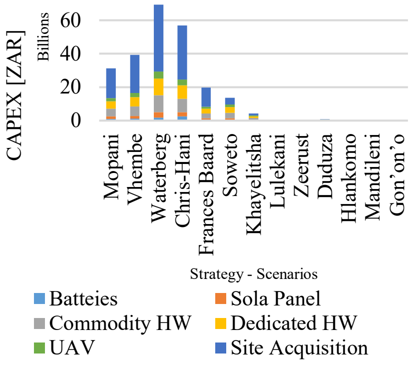
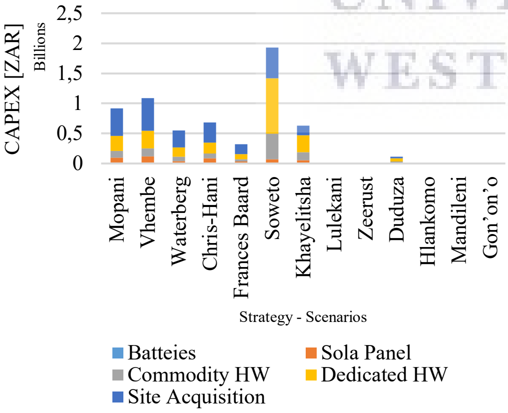


Figure 73 – Unmanned Aerial Vehicle capital expenditure breakdown over selected scenarios based on the highest number of cells required.

C. *Expense Analysis for Virtualised Network.*



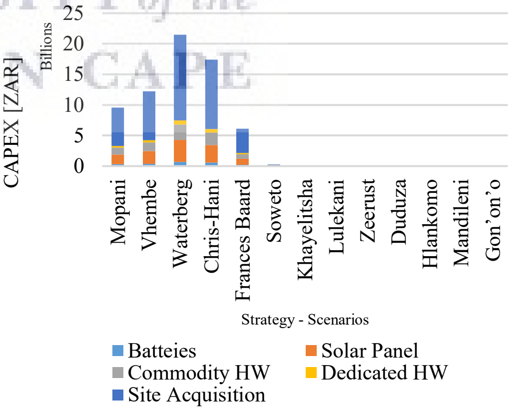


Figure 74 – Large Cell Sliced Network capital expenditure breakdown over selected scenarios based on the highest number of cells required.

Figure 75 – Hotspot Sliced Network capital expenditure breakdown over selected scenarios based on the highest number of cells required.

The total Capital Expenditure concerning the virtualised Remote Access Network architecture computed as:

Equation 28 – Virtual Remote Access Network Capital Expenditure.

$$CAPEX_{V-RAN} = \frac{N_c}{n_{vs}}(C_B N_B + C_{SP} P_{SP} + \ C_{CHW} + C_{DHW} + C_{SA})$$

Where n_{vs} is the total number of slices per cell node. Figure 74 and Figure 75 depict the CAPEX breakdown bar graph for a virtualised network to share the cost with other tenants on the network. Since considers both users and the targeted area, it is used to obtain the total number of required nodes for V-RAN expenses for a single tenant in this section. Furthermore, Table 12 briefly discusses hardware specifications. With a generalised focus on the figures, the costs for each scenario follow expense analysis for RAN based on the number of highest cells required. Soweto township and Vhembe district still need the highest CAPEX for a network based on LC. Also, as in Hotspot based cells, Waterberg and Chris-Hani municipalities require the most CAPEX against the rest of the scenarios.

4.5.2 Operational Expenditure.

Operational Expenditure (OPEX) refers to costs incurred in the course of operating the 5G network., It includes but not limited to, maintenance and administrative expenses. For this work, taxes, insurance, depreciation, and interest are excluded from the OPEX, Equation below is used to compute the OPEX for an entire year:

Equation 29 – Operational Expenditure.

$$OPEX_i = \ N_C \left[365 \cdot \left(\sum_h P_h C_E \right) + C_M \right]$$

Where N_c is the number of deployed network cell nodes, $P_h$is the power required from the electricity grid by the site at hour h, C_E is the cost for one kilowatt-hour [kWh] of energy, and C_M is the maintenance cost.

The line graph in Figure 76 depicts expenses required to supply coverage for a year with three type cells over selected scenarios. All the scenarios have the same pattern with CAPEX when considering clients and location size to find the best number of cells required. In all scenarios, LC-Based network cost less than others to operate. However, Soweto township requires at least R90M a year while other require at most R30M. Hotspot and UAV-Based systems cost more when considering the coverage of entire municipals.

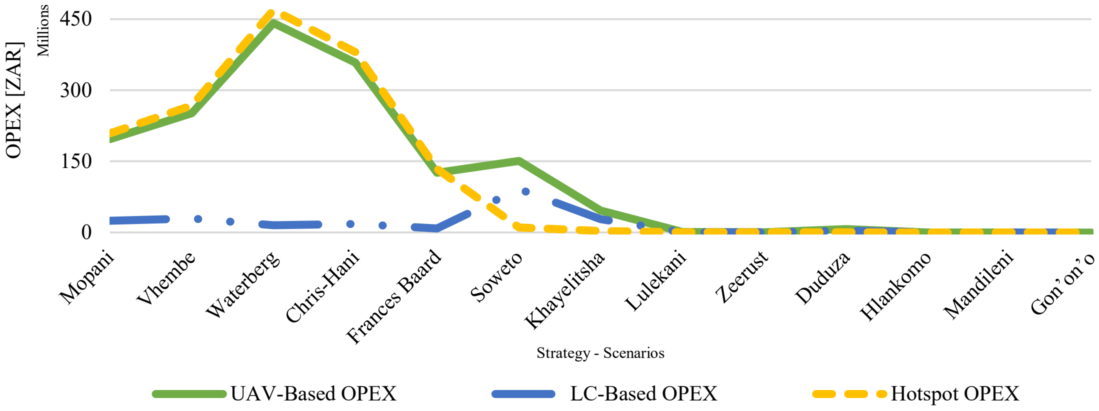


Figure 76 – Operating Expenditure Over Selected Scenario.

Moreover, Waterberg has the most significant area, and as a result, is the priciest scenario to run the short-range cells and Chris-Hani follows it. On the contrary, based on size, Soweto has the smallest area compared to the district municipalities, nevertheless, it is far more expensive to run UAV-Based network because of overpopulation within the township. The low-income town and rural residential areas have the lowest OPEX on all network types due to their small area sizes and low population, therefore requiring fewer cells for coverage. From Lulekani to Gon'on'o all three types of cells require, at most, half a million Rands to run.

4.6 REVENUES OVER TIME.

This section analyses Return on Investment (ROI) for deploying the proposed 5G network in some of the currently disadvantaged South African areas. The standard statistical profitability ratio helps to determine the loss or profit obtained in each network type for the total CAPEX. Figure 77 depicts censors and generalised regional service charge for the clients over targeted scenarios. It is safe to assume that the number of users stays the same, and they pay their suggested fees every month. The values on the graph are discussed in Table 11.

The Revenue (REV) is the income generated from network coverage service operations including discounts and network sharing, while Cash Flow (CF) is the net amount of money that moves into and out of business. Furthermore, the IRR discount rate estimates the overall profitability of potential investments during CAPEX budgeting. It makes the Net Present Value (NPV) of all CF from a network deployment project to be equal to zero. Moreover, IRR computations depend on the same formula as the NPV does.

Figure 77 – Population and Service charge over scenarios.

4.6.1 Revenue Analysis.

The yearly Revenue (REV_i) forecasts profits to be made throughout the expected lifetime of the cell over the chosen areas, where i is the number of years, assuming each user pays a monthly subscription fee F to use the network, equation T below can be used to calculates income based on this constant monthly subscription:

Equation 30 – Yearly Revenue.

$$REV_i = N_U \cdot 12 \cdot F$$

To compute the profitability of V-RANs, the value ofN_U in equation T is swapped with the number of clients each tenant has. Figure 78 shows a line graph for the annual income of all cell types. Table 11 discusses each scenario parameters. From a glance, all five district municipalities generate more revenue compared to rural residential areas and townships, while France Baard region is the lowest producer, generating over R2B income. Vhembe district municipality and Soweto township both have a vast population, and as expected also have considerably higher revenue per year. Vhembe has the highest revenue, but it is only marginally higher than Soweto. This is due to its lower average population density (number of people per unit area), when compared to Soweto. Finally, for the rural residential areas, only about a billion Rands is attainable as revenue.

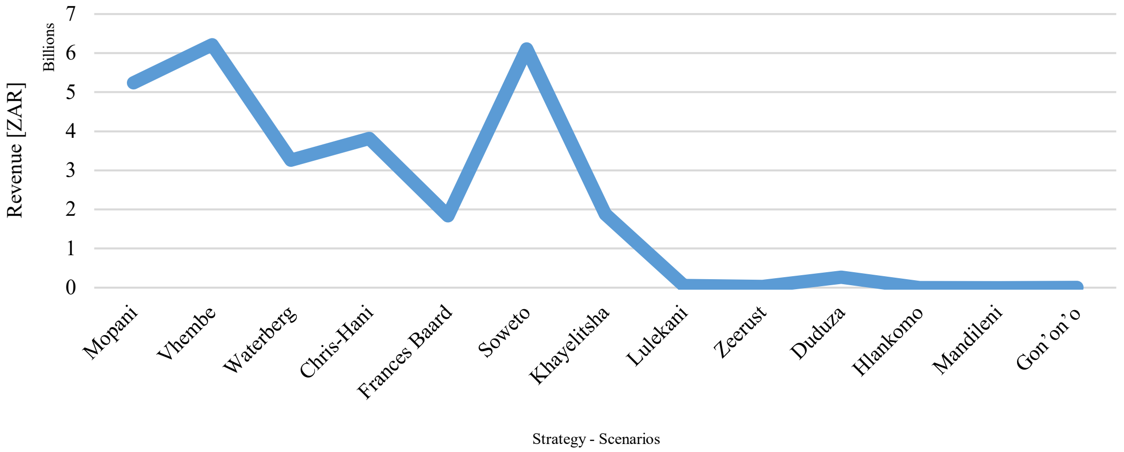


Figure 78 – Revenue Over Selected Scenario.

4.6.2 Cash Flows Analysis.

Equation 31 – Net Cash Flow.

$$-OPEX \; for \; year \; i = 0$$

$$CF_i = REV_i - OPEX_i \; for \; year \; 0 < i < l$$

The expression above is a yearly Net CashFlows (CF_i) of operators, where i is a specific year during the network operation, and l is the lifetime of the architecture in years. CF_i represent the profit or loss value of the network operator during a specific time.

Given the requisite knowledge of CF_i, it is important to first determine if the revenues can compensate the CAPEX and OPEX, by computing the NPV. Specifically, by definition, NPV is the summation of cashflows CF_i over the entire lifetime, each normalised by $(1 + \eta)$, where η is the discount rate, i.e., the return (in percentage) that could be earned with an ideal financial investment (such as bank funding, loans, etc.) (Chiaraviglio, et al., Bringing 5G into rural and low-income areas: Is it feasible?, 2017). The expression below calculates the Net Present Value (Adam, 2019):

Equation 32 – Net Present Value.

$$NPV = \sum_{i=1}^{L} \frac{CF_i}{(1+\eta)^i} - CF_0$$

Where CF_0 is the first total investment expense and i is the period in years. The analysis starts with a current balance and produces a closing balance sheet after accounting for all cash inflows and outflows during the period. Considering the NPV based on monthly subscription fee shown in the graph on Figure 77, NPV can be calculated using Equation 32 with a 5% discount rate, while the OPEX is computed using Equation 29, and yearly revenue is computed using Equation 30, with scenario parameter sets reported in Table 11.

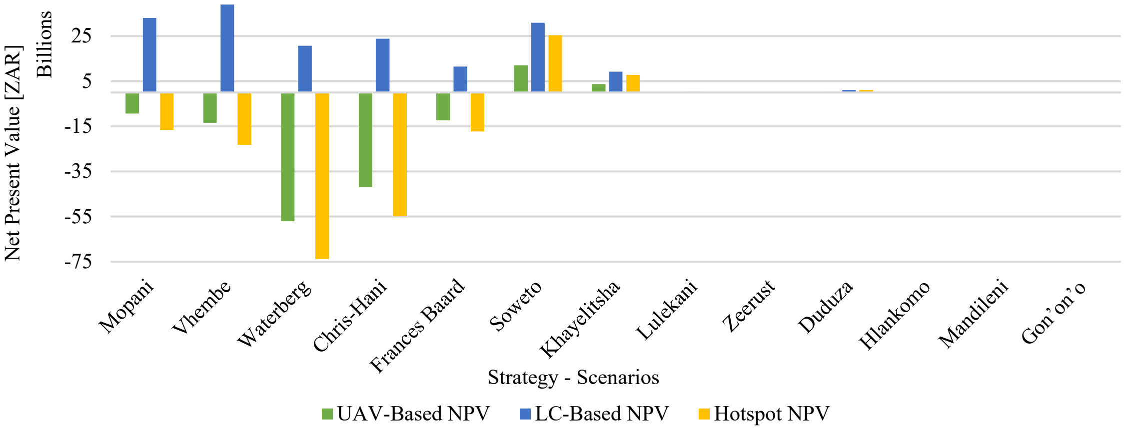


Figure 79 – Net Present Value Over Selected Scenario.

The clustered column bar graph in Figure 79 above, depicts the NPV for the three cell types, namely UAV-Based, LC-Based, and Hotspot over the considered scenarios. Interestingly, in each scenario, the LC-based solutions with the proposed monthly subscription fee in Figure 77 have a more profitable return than both the UAV-Based and Hotspot solutions. Using Small Cells (SC) only to supply 5G services to any district municipalities, the operator will not be able to recover the initial CAPEX, Waterberg region requires more than R55B for both UAV and Hotspot based solutions to run until their lifetime expires. Vhembe has a larger population compared to the other municipalities and thus requires more SCs to fully supply coverage to the entire area. To this end, SCs solution is not lucrative in the district municipalities. On the contrary, LC-based solutions are more profitable. For instance, Vhembe produces the highest returns (approximately R40B) when using the LC-Based solution. Both low-income and rural residential areas are profitable to all architectural solutions. Soweto and Khayelitsha townships, with the highest population density, have the highest positive cashflow.

4.6.3 Internal Rate of Returns.

The internal rate of return (IRR) is a measure of an investment's rate of return. The term internal refers to the fact that the calculation excludes external factors, such as the risk-free rate, inflation, the cost of capital, or various financial risks. This subsection focuses on the Internal Rate of Returns from 5G architectural investments. To calculate the Internal Rate of Returns (IRR), Equation 32 is set to zero, with other values given, we then solve for the discount rate η, which is the IRR.

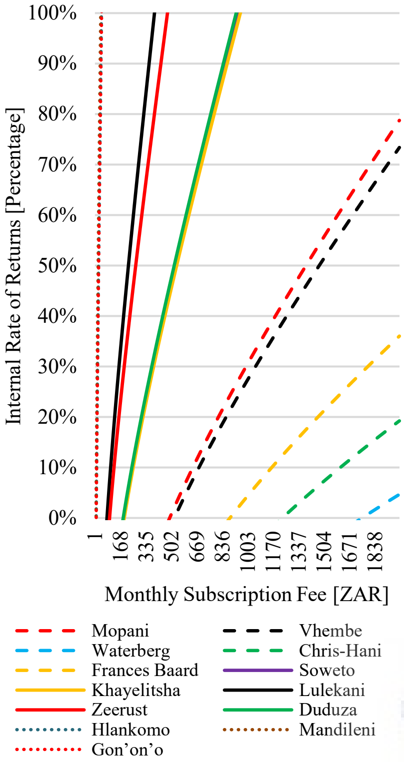


Figure 80 – Internal Rate of Returns with Large Cells over considered scenarios.

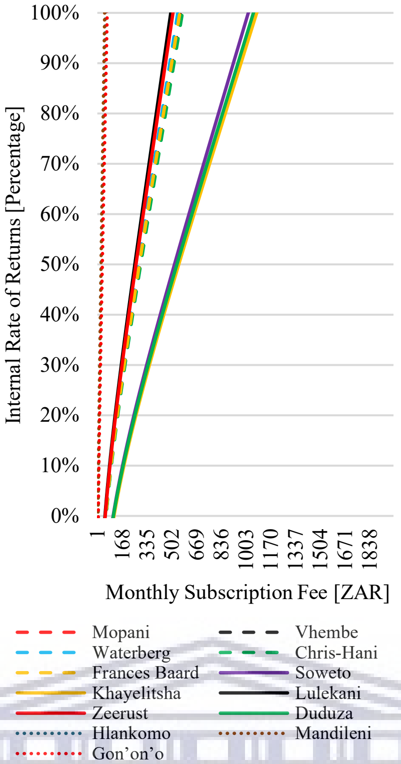


Figure 81 – Internal Rate of Returns with Unmanned Aerial Vehicle over considered scenarios.

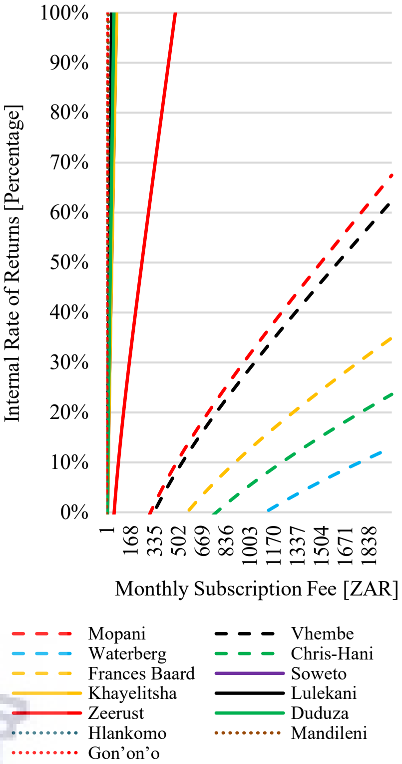


Figure 82 – Internal Rate of Returns with Hotspots over considered scenarios.

The graphs in Figure 82, Figure 81, and Figure 80 depict IRR for SC and LC solutions over the low-income areas. In all cases, the UAV-Based solution has a considerably higher IRR despite having less CAPEX. The LC and Hotspot based solutions require users to pay over R300 monthly subscription fee for positive returns. For the rural residential areas and across all solutions, with a minimum monthly subscription fee of R30, a 50% IRR can be obtained. Focusing on all residential designated areas with just R200, any architecture is lucrative.

Equation 33 – Net Present Operational Expenditure.

$$NPO = \sum_{i=1}^{L} \frac{OPEX_i}{(1+\eta)^i}$$

Equation 34 – Net Present Payment for Clients.

$$NPP = \sum_{i=1}^{L} \frac{N_U \cdot 12}{(1+\eta)^i}$$

Equation 35 – Monthly User Subscription Fee.

$$F = \frac{NPV + NPO + C_0}{NPP_{N_U}}$$

Equation 35 yields a best monthly subscription fee, while Figure 83 depicts an IRR graph based on the ideal price. The graph focuses on using 30% discount rate (η) to yield the subscription fee over the selected scenarios. Generalised prices in Figure 77 shows this graph. However, residential areas like Soweto, Khayelitsha, and Duduza have lucrative growth than any of the entire district municipal. Rural areas require less than R50 yield 100% IRR.

4.7 END-USER SUBSCRIPTION FEE.

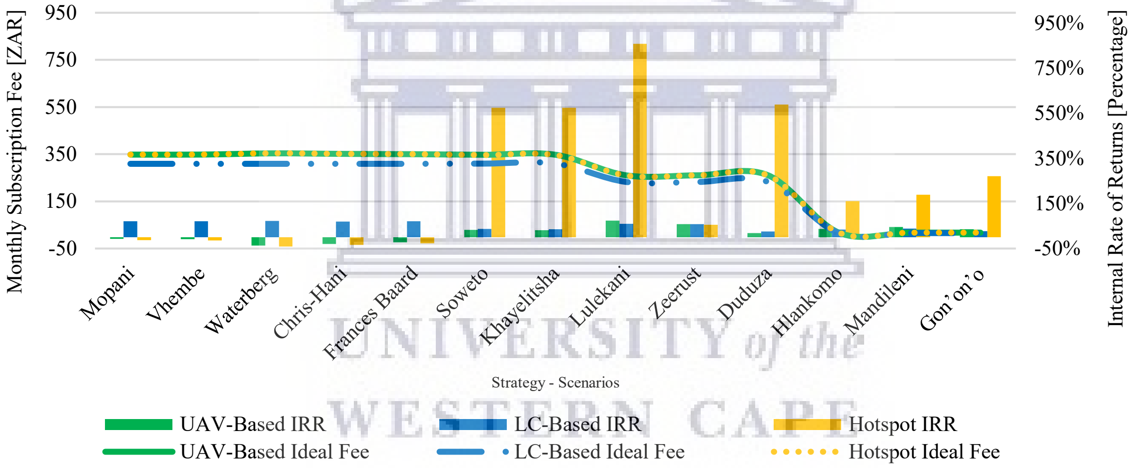


Figure 83 – Internal Rate of Return Based on Monthly Subscription Fee Over Selected Scenario.

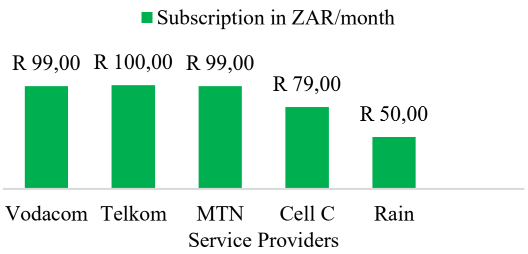


Figure 84 – Monthly Subscription Fee Comparison.

In an article published by Fin24, it was claimed that the South African telecommunication services providers MTN and Vodacom charged up to 2,639% more for out-of-bundle data. It was also reported that while on contract, a Vodacom 20 GB data bundles cost R329 (or R0.02 per megabyte), while out-of-bundles the rate per megabyte was R0.44. This is an estimate of about 2,630% higher for out-bundle than in-bundle. Similarly, MTN's 25 GB prepaid bundle costs R1 250, equating to R0.05 per megabyte and out-of-bundle cost R0.99 per megabyte. This represents a1,928% difference between in and out-bundle charges. Data bundle prices for major operators in ZA are compared in Table 13. Monthly data usage is estimated by Verizon Wireless (2020).

Table 13 – Data Bundle Price Comparison Among Telecommunication Service Providers.

	USAGE	SIZE [GB/MONTH]	PRICE [ZAR]			
			Vodacom[12]	Telkom[13]	MTN[14]	Cell-C[15]
e-Mail [Text only]	7500 [e-Mail]	0.07	R29			
Web Access	7500 [pages]	10.99	R748	R598	R648	R748
Stream Music	60 [hrs]	3.52	R399	R275.25	R398	
Stream HD Video	15 [hrs]	30	R1 598	R1 398	R1 249	R899
Stream SD Video	30 [hrs]	19.04	R999	R899		R799
Upload and Download Photos	3000 [photos]	14.65	R999	R798	R899	R799
4G VoIP	60 [hrs]	2.64	R299	R199	R378	R299
4G VoIP with Video	60 [hrs]	15.23	R999	R837	R899	R799

4.7.1 Monthly Subscription Fee.

This section compares the average monthly subscription fees for uncapped data user (as at the time of writing) versus prepaid users. Figure 84 depicts uncapped subscription fees for five service providers in ZA and the proposed average monthly fee with a recommended 5G network architecture to provide coverage in rural areas. The average price in Figure 83 yields an R282 fee, including the 15% tax.

4.7.2 Capped Subscription Fee.

Table 14 – Network Cells Capable Capacity.

	SYMBOL	UAV-BASED	LC-BASED	HOTSPOT
Peak Capacity	γ^{MAX}	15.12 Tbph	45.36 Tbph	241.92 Tbph
Min. Capacity	γ^{MIN}	3.024 Tbph	9.072 Tbph	48.384 Tbph
Mid. Capacity	m	6.048 Tbph	18.144 Tbph	96.768 Tbph
Traffic per Day	ω	27.216 TB	81.648 TB	435.456 TB

---

[12] http://www.vodacom.co.za/vodacom/shopping/data/prepaid-data
[13] https://secure.telkom.co.za/today/shop/personal/plan/100-gb-data-bundles/
[14] https://www.mtn.co.za/Pages/MTNDataBundle.aspx
[15] https://www.cellc.co.za/cellc/bundles-contract-detail/DataBundles#/sku6850032

A Gigabit (Gb) is a unit measurement of digital storage that is based on “Binary multiples of bits”. Almost 0.0079 Gigabits exist in a Megabyte. Moreover, a Megabyte is based on “Binary multiples of Bytes” with MB being a standard symbol. There are 128 Megabytes in a Gigabit. Hence, 1 Gb/s is equal to 125 MB/s being transferred. Table 14 shows the daily transfer capacity of different cells based on the sinusoidal function of power consumption discussed in Table 12. The equation below is used to obtain the prepaid subscription fee per GB per and per minute. This fee is inclusive of mandatory tax (es).

$$P_{GB} = \frac{N_c \cdot F}{\omega \cdot \alpha \cdot \beta} + Tax$$

Equation 36 – Capped User Subscription Fee per Gigabyte.

$$P_t = \frac{N_c \cdot F}{t \cdot \alpha \cdot \beta} + Tax$$

Equation 37 – Capped User Subscription Fee per Time.

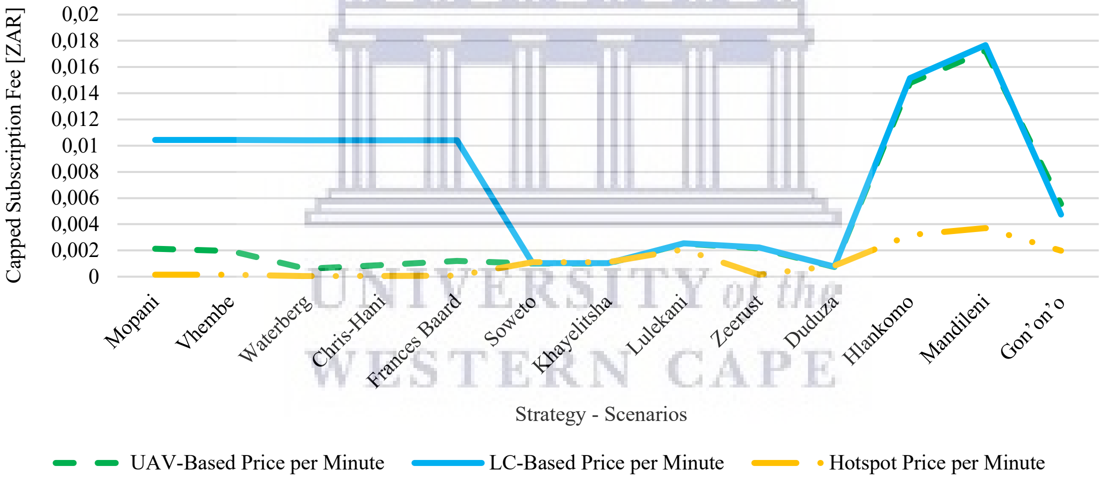


Figure 85 – Capped User Subscription Fee Returns Over Selected Scenario.

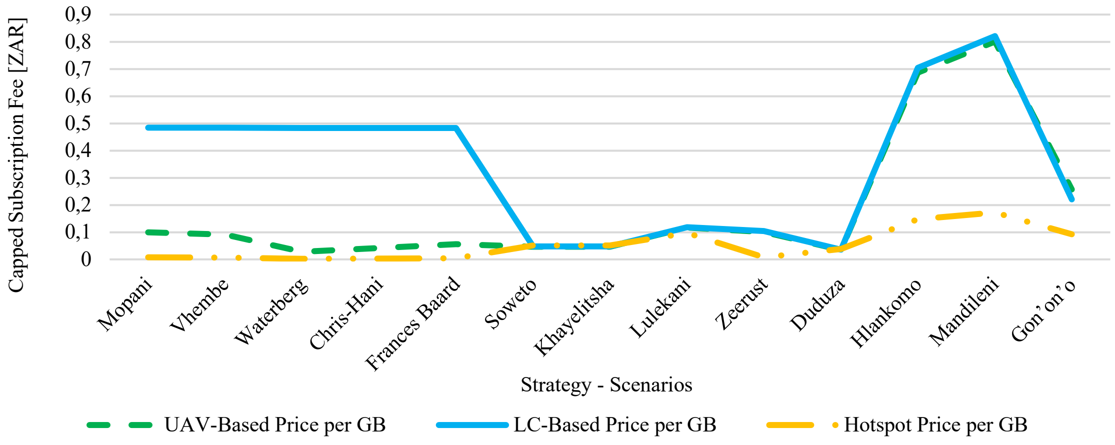


Figure 86 – Capped User Subscription Fee Over Selected Scenario.

The line graphs in Figure 86 and Figure 85 depict prepaid price for SC and LC solutions over the selected scenarios. The price modelling framework is based on Figure 83 that laid the ground for Equation 36 and Equation 37, where t is time in minutes. Furthermore, the expression considers the probability of active users on the network and how long each user will be active. Both costs per GB and minute graphs have different charge curves. Overall, a cost per GB is more expensive than an ideal charge per minute. Correspondingly, district municipalities have higher user subscription fees across all graphs. Hlankomo and Mandileni rural residential areas have the highest fee for LC and UAV based solutions. They also have the highest price for all scenarios compared to Hotspot-based solutions. Our average proposed price for all three cases (UAV, LC, and Hotspot based network) is R0.20 for 1 GB of data bundles, which is extremely low compared to the service providers. Telkom charges R60.00, while Cell C requires R75.66 for 1 GB of data bundles.

4.8 SUMMARY.

This chapter on economic analysis focused on the financial feasibilities of deploying 5G networks in 13 different locations in South Africa. Five district municipalities, four township areas, three villages and one low-income area. The focus was on Capital Expenditure (CAPEX), Operation Expenditure (OPEX), Internal Rate of Return (IRR), Return on Investment (ROI) and recommended monthly user subscription fee per GB per minute. Various scenarios were and depicted in Table 11 for the deployment of the 5G network architecture in Low-Income and Rural Areas. Furthermore, the power requirement was also modelled by using sinusoidal functions. Thus, it is easy to conclude by saying that it is expensive to deploy the proposed 5G coverage in slightly populated areas with vast area size. For such areas, the traditional LC-based system is more profitable. On the contrary, implementing this architecture in rural residential areas costs less and yields higher revenue than low-income areas. From the analysis, with the proposed model, the best monthly subscription fee will cost less than current competitive prices for data bundles. The goal of this chapter (Economic Feasibility) is to check the possibility of deploying the proposed 5G network architecture in Chapter III.

V. NETWORK ENGINEERING

This chapter presents an overview of the network engineering model used to provide 5G coverage in selected areas of interest defined by the deployment scenarios described in chapter 4. It also proposes clustering techniques used to build the network coverage in the 3.5 GHz and 28GHz broadband spectrums over the terrain map selected for the 5G infrastructure. The deployment scenarios have been tailored to demonstrate that a clustered network can improve the number of nodes connected to the gateway in selected areas, but the expense of a higher CAPEX. The chapter starts by discussing the network foundation in terms of scope, deployment scenarios and the objectives of the study. Thereafter, the clustering techniques used to provide coverage are presented. Finally, simulation results from the application of these clustering techniques over the deployment scenarios are discussed. These results reveal that the use of multiple gateways in a clustered network can increase the base station's coverage range.

This chapter aims to provide answers to the following questions related to the network engineering process:

i. Which are the most relevant deployment scenarios to be used to simulate the network coverage?
ii. Which spectrum bands are ideal for the forthcoming network generation?
iii. Can the use of multiple gateways reduce single points of failure?
iv. How can the local gateways and the LAP be used to manage traffic?
v. Can coverage be improved by grouping together flexible nodes with better signal-to-noise ratios?

This chapter presents the network engineering process is as follows:

i. Model formulation, including:
    a. The aim and assumptions made with regards to network coverage.
    b. The deployment scenarios.
    c. The network engineering tools and configurations.
ii. Clustering techniques:
    a. A balanced Myopic clustering model
    b. A multi-sink with LAP gateway model
    c. A multi-sink with UAV gateway model.
iii. Performance results presentation by discussing:
    a. Monte-Carlo simulations for the clustering techniques.
    b. The cellular signal feasibility from the fixed node to the base station.
    c. The signal-to-noise ratio coverage map from the clustering methods.
iv. UAV coverage task allocation.

5.1 INTRODUCTION.

Portable computers have become incredibly convenient in bringing multimedia functionalities to everyone and are slowly replacing several other devices. They have paved the way for unparalleled availability of new services, applications, and cheaper data rates to meet the increasing need to share or access information wirelessly. Moreover, the introduction of 5G comes with the promises unlimited bandwidth and lower latencies, the technology compels network operators to prepare their network architecture accordingly to meet the expected capacity demand (Gonçalves, Sebastião, Souto, & Correia, 2019).

Location management is one of the key features of the cellular networks as it enables mobility management entities to track areas where every user is located (Aamer, et al., 2019). Being aware of the users' locations, enable the network operators can define the specific service(s) to be provided to users in such locations. This provides insight into the ideal solutions to invest in with the hope of fruitful returns. The knowledge of the number of users in a specific location can be used to determine the number of nodes to supply coverage in the areas based on the size of these areas. This can guide the networking engineering process as it can be used to compute the total number of radio transceivers needed to connect to the public gateway to increase the QoS provided to connected clients/users.

Building around the guidelines defined above, this work investigates clustering mechanisms which can be used to improve QoS, extend the energy lifespan for battery operated nodes and improve coverage range for public gateway(s). The clustering techniques used are adapted heuristic solutions of well-known optimisation problems.

5.2 RESEARCH QUESTIONS.

This chapter contains the results of the grounded theory methodology study conducted to answer the following research questions from Chapter I:

i. *What is the current state-of-the-art regarding 5G?*
ii. *What are the main challenges currently being faced and those that might potentially be faced?*
iii. *Is it beneficial to utilise UAVs for multiple tiers communication network instead of a separate dedicated tier?*
iv. *If it is beneficial, then what ought to be an independent optimal altitude for UAV hovering at the different tiers?*
v. *How can spectrum bands be efficiently used to accommodate 5G services and standards?*

5.3 NETWORK FOUNDATION.

Advancements in mobile Evolved Packet Core (EPC) networks have paved the way for numerous applications that require dynamic network functionalities and scalable radio transceivers (Costa-Requena, et al., 2015). In these networks, both commodity hardware (CHW) and dedicated hardware (DHW) will be more and more used to form a remote radio heads (RRH) network node, where transceivers are strategically positioned to deliver network services to a targeted area. In our proposed network engineering approach, nodes are organized into clusters where the cluster head (CH) is the only one that communicates with the low altitude platform (LAP) directly. Other nodes will go through the CH to communicate with the LAP. This clustering approach can mitigate energy efficiency issues since based on their nature, UAVs might not accommodate high processing units because of energy limitations. The combination of the proposed closeting approach with the adoption of service-defined networking (SDN) and network function virtualization (NFV) technologies will enable much richer functionalities for the deployed network such as: i) end-to-end (E2E) network slicing, ii) on-demand deployment, and iii) component-based network functions. In such networks, virtualisation within UAVs can be customisation to meet high-level slicing specifications that focus on individual end-users.

Small Cell (SC) and Large Cell (LC) classify the 5G cellular network into two groups of network nodes. The recommendations submitted to the ITU for the operation of RRHs with 5G frequencies across African require support for backwards compatibility. Figure 9 discusses the frequencies that were to be studied. In the proposed deployment scenarios, the wireless hotspots and UAVs are equipped to play the role of SCs, while the traditional terrestrial nodes are equipped to play the role of LCs. SCs can send data using millimetre waves occupying frequencies between 27 GHz and 300 GHz range and avoiding interference from surrounding signals. This section discusses the proposed clustering techniques used to build the 5G network for the considered deployment scenarios and present the simulation experiments and the results derived from these experiments.

5.3.1 Assumptions.

We assume the network configuration can be expressed as a graph, $G(N_c, N_b, \ell_c, \ell_b, \omega)$, where N_c is the set of 5G cellular nodes, N_b is the base station, ℓ_c is the set of fronthaul communication links, ℓ_b is the set of backhaul communication links, and $\omega \rightarrow \omega(\Gamma_{SNR}, \phi)$ represents the link weight of SNR between UAVs and LAP. We also assume that communication links are Air-to-Ground and that nodes have an autopilot feature. Furthermore, all cellular nodes are considered to have the same characteristics for the radio transceiver.

5.3.2 Deployment Scenarios.

The primary purpose of this work is to prove that the forthcoming 5G network can be lucrative when deployed in rural areas. Hence, the selected scenarios are classified as such. As a use-case, educational sites such as public and private schools obtained from Google Maps in targeted areas are considered to host the network nodes. Table 15 present the areas that are to be studied in the deployment scenarios. The deployment scenarios studied in this chapter are the same as those considered in Chapter IV for economic feasibility. While Chapter IV focus was on the CAPEX and OPEX evaluation, this chapter focus lies on a network engineering model revealing that clustering techniques can be used to extend the LAP coverage. In line with the primary aims discussed above, this chapter considers five low-income areas (Soweto, Khayelitsha, Lulekani, Zeerust, and Duduza) and three rural areas (Hlankomo, Mandileni and Gon'on'o) in South Africa to perform the network analysis, as shown in Table 15. Furthermore, Figure 64 gave the total number of required cells.

Table 15 – Considered areas to deploy a proposed network.

MUNICIPALITY	AREA	TYPE	LOCATION		CELL REQUIRED			SITE
			Latitude	Longitude	UAV-Based	LC-Based	Hotspot	
City of Johannesburg	Soweto	Township	-26.266111	27.865833	23,654	7885	1514	86
City of Cape Town	Khayelitsha	Township	-34.040278	18.677778	7287	2429	467	23
Ba-Phalaborwa	Lulekani	Township	-23.864441	31.080306	127	43	11	17
Ramotshere Moiloa	Zeerust	Low-Income	-25.533333	26.083333	88	29	88	25
Ekurhuleni	Duduza	Township	-26.383333	28.400000	1364	455	88	33
Alfred Nzo	Hlankomo	Rural Residential	-30.902100	29.371400	3	1	1	0
King Sabata Dalindyebo	Mandileni	Rural Residential	-31.678446	29.125058	3	1	1	0
Giyani	Gon'on'o	Rural Residential	-23.272011	30.487295	5	2	1	1

5.3.3 Network Analysis Objectives.

The mutual goals in a wireless cellular system comprise of network lifetime, transmission reliability, and network latency (Xu, Collier, & O'Hare, 2017). Hence, to prove that the 5G cellular network can deliver full wireless coverage in targeted areas, we propose a partitioning of nodes into clusters to reduce the LAP load and achieve an efficient 5G coverage which is simulated over the terrain map to assess the real-time coverage to be achieved. The objectives are to: i) suggest improvements on the traditional clustering techniques to best suit the forthcoming cellular network, ii) propose backhauling models for both networks with and without gateway nodes, and iii) evaluate the performance of the proposed models through simulations.

5.4 CLUSTERING TECHNIQUES.

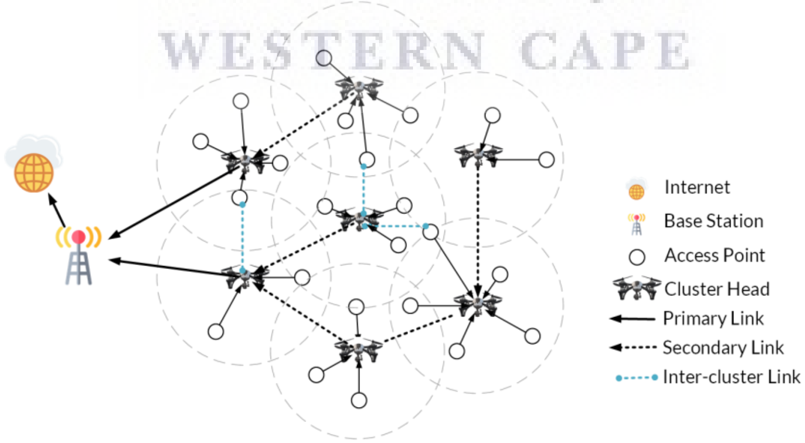


Figure 87 – Communication clustering technique.

The fast-growing deployment of 5G and its parallel need for efficient Internet connection compels for efficient network engineering techniques to prolong the 5G network's lifetime and balance workload. To support high-speed Internet connection through efficient network organisation in remote areas, nodes can be partitioned into several small groups, called clusters, as depicted in Figure 87, which shows a common clustered network structure. Each cluster has a coordinator, referred to as the cluster head (CH), and several member nodes (CM) (Younis, Krunz, & Ramasubramanian, 2006). CHs are nominated such that: i) the members of a cluster can communicate with their CH directly, and ii) the CH can aggregate and forward the aggregated data to the central BS through other CHs. Moreover, clustering algorithms usually structure networks into Voronoi diagrams, with some exceptions having non-Voronoi structures, such as spectrum shapes (Xu, Collier, & O'Hare, 2017). In this section, two types of clustering techniques for network coverage are proposed and compared.

5.4.1 Coordinator Selection using a Profit Function.

In one of the earlier clustered network models traffic is to aggregate to a central BS for further processing. However, this work takes a step further by offloading the gateway capabilities to normal nodes, thus enabling it to become a secondary gateway for the UAV cluster. This addition is advantageous in certain situations such as in medical emergencies whereby dedicated Internet connection is required to perform a surgical procedure. In this instance, the CH is dedicated to the procedure, while other UAVs in the cluster redirect their traffic to a secondary gateway. By parameterising the Residual Energy (RE) and SNR, we got new function $P(i)$ that nominates CH candidates based on profit. It is expressed as:

Equation 38 – Node Profit on a Network with LAP as a Gateway.

$$P(i) = \alpha \cdot \Gamma_{SNR}(i) + \beta \cdot E(i)$$

Equation 39 – Node Residual Energy.

$$E(i) = \bar{E} - E_{RSD}(i)$$

Equation 40 – Node Profit on a Network with UAVs as Gateways.

$$P(i) = \alpha \cdot \mathcal{C}_{UAV}(i) + \beta \cdot \mathcal{C}_{nodes} + \gamma \cdot E(i)$$

Where $\bar{E}$ and $E_{RSD}(i)$ are respectively the average energy in the network and the residual energy of node i and $HGT(i)$ is the height of i computed on-the-fly from the height of the parent node. $\Gamma_{SNR}(i)$ is the signal-to-noise-ratio of the LAP link to node i. $\mathcal{C}_{UAV}(i)$ is the centrality measure for UAVs, $\mathcal{C}_{nodes}(i)$ is the centrality measure related to normal nodes. CM selection is based on different formulas including radius, distance and number of cluster nodes.

5.4.2 Clustering Models.

The utilisation of UAV-BSs is a promising solution to address coverage and carrying capacity of the new 5G network (Iellamo, Lehtomaki, & Khan, 2017). The earlier chapters proved that the deployment of the network in rural and low-income areas is possible with our proposed heterogeneous architecture. The BSs provide coverage that is feasible in terms of CAPEX and OPEX. Users have better service at an affordable price. In this section, we introduce our proposed clustering models that extend the battery cycle and the LAP coverage range. We discuss the biased clustering algorithm for air-to-ground networks called Myopic. Furthermore, we discuss the balanced and multi-sink algorithms.

A. *Myopic algorithm (Chandrasekharan, et al., 2013).*

The proposed clustering mechanism in Chandrasekharan, *et al.* (2013), was to improve energy efficiency in aerial-based access systems suitable for disaster recovery scenarios and large scale public events. The LAP station provides access to several cellular nodes on the ground over a given coverage area. These terrestrial nodes are battery-operated power-constrained terminals that have got no base station access except for the LAP.

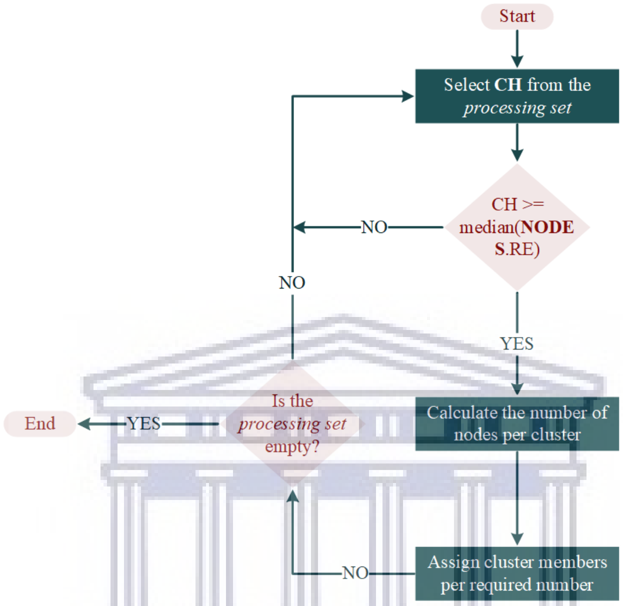


Figure 88 – Myopic Backhauling Model.

Subsequently, the aerial uplink requires more energy, hence they proposed a cluster-based approach for LAP access, depicted in Figure 88. In this work, we call the proposed clustering mechanism Myopic. The algorithm was simulated and compared with the well-known clustering technique HEED for energy efficiency. Their results proved that their proposed clustering technique improves energy efficiency as compared to the non-clustering situation, as well as to the HEED clustering technique. In this work, we implemented the Myopic algorithm to the best of our understanding from the literature. After implementing the technique, we simulated to better understand the model. However, we found that the algorithm had areas need to be improved. The backhauling model left nodes isolated without clusters and created empty clusters. Furthermore, it allowed CHs to have a huge number of possible CMs, causing the network to be imbalanced.

B. *Balanced algorithm.*

The improved Myopic backhauling model presented in Figure 89 borrow from the air-to-ground network from Chandrasekharan, et al. (2013) its clustering algorithm but adds network balancing to avoid resources wastage as stipulated earlier. Our model differs from Chandrasekharan in two ways: Firstly, we use a different reward function for the selection of a cluster head. Secondly, we implement network balancing to avoid building a network with isolated UAVs which can result in resource waste as they do not provide any useful task while consuming resources. Lastly, we consider two different backhauling models where communication between UAVs can be done via another UAV used as a gateway or through the LAP. The UAV can communicate telemetric information such as the Residual Energy (RE) and location in the network. With these data, we create a processing set and then select the node from the set that has the highest SNR with the LAP. We then check if the residual energy of the selected node is greater or equal to the median residual energy of the nodes in the processing set. We further calculate the number of cluster members per cluster and assign them from the processing set, and they must be in the coverage range of the cluster head. The expression below compute z_c, where the maximum number of cluster members per cluster z_c^{max}.

Equation 41 – Maximum number of cluster members per cluster.

$$z_c = \frac{z_c^{max} \cdot \Gamma_{SNR_i}}{\Gamma_{SNR_{max}} - \Gamma_{SNR_{min}}}$$

Remove nodes select as the cluster head and sub-nodes from the processing set and append the to a cluster set. Balance nodes left in the processing set and create inter-cluster heads. The cluster members must be within the maximum coverage radius R_c of the cluster head.

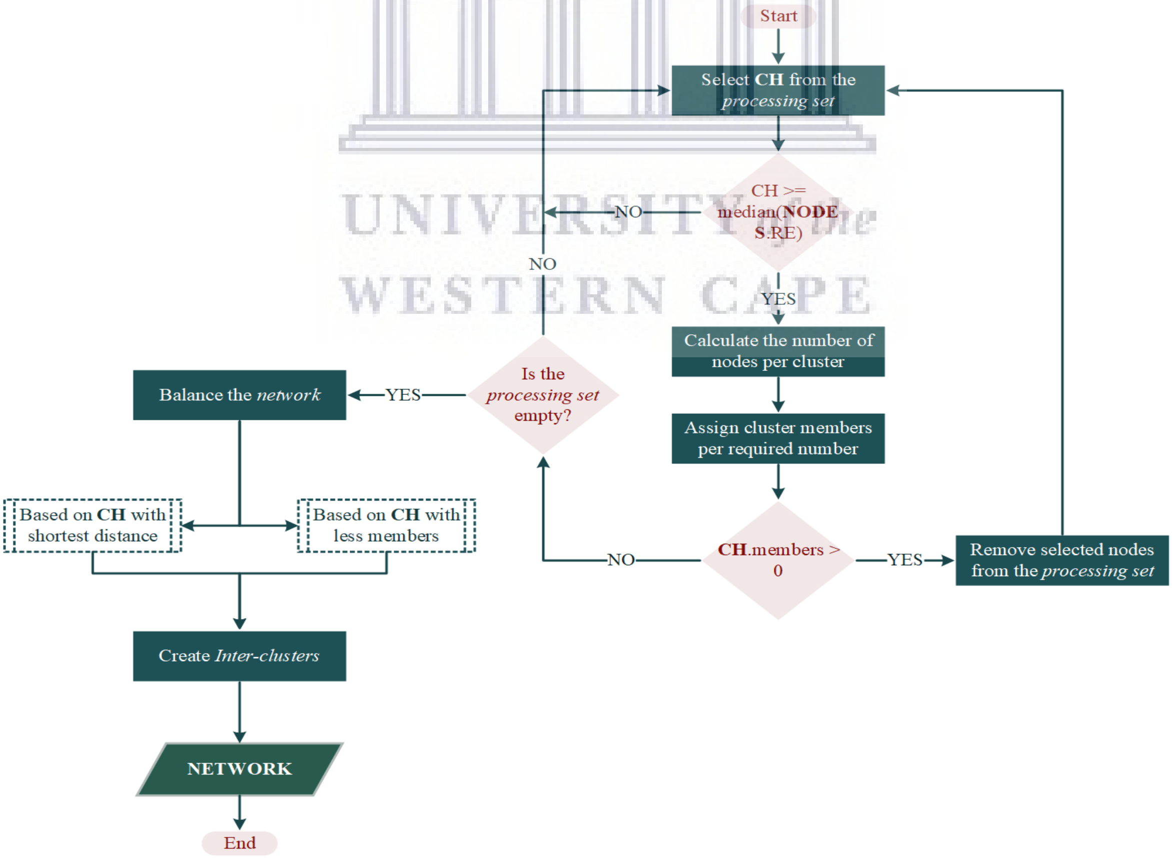


Figure 89 – Improved Balanced Backhauling Model.

As noted in Chandrasekharan, *et al.*, (2013), the algorithm needs to check the node selected as the CH to determine if there are cluster members assigned to it. If there are no cluster members assigned, the node must go back to the processing set. After obtaining the backhaul clustering set, we find the optimal inter-cluster communication links by: i) creating a fronthaul link that hops CHs that have SNR greater than the average links among the cluster head, and ii) find the nearest CH that has better residual energy and signal-to-noise ratio to the base station and create an inter-cluster link through it. By following this process, we create a virtual image depicted in Figure 87, where primary links of cluster heads are backhauling communication links and the secondary links are fronthaul links.

Equation 42 – Maximum number of cluster members per cluster using the logistic function.

$$z_c = \frac{z_c^{max}}{e^{1-{\Gamma_{SNR_i}}/{\Gamma_{SNR_{max}}}}}$$

Figure 89 and Algorithm 1 (discussed in the appendices) depict the improved backhauling mechanism. As in the original model, UAV telemetry aid with the nomination of CHs while portioning the network by the LAP. However, the inter-cluster and fronthaul links are done respectively by the UAVs. By splitting the mechanism this way, we reduce the complexity of managing clusters and routing traffic. Besides, the clusters are reassigned periodically using updated beacon packets from UAVs reporting their corresponding parameters in the network. Furthermore, we use a basic logistic function (Equation 42) to determine the total number of CMs connected to the coordinator. By following the nature of the function, it implies that the chosen CH is assigned the number of CMs based on the SNR strength to the LAP.

C. *Multi-sink Backhauling algorithms: MSGBACK and MSLBACK.*

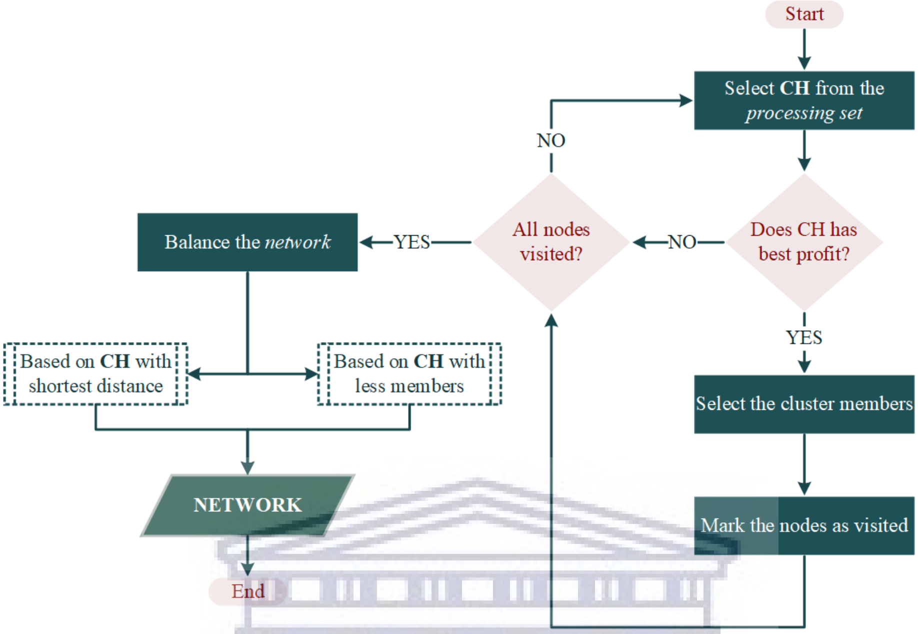


Figure 90 – Greedy Cluster Head Selection with cluster Membership Balancing model.

We propose a second algorithm based on a Greedy cluster-head selection with cluster membership balancing (GSMB) for backhauling, as illustrated in Figure 90. Algorithm 2 (discussed in the appendices) details the pseudo-code for the model and can be described as follows: firstly, it starts by marking all nodes of the network as non-visited. It then loops until all nodes are visited to: i) select the best CH candidate node, ii) select its CMs, and iii) mark the node as visited. We employ two mechanisms to balance the cluster memberships: i) redistribution of CMs based on distance, ii) redistribution of CMs crowdedness. In this model, CH is nominated using the profit function described in the earlier section.

5.4.3 Backhauling Models.

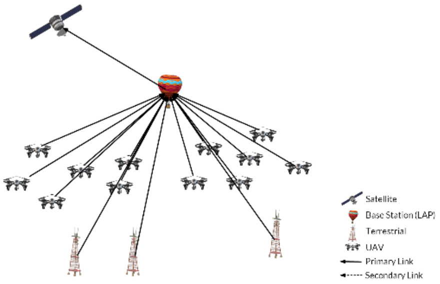


Figure 91 – Unclustered network tier.

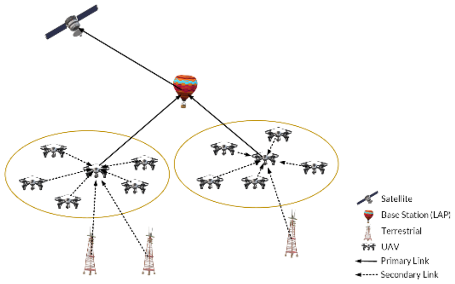


Figure 92 – MSLBACK network tier.

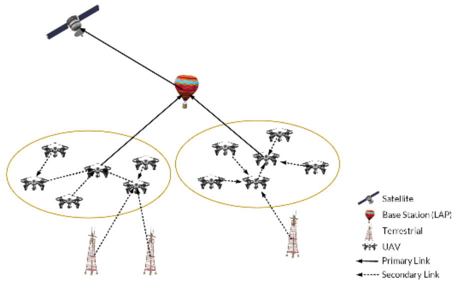


Figure 93 – MSGBACK network tier.

As implemented, the Greedy cluster-head Selection with cluster Membership Balancing (GSMB) will lead to two network topologies below:

i. Multi-sink with LAP backhauling referred to as MSLBACK, illustrated in Figure 92.
ii. Multi-sink with UAV Gateway backhauling referred to as MSGBACK, illustrated in Figure 93.

The above images reveal three different backhauling models:

i. Unclustered backhauling where (shown in Figure 91):
    - There are no clusters.
    - All UAVs communicate through the LAP.
    - Terrestrial BS communicates with the LAP directly.
    - There are no secondary links.
ii. MSLBACK backhauling where (shown in Figure 92):
    - There are clusters.
    - Primary links are used by CHs to communicate with the LAP.
    - Terrestrial towers (BSs) communicate with the CH via secondary links.
    - The CHs communicate with each other via the LAP used as a gateway.
iii. MSGBACK backhauling where (shown in Figure 93):
    - There are clusters.
    - Primary links are used by CHs to communicate with the LAP.
    - Terrestrial towers (BSs) communicate with the CH via secondary links.
    - The CHs can communicate with each other via UAVs used as gateways.

5.4.4 Summary of Clustering Techniques.

Table 16 – Clustering Techniques.

		STRUCTURE	CLUSTER HEAD	CLUSTER MEMBER	GATEWAYS	NODES	SELECTION
Myopic	Myopic with the possibility of leading to isolated/orphan nodes.	Voronoi	Hierarchal based on SNR, RE	Equal distance from CH	LAP	Terrestrial	Static
Traditional (Balanced)		Non-Voronoi	Hierarchal based on SNR, RE	Best distance or SNR from CH	LAP, UAV, Terrestrial	UAV, Terrestrial	Static
GSMB (MSLBACK & MSGBACK)	A balanced model where all the nodes are either cluster heads or cluster members.	Non-Voronoi	Hierarchal based on SNR, RE	Equal distance from CH	LAP, UAV	UAV, Terrestrial	Static and Dynamic
K-Means		Non-Voronoi	Randomly	Shortest distance	LAP	Terrestrial	Static

Table 16 below discusses the clustering techniques considered in this section by categorising the genre in two distinct relations: i) backhauling, and ii) backbone model. Where "*cluster head*" discusses parameters used to nominate CH and "*cluster member*" discuss how membership is assigned. Dynamic selection is where a CM can become a CH.

5.5 WIRELESS NETWORK SIMULATIONS.

A wireless network is a computer telecommunication network which is cordless, and interconnections among nodes are deployed without requiring the use of wires (Ezreik & Gheryani, 2012). Earlier sections proposed and compared various clustering methods, however, since these techniques are used in a worldwide network, it makes financial sense to simulate the real network before deployment (Xu, Collier, & O'Hare, 2017). While the performance of proposed clustering solutions in the real network can be predicted from simulations, in this section, Monte-Carlos simulations prove that our backhauling and backbone methods do not leave node isolated and the solution can provide wireless coverage in rural areas by computing SNR strength on a clustered network.

5.5.1 Experimental Configurations.

Monte-Carlos simulations were on the algorithms implemented in Python programming language, and then Microsoft Excel plots the CSV results generated by the simulations. Furthermore, Appendix B lists all package used. MATLAB R2019a computed the LoS and SNR coverage maps. In short, all simulations are conducted with parameter from Table 15. Our simulation environment adopts the guidelines for 5G by reusing a test network layout for the current network technologies defined in Section 8.3 of Report ITU-R M.2135-1 (Series, 2009), which is shown in Figure 94. However, our node placement depends on the designated site for each case scenario, listed in Appendix B. Distances between the adjacent sites is the Inter-Site Distance (ISD) and depends on the test usage scenario.

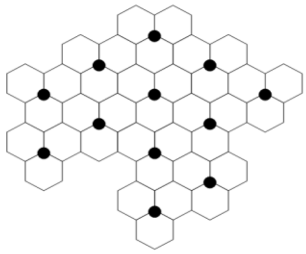


Figure 94 – Network layout with three cells per

5.5.2 Comparing the Clustering Techniques.

All six non-Voronoi line graphs depict clustered networks for educational sites in Soweto township, as discussed in Table 15 and the exact locations listed in Appendix B. A specific colour signifies a cluster: CMs are illustrated with dots, while the dots representing CHs is surrounded by black borders. Nevertheless, the isolated nodes are represented with grey dots. Hauling links are represented by the line from CM to CH. Both the backhauling and backbone models were implemented in Python developing environment (plug-in packages are listed in Appendix B). The GSMB backhauling technique is implemented in two ways, one with gateway nodes and the other without. They are multi-sinks airborne network with an inter-cluster connection through UAV gateways called MSGBACK and multi-sink airborne network with an inter-cluster connection through the LAP called MSLBACK. The only Myopic technique developed to our best knowledge was that proposed by Chandrasekharan, et al. (2013). For comparison purpose, we also tested our models against the well-known K-means clustering technique. For this work, we used the K-means algorithm available in SciPy and NumPy Python packages. We called our improved technique a Traditional Backhauling.

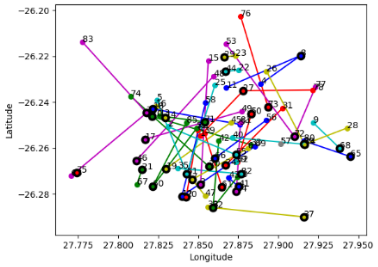


Figure 95 – Myopic Backhauling network in Soweto.

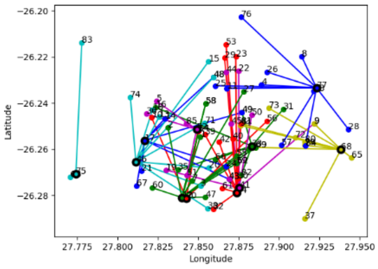


Figure 96 – Traditional Backhauling network in Soweto.

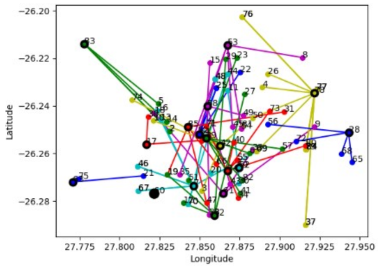


Figure 97 – MSGBACK network in Soweto.

We considered Monte-Carlo simulations by running each technique under similar conditions and having the remaining energy (RE) and signal-to-noise (SNR) randomly selected from Normal, Log-Normal, Chia-Square, and Uniform distributions as specified in Table 17, where it discusses the specific parameter used for each distribution. Despite several tries, the Myopic model kept leaving some nodes isolated.

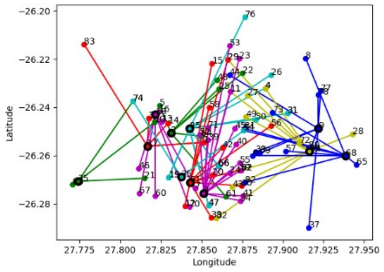


Figure 98 – MSLBACK network in Soweto.

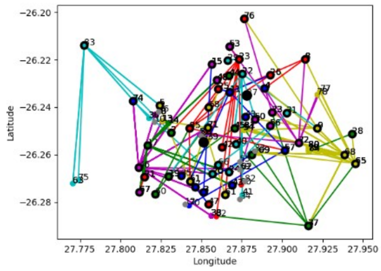


Figure 99 – K-Means clustered network in Soweto.

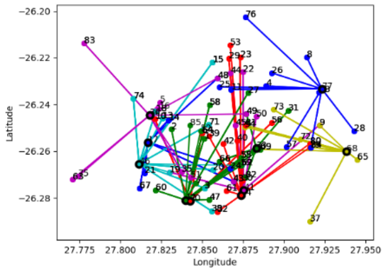


Figure 100 – Traditional Backhauling with Redistribution network in Soweto.

Figure 95 prove our observation by illustrating node 57 (South West College) which does not belong to any cluster, even when the node is near a CH that could assign it as a member. Furthermore, the model created many clusters defeating the whole purpose of reducing the load from the BS. Figure 99 also shows the K-Means leaving nodes isolated. K-Means also assigned CHs as members to other clusters, thus creating multi-link sets and some CMs with more coordinators. These results prompted the necessary improvement on the Myopic algorithm and lead to the proposal of the GSMB. Hence, MSGBACK, MSLBACK, Traditional performed incredibly leaving no isolated nodes and creating an ideal number of clusters with the logistics function in Equation 42.

5.5.3 Monte-Carlos Simulations.

Table 17 – Distribution functions with parameters to generate random values.

	SYMBOL		DISTRIBUTION			
			NORMAL	LOG-NORMAL	CHIA-SQUARE	UNIFORM
Residual Energy (RE)	Mean	$\mu_{E_{RSD}}$	1340	9.5		
	Standard Deviation	$\sigma_{E_{RSD}}$	428.547	0.5		
	High	$H_{E_{RSD}}$				2400
	Low	$L_{E_{RSD}}$				0
	Degree of Freedom	$DF_{E_{RSD}}$			1340	
Signal-to-Noise Ratio (SNR)	Mean	$\mu_{\Gamma_{SNR}}$	-78	2.5		
	Standard Deviation	$\sigma_{\Gamma_{SNR}}$	16.59	0.6		
	High	$H_{\Gamma_{SNR}}$				-10
	Low	$L_{\Gamma_{SNR}}$				-160
	Degree of Freedom	$DF_{\Gamma_{SNR}}$			20	

Clustering is one of the well-known optimisation problems which are well researched for developing many nature-inspired algorithms in computer networking field (Kuila & Jana, 2014). In this section, Monte-Carlo simulations are carried out using random data in Table 17 and the proposed multi-sink airborne network clustering algorithms are compared with other Myopic clustering algorithms. We considered Monte-carlo simulations by running each technique under similar conditions and having the remaining energy (RE) and signal-to-noise (SNR) randomly selected from Normal, Log-Normal, Chia-Square, and Uniform distributions as specified in Table 17, where it discusses the specific parameter used for each distribution. Despite several tries, the Myopic model kept leaving some nodes isolated.

Figure 95 proves our observation by illustrating node 57 (South West College) which does not belong to any cluster, even when the node is near a CH that could assign it as a member. Furthermore, the model created many clusters defeating the whole purpose of reducing the load from the BS. Figure 99 also shows the K-Means leaving nodes isolated. K-Means also assigned CHs as members to other clusters, thus creating multi-link sets and some CMs with more coordinators. These results prompted the necessary improvement on the Myopic algorithm and lead to the proposal of the GSMB. Hence, MSGBACK, MSLBACK, Traditional performed incredibly well leaving no isolated nodes and creating an ideal number of clusters with the logistics function in Equation 42.

A. Balanced Algorithm Versus Other Backhauling Mechanisms.

Despite the fundamental similarities of the proposed mechanism and the Myopic backhauling algorithm in Chandrasekharan, et al. (2013), the Traditional and GSMB models (MSGBACK and MSLBACK) supplement by checking that there are no isolated nodes and no cluster set without members. In contrast to having only a direct backhauling link to the LAP, these proposed algorithms create secondary links to send packets outside the sub-network by hopping through CHs with the highest SNR to the LAP. Moreover, a multi-sink node improves the transmission of local packets. From this design, routing all communication through the LAP is beneficial, as messages can easily be checked and controlled. However, this design can shorten the operational lifespan of the nodes running on batteries. To cater for this, MSGBACK and MSLBACK take another step further by creating best fronthaul communication links that form the basis of traffic routing. Below are Myopic based techniques compared with our proposed algorithm:

i. **Random Selection Backhauling:** in this clustering technique, CHs are selected randomly from the processing set.
ii. **Energy-Aware Selection Backhauling:** this clustering technique extends the Random Selection by preferring nodes with residual energy that is higher than the median RE of the processing set.
iii. **Ranked Energy-Aware Selection Backhauling:** in this algorithm, starts with sorting the processing set in descending order regarding RE and select the nodes from the processing set, respectively.

In our graph presentation, we used the following labels as legends to represent the lines. We choose "*Technique Name [Considered Node/s]*" as a structure for naming these legends, where CH means the number of Cluster Heads and Unassigned represent isolated nodes in the network:

i. Cluster Heads in the network per each algorithm.

    a. Myopic [CH].
    b. Backhauling [CH].
    c. MSGBACK [CH].
    d. MSLBACK [CH].
    e. K-Means [CH].
    f. Random Selection [CH].
    g. Energy-Aware Selection [CH].
    h. Ranked Energy-Aware Selection [CH].

ii. Unassigned/Isolated nodes in the clustered network.
    a. Myopic [Unassigned].
    b. Backhauling [Unassigned].
    c. MSGBACK [Unassigned].
    d. MSLBACK [Unassigned].
    e. K-Means [Unassigned].
    f. Random Selection [Unassigned].
    g. Energy-Aware Selection [Unassigned].
    h. Ranked Energy-Aware Selection [Unassigned].

B. Effect of Signal-to-Noise Ratio Distribution.

This subsection discusses how SNR distribution affects the clustered network. We sample SNR and RE with regular Gaussian distribution to demonstrate that the proposed algorithms do not leave nodes isolated. After rigorously testing the proposed algorithm against the Myopic backhauling algorithms, we discovered that the distribution of received SNR at the LAP and the size of the network caused the dip in performance of rival algorithms. The results of simulations carried out to affirm this claim are depicted in figures below. The experiments were conducted 20 times, respectively, with different SNR and RE distributions selected from a million random values. A bar in the grey colour represents the bounds of SNR distribution in each simulation and values are on the right scale. A line with a circle represents a total number of nodes assigned as CHs, while a broken line with a triangle represents a total number of isolated nodes. Figure 101 and Figure 103 depict the network simulation result for the Soweto township. In both figures, Traditional Backhauling, MSGBACK, and MSLBACK had no isolated nodes, and they had the lowest number of CHs. Clearly, Figure 103 shows that K-Means and Myopic left more nodes isolated with a considerably higher number of CHs. Our improved Backhauling method outperformed the other techniques in Figure 101. Energy-Aware Selection left several nodes unassigned to any cluster set, trailed by the Myopic algorithm. While the Ranked Energy-Aware Selection method did not leave any node unassigned except for twice, where SNR had the highest dB bound.

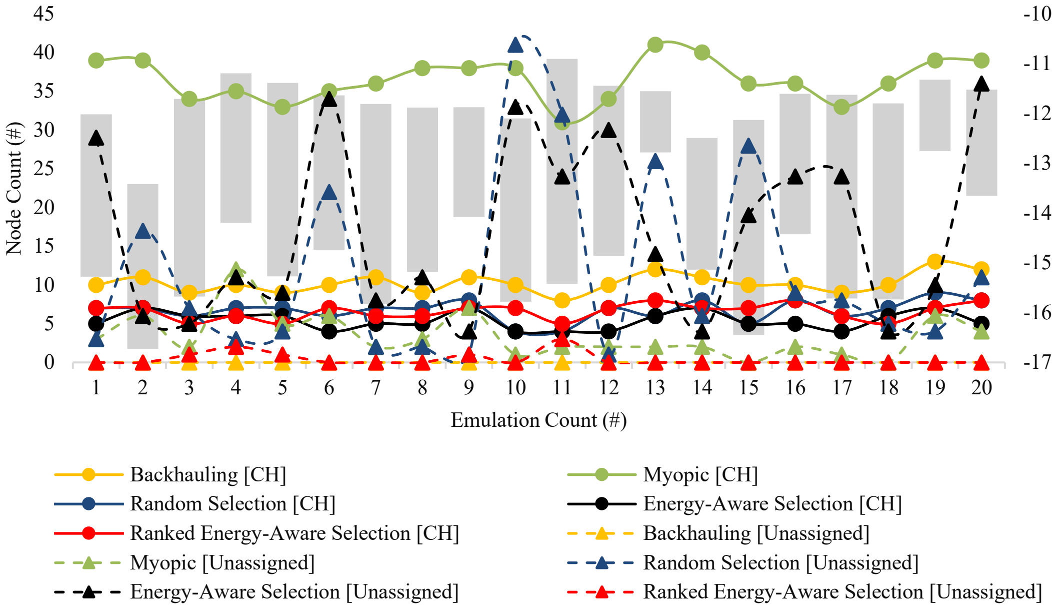


Figure 101 – Emulation of other improved techniques in Soweto township.

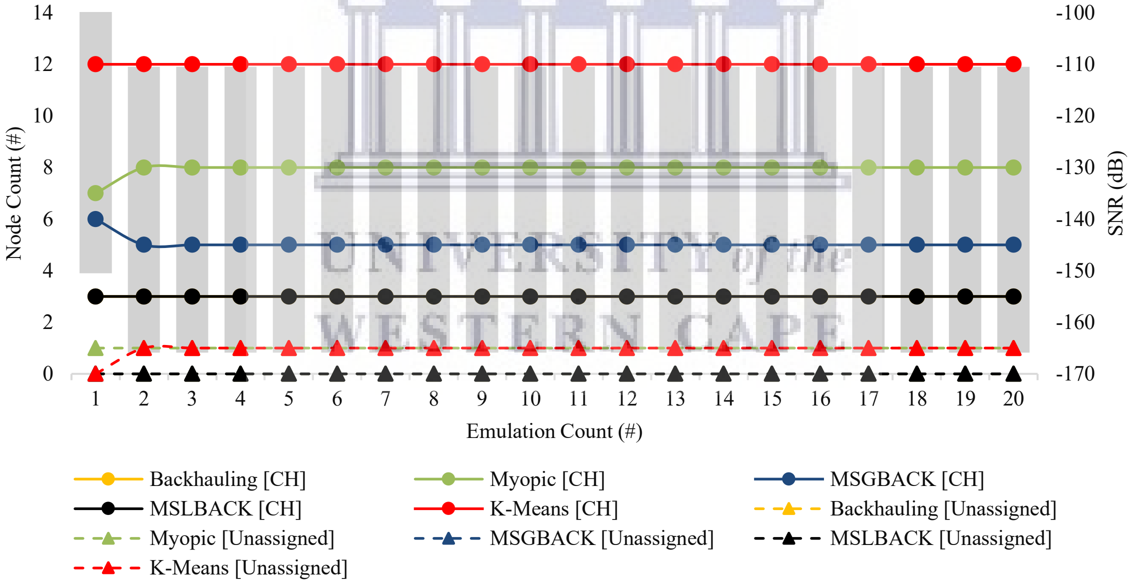


Figure 102 – Emulation of other improved techniques in Zeerust low-income town.

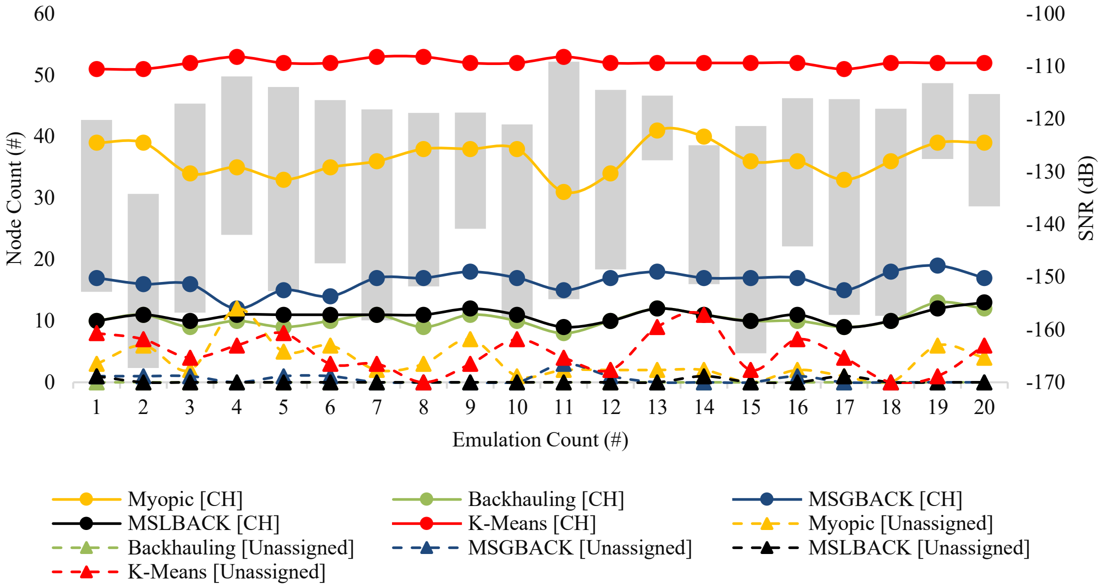


Figure 103 – Emulation of Traditional Backhauling models in Soweto township.

The same simulation condition was repeated in Zeerust town with a uniform random distribution of SNR and RE, shown in Figure 102 and Figure 104. From the result shown in the figures, it can be concluded that compared to the other algorithms, the Traditional Backhauling, MSGBACK, and MSLBACK models proposed in this work is most suited for 5G wireless networks provided using UAVs; especially if the UAVs are in constant motion. However, when the UAVs are hovering in place, there is a higher chance that they have perfect LoS. With a perfect LoS, the UAVs would have a remarkably similar received SNR at the LAP and thus equally effective. The Myopic, Odd and OddRange algorithms left many nodes unassigned to any cluster set compared to our proposed algorithm. With the result from in Figure 102 and Figure 104, we can see that the other backhauling algorithms are not suitable for a 5G wireless network that is provided using UAVs.

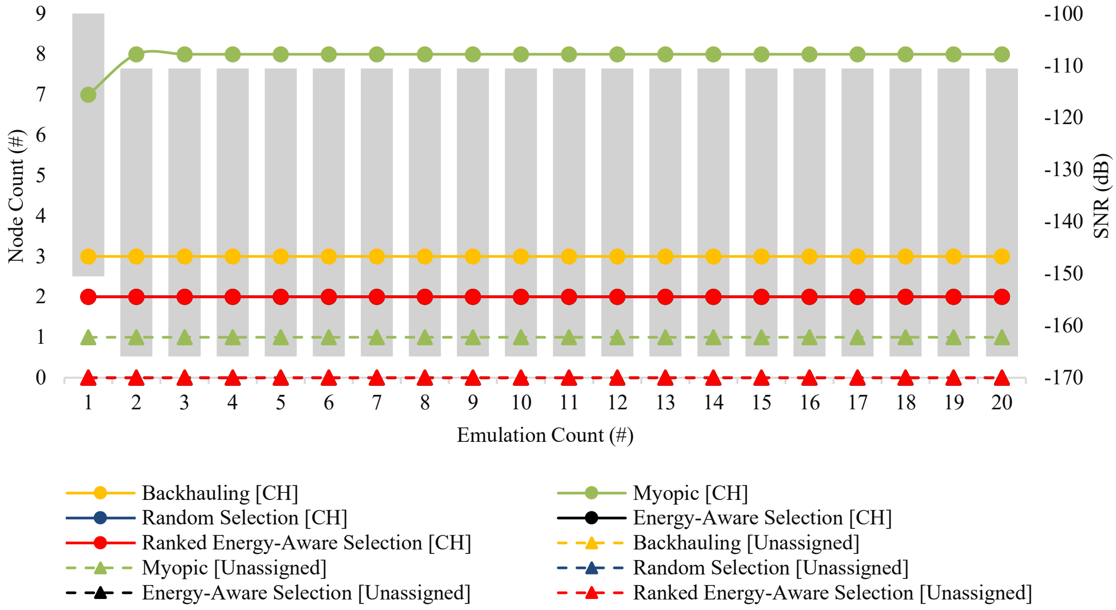


Figure 104 – Emulation of other improved techniques in Zeerust low-income town.

5.5.4 Coverage over a Terrain Map.

This section designs a Fixed Wireless Access (FWA) link over terrain that uses 5G technologies. FWA is a use case for 5G to support broadband service to homes or enterprises in rural areas where optical services are inaccessible. FWA can be a UAV-based or terrestrial-based node that connects a LAP with Fixed Wireless Terminal (FWT) used by EU (Laraqui, et al., 2017). The MATLAB simulation rests on guidelines defined in Report ITU-R M. [IMT-2020.EVAL] for evaluating 5G radio technologies (ITUR, 2017). Also, the section defines several test environments and usage scenarios in Section 8.2. To evaluate our envisioned 5G network in a realistic setup, we simulate a network with the parameters in Table 18, and the same use cases in the Monte-Carlos simulations.

Table 18 – Cellular Parameters.

PARAMETER	VALUE	
	Macrocell	**Microcell**
Frequency	3.5 GHz	28 GHz
Transmitter Height	25 Metres	25 Metres
Transmission Power	1 Watt	1 Watt
Receiver Noise		
Receiver Height	30 Metres	30 Metres
System Loss	0	0
Receiver Sensitivity	-100 dBm	-100 dBm
Propagation Model	Longley-Rice	
Signal Strength	-84 dB: -50 dB	
Pathloss	Free Space	Free Space
Range	10 Kilometres	500 Metres

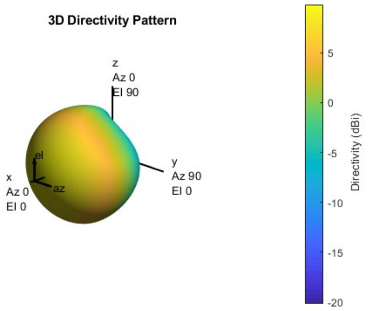


Figure 105 – Antenna Element.

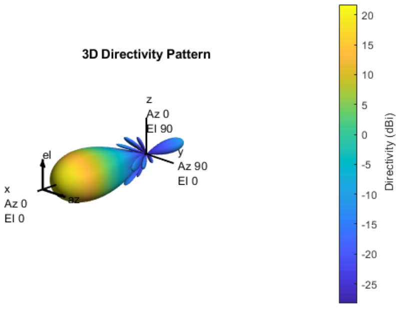


Figure 106 – 8-by-8 Rectangular Antenna

Terrain and path loss deficiencies like foliage and weather have an essential role in the high frequencies required for 5G technologies when determining connection success. Section 8.5 of ITU-R article sets out antenna features for BS antennas (ITUR, 2017). The ideal antenna is patterned as having one or several antenna panels, in which every panel also has one or more antenna elements. We used the Phased Array System Toolbox in MATLAB to implement the antenna element pattern that is defined in the ITU-R report, shown in Figure 105. Furthermore, we have increased the peak Signal-to-Interference-plus-Noise Ratio (SINR) values and define an antenna array to boast multi-directional gain. Then we created an 8-by-8 uniform rectangular array, shown in Figure 106.

A. *Antenna Coverage Dense Network.*

This section shows signal strength between a transmitter and multiple receivers. The visualisations include an area coverage map and coloured communication links, where green line represents a strong link while red is a poor one.

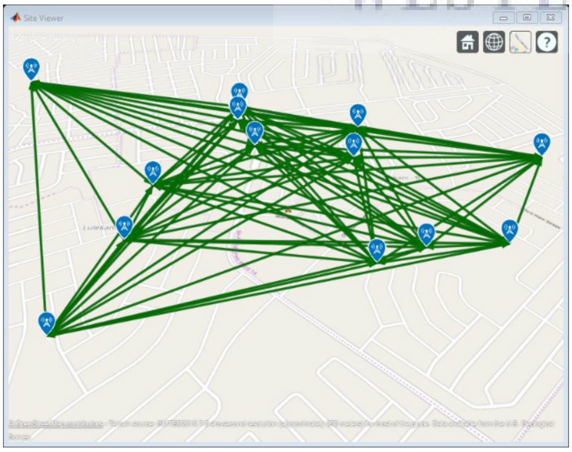


Figure 107 – LoS Dense Network in Lulekani.

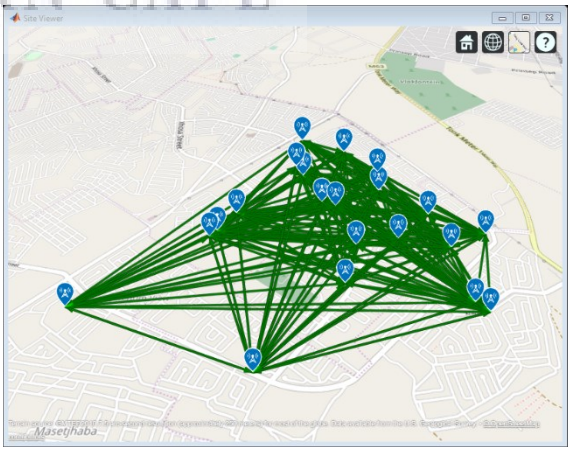


Figure 108 – LoS Dense Network in Duduza.

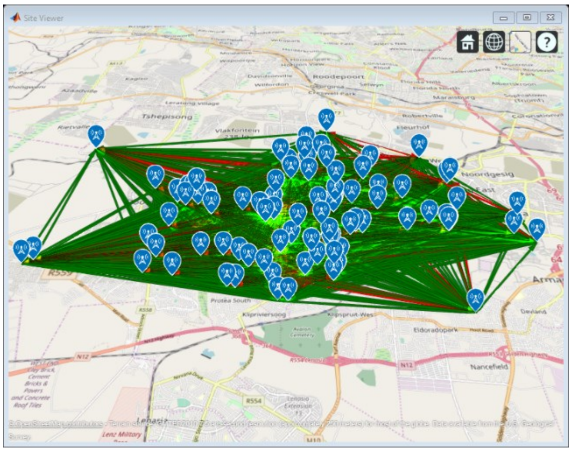


Figure 109 – LoS Dense Network in Soweto.

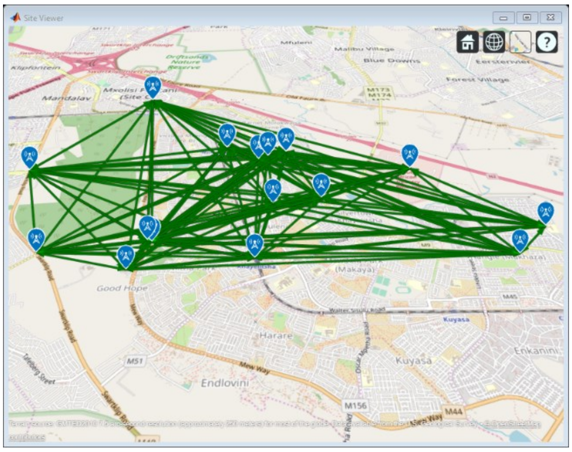


Figure 110 – LoS Dense Network in Khayelitsha.

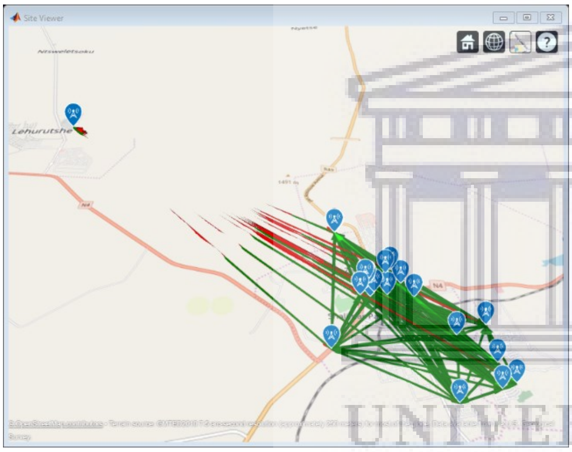


Figure 111 – LoS Dense Network in Zeerust.

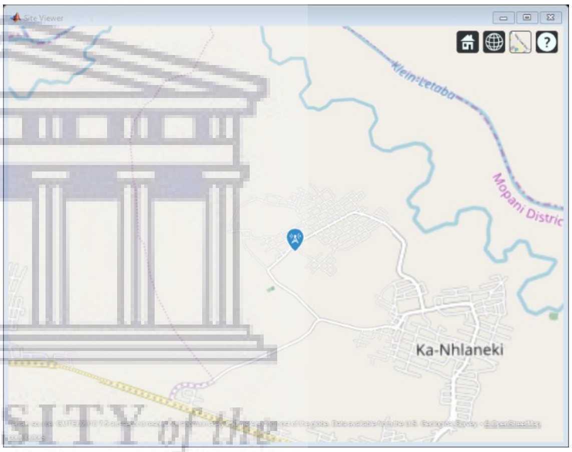


Figure 112 – LoS Dense Network in Gonono.

B. The Fifth Generation Network Coverage Performance.

In the simulator we create BS and multiple receiver sites in a rural or low-income environment, situating the antennas in a specific site with a possible LoS. The MU-MIMO system with high-gain antennas is designed using Antenna Toolbox™ and Phased Array System Toolbox™. We also redesign the MU-MIMO system for 3.5 GHz lower frequency to reach the more favourable path loss. The 3.5 GHz band is a leading band under review for 5G wireless radio (Laraqui, et al., 2017). The free space propagation model is used to compute incoming signal strength for every receiver site. Besides, the Longley-Rice propagation model with rain impairments are added to generate a coverage map when calculating 3.5 GHz signal strength at each receiver site. The Longley-Rice model, otherwise known as the Irregular Terrain Model (ITM), estimates path loss based on diffraction and other losses derived from the terrain. The Longley-Rice model is effective from 20 MHz to 20 GHz. The minimum receiver sensitivity is assumed to -84 dBm to produce favourable conditions for free space loss the receiver sites (Roessler, 2018).

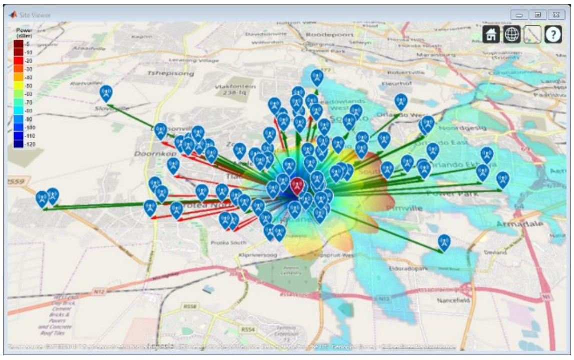


Figure 113 – Single Base Station coverage map with the line of sight in Soweto township.

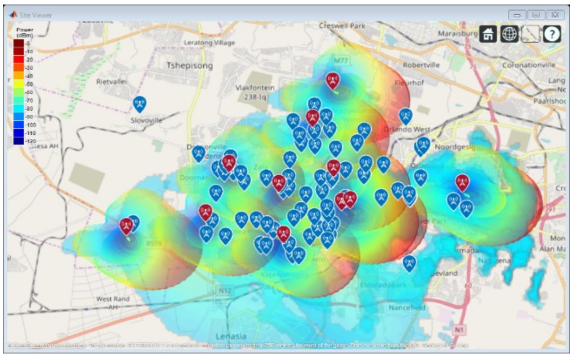


Figure 114 – Multi Base Stations coverage map in Soweto township.

Figure 115 – Single Base Station coverage map with a line of sight in Khayelitsha township.

Figure 116 – Multi Base Stations coverage map in Khayelitsha township.

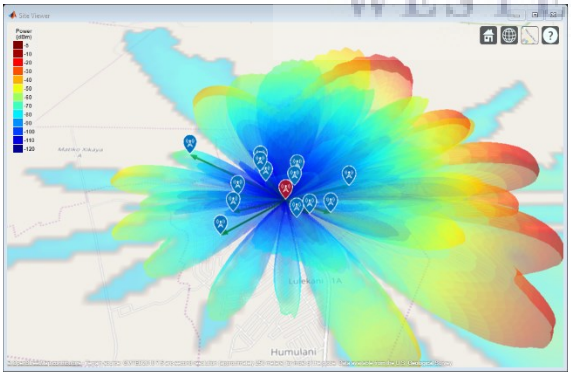


Figure 117 – Single Base Station coverage map with a line of sight in Lulekani township.

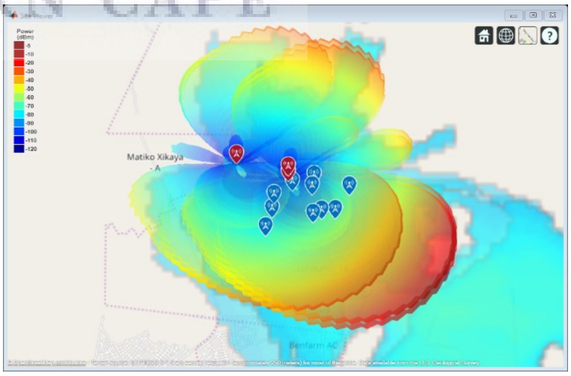


Figure 118 – Multi Base Stations coverage map in Lulekani township.

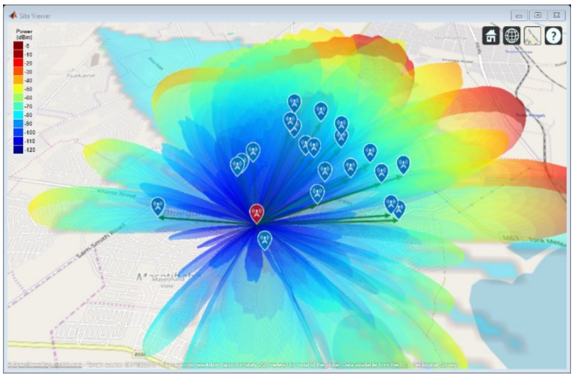


Figure 119 – Single Base Station coverage map with a line of sight in Duduza township.

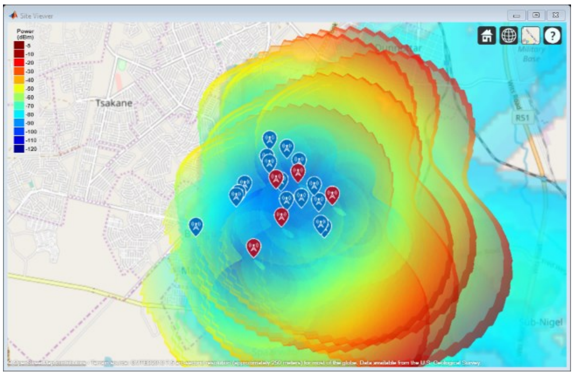


Figure 120 – Multi Base Stations coverage map in Duduza township.

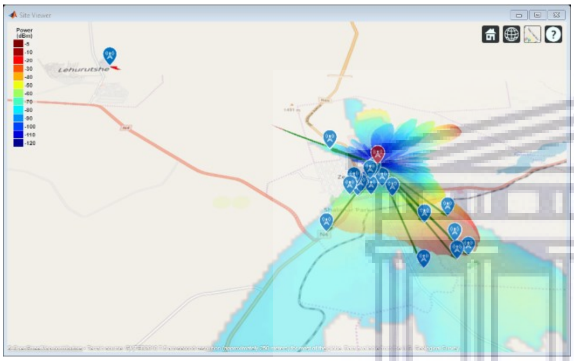


Figure 121 – Single Base Station coverage map with a line of sight in Zeerust low-income town.

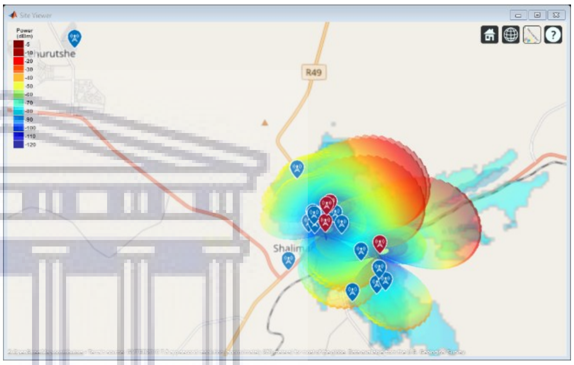


Figure 122 – Multi Base Stations coverage map in Zeerust low-income town.

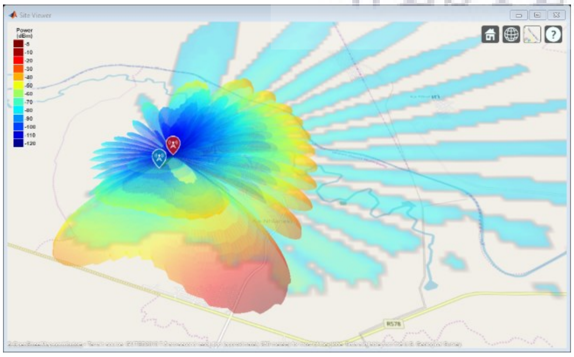


Figure 123 – Single Base Station coverage map with a line of sight in Gon'on'o rural residential area.

The images above visualise SINR map for the test scenario using a uniform rectangular antenna array, the free space propagation, and the Close-In propagation models (Sun, et al., 2016). Weissberger's model was used to estimate path loss through foliage and lousy weather

(Seybold, 2005). Furthermore, the rain propagation model was used to estimate signal strength in heavy rainfall. Hence, in the presence of path loss diminishing the estimated signal strength gets weak and falls below the receiver sensitivity of -84 dBm. The models produce an SINR map that shows reduced interference effects compared to the free space propagation model. Where LoS is represented by a green directional line pointing from BS to a receiver site and from CH to CM belonging to its cluster. On the single BS map, we consider that all the nodes are connected to the LAP denoted in red cellular landmarks, while on the map CH becomes BS. The multi-BSs network is imported from implemented clustering algorithms in Python.

Clearly, with these simulations, we have managed to prove our network objectives. The cluster network in multi-BS maps depicts most nodes with both 3.5 and 28 GHz, the nodes without coverage is due to signal propagation loses. In Figure 113, the western Soweto had many nodes that could connect to the BS, and with the clustered network in Figure 114, only two of the nodes had no coverage in the west of Soweto. These limitations continued in most of the scenarios. However, it is essential to bear in mind that our methods are dynamic and can re-cluster the network on the fly. In Gon’on’o area clustering was not necessary since there was a single receiver that had coverage from the BS.

5.6 NETWORK LINKS ALLOCATION.

The work presented in this chapter contributed to the design of a hybrid network, where a team of UAVs (playing the role of access points) are tasked with providing wireless connectivity to the users located on the ground. A Low-Altitude Platform (LAP), layered above the UAV team acts as a public gateway, providing 5G access in the location of interest. This hybrid network is built around a multi-layer architecture with users located in the first tier, the UAVs are in the second tier and the LAP in the third tier. The resulting 5G network has been engineered using: i) clustering techniques to organize the team of UAVs into clusters to optimize their utilization and ii) matching techniques to optimally allocate UAVs to users with the expectation of maximizing user satisfaction. These network engineering methods were augmented by simulation modelling in the 3.5 GHz and 28 GHz frequencies used by 5G in the mid-band and millimetre-wave frequency bands respectively. While recent works have shown that network devices can be steered to preferred access points using a probability function (Han & Ram, 2020), to the best of our knowledge, no previous research has investigated matching techniques such as the Stable Roommate allocation to allocate links between access points and users as in our envisioned network. One approach to solve this problem involves the use of location points. We considered schools in Soweto, South Africa as 5G node locations while the healthcare centres are considered as clients requiring network access. The ultimate goal is to compare the performance of two task allocation models, namely Stable Roommate and Gamma Random in allocating users to UAVs.

5.6.1 Allocation Models.

The allocation algorithms proposed in this work for UAVs’ task allocation were implemented in Python. The implementation was based on the assumption that: i) clients preferred access points that have better Signal-to-Noise Ratio (to the LAP) and Residual Energy (RE), as well as a maximum displacement of 5 km and ii) the access points (UAVs) prefer all clients that are within its coverage range. The locations of points of interest in Soweto were extracted from

Google maps. For the current work, it is sufficient to point out that only two algorithms were considered and their performance evaluated: the stable roommate allocation (SRA) algorithm and a gamma random allocation (GRA) algorithm. The algorithms are described in the next subsections.

A. Stable Roommate Allocation (SRA).

The SRA problem is one of finding a stable matching of people to rooms, wherein there is no pairing where both members prefer their partner in a different matching over their partner in the stable matching (Iwama & Miyazaki, 2008). In contrast to the stable marriage problem, the stable roommate problem allows 1-to-many matching between two elements, not just between classes of "men" and "women". Hence, we used the algorithm to match UAVs to clients/users in the 5G network fronthaul. The algorithm used in this work was proposed in (Gusfield & Irving, 1989) to match stable preferences. The algorithm has $O(n^2)$ complexity, provided suitable data structures are used to implement the necessary manipulation of the preference lists.

B. Gamma Random Allocation (GRA).

The GRA model builds around a probabilistic approach using the gamma distribution to match UAVs to clients/users. The probability density for the Gamma distribution is given by Equation 43 below.

Equation 43 - Gamma Distribution Density Function.

$$p(x) = x^{k-1}\frac{e^{-x/\theta}}{\theta^k\Gamma(k)},$$

Where k is the shape and θ the scale, and Γ(k,θ) is the Gamma function. The Gamma distribution is often used to model the times to failure of electronic components and arises naturally in processes for which the waiting times between Poisson distributed events are relevant (Weisstein, 2004). The Γ probability density sample distances are obtained with $k = min\ (\mu_{distance}, R_{coverage})$ and $\theta = \sigma_{distance}$, where the population in our case represents the distances from the access point to their clients. $R_{coverage}$ is the coverage range of network node. The images below depict sample data generated from Γ distribution, the results in Figure 124 are used to produce the results for link allocation. Significant similarities in the skewness of the sample data remained due to the θ which was computed from the real distances.

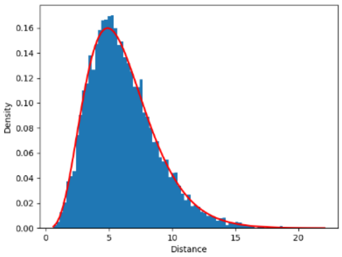


Figure 124 – Third Sample Generated from Gamma Distribution.

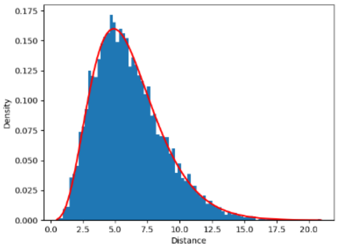


Figure 125 – Second Sample Generated from Gamma Distribution.

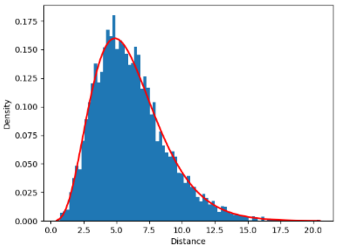


Figure 126 – First Sample Generated from Gamma Distribution.

5.6.2 Results.

For the UAVs task allocation experiment, we selected a total of 161 health centres acting as clients in the network and 85 UAVs acting as access points located in educational centres. We used the two allocation techniques to evaluate the performance of each technique in terms of the number of clients who were left unallocated to any access point. The Gamma Random algorithm randomly selects distances from the *Γ* probability density sample and creates a network link. As revealed by the results presented in this section, the SRA outperforms the GRA. The results show that a 152 of the 161 clients were assigned to their preferred access points by a SRA, while with GRA only 14 of the 161 clients were assigned to their preferred node. These results are as depicted as legends in Figure 127 and Figure 128.

*Figure 127 – **Client**: Health Centre.*

*Figure 128 – **Access Point**: Educational Centre.*

A. *Single Unit Allocation Analysis.*

In this subsection, a visualization of the results is presented from two different perspectives: i) a user/client perspective that gives a visual representation of how the clients/users are connected to a single access point and ii) the access point perspective which shows how the access point is connected to its users/clients.

(i) *The User/Client Perspective.*

From a user/client perspective, distinct colours are used to represent different links and wireless coverage for different algorithms.

- Green line represents a potential link to an access point.
- Red line represents a link to an access point assigned by GRA.
- The blue line represents a link to an access point assigned by SRA.
- The red circle depicts a network coverage area of a GRA access point.

- The blue circle depicts the network coverage area of a SRA access point.

In Figure 129 and Figure 132, Mapetla High School was chosen as a gateway by SRA and its preferred clients were assigned to it. However, in Figure 132 Protea Glen College was assigned as the access point by both GRA and SRA which happens to be in the coverage range. Figure 131 points out one of the limitations that are found in this experiment, which is - Slovoville clinic is located near a school, this school was not selected as an access point instead the clinic was allocated to access points that are far away by both algorithms. Figure 137, shows another limitation, wherein the client did not have any access point preference, SRA assigned it to an access point that was far away, while GRA randomly selected any access point capable that could provide coverage to it.

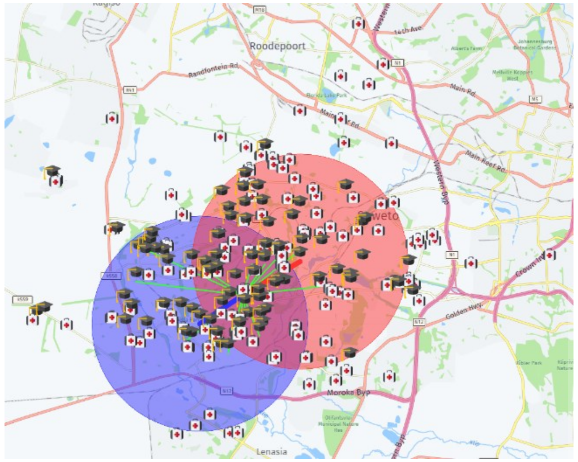


Figure 129 – **Client**: Moroka Clinic
Preferred Access Points: Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School
SRA Access Point: Mapetla High School
GRA Access Point: South West College

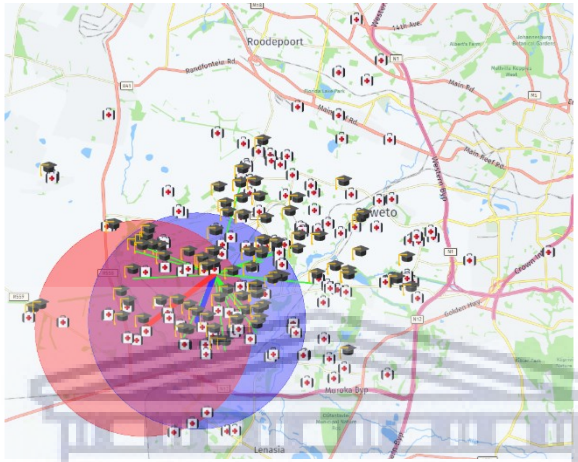


Figure 130 – **Client**: Surgery Medicare Centre
Preferred Access Points: Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School
SRA Access Point: Mapetla High School
GRA Access Point: Protea Glen College

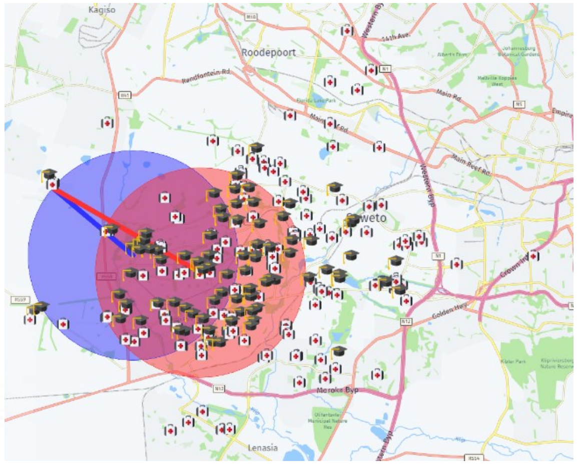


Figure 131 – **Client**: Slovoville clinic
Preferred Access Points: Impumelelo Junior Primary School
SRA Access Point: Impumelelo Junior Primary School
GRA Access Point: LechekoPowerYourMind

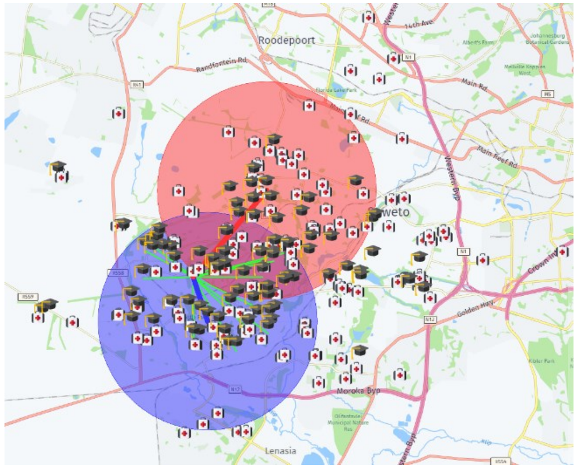


*Figure 132 – **Client**: Dr AD Makhubelas*
***Preferred Access Points**: Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School*
***SRA Access Point**: Mapetla High School*
***GRA Access Point**: Makhoarane Primary School*

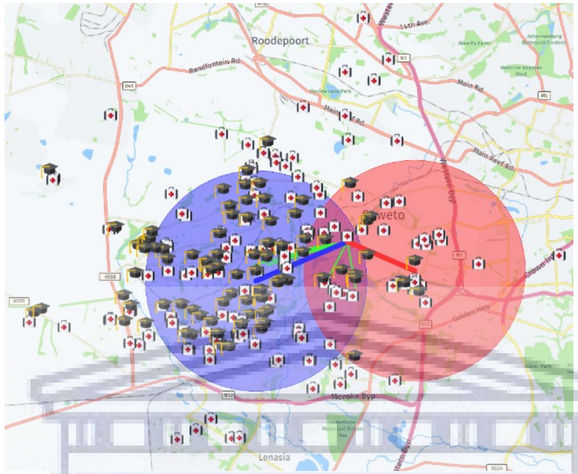


*Figure 133 – **Client**: Dr TC NGWENYA MEDICAL AND DENTAL CENTRE*
***Preferred Access Points**: Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School*
***SRA Access Point**: Molaetsa Primary School*
***GRA Access Point**: Bopasenatla Secondary School*

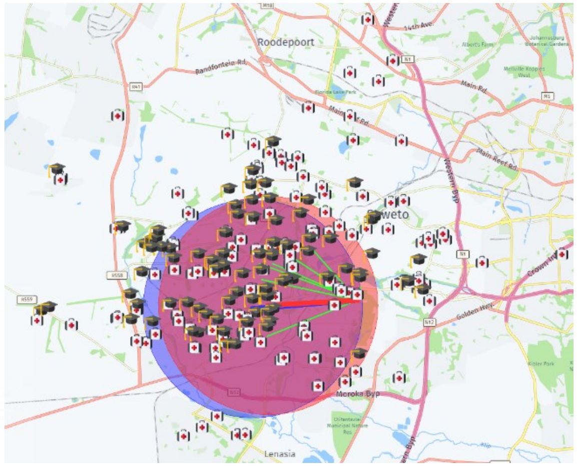


*Figure 134 – **Client**: First Care Medical Centre*
***Preferred Access Points**: Phafogang Secondary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School*
***SRA Access Point**: Phafogang Secondary School*
***GRA Access Point**: Teacher Development Centre (Central District D14)*

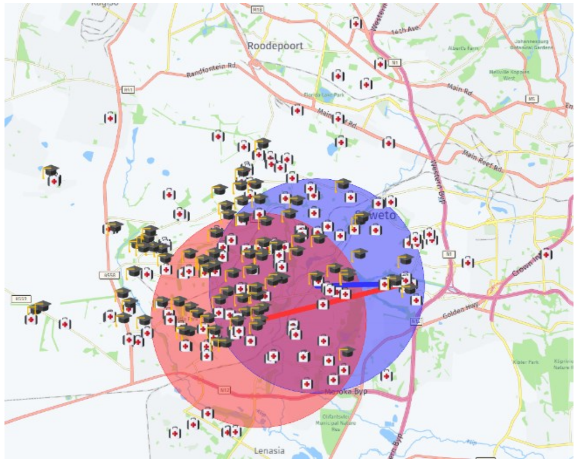


*Figure 135 – **Client**: Dr. BM Hlatshwayo*
***Preferred Access Points**: Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School*
***SRA Access Point**: Boston City Campus & Business College - Maponya Mall*
***GRA Access Point**: Ibhongo Secondary School*

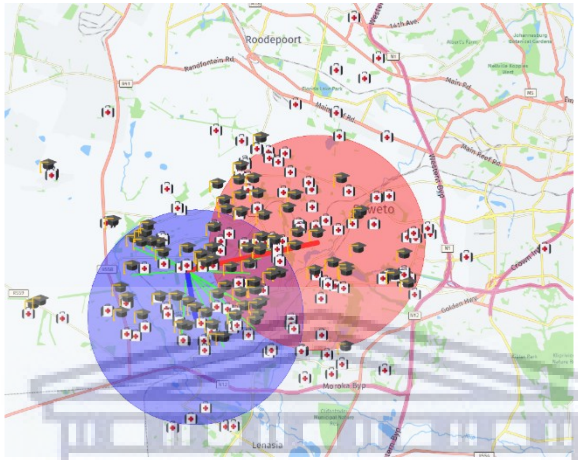


*Figure 136 – **Client**: Tladi Clinic*
***Preferred Access Points**: Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School*
***SRA Access Point**: Mapetla High School*
***GRA Access Point**: Thabisang Primary School*

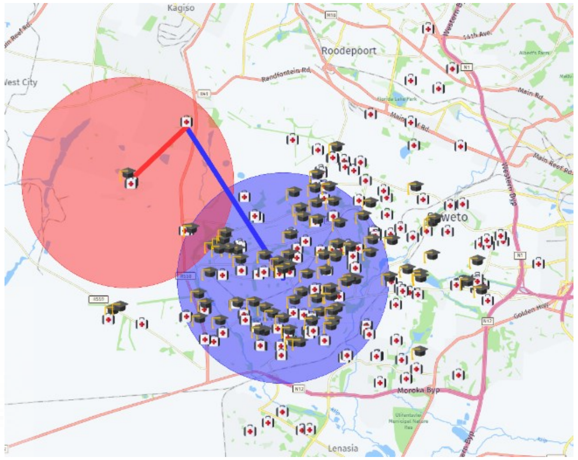


*Figure 137 – **Client**: Tshepisong Clinic*
***Preferred Access Points**: -*
***SRA Access Point**: Moletsane High School*
***GRA Access Point**: Slovoville Primary School*

(ii) *Access Point Perspective.*

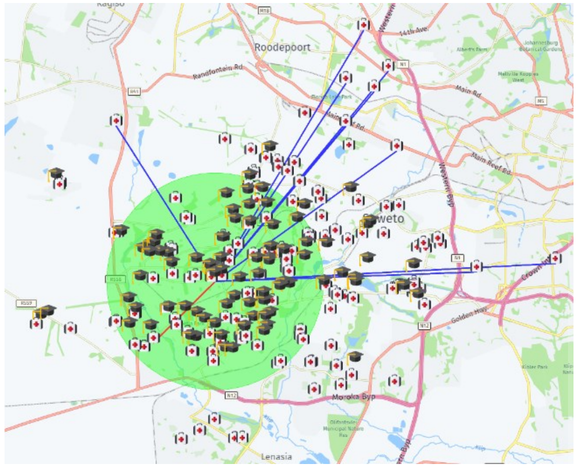


*Figure 138 – **Access Point**: Moletsane High School*
***SRA Clients**: Tshepisong Clinic, Aeroton Medical Centre, Goldman Medical Centre, Life Esidimeni, UPD, The South African Healthcare Foundation, OMOLEMO HEALTH CARE PRIVATE CLINIC, Unique Health, Orthopaedic Suppliers*
***GRA Clients**: Medical Surgery*

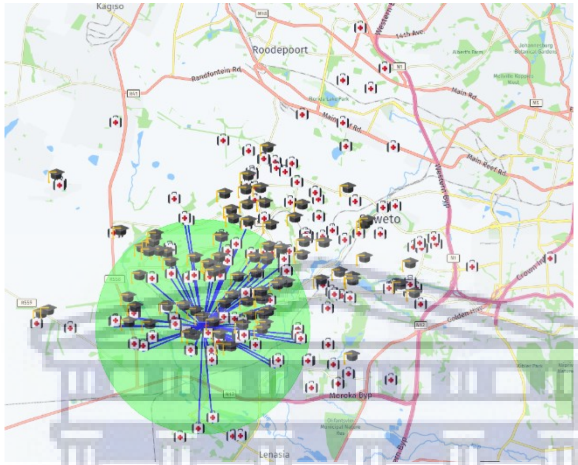


*Figure 139 – **Access Point**: Mapetla High School*
***SRA Clients**: Zola Gateway Clinic, Zola Clinic, Chiawelo Community Healthcare Centre, Jabavu Clinic - T.B Unit, Tladi Clinic, Zondi Clinic, Chiawelo Community Practice, Moroka Clinic, Protea Glen Clinic, Protea South Clinic, Senaoane Clinic, Klipspruit West Clinic - T.B Unit, Eldorado Park Ext 9 T.B Clinic, Dr. C.K. Amos, Region D clinics, Dr AD Makhubelas, Surgery & Optometrist, Dr B A Hussain, Dr. R. V. Taunyane, Dr Latib's Acupuncture and Chinese Medicine Clinic, Lenasia Community Health Centre (Hospital), Dr. M.T.D Qobose, Medical Centre, ZAN Gardens, Kliptown Medical & Dental Centre, Soweto Community Health Centre, Mofolo Community Health Centre, CWJ Medical Center, My Clinic, Iso Lempilo Health Organization, Tladi Community Health Centre, Glencare Specialist Medical*

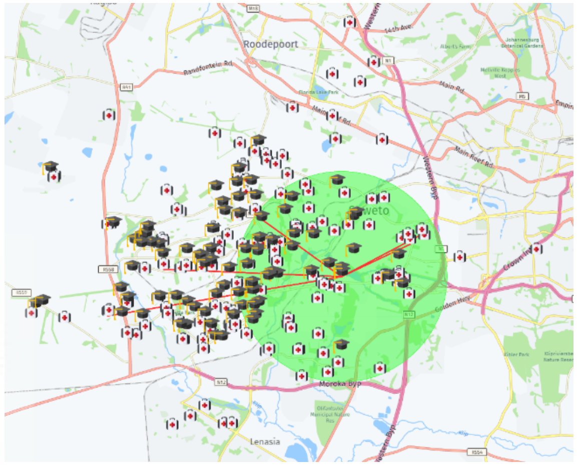


*Figure 140 – **Access Point**: Johannesburg Bible College*
***SRA Clients**: -*
***GRA Clients**: Diepkloof Clinic, Ekhaya Lethu Medical Centre, Glencare Specialist Medical Centre, Dr Michisi S Mbatsana, Naledi Surgery*

Centre, Soweto Community Health Centre Pharmacy, Bheki Mlangeni District Hospital, Total Care Medical Center, …
***GRA Clients**: Tladi Community Health Centre, Dr. T Phefo*

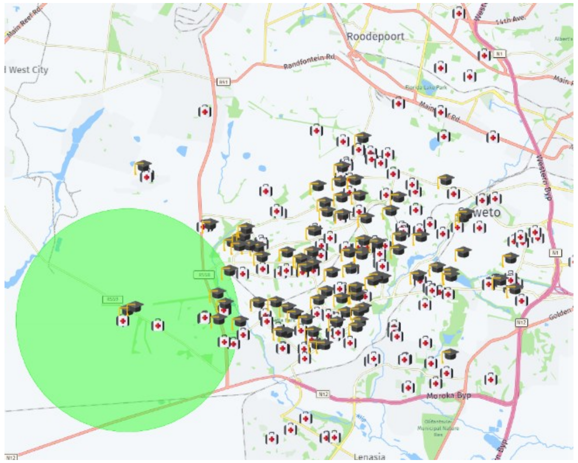


*Figure 141 – **Access Point**: Prestige College*
***SRA Clients**:*
***GRA Clients**: Protea South Clinic, Eldorado Park Ext 9 T.B Clinic, First Care Medical Centre*

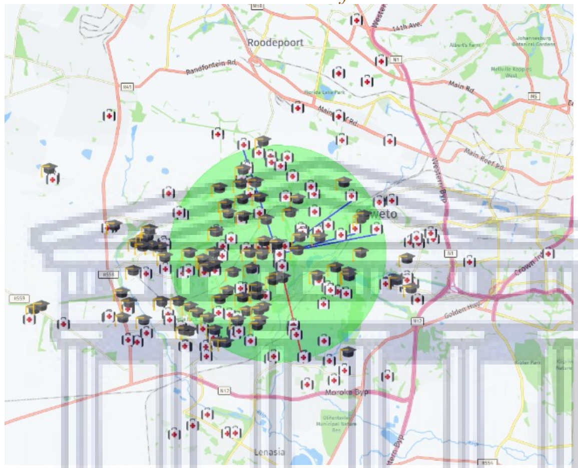


*Figure 142 – **Access Point**: Tlhatlogang Junior Secondary School*
***SRA Clients**: Orlando Clinic, Elias Motsoaledi Clinic, Dr P.S Mabela, Dr. K. Mosalakae*
***GRA Clients**: Eldorado Park Ext 8 Clinic*

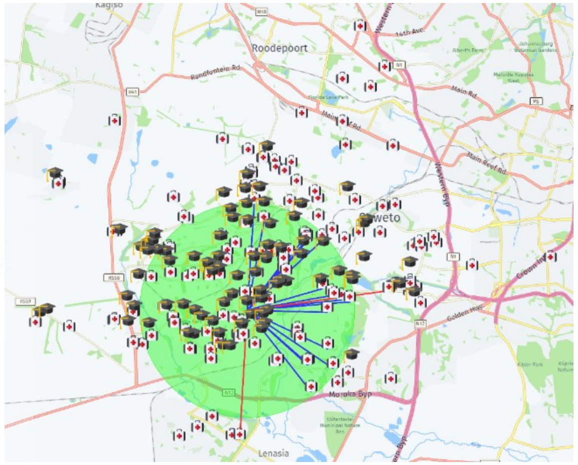


*Figure 143 – **Access Point**: Phafogang Secondary School*
***SRA Clients**: Top Care Women's Clinic -Dube, Soweto, Prime Cure Dube, Eldorado Park Ext 8 Clinic, Pimville Clinic, Eldorado Park Ext 2 Clinic, Ringane & Associates Inc, Dr. B K C Sithole, Ekhaya Lethu Medical Centre, HEALTH CENTRE, Medical & Dental Centre, Vilakazi Healthcare, Ubuntu Health Care Clinic, First Care Medical Centre, Qengeba Medical Center, Kinky world of hair, Soweto Independent Living Center, TM Mkhize Dental Surgery, Dube Dental Surgery, Dr. Ismail Mia*
***GRA Clients**: Skin & Body International, Dr. B.L. Khulu*

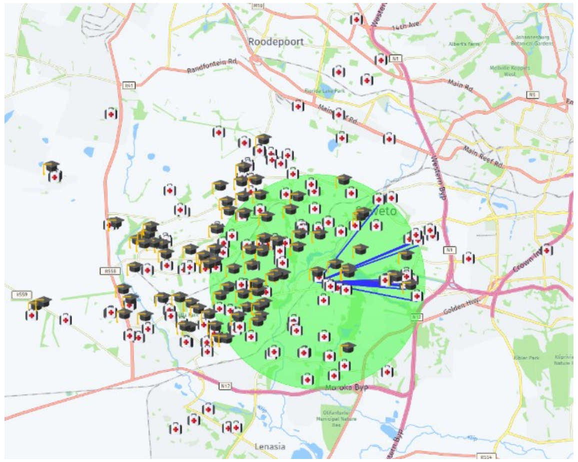


Figure 144 – ***Access Point***: *Boston City Campus & Business College - Maponya Mall*
SRA Clients: *Marie Stopes Soweto, St John's Eye Hospital, Zone 1 Diepkloof Clinic, Opti Eyewear Optometrist, Dr. Haroon Essa, Lillian Ngoyi Community Health Centre, The Roots Health Centre, Baragwanath Medical Centre, Lilian Ngoyi Community Clinic - Medical, Chris Hani Baragwanath Academic Hospital, Dr SK Matseke Memorial Hospital, Chris Hani Baragwanath Hospital - Oncology, Dr Michisi S Mbatsana, U-care Walk In Clinic, Roman H A and Partners T/a Fresenius Medical Care - Soweto Kidney and Dialysis Centre, Dr. SF Mthembu, Dr. EA Mjuza, Surgery - Dr. A.N Mmusi, S And S Orthopedic Services, Dr. B.L. Khulu, Dr. Mosidi G. Sehume, Dr. Charles N. Mujakachi, Dr. T. E. Ndzeru, Dr. BM Hlatshwayo*
GRA Clients: *Marie Stopes Soweto*

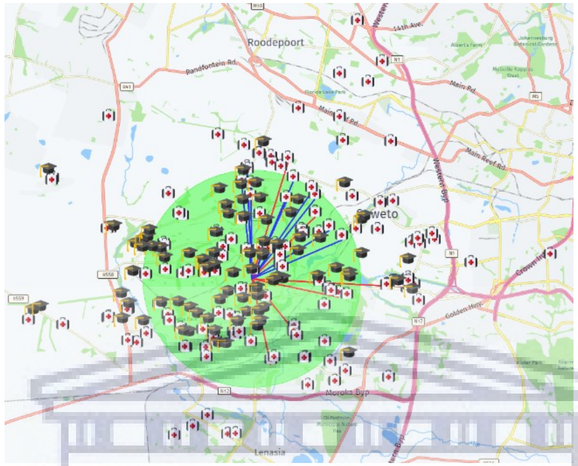


Figure 145 – ***Access Point***: *Molaetsa Primary School*
SRA Clients: *Itireleng Community Health Centre, Mandela Sisulu Clinic, Meadowlands Zone 11 Portacabin Clinic, Meadowlands Clinic, Yebohealth Medical Centre, Dobsonville Medical & Dental Surgery's, Dr TC NGWENYA MEDICAL AND DENTAL CENTRE, T & D Medical Health Services, Nkuna L E, DR MS MUSHADU, Dr TC Moloto*
GRA Clients: *Dr. Haroon Essa, Qengeba Medical Center, Dr D Ngwenya Medical Practice, Dr M.A. Muhammad Medical Practice, Dr A I Jada, Nkuna L E*

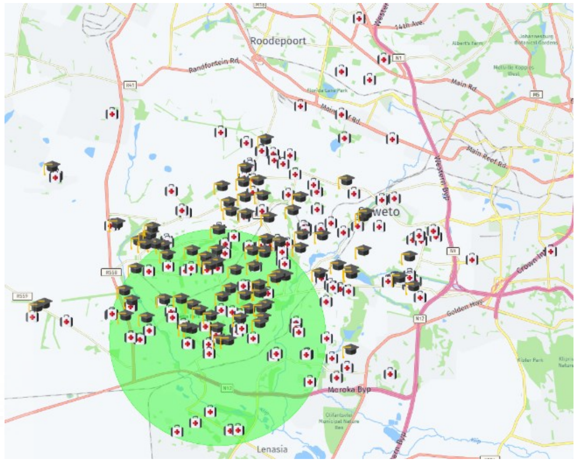


Figure 146 – ***Access Point***: *Mambo Primary School*
SRA Clients: *-*
GRA Clients: -

Similarly to the user/client perspective, in this subsection colours were also used to represent network coverage and links as follows

- The green circle depicts an access point's network coverage area.
- Red line represents a link to an access point assigned GRA.
- Blue line represents a link to an access point assigned by SRA.

We analysed the same results looking at the access point perspective and obtained results revealed that in most cases, SRA assigned links were within the coverage zone of the access point. However, as revealed by Figure 138, the links are outside coverage zone, while for GRA the links remained within the zones. In Figure 140 and Figure 141 the access points have clients that were allocated by GRA because they did not fit the requirements to be a potential local gateway. Figure 146 reveals that Mambo Primary School was not assigned to any clients by both allocation techniques.

B. Complete Network Allocation.

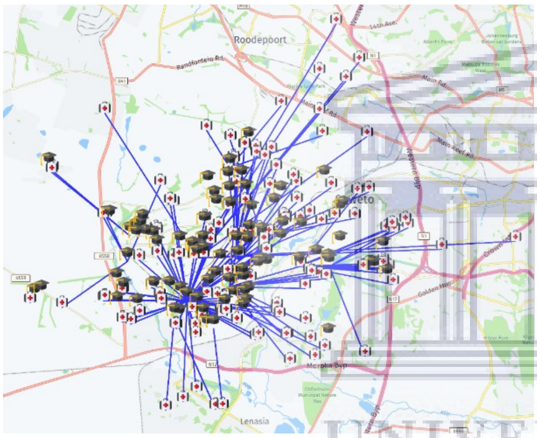


Figure 147 – Stable Roommate Task Allocation.

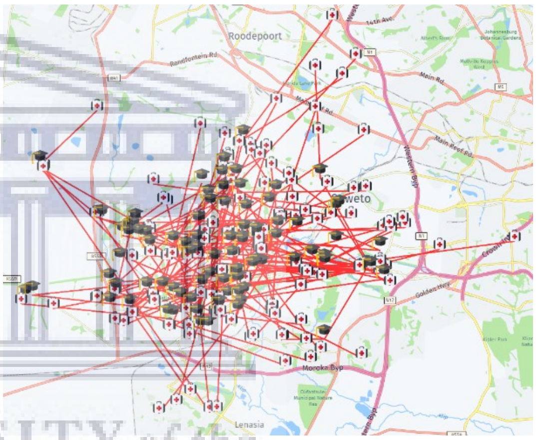


Figure 148 – Gamma Random Algorithm Task Allocation

Table 19 (in Appendix B) shows clients with their preferred access points as well as the specific access point allocated to the clients by the two algorithms. On the other hand, Table 20 (in Appendix B) depicts the access points with their allocated clients for each allocation model. These tables are summarised in Figure 149 and Figure 150 respectively. The two figures provide the total number of clients that were allocated to every access point by a specific algorithm. In this experiment, the access points preferred users that were within five kilometres of the coverage range, while the clients preferred closer access points with better SNR (to the LAP) and RE. The SNR and RE values were generated in the same manner as the Monte-Carlo simulations in the previous chapter.

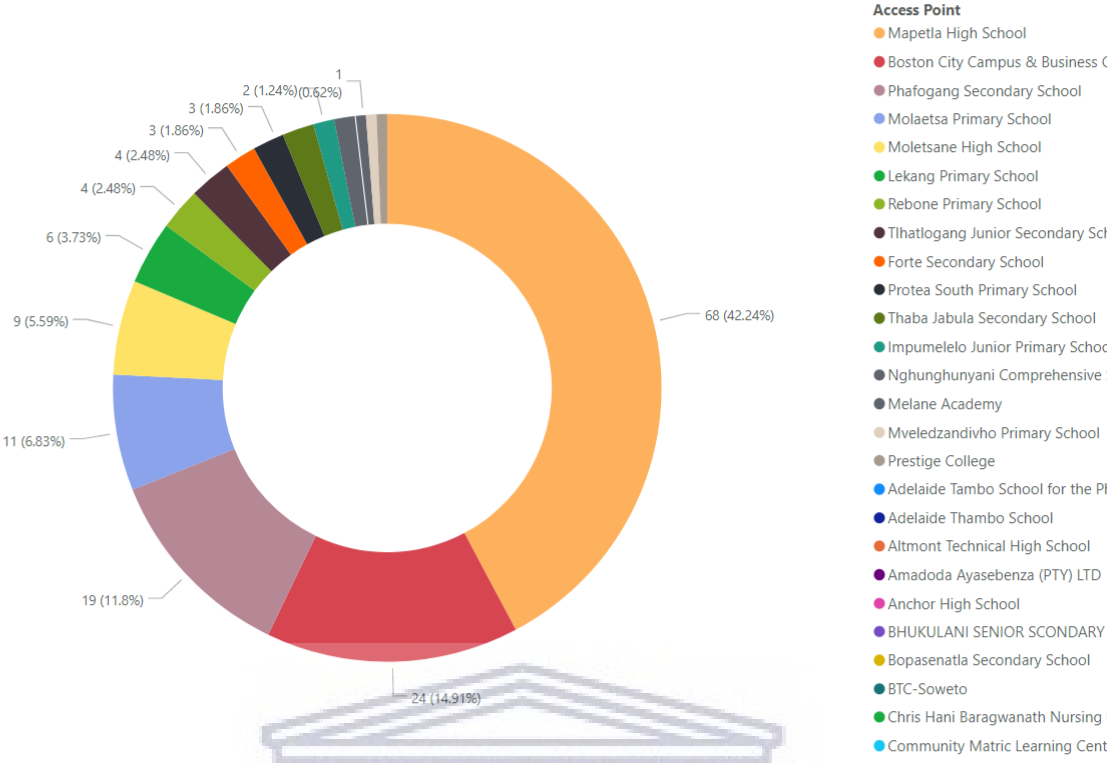


Figure 149 – Stable Roommate Task Allocation in Descending Order.

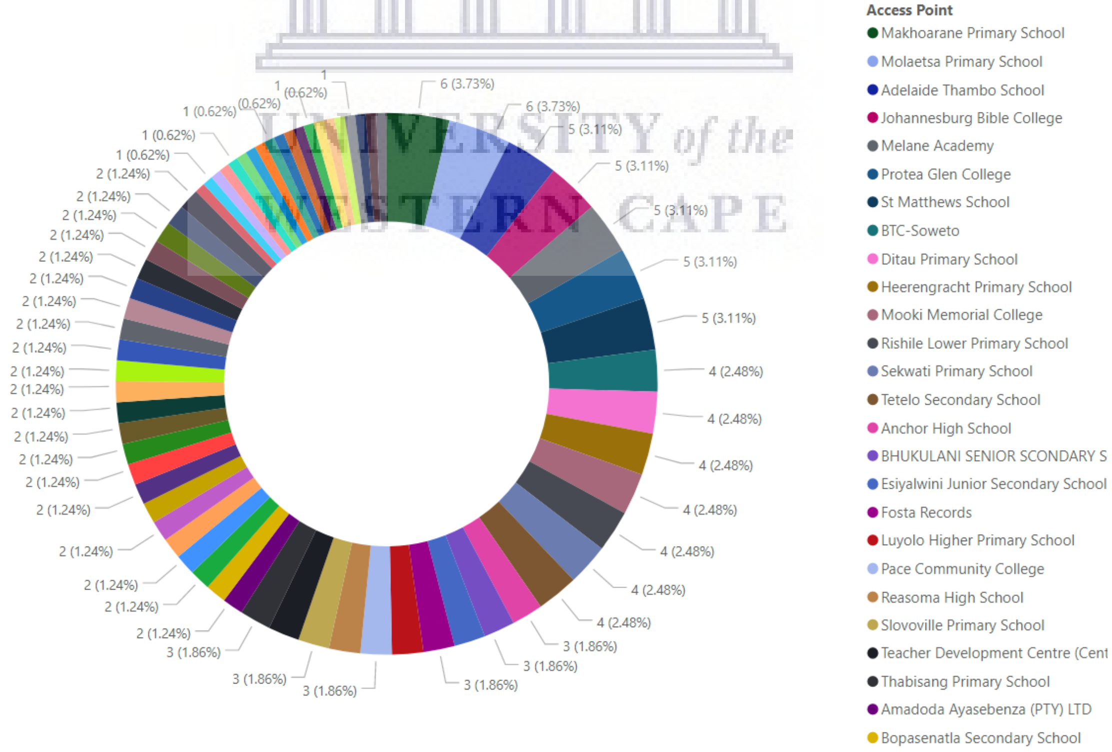


Figure 150 – Gamma Random Algorithm Task Allocation by Access Point in Descending Order.

As revealed by Figure 148, SRA resulted in a more clustered network, with a small number of access points playing the role of backbone for many users. GRA led to a more mesh-like topology, with many access points being used to carry the traffic of a few clients. These are as shown in Figure 147. In terms of energy consumption, if the network is assumed to be powered using batteries, access points in the GRA based network would last longer than those in the SRA network. This is because, with GRA each access point has to cater for only a few number of clients, while SRA access points have to cater to much more clients. For example, considering Mapetla High School in Figure 149, SRA assigned 68 clients (or 43% of the total users in the network) to it. In this case, Mapetla High School will drain its battery fast trying to accommodate all of its clients. This is in sharp contrast to GRA, wherein no access point had more than 6 users connected to it (Figure 150). Furthermore, both algorithms allocated Marie Stopies Soweto and Nkuna L E to their preferred access point. Megatong Primary School, Daliwonga Secondary School, Curtis Nkondo School of Specialization, and St Matthews School were allocated clients by GRA, while SRA did not assign any client to them.

5.7 SUMMARY

In this chapter on network engineering, the focus was on proposing and simulating the clustering algorithms in various rural case scenarios to show how they perform realistically. The proposed model models build upon existing models, incorporating features that improve the backhaul connection to the BS and the fronthaul links interconnecting the UAVs. Moreover, they conserve energy and efficiently utilise all UAVs in a cluster set, ensuring none is left out. The developed models called MSGBACK and MSLBACK based on the multi-sink clustering algorithm and is backhaul aware. They were benchmarked against Myopic technique, the classic K-Means clustering algorithm as well as several other backhauling algorithms. Simulation results showed that MSGBACK and MSLBACK performed better than the other algorithms in terms of utilising the highest SNR as well as engaging all the UAVs in a cluster set, ensuring that none was isolated. The 3.5 and 28 GHz SINRs coverage is visualised on a map in the second simulations for various rural and low-income areas. When using a rectangular antenna array, a propagation model that estimates increased path loss has higher SINR values due to less interference. Clients can use the Stable Roommate algorithm to select their preferred access point. The goal of Chapter V is to simulate the feasibility of clustered 5G network from the results in Chapter IV, using system models defined in Chapter III.

VI. CONCLUSION

6.1 DISSERTATION OBJECTIVES.

The objectives of this dissertation are in twofold, which are;

i. *To design a "heterogeneous air-to-ground network infrastructure" to provide services to terrestrial users in rural and low-income areas.*
ii. *To use unmanned aerial vehicles to provide 5G network coverage in a rural or low-income area to reduce capital and operational expenditure.*

6.2 CONCISE SUMMARY.

This work managed to accomplish the research objective in the following brief manner discussed below.

6.2.1 Literature Review.

Recent literature revealed that most energy consumption occurs during data transmission and packets control. Hence, clustering protocols must ensure reliability and connectivity in wireless 5G network coverage. Using UAVs to provide the forthcoming network generation has many research areas such as: i) UAV coalition to seamlessly handover packet, ii) find the optimal placement of the UAV, iii) energy management and many more. There are current 5G projects that show much more promise that can be deployed for commercial usages such as Nokia Saving Lives and Project Loon. South African government and ICASA have not started issuing spectrum licensing for the forthcoming network. Service providers claim that the total cost of deploying and supporting a network is prohibitive while they are worth more in the Johannesburg Stock Exchange (JSE).

6.2.2 Network Orchestration.

Many researchers have conceptualised the prospective network since the 5G standards were released. For this work, we chose to build upon the model by (Luca, et al., Bringing 5G in Rural and Low-Income Areas: Is it Feasible?, 2017). In our envisioned model, we introduce 5G hotspots that can be mounted on streetlights and residential complexes. The 5G architecture enables: i) network programming, ii) cloud computing, iii) virtual technology, and iv) multi-tenancy. Also, its service orchestration and management guarantee service all the time. Through VF, multi-operators can efficiently run and upgrade their service on the shared hardware without interference from others, which improves the network lifecycle management. Radio energy consumption is model over a twenty-four-hour period with a sinusoidal function.

6.2.3 Economic Analysis.

In economic analysis, we found out that deploying the MiC-based network in concentrated areas is cheaper than LC-based. Multiple operators can share CAPEX and use standard hardware to provide their service with 5G virtual technology. Hotspot networks are economical to maintain and operate mainly in densely populated areas such as Soweto, Duduza, and Khayelitsha townships. However, deploying them to cover an entire district municipality is extremely expensive to support negative cashflow. Revenue generation shadows the number of potential users. The section proved that it is possible to provide cheaper 5G network in rural and low-income areas with users paying as low as R282 monthly subscription fee.

6.2.4 Network Review.

The Myopic backhauling algorithm in the article (Chandrasekharan, et al., 2013) leaves nodes isolated. Hence, we propose improvements to the technique. Our backhauling method does not leave any node an orphan. The GSMB backhauling also balance the network based on node crowdedness and the shortest path. GCHC introduces profit function to select coordinators on the traditional graph colouring technique. Our simulation observation is in line with our analytical expressions. The network review chapter shows a fixed wireless access link over terrain using 5G technologies in multi-user rural scenarios. As a result, the maps illustrate the sensitivity of higher and lower 5G carrier frequencies to path loss deficiencies. Furthermore, the maps visualise SINR for different antennas.

6.3 DEDUCTIONS AND VIEWS.

In summary, this work showed that there is still much research of network provision that needs to be customised for rural and low-income areas in South Africa. Wireless connections are now the de facto method for mobile devices connection to the Internet. The Internet has now become a necessity as it indirectly powers industries, economies, and inter-societal lives. Great strides have been made in Internet technologies, and the 5G network is one of such recent developments. Unfortunately, Internet facilities are not available everywhere in the world, particularly in remote and low-income areas. UAVs have emerged as a potentially cheap way of providing wireless cellular coverage to these areas.

In this thesis, we proposed an efficient multi-sink clustering algorithm that is aware of backhaul communication links and balances the network. Furthermore, we showed that our prosed algorithm does not leave nodes isolated or create an empty cluster set. More generally, these essential findings are consistent with research showing that: i) it is economically feasible to deploy a 5G network in remote areas with either UAVs or terrestrial nodes, ii) the LAP needs gateways to extend its reach to every node in the network. We noticed that the Backhauling technique might take longer when balancing the nodes. A rectangular antenna array provides higher directionality peak SINR values than a single antenna element.

Government and private network service providers are not keen to invest in rural areas as there are deemed unprofitable. The current realised 5G projects target urban areas, and use cases are tailored for developed countries. Hence, it allows us to conclude that service providers stand to have lucrative revenue when providing 5G network in rural and low-income areas with UAVs. The possibility of a more realistic modelling technique in MATLAB would be replicating cell sites to expand the geometry in such a way that perimeter zones experience similar interference as interior regions and clustering methods be implemented directly with the simulation.

6.4 FUTURE WORK.

This dissertation focuses on the economic feasibility of providing 5G network in rural areas of South Africa and clustering methods that ensures all nodes are engaged without any orphan. However, there are still areas that require in-depth research. In the future research should focus on: i) renewable energy for UAVs and terrestrial nodes, ii) check battery performance for 5G technologies in the UAV based cellular, iii) make an extensive research on Deep Continuous Clustering method that allows nodes to join or leave the network and allow node movement, iv) considering an exact location of users when clustering, and v) testing on the real world with 5G technologies.

APPENDICES

A. REFERENCE HYPERLINKS.

i. Acronyms.

1G	First Generation Network.
3D	Three-Dimensional.
3GPP	Third Generation Partnership Project.
4G	Fourth-Generation Cellular Network.
4IR	Fourth Industrial Revolution.
5G	Fifth Generation.
5G-PPP	5G Infrastructure Public-Private Partnership.
ACO	Ant Colony Optimisation.
AP	Access Points.
ATM	Asynchronous Transfer Mode.
ATN	Aerial-Terrestrial Network.
BBU	Base Band Unit.
BS	Base Station.
BTS	Base Transceiver Station.
BVLOS	Beyond Visual Line of Sight.
CAPEX	Capital Expenditure.
CF	Cash Flow.
CH	Cluster Head.
CHW	Commodity Hardware.
Cloud-RAN	Cloud Radio Access Network.
CM	Cluster Members.
CN	Cellular Network.
CPU	Central Processing Unit.
CR	Cognitive Radio.
CSE	Cognitive Smart Engine.
D2D	Device-to-Device.
dB	Decibels.
DHW	Dedicated Hardware.
DoF	Decode-and-Forward.
DTN	Delayed Network Torrent.
E2E	Exchange to Exchange.
eMBB	Enhanced Mobile Broadband.
EPC	Evolved Packet Core.
EU	End User.
EVA	Economic Value Added.
F	Subscription Fee.
FANET	Flying Ad Hoc Network.
FTTH	Fibre-to-the-Home.
FWA	Fixed Wireless Access.
FWT	Fixed Wireless Terminal.
Gb	Gigabit.
GCHC	Graph Colouring with Height Control.
GDP	Gross Domestic Product.
GPS	Global Positioning System.
GRA	Gamma Random Allocation.
GSM	Global System for Mobile Commutations.
GSMB	Greedy Cluster-Head Selection with cluster Membership Balancing.
HASP	High-Altitude Platform Station.
HW	Hardware.
Hz	Frequency Hertz.
ICASA	Independent Communications Authority of South Africa.
IEEE	Institute of Electrical and Electronics.
IETF	Internet Engineering Task Force.
IoT	Internet of Things.
IRR	Internal Rate of Returns.
ISD	Inter-Site Distance.
ITM	Irregular Terrain Model.
ITU	International Telecommunication Union.
JS	JavaScript.
JSE	Johannesburg Stock Exchange.
kWh	kiloWatt-hour.
LAP	Low-Altitude Platform.
LC	Large Cell.
LoS	Line of Sight.
LTE	Long-Term Evolution.
M	Modem.
MaC	Macro Cell.
MB	Megabyte.
MBS	Macro Base Station.
ME	Metro Ethernet.
MEC	Multi-Access Edge Computing.
MiC	Microcell.
MIH	Media Independent Handover.
MIHF	Media Independent Handover Function.
MIMO	Massive Multiple-Input Multiple-Output
MME	Mobility Management Entity.
mMTC	Massive Machine-Type Communications.
mmWave	Millimetre-Wave.
MSAN	Multi-Service Access Node.
MSGBACK	Multi-Sink airborne network with an inter-cluster connection through UAV gateways Backhauling.
MSLBACK	Multi-Sink airborne network with inter-cluster communication through the LAP Backhauling.
MSP	Mobile Service Providers.
MTN	Mobile Telephone Network.
MU-MIMO	Multiple-Input Multiple-Output technology.
NFV	Network Function Virtualisation.
NLoS	Non-Line of Sight.
NMS	Network Management System.
NN	Network Node.
NO	Network Orchestration.
NP	Network Programmability.
OLSR	Optimise Link-State Routing.
OPEX	Operational Expenditure.
OS	Operating System.
OSM	OpenStreetMap.
PNF	Physical Network Function.
P-OLSR	Predictive – Optimize Link-State Routing.
PSO	Particle Swarm Optimisation.
QoS	Quality of Service.
QTM052	Qualcomm 5G Module.
R	Router.
RAN	Remote Access Network.
RE	Residual Energy.
REV	Revenue.
ROC	Remote Operator's Certificate.
ROI	Return on Investment.
RRH	Remote Radio Heads.
RRH-UAV	Remote Radio Head-Unmanned Aerial Vehicle.
RRU	Remote Radio Unit.
SC	Small Cell.
SDN	Software-Defined Networking.
SDR	Software Defined Radio.
SFC	Service Function Chaining.
SINR	Signal-to-Interference-plus-Noise Ratio
SLA	Service-Level Agreement.
SMS	Short Message Service.
SNR	Signal-to-Noise Ratio.
SRA	Stable Roommate Allocation.

Tb	Terabit.
TB	Terabyte.
TCO	Total Cost of Ownership.
TSP	Telecommunication Service Providers.
UAV	Unmanned Aerial Vehicle.
UAV-BS	Unmanned Aerial Vehicle Base Station.
UE	User Equipment.
UMTS	Universal Mobile Telecommunication Systems.
URLLC	Ultra-Reliable and Low Latency Communication.
VANET	Vehicular Adhoc Networks.
VF	Virtual Function.
VM	Virtual Machine.
VNF	Virtual Network Functions
V-RAN	Virtualised Radio Access Network.
WLAN	Wireless Local Area Network.
WRC-15	World Radiocommunication Conference 2015.
WSN	Wireless Sensor Network.
ZA	South Africa.

ii. List of Figures.

iii. List of Tables.

iv. *List of Equations.*

v. *List of Algorithms.*

B. SUPPORTING EXTRAS.

i. Algorithms.

Algorithm 1 – Clustering Technique, cluster head selection, cluster member assignment process and optimal communication path.

```
INPUT
        $S(N_{c_i})$ set of network nodes.
        Where $N_{c_i}$ is the sequence of cell node $\{N_{c_1}, N_{c_2}, \dots, N_{c_n}\}$.
OUTPUT
        A clustered network of $S$.

Part A
WHILE (processing set is not empty) DO
    Select node $N_{c_i}$ from the processing set that has the highest received SNR at the LAP base station.
    IF ($N_{c_i}$ residual energy is greater than or equal to the median residual energy of the nodes in processing set) THEN
        Assign node $N_{c_i}$ as a CH $C_{c_i}$.
        Compute number of CMs $z$ to assign $N_{c_i}$.
        Assign up to $z$ number of nodes from the processing set as CMs to this cluster such that $\wp_{ij} < R_i$.
    ENDIF
    IF ($C_{c_i}$ has CMs assigned) THEN
        Remove nodes selected as the CH and CMs from the processing set and assign them to the cluster set.
        Select $N_{c_{i+1}}$ with highest received SNR at the LAP from the processing set.
    ENDIF
ENDWHILE

Part B
FOR ($N_{c_i}$ in cluster set $C_{c_i}$) DO
    FIND a new $C_{c_j}$ that has a shortest roundtrip to $N_{c_i}$ such that $\wp_{ik} < R_i \cap \wp_{jk} < R_j$ and $Z < z_i$) THEN
        Assign node $N_{c_i}$ as CM to $C_{c_j}$.
        Remove node $N_{c_i}$ as CM to $C_{c_i}$.
    ENDFIND
ENDFOR

Part C
FOR (cluster $C_{c_i}$ in network) DO
    FIND a new $C_{c_j}$ that has a few members compared to $C_{c_i}$ THEN
        FIND $N_{c_i}$ that has a link to $C_{c_j}$ such that $\wp_{ik} < R_i \cap \wp_{jk} < R_j$ and $Z < z_j$) THEN
            Assign node $N_{c_i}$ as CM to $C_{c_j}$.
            Remove node $N_{c_i}$ as CM to $C_{c_i}$.
        ENDFIND
    ENDFIND
ENDFOR

Part D
FOR ($N_{c_i}$ in cluster set $C_{c_i}$) DO
    Find a new highest received SNR at the LAP by checking roundtrip paths among CHs.
    Assign secondary links to CHs in the path with highest SNR compared to the primary link.
    FOR ($N_{c_j}$ in cluster set $C_{c_i}$) DO
        FOR ($N_{c_k}$ in cluster set with $C_{c_j}$) DO
            IF ($N_{c_k}$ is in coverage range such that $\wp_{ik} < R_i \cap \wp_{jk} < R_j$ and $Z < z_i$) THEN
                Assign node $N_{c_k}$ a secondary link to $N_{c_i}$
            ENDIF
        ENDFOR
    ENDFOR
ENDFOR
```

Algorithm 2 – Backbone Technique, Greedy Cluster-Head Selection with Membership Balancing (GSMB).

```
                INPUT
          $S(N_{c_i}, \ell_x)$ set of network nodes with communication links.
          Where $N_{c_i}$ is the sequence of cell node $\{N_{c_1}, N_{c_2}, \dots, N_{c_n}\}$ and $i \neq j$.
      OUTPUT
          A clustered network of $S$ based on backbone model.
-----------------------------------------------------------------------------
Part A  WHILE (node in processing set is not visited) DO
          Select node $N_{c_i}$ from the processing set that has the best profit and assign
          node $N_{c_i}$ as a CH $C_{c_i}$.
          FOR ( $N_{c_j}$ in processing set) DO
              IF ($C_{c_i}$. has feasible link with $N_{c_j}$) THEN
                  Assign node $N_{c_j}$ as CM to $C_{c_i}$.
                  Mark $N_{c_j}$ as a visited node.
              ENDIF
          ENDFOR
          Mark $C_{c_i}$ as a visited node.
        ENDWHILE
-----------------------------------------------------------------------------
Part B  FOR ($N_{c_i}$ in cluster set $C_{c_i}$) DO
          FIND a new $C_{c_j}$ that has a shortest roundtrip to $N_{c_i}$ such that $\wp_{ik} < R_i \cap$
          $\wp_{jk} < R_j$ and $\mathcal{Z} < z_i$) THEN
              Assign node $N_{c_i}$ as CM to $C_{c_j}$.
              Remove node $N_{c_i}$ as CM to $C_{c_i}$.
          ENDFIND
        ENDFOR
-----------------------------------------------------------------------------
Part C  FOR (cluster $C_{c_i}$ in network) DO
          FIND a new $C_{c_j}$ that has a few members compared to $C_{c_i}$ THEN
              FIND $N_{c_i}$ that has a link to $C_{c_j}$ such that $\wp_{ik} < R_i \cap \wp_{jk} < R_j$
              and $\mathcal{Z} < z_j$) THEN
                  Assign node $N_{c_i}$ as CM to $C_{c_j}$.
                  Remove node $N_{c_i}$ as CM to $C_{c_i}$.
              ENDFIND
          ENDFIND
        ENDFOR
```

ii. Simulation Tools.

1. MATLAB.

MATLAB is a high-performance language for technical computing. This language integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include Math and computation, Algorithm development, Modelling, simulation, and prototyping, Data analysis, exploration, and visualization, Scientific and engineering graphics. MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows a user to solve multiple technical computing problems, especially those with matrix and vector formulations, in a shorter time-frame than that which it would take to write a similar program in a scalar noninteractive language such as C or Fortran.

Link: https://www.mathworks.com/products/matlab.html

2. Google Maps.

Google Maps are flat maps that are used through a web browser. The Maps are commonly used to assist drivers with directions, a purpose with which the services were created. The maps provide different views such as the Street, Traffic, Map, Satellite, and Terrain views. In addition to traditional roadmaps, Google Maps offers both aerial and satellite views and detailed information about geographic regions and sites worldwide. It also offers photographs taken from vehicles around most cities. As part of the larger Web application, Google Maps provides services such as a route planner, which offers directions for drivers, bikers, walkers and users of public transport wishing to complete a trip.

Link: https://www.google.com/maps

3. *OpenStreetMap.*

The name OpenStreetMap refers to a licensed single database covering the entire world and is sometimes erroneously referred to as Open Street Map or OpenStreetMap (OSM). Per its website: “OSM is a free worldwide map, created by ordinary people. It is a database product. There are, however, a number of open-source software projects and proprietary products built specifically to edit the database. They are built on the OSM API. There are also open-source projects and proprietary products that allow viewing and routing on maps created with the data.”

Link: https://www.javascript.com

4. *JavaScript.*

JavaScript (JS) is an interpreted scripting language that is primarily used on the Web. Since JS is interpreted language, it doesn’t need to be compiled. It is frequently found rooted in an HTML code and it used to enhance HTML pages. JS renders web pages in an interface that is dynamic and easy to use, its pages allow reactions to events, exhibit special effects, accept variable text, validate data, create cookies, detect a user’s browser etc.

Link: https://www.javascript.com

5. *Microsoft Excel.*

Excel is a commercial spreadsheet application produced and distributed by Microsoft for Microsoft Windows and Mac OS operating systems. It contains features that allow the user to basic calculations, use graphing tools, create pivot tables and create macros. Excel contains the same basic interface as all other spreadsheet applications, which is a collection of cells arranged into rows and columns to organise and manipulate data. Like most others, it has features such as displaying data as charts, histograms and line graphs.

Link: https://products.office.com/en-za/excel

6. *Python Programming Language.*

Python is an interpreted, object-oriented, high-level programming language with dynamic semantics. Its high-level built-in data structures, combined with dynamic typing and dynamic binding, make it very attractive for Rapid Application Development, as well as for use as a scripting or glue language to connect existing components together. Python has a simple, easy to learn syntax that emphasizes readability the cost of program maintenance. Python’s support of modules and packages encourages program modularity and code reuse. The Python interpreter and the extensive standard library are available in source or binary form for all major platforms at no cost and can be freely distributed.

Link: https://www.python.org

(a) *Packages.*

1. atomicwrites==1.3.0
2. attrs==19.3.0
3. backcall==0.1.0
4. certifi==2019.9.11
5. chardet==3.0.4
6. Click==7.0
7. colorama==0.4.1
8. cycler==0.10.0
9. decorator==4.4.1
10. Flask==1.1.1
11. geographiclib==1.50
12. geopy==1.20.0
13. googlemaps==3.1.4
14. idna==2.8
15. importlib-metadata==0.23
16. ipykernel==5.1.3
17. ipython==7.9.0
18. ipython-genutils==0.2.0
19. itsdangerous==1.1.0
20. jedi==0.15.1
21. Jinja2==2.10.3
22. joblib==0.14.0
23. jupyter-client==5.3.4
24. jupyter-core==4.6.1
25. kiwisolver==1.1.0
26. lxml==4.4.1
27. MarkupSafe==1.1.1
28. matplotlib==3.1.1
29. more-itertools==7.2.0
30. networkx==2.4
31. numpy==1.17.4
32. packaging==19.2
33. pandas==0.25.3
34. parso==0.5.1
35. pickleshare==0.7.5
36. pip==19.3.1
37. pluggy==0.13.0
38. progressbar2==3.47.0
39. prompt-toolkit==2.0.10
40. py==1.8.0
41. Pygments==2.4.2
42. pyparsing==2.4.5
43. pytest==5.1.2
44. python-dateutil==2.8.1
45. python-utils==2.3.0
46. pytz==2019.3
47. pywin32==227
48. pyzmq==18.1.1
49. requests==2.22.0
50. scikit-learn==0.21.3
51. scipy==1.3.2
52. setuptools==41.6.0
53. six==1.13.0
54. tornado==6.0.3
55. traitlets==4.3.3
56. urllib3==1.25.3
57. wcwidth==0.1.7
58. Werkzeug==0.16.0
59. XlsxWriter==1.2.6
60. zipp==0.6.0

7. *Host System.*

LENOVO LEGION Y53	
CPU	Intel i5 8th generation
RAM	16 GB DDR4
HDD	512 GB SSD + 2 TB
GPU	Intel UHD Graphics 630 + NVIDIA GeForce GTX 1050

iii. Network Links.

Table 19 – Preferred Access Point by Clients.

			ALLOCATED ACCESS POINT	
CLIENT/USER	**PREFERRED ACCESS POINT/S**		**STABLE ROOMMATE**	**GAMMA RANDOM**
Marie Stopes Soweto	Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School	2	Boston City Campus & Business College - Maponya Mall	Boston City Campus & Business College - Maponya Mall
St John's Eye Hospital	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	St Matthews School
Freedom Park Clinic	Thaba Jabula Secondary School	1	Thaba Jabula Secondary School	Heerengracht Primary School
Tshepisong Clinic		0	Moletsane High School	Slovoville Primary School
Slovoville Clinic	Impumelelo Junior Primary School	1	Impumelelo Junior Primary School	Makentse
Zola Gateway Clinic	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	18	Mapetla High School	Ditau Primary School
Zola Clinic	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Forte Secondary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	13	Mapetla High School	Enkolweni Primary School
Top Care Women's Clinic -Dube, Soweto	Phafogang Secondary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	12	Phafogang Secondary School	Pace Community College
Chiawelo Community Healthcare Centre	Mapetla High School, Protea South Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	14	Mapetla High School	Emadlelweni Primary School
Green Village Clinic	Rebone Primary School, Emndeni Primary School, Impumelelo Junior Primary School, Tlholohelo Primary School, Pq vundla	5	Rebone Primary School	HB Technology
Jabavu Clinic - T.B Unit	Mapetla High School, Protea South Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	16	Mapetla High School	The Plumbing Academy
Tladi Clinic	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	15	Mapetla High School	Thabisang Primary School
Zondi Clinic	Mapetla High School, Emndeni Primary School, Phafogang Secondary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	13	Mapetla High School	Amadoda Ayasebenza (PTY) LTD
Chiawelo Community Practice	Mapetla High School, Protea South Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	13	Mapetla High School	Curro Academy Protea Glen Independent School
Moroka Clinic	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	16	Mapetla High School	South West College
Orlando Clinic	Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	5	Tlhatlogang Junior Secondary School	Lekang Primary School
Elias Motsoaledi Clinic	Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	5	Tlhatlogang Junior Secondary School	Megatong Primary School

			ALLOCATED ACCESS POINT	
CLIENT/USER	**PREFERRED ACCESS POINT/S**		**STABLE ROOMMATE**	**GAMMA RANDOM**
Protea Glen Clinic	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Impumelelo Junior Primary School, Tlholohelo Primary School, Prestige College, Pq vundla	8	Mapetla High School	Makhoarane Primary School
Zone 1 Diepkloof Clinic	Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School	2	Boston City Campus & Business College - Maponya Mall	Tetelo Secondary School
Itireleng Community Health Centre	Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Melane Academy, Adelaide Thambo School	7	Molaetsa Primary School	Isipho Lower Primary School
Mandela Sisulu Clinic	Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	8	Molaetsa Primary School	Luyolo Higher Primary School
Protea South Clinic	Mapetla High School, Protea South Primary School, Rebone Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office	10	Mapetla High School	Teacher Development Centre (Central District D14)
Prime Cure Dube	Phafogang Secondary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	11	Phafogang Secondary School	Adelaide Thambo School
Senaoane Clinic	Mapetla High School, Protea South Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	14	Mapetla High School	Chris Hani Baragwanath Nursing College
Klipspruit West Clinic - T.B Unit	Mapetla High School, Protea South Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School, Thaba Jabula Secondary School	13	Mapetla High School	Ditau Primary School
Lenasia Travel Clinic	Protea South Primary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Izipho Zomphakathi Multiskills	4	Protea South Primary School	Slovoville Primary School
Noordgesig Municipal Clinic	Melane Academy, Thaba Jabula Secondary School	2	Melane Academy	Esiyalwini Junior Secondary School
Eldorado Park Ext 8 Clinic	Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School, Thaba Jabula Secondary School	9	Phafogang Secondary School	Tlhatlogang Junior Secondary School
Eldorado Park Ext 9 T.B Clinic	Mapetla High School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	13	Mapetla High School	Teacher Development Centre (Central District D14)
Pimville Clinic	Phafogang Secondary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	11	Phafogang Secondary School	Ditau Primary School
Dr. C.K. Amos	Mapetla High School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	15	Mapetla High School	Vuwani Secondary School
Region D clinics	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Forte Secondary School, South West Gauteng College Head Office, Adelaide Thambo School	12	Mapetla High School	Bopasenatla Secondary School
Siphumlile Coj Clinic	Rebone Primary School, Emndeni Primary School, Impumelelo Junior Primary School, Lekang Primary School, Tlholohelo Primary School, Forte Secondary School	6	Rebone Primary School	Community Matric Learning Centre
Dr AD Makhubelas	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	15	Mapetla High School	Makhoarane Primary School
Surgery & Optometrist	Mapetla High School, Protea South Primary School, Rebone Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	12	Mapetla High School	Fosta Records
Dr B A Hussain	Mapetla High School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	13	Mapetla High School	Melane Academy
Skin & Body International	Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Izipho Zomphakathi Multiskills	3	Mveledzandivho Primary School	Phafogang Secondary School
S.A.M.S - Lenz Sick Bay	Rebone Primary School, Emndeni Primary School, Impumelelo Junior Primary School, Tlholohelo Primary School, Pq vundla	5	Rebone Primary School	Tetelo Secondary School
Meadowlands Zone 11 Portacabin Clinic	Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston	9	Molaetsa Primary School	Nghunghunyani Comprehensive School

			ALLOCATED ACCESS POINT	
CLIENT/USER	**PREFERRED ACCESS POINT/S**		**STABLE ROOMMATE**	**GAMMA RANDOM**
	City Campus & Business College - Maponya Mall, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School			
Eldorado Park Ext 2 Clinic	Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School, Thaba Jabula Secondary School	9	Phafogang Secondary School	Heerengracht Primary School
Dr. R. V. Taunyane	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	14	Mapetla High School	Melane Academy
Eldorado Park Clinic Ext 8	Nghunghunyani Comprehensive School, Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School	3	Nghunghunyani Comprehensive School	Protea South Primary School
Meadowlands Clinic	Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	8	Molaetsa Primary School	LechekoPowerYourMind
Phenyo's SPATHERAPY &WELLNESSCAFE'	Lekang Primary School, Tlhatlogang Junior Secondary School, Forte Secondary School, Melane Academy, Adelaide Thambo School	5	Lekang Primary School	Zibambele Lower Primary School
Dr Latib's Acupuncture and Chinese Medicine Clinic	Mapetla High School, Protea South Primary School, Mveledzandivho Primary School	3	Mapetla High School	Sekwati Primary School
Lenasia Community Health Centre (Hospital)	Mapetla High School, Protea South Primary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Izipho Zomphakathi Multiskills	5	Mapetla High School	Protea Glen College
Dr. M.T.D Qobose	Mapetla High School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	15	Mapetla High School	Protea Glen College
Ringane & Associates Inc	Phafogang Secondary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	12	Phafogang Secondary School	The Plumbing Academy
Opti Eyewear Optometrist	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	Anchor High School
Protea Medical Centre	Protea South Primary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Izipho Zomphakathi Multiskills	4	Protea South Primary School	Vuwani Secondary School
Medical Centre	Mapetla High School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	15	Mapetla High School	Thaba Jabula Secondary School
ZAN Gardens	Mapetla High School, Protea South Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	15	Mapetla High School	Makhoarane Primary School
Diepkloof Clinic	Thaba Jabula Secondary School	1	Thaba Jabula Secondary School	Johannesburg Bible College
Dr. B K C Sithole	Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	12	Phafogang Secondary School	Forte Secondary School
Kliptown Medical & Dental Centre	Mapetla High School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	13	Mapetla High School	Melane Academy
Slovoville clinic	Impumelelo Junior Primary School	1	Impumelelo Junior Primary School	LechekoPowerYourMind
Dr. Haroon Essa	Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School	2	Boston City Campus & Business College - Maponya Mall	Molaetsa Primary School
Lillian Ngoyi Community Health Centre	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	Moriting Primary School
Soweto Community Health Centre	Mapetla High School, Protea South Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	13	Mapetla High School	Reasoma High School
The Roots Health Centre	Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School	2	Boston City Campus & Business College - Maponya Mall	BTC-Soweto
Quali Health Braamfischer	Forte Secondary School	1	Forte Secondary School	Reasoma High School

			ALLOCATED ACCESS POINT	
CLIENT/USER	PREFERRED ACCESS POINT/S		STABLE ROOMMATE	GAMMA RANDOM
U-Care Medical Centre	Lekang Primary School, Tlhatlogang Junior Secondary School, Forte Secondary School, Melane Academy, Adelaide Thambo School	5	Lekang Primary School	Rishile Lower Primary School
Baragwanath Medical Centre	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	Mooki Memorial College
Mofolo Community Health Centre	Mapetla High School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	15	Mapetla High School	Mooki Memorial College
Ekhaya Lethu Medical Centre	Phafogang Secondary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	10	Phafogang Secondary School	Johannesburg Bible College
Eldorado Park Medical Centre	Nghunghunyani Comprehensive School, Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School	3	Nghunghunyani Comprehensive School	P J Simelane Secondary School
CWJ Medical Center	Mapetla High School, Protea South Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	17	Mapetla High School	Curro Academy Protea Glen Independent School
Yebohealth Medical Centre	Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Melane Academy, Adelaide Thambo School	7	Molaetsa Primary School	Melane Academy
HEALTH CENTRE	Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Boston City Campus & Business College - Maponya Mall,Izipho Zomphakathi Multiskills	5	Phafogang Secondary School	Protea Glen College
Medical & Dental Centre	Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, Thaba Jabula Secondary School	6	Phafogang Secondary School	Jabavu East Primary School
My Clinic	Mapetla High School, Protea South Primary School, Rebone Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	12	Mapetla High School	Luyolo Higher Primary School
Dobsonville Medical & Dental Surgery's	Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Melane Academy, Adelaide Thambo School	7	Molaetsa Primary School	Reasoma High School
FLEURHOF GOOD HEALTH CENTRE POINT	Forte Secondary School	1	Forte Secondary School	Anchor High School
Iso Lempilo Health Organization	Mapetla High School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	15	Mapetla High School	Luyolo Higher Primary School
Vilakazi Healthcare	Phafogang Secondary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	9	Phafogang Secondary School	Emadlelweni Primary School
Ubuntu Health Care Clinic	Phafogang Secondary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	11	Phafogang Secondary School	Impumelelo Junior Primary School
Tladi Community Health Centre	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	17	Mapetla High School	Mapetla High School
First Care Medical Centre	Phafogang Secondary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	9	Phafogang Secondary School	Teacher Development Centre (Central District D14)
Glencare Specialist Medical Centre	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Impumelelo Junior Primary School, Prestige College, Pq vundla	7	Mapetla High School	Johannesburg Bible College
Soweto Community Health Centre Pharmacy	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, South West Gauteng College Head Office, Adelaide Thambo School	11	Mapetla High School	Esiyalwini Junior Secondary School
Lilian Ngoyi Community Clinic - Medical	Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School	2	Boston City Campus & Business College - Maponya Mall	Sekwati Primary School
Chris Hani Baragwanath Academic Hospital	Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School	2	Boston City Campus & Business College - Maponya Mall	St Matthews School
Bheki Mlangeni District Hospital	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi	18	Mapetla High School	Makentse

			ALLOCATED ACCESS POINT	
CLIENT/USER	PREFERRED ACCESS POINT/S		STABLE ROOMMATE	GAMMA RANDOM
	Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School			
Tshepo Themba Private Hospital	Lekang Primary School, Tlhatlogang Junior Secondary School, Forte Secondary School, Melane Academy, Adelaide Thambo School	5	Lekang Primary School	BHUKULANI SENIOR SCONDARY SCHOOL
Dr SK Matseke Memorial Hospital	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	Entandweni Primary School
Chris Hani Baragwanath Hospital - Oncology	Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School	2	Boston City Campus & Business College - Maponya Mall	Ditau Primary School
Total Care Medical Center	Mapetla High School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	15	Mapetla High School	Chris Hani Baragwanath Nursing College
Dr Shingange Medical Centre	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office	13	Mapetla High School	South West Gauteng College Head Office
Advanced Soweto Day Hospital	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Mveledzandivho Primary School, Impumelelo Junior Primary School, Tlholohelo Primary School, Prestige College, Pq vundla	9	Mapetla High School	St Matthews School
Dr TC NGWENYA MEDICAL AND DENTAL CENTRE	Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	7	Molaetsa Primary School	Bopasenatla Secondary School
Hlophe T	Mapetla High School, Protea South Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	15	Mapetla High School	Pq vundla
Dr Michisi S Mbatsana	Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School	2	Boston City Campus & Business College - Maponya Mall	Johannesburg Bible College
Qengeba Medical Center	Phafogang Secondary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	10	Phafogang Secondary School	Molaetsa Primary School
Medical Surgery	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Impumelelo Junior Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Pq vundla	11	Mapetla High School	Moletsane High School
Drs. Moosajee & Partner	Protea South Primary School, Mveledzandivho Primary School	2	Protea South Primary School	Nghunghunyani Comprehensive School
Dr D Ngwenya Medical Practice	Lekang Primary School, Tlhatlogang Junior Secondary School, Forte Secondary School, Melane Academy, Adelaide Thambo School	5	Lekang Primary School	Molaetsa Primary School
Aeroton Medical Centre		0	Moletsane High School	Ibhongo Secondary School
Dr M.A. Muhammad Medical Practice	Mapetla High School, Protea South Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	11	Mapetla High School	Molaetsa Primary School
Goldman Medical Centre		0	Moletsane High School	Fosta Records
Sonar X-Ray	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Mveledzandivho Primary School, Impumelelo Junior Primary School, Tlholohelo Primary School, Prestige College, South West Gauteng College Head Office, Pq vundla	10	Mapetla High School	Sekwati Primary School
Surgery	Mapetla High School, Protea South Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office	10	Mapetla High School	Makhoarane Primary School
Life Esidimeni		0	Moletsane High School	Rishile Lower Primary School
Catnap Day Care Centre	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	18	Mapetla High School	Nurses Home
Meadowlands Welfare Centre	Lekang Primary School, Tlhatlogang Junior Secondary School, Forte Secondary School, Melane Academy, Adelaide Thambo School	5	Lekang Primary School	Mooki Memorial College
U-care Walk In Clinic	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	Nqobile Mhaleni
LechekoMindPower	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	17	Mapetla High School	Amadoda Ayasebenza (PTY) LTD

			ALLOCATED ACCESS POINT	
CLIENT/USER	PREFERRED ACCESS POINT/S		STABLE ROOMMATE	GAMMA RANDOM
T & D Medical Health Services	Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Melane Academy, Adelaide Thambo School	7	Molaetsa Primary School	Protea Glen College
UPD		0	Moletsane High School	BTC-Soweto
Ebom Consultancy	Mapetla High School, Phafogang Secondary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	14	Mapetla High School	Moriting Primary School
Roman H A and Partners T/a Fresenius Medical Care - Soweto Kidney and Dialysis Centre	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	BTC-Soweto
Roodepoort Healthcare Risk Waste Facility	Forte Secondary School	1	Forte Secondary School	Makhoarane Primary School
Verimark	Mapetla High School, Protea South Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	13	Mapetla High School	BHUKULANI SENIOR SCONDARY SCHOOL
Clinix Health Group	Lekang Primary School, Tlhatlogang Junior Secondary School, Forte Secondary School, Melane Academy, Adelaide Thambo School	5	Lekang Primary School	BHUKULANI SENIOR SCONDARY SCHOOL
Kinky world of hair	Phafogang Secondary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	11	Phafogang Secondary School	Itemogele Primary School
Soweto Independent Living Center	Phafogang Secondary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	13	Phafogang Secondary School	Rishile Lower Primary School
The South African Healthcare Foundation		0	Moletsane High School	Thaba Jabula Secondary School
OMOLEMO HEALTH CARE PRIVATE CLINIC		0	Moletsane High School	Anchor High School
Unique Health		0	Moletsane High School	Fosta Records
Dr. F. E. Geldenhuys Surgery	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	14	Mapetla High School	BTC-Soweto
Naledi Surgery	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	13	Mapetla High School	Johannesburg Bible College
Dr TT Muthambi - General Surgeon	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Mveledzandivho Primary School, Impumelelo Junior Primary School, Tlholohelo Primary School, Prestige College, Pq vundla	9	Mapetla High School	Tetelo Secondary School
Dr A I Jada	Mapetla High School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	13	Mapetla High School	Molaetsa Primary School
Dr. SF Mthembu	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	Enkanyezini Primary School
Dr PR Makaulule - Ear, Nose & Throat	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Mveledzandivho Primary School, Impumelelo Junior Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, Prestige College, South West Gauteng College Head Office, Pq vundla	11	Mapetla High School	Isipho Lower Primary School
Dr. L. Mokatedi	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office	13	Mapetla High School	St Matthews School
Dr. EA Mjuza	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	Adelaide Thambo School
Dr Wisani Chauke	Mapetla High School, Protea South Primary School, Rebone Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	12	Mapetla High School	Esiyalwini Junior Secondary School
Moloi Surgery	Mapetla High School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	15	Mapetla High School	HB Technology
Surgery - Dr. A.N Mmusi	Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School	2	Boston City Campus & Business College - Maponya Mall	Melane Academy

			ALLOCATED ACCESS POINT	
CLIENT/USER	**PREFERRED ACCESS POINT/S**		**STABLE ROOMMATE**	**GAMMA RANDOM**
S And S Orthopedic Services	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	Heerengracht Primary School
Protea Glen Ext 31 Surgery and Accomodation	Rebone Primary School, Impumelelo Junior Primary School, Prestige College, Pq vundla	4	Rebone Primary School	Tetelo Secondary School
Dr NS Mogodi	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office	11	Mapetla High School	Heerengracht Primary School
Dr. M.S. Molefe	Mapetla High School, Protea South Primary School, Rebone Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	15	Mapetla High School	South West College
Surgery Medicare Centre	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	18	Mapetla High School	Protea Glen College
Dr. B.L. Khulu	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	Phafogang Secondary School
TM Mkhize Dental Surgery	Phafogang Secondary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	10	Phafogang Secondary School	Daliwonga Secondary School
Dr. Mosidi G. Sehume	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	Adelaide Thambo School
Dube Dental Surgery	Phafogang Secondary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	11	Phafogang Secondary School	Curtis Nkondo School Of Specialization
Dr. Charles N. Mujakachi	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	Adelaide Thambo School
Surgery Dr Thlabi	Thaba Jabula Secondary School	1	Thaba Jabula Secondary School	Thabisang Primary School
Dr. T. E. Ndzeru	Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	3	Boston City Campus & Business College - Maponya Mall	Adelaide Thambo School
Dr .M. Isabelle	Mapetla High School, Rebone Primary School, Emndeni Primary School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, South West Gauteng College Head Office, Adelaide Thambo School	11	Mapetla High School	Curtis Nkondo School Of Specialization
Dr Avhashoni T Mavhungu	Mapetla High School, Protea South Primary School, Rebone Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	12	Mapetla High School	Slovoville Primary School
Mkhawana C T	Mapetla High School, Protea South Primary School, Rebone Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office	10	Mapetla High School	Makhoarane Primary School
Dr P.S Mabela	Tlhatlogang Junior Secondary School, Forte Secondary School	2	Tlhatlogang Junior Secondary School	Pace Community College
Rammutla	Prestige College, Pq vundla	2	Prestige College	Protea South Primary School
Dr. T Phefo	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	17	Mapetla High School	Mapetla High School
Dr S Ismail	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School	18	Mapetla High School	Mooki Memorial College
Dr. V.S. Nhlapo Inc.	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Mveledzandivho Primary School, Impumelelo Junior Primary School, Tlholohelo Primary School, Prestige College, South West Gauteng College Head Office, Pq vundla	10	Mapetla High School	Emndeni Primary School
Nkuna L E	Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	8	Molaetsa Primary School	Molaetsa Primary School
Dr. Ismail Mia	Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Tlhatlogang	11	Phafogang Secondary School	Pq vundla

CLIENT/USER	PREFERRED ACCESS POINT/S		ALLOCATED ACCESS POINT	
			STABLE ROOMMATE	GAMMA RANDOM
	Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School			
Dr. T.M. Tshabalala	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Impumelelo Junior Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Pq vundla	11	Mapetla High School	St Matthews School
DR MS MUSHADU	Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Forte Secondary School, Boston City Campus & Business College - Maponya Mall, Melane Academy, Adelaide Thambo School, Thaba Jabula Secondary School	8	Molaetsa Primary School	Thabisang Primary School
Dr E Nanabhai	Mapetla High School, Protea South Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Boston City Campus & Business College - Maponya Mall, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office, Adelaide Thambo School	13	Mapetla High School	Jabavu Oos Primary School
Dr. K. Mosalakae	Tlhatlogang Junior Secondary School, Boston City Campus & Business College - Maponya Mall, Melane Academy, Thaba Jabula Secondary School	4	Tlhatlogang Junior Secondary School	Daliwonga Secondary School
Dr K.M Bopalamo	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Mveledzandivho Primary School, Nghunghunyani Comprehensive School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlholohelo Primary School, Izipho Zomphakathi Multiskills, South West Gauteng College Head Office	13	Mapetla High School	DSJ Primary School
Dr TC Moloto	Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, Melane Academy, Adelaide Thambo School	7	Molaetsa Primary School	Sekwati Primary School
Dr M Machaka	Mapetla High School, Protea South Primary School, Rebone Primary School, Emndeni Primary School, Mveledzandivho Primary School, Impumelelo Junior Primary School, Tlholohelo Primary School, Prestige College, Pq vundla	9	Mapetla High School	Rishile Lower Primary School
Dr. David E. Mashigo	Mapetla High School, Rebone Primary School, Emndeni Primary School, Phafogang Secondary School, Impumelelo Junior Primary School, Molaetsa Primary School, Lekang Primary School, Tlhatlogang Junior Secondary School, Tlholohelo Primary School, Forte Secondary School, South West Gauteng College Head Office, Adelaide Thambo School	12	Mapetla High School	Megatong Primary School
Dr. BM Hlatshwayo	Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School	2	Boston City Campus & Business College - Maponya Mall	Ibhongo Secondary School
Orthopaedic Suppliers	Boston City Campus & Business College - Maponya Mall, Thaba Jabula Secondary School	0	Moletsane High School	Pace Community College

Table 20 – Users/Clients Allocation with Respect to the Access Point.

ACCESS POINT	PREFERRED	STABLE ROOMMATE		GAMMA RANDOM	
Moletsane High School	76	Tshepisong Clinic, Aeroton Medical Centre, Goldman Medical Centre, Life Esidimeni, UPD, The South African Healthcare Foundation, OMOLEMO HEALTH CARE PRIVATE CLINIC, Unique Health, Orthopaedic Suppliers	9	Medical Surgery	1
Naledi High School	60		0		0
Megatong Primary School	69		0	Elias Motsoaledi Clinic, Dr. David E. Mashigo	2
Daliwonga Secondary School	61		0	TM Mkhize Dental Surgery, Dr. K. Mosalakae	2
Curtis Nkondo School Of Specialization	41		0	Dube Dental Surgery, Dr .M. Isabelle	2
St Matthews School	73		0	St John's Eye Hospital, Chris Hani Baragwanath Academic Hospital, Advanced Soweto Day Hospital, Dr. L. Mokatedi, Dr. T.M. Tshabalala	5
Mapetla High School	68	Zola Gateway Clinic, Zola Clinic, Chiawelo Community Healthcare Centre, Jabavu Clinic - T.B Unit, Tladi Clinic, Zondi Clinic, Chiawelo Community Practice, Moroka Clinic, Protea Glen Clinic, Protea South Clinic, Senaoane Clinic, Klipspruit West Clinic - T.B Unit, Eldorado Park Ext 9 T.B Clinic, Dr. C.K. Amos, Region D clinics, Dr AD Makhubelas, Surgery & Optometrist, Dr B A Hussain, Dr. R. V. Taunyane, Dr Latib's Acupuncture and Chinese Medicine Clinic, Lenasia Community Health Centre (Hospital), Dr. M.T.D Qobose, Medical Centre, ZAN Gardens, Kliptown Medical & Dental Centre, Soweto Community Health Centre, Mofolo Community Health Centre, CWJ Medical Center, My Clinic, Iso Lempilo Health Organization, Tladi Community Health Centre, Glencare Specialist Medical Centre, Soweto Community Health Centre Pharmacy, Bheki Mlangeni District Hospital, Total Care Medical Center, Dr Shingange Medical Centre, Advanced Soweto Day Hospital, Hlophe T, Medical Surgery, Dr M.A. Muhammad Medical Practice, Sonar X-Ray, Surgery, Catnap Day Care Centre, LechekoMindPower, Ebom Consultancy, Verimark, Dr. F. E. Geldenhuys Surgery, Naledi Surgery, Dr TT Muthambi - General Surgeon, Dr A I Jada, Dr PR Makaulule - Ear, Nose & Throat, Dr. L. Mokatedi, Dr Wisani Chauke,	68	Tladi Community Health Centre, Dr. T Phefo	2

ACCESS POINT	PREFERRED	STABLE ROOMMATE		GAMMA RANDOM	
		Moloi Surgery, Dr NS Mogodi, Dr. M.S. Molefe, Surgery Medicare Centre, Dr .M. Isabelle, Dr Avhashoni T Mavhungu, Mkhawana C T, Dr. T Phefo, Dr S Ismail, Dr. V.S. Nhlapo Inc., Dr. T.M. Tshabalala, Dr E Nanabhai, Dr K.M Bopalamo, Dr M Machaka, Dr. David E. Mashigo			
Anchor High School	65		0	Opti Eyewear Optometrist, FLEURHOF GOOD HEALTH CENTRE POINT, OMOLEMO HEALTH CARE PRIVATE CLINIC	3
Ditau Primary School	64		0	Zola Gateway Clinic, Klipspruit West Clinic - T.B Unit, Pimville Clinic, Chris Hani Baragwanath Hospital - Oncology	4
Fundani Primary School	43		0		0
BHUKULANI SENIOR SCONDARY SCHOOL	62		0	Tshepo Themba Private Hospital, Verimark, Clinix Health Group	3
Protea South Primary School	56	Lenasia Travel Clinic, Protea Medical Centre, Drs. Moosajee & Partner	3	Eldorado Park Clinic Ext 8, Rammutla	2
Luyolo Higher Primary School	48		0	Mandela Sisulu Clinic, My Clinic, Iso Lempilo Health Organization	3
Jabavu East Primary School	56		0	Medical & Dental Centre	1
DSJ Primary School	54		0	Dr K.M Bopalamo	1
Zibambele Lower Primary School	40		0	Phenyo's SPATHERAPY &WELLNESSCAFE'	1
Rebone Primary School	45	Green Village Clinic, Siphumlile Coj Clinic, S.A.M.S - Lenz Sick Bay, Protea Glen Ext 31 Surgery and Accomodation	4		0
Emndeni Primary School	39		0	Dr. V.S. Nhlapo Inc.	1
Tetelo Secondary School	55		0	Zone 1 Diepkloof Clinic, S.A.M.S - Lenz Sick Bay, Dr TT Muthambi - General Surgeon, Protea Glen Ext 31 Surgery and Accomodation	4
Enkanyezini Primary School	72		0	Dr. SF Mthembu	1
Curro Academy Protea Glen Independent School	43		0	Chiawelo Community Practice, CWJ Medical Center	2
Esiyalwini Junior Secondary School	60		0	Noordgesig Municipal Clinic, Soweto Community Health Centre Pharmacy, Dr Wisani Chauke	3
Makhoarane Primary School	58		0	Protea Glen Clinic, Dr AD Makhubelas, ZAN Gardens, Surgery, Roodepoort Healthcare Risk Waste Facility, Mkhawana C T	6
Phafogang Secondary School	76	Top Care Women's Clinic -Dube, Soweto, Prime Cure Dube, Eldorado Park Ext 8 Clinic, Pimville Clinic, Eldorado Park Ext 2 Clinic, Ringane & Associates Inc, Dr. B K C Sithole, Ekhaya Lethu Medical Centre, HEALTH CENTRE, Medical & Dental Centre, Vilakazi Healthcare, Ubuntu Health Care Clinic, First Care Medical Centre, Qengeba Medical Center, Kinky world of hair, Soweto Independent Living Center, TM Mkhize Dental Surgery, Dube Dental Surgery, Dr. Ismail Mia	19	Skin & Body International, Dr. B.L. Khulu	2
Entandweni Primary School	60		0	Dr SK Matseke Memorial Hospital	1
Rishile Lower Primary School	60		0	U-Care Medical Centre, Life Esidimeni, Soweto Independent Living Center, Dr M Machaka	4
Vukazenzele Primary School	68		0		0
Bopasenatla Secondary School	41		0	Region D clinics, Dr TC NGWENYA MEDICAL AND DENTAL CENTRE	2
St Angela's Primary School	55		0		0
Ibhongo Secondary School	70		0	Aeroton Medical Centre, Dr. BM Hlatshwayo	2
Thabisang Primary School	82		0	Tladi Clinic, Surgery Dr Thlabi, DR MS MUSHADU	3
Mveledzandivho Primary School	67	Skin & Body International	1		0
Jabavu Oos Primary School	75		0	Dr E Nanabhai	1
Nghunghunyani Comprehensive School	68	Eldorado Park Clinic Ext 8, Eldorado Park Medical Centre	2	Meadowlands Zone 11 Portacabin Clinic, Drs. Moosajee & Partner	2
Reasoma High School	60		0	Soweto Community Health Centre, Quali Health Braamfischer, Dobsonville Medical & Dental Surgery's	3
Impumelelo Junior Primary School	39	Slovoville Clinic, Slovoville clinic	2	Ubuntu Health Care Clinic	1
Heerengracht Primary School	42		0	Freedom Park Clinic, Eldorado Park Ext 2 Clinic, S And S Orthopedic Services, Dr NS Mogodi	4
Vuwani Secondary School	63		0	Dr. C.K. Amos, Protea Medical Centre	2
Tshilidzi Primary School	75		0		0
Molaetsa Primary School	84	Itireleng Community Health Centre, Mandela Sisulu Clinic, Meadowlands Zone 11 Portacabin Clinic, Meadowlands Clinic, Yebohealth Medical Centre, Dobsonville Medical & Dental Surgery's,	11	Dr. Haroon Essa, Qengeba Medical Center, Dr D Ngwenya Medical	6

ACCESS POINT	PREFERRED	STABLE ROOMMATE		GAMMA RANDOM	
		Dr TC NGWENYA MEDICAL AND DENTAL CENTRE, T & D Medical Health Services, Nkuna L E, DR MS MUSHADU, Dr TC Moloto		Practice, Dr M.A. Muhammad Medical Practice, Dr A I Jada, Nkuna L E	
Emadlelweni Primary School	68		0	Chiawelo Community Healthcare Centre, Vilakazi Healthcare	2
Sekwati Primary School	79		0	Dr Latib's Acupuncture and Chinese Medicine Clinic, Lilian Ngoyi Community Clinic - Medical, Sonar X-Ray, Dr TC Moloto	4
Winnie Madikizela-Mandela School	72		0		0
Enkolweni Primary School	58		0	Zola Clinic	1
Lekang Primary School	86	Phenyo's SPATHERAPY &WELLNESSCAFE', U-Care Medical Centre, Tshepo Themba Private Hospital, Dr D Ngwenya Medical Practice, Meadowlands Welfare Centre, Clinix Health Group	6	Orlando Clinic	1
Itemogele Primary School	40		0	Kinky world of hair	1
Mambo Primary School	71		0		0
P J Simelane Secondary School	59		0	Eldorado Park Medical Centre	1
Thulare Secondary School	79		0		0
Tlhatlogang Junior Secondary School	74	Orlando Clinic, Elias Motsoaledi Clinic, Dr P.S Mabela, Dr. K. Mosalakae	4	Eldorado Park Ext 8 Clinic	1
Moriting Primary School	65		0	Lillian Ngoyi Community Health Centre, Ebom Consultancy	2
Tlholohelo Primary School	74		0		0
Forte Secondary School	51	Quali Health Braamfischer, FLEURHOF GOOD HEALTH CENTRE POINT, Roodepoort Healthcare Risk Waste Facility	3	Dr. B K C Sithole	1
Adelaide Tambo School for the Physically Challenged	84		0		0
Isipho Lower Primary School	77		0	Itireleng Community Health Centre, Dr PR Makaulule - Ear, Nose & Throat	2
South West College	84		0	Moroka Clinic, Dr. M.S. Molefe	2
Boston City Campus & Business College - Maponya Mall	87	Marie Stopes Soweto, St John's Eye Hospital, Zone 1 Diepkloof Clinic, Opti Eyewear Optometrist, Dr. Haroon Essa, Lillian Ngoyi Community Health Centre, The Roots Health Centre, Baragwanath Medical Centre, Lilian Ngoyi Community Clinic - Medical, Chris Hani Baragwanath Academic Hospital, Dr SK Matseke Memorial Hospital, Chris Hani Baragwanath Hospital - Oncology, Dr Michisi S Mbatsana, U-care Walk In Clinic, Roman H A and Partners T/a Fresenius Medical Care - Soweto Kidney and Dialysis Centre, Dr. SF Mthembu, Dr. EA Mjuza, Surgery - Dr. A.N Mmusi, S And S Orthopedic Services, Dr. B.L. Khulu, Dr. Mosidi G. Sehume, Dr. Charles N. Mujakachi, Dr. T. E. Ndzeru, Dr. BM Hlatshwayo	24	Marie Stopes Soweto	1
Pace Community College	73		0	Top Care Women's Clinic -Dube, Soweto, Dr P.S Mabela, Orthopaedic Suppliers	3
WO BIBLE COLLEGE	74		0		0
Protea Glen College	47		0	Lenasia Community Health Centre (Hospital), Dr. M.T.D Qobose, HEALTH CENTRE, T & D Medical Health Services, Surgery Medicare Centre	5
Izipho Zomphakathi Multiskills	70		0		0
Teacher Development Centre (Central District D14)	74		0	Protea South Clinic, Eldorado Park Ext 9 T.B Clinic, First Care Medical Centre	3
Prestige College	10	Rammutla	1		0
LechekoPowerYourMind	74		0	Meadowlands Clinic, Slovoville clinic	2
Chris Hani Baragwanath Nursing College	42		0	Senaoane Clinic, Total Care Medical Center	2
South West Gauteng College Head Office	75		0	Dr Shingange Medical Centre	1
Lebo Sibi	38		0		0
Nurses Home	45		0	Catnap Day Care Centre	1
BTC-Soweto	76		0	The Roots Health Centre, UPD, Roman H A and Partners T/a Fresenius Medical Care - Soweto Kidney and Dialysis Centre, Dr. F. E. Geldenhuys Surgery	4
Altmont Technical High School	62		0		0
Nqobile Mhaleni	73		0	U-care Walk In Clinic	1
Amadoda Ayasebenza (PTY) LTD	74		0	Zondi Clinic, LechekoMindPower	2
Melane Academy	79	Noordgesig Municipal Clinic	1	Dr B A Hussain, Dr. R. V. Taunyane, Kliptown Medical & Dental Centre, Yebohealth Medical Centre, Surgery - Dr. A.N Mmusi	5

ACCESS POINT	PREFERRED	STABLE ROOMMATE		GAMMA RANDOM	
Makentse	28		0	Slovoville Clinic, Bheki Mlangeni District Hospital	2
Pq vundla	14		0	Hlophe T, Dr. Ismail Mia	2
Fosta Records	43		0	Surgery & Optometrist, Goldman Medical Centre, Unique Health	3
Community Matric Learning Centre	61		0	Siphumlile Coj Clinic	1
Mooki Memorial College	62		0	Baragwanath Medical Centre, Mofolo Community Health Centre, Meadowlands Welfare Centre, Dr S Ismail	4
Peter Lengene Community Learning Centre	71		0		0
Johannesburg Bible College	71		0	Diepkloof Clinic, Ekhaya Lethu Medical Centre, Glencare Specialist Medical Centre, Dr Michisi S Mbatsana, Naledi Surgery	5
Adelaide Thambo School	85		0	Prime Cure Dube, Dr. EA Mjuza, Dr. Mosidi G. Sehume, Dr. Charles N. Mujakachi, Dr. T. E. Ndzeru	5
The Plumbing Academy	71		0	Jabavu Clinic - T.B Unit, Ringane & Associates Inc	2
Slovoville Primary School	5		0	Tshepisong Clinic, Lenasia Travel Clinic, Dr Avhashoni T Mavhungu	3
Thaba Jabula Secondary School	71	Freedom Park Clinic, Diepkloof Clinic, Surgery Dr Thlabi	3	Medical Centre, The South African Healthcare Foundation	2
HB Technology	70	Tshepisong Clinic, Aeroton Medical Centre, Goldman Medical Centre, Life Esidimeni, UPD, The South African Healthcare Foundation, OMOLEMO HEALTH CARE PRIVATE CLINIC, Unique Health, Orthopaedic Suppliers	0	Green Village Clinic, Moloi Surgery	2

iv. Case Study.

(a) *Network Nodes.*

PLACE	ID	NAME	LATITUDE	LONGITUDE	ADDRESS
Soweto	1	Moletsane High School	-26.254550	27.851190	1644, Moletsane, Soweto, 1868, South Africa
	2	Naledi High School	-26.250609	27.831194	Nyakale St., Soweto, Johannesburg, 1868, South Africa
	3	Megatong Primary School	-26.275730	27.851400	2984, Mapetla, Soweto, 1818, South Africa
	4	Daliwonga Secondary School	-26.232041	27.889102	Koma St., Dube, Soweto, 1800, South Africa
	5	Curtis Nkondo School Of Specialization	-26.239144	27.824118	2362 Biyela St., Emdeni South, Soweto, 1861, South Africa
	6	St Matthews School	-26.259996	27.881219	818 Ndebele St., Moroka, Soweto, 1818, South Africa
	7	Mapetla High School	-26.273646	27.846185	2189 Monotshe St., Mapetla, Soweto, 1818, South Africa
	8	Anchor High School	-26.219638	27.914014	Rev Frederick S Modise Drive, Soweto, Johannesburg, 1803, South Africa
	9	Ditau Primary School	-26.248790	27.921740	6604, Klipspruit 318-Iq, Soweto, 1809, South Africa
	10	Fundani Primary School	-26.246190	27.821020	1517, Emdeni South, Soweto, 1861, South Africa
	11	BHUKULANI SENIOR SCONDARY SCHOOL	-26.233524	27.867531	Zondi 2, 666 Masingafi St., EET Soweto, Johannesburg, 1868, South Africa
	12	Protea South Primary School	-26.280852	27.839797	02016 Colman St., Protea South, Soweto, 1818, South Africa
	13	Luyolo Higher Primary School	-26.245909	27.825657	1026 A Dakamani St., Soweto, Johannesburg, 1868, South Africa
	14	Jabavu East Primary School	-26.246580	27.829410	819 Tshabalala St., Emdeni South, Soweto, 1861, South Africa
	15	DSJ Primary School	-26.221965	27.856304	4057, Dobsonville, Soweto, 1863, South Africa
	16	Zibambele Lower Primary School	-26.241830	27.823420	388 Radebe St., Emdeni South, Soweto, 1861, South Africa
	17	Rebone Primary School	-26.256110	27.816660	50, Naledi, Soweto, 1861, South Africa
	18	Emndeni Primary School	-26.242917	27.821562	Zwane St., Soweto, Johannesburg, 1861, South Africa

PLACE	ID	NAME	LATITUDE	LONGITUDE	ADDRESS
	19	Tetelo Secondary School	-26.268948	27.829818	Letsatsi St., Soweto, Johannesburg, 1819, South Africa
	20	Enkanyezini Primary School	-26.267974	27.856670	157, Phiri, Soweto, 1818, South Africa
	21	Curro Academy Protea Glen Independent School	-26.269401	27.814735	Corner of Sagewood and, Wild Chestnut St., Protea Glen, Soweto, 1818, South Africa
	22	Esiyalwini Junior Secondary School	-26.225864	27.875065	Gumede St., Soweto, Johannesburg, 1801, South Africa
	23	Makhoarane Primary School	-26.219636	27.873228	Vuzane St., Dobsonville, Soweto, 1863, South Africa
	24	Phafogang Secondary School	-26.267320	27.867198	2226 Gumede St., Moroka, Soweto, 1818, South Africa
	25	Entandweni Primary School	-26.232400	27.860500	672, Zondi, Soweto, 1868, South Africa
	26	Rishile Lower Primary School	-26.226479	27.892697	337 Phiri St., Meadowlands, Soweto, 1852, South Africa
	27	Vukazenzele Primary School	-26.234960	27.878120	999, Mofolo North, Soweto, 1801, South Africa
	28	Bopasenatla Secondary School	-26.251199	27.943039	2063B Sono St., Soweto, Johannesburg, 1864, South Africa
	29	St. Angela's Primary School	-26.220283	27.866275	Mokhesi St., Dobsonville, Soweto, 1863, South Africa
	30	Ibhongo Secondary School	-26.272504	27.874548	Chris-Hani Rd, Soweto, Johannesburg, 1818, South Africa
	31	Thabisang Primary School	-26.242530	27.902750	11227, Orlando West, Soweto, 1804, South Africa
	32	Mveledzandivho Primary School	-26.285980	27.859250	3350, Chiawelo, Soweto, 1818, South Africa
	33	Jabavu Oos Primary School	-26.258527	27.883220	Vilalazi Street, Soweto, Johannesburg, 1860, South Africa
	34	Nghunghunyani Comprehensive School	-26.278690	27.873880	508 Hlaisi St., Chiawelo, Soweto, 1818, South Africa
	35	Reasoma High School	-26.268770	27.837396	Ntloko St., Soweto, Johannesburg, 1818, South Africa
	36	Impumelelo Junior Primary School	-26.244632	27.817722	2858, Kewale Street, Emdeni Ext, Soweto, 1868, South Africa
	37	Heerengracht Primary School	-26.289880	27.916020	Eldorado Park, Soweto, 1811, South Africa
	38	Vuwani Secondary School	-26.285653	27.855983	3346, Chiawelo, Soweto, 1818, South Africa
	39	Tshilidzi Primary School	-26.281711	27.868001	1212 Thoho Ya Ndou St., Chiawelo, Soweto, 1818, South Africa
	40	Molaetsa Primary School	-26.255360	27.871275	3130 Maliza St., Jabavu, Soweto, 1809, South Africa
	41	Emadlelweni Primary School	-26.276744	27.875326	Soweto, Johannesburg, 1818, South Africa
	42	Sekwati Primary School	-26.256738	27.862836	752 Metlatoe St., Molapo, Soweto, 1818, South Africa
	43	Winnie Madikizela-Mandela School	-26.272912	27.868963	Limpopo St., Senaoane, Soweto, 1818, South Africa
	44	Enkolweni Primary School	-26.226629	27.867200	27 Khosa St., Dobsonville, Soweto, 1863, South Africa
	45	Lekang Primary School	-26.248767	27.870457	05327 Kadebe St., Jabavu, Soweto, 1809, South Africa
	46	Itemogele Primary School	-26.265382	27.811306	590 Quinine St., Protea Glen, Soweto, 1819, South Africa
	47	Mambo Primary School	-26.280690	27.854290	2324, Chiawelo, Soweto, 1818, South Africa
	48	P J Simelane Secondary School	-26.228626	27.859526	Dobsonville, Soweto, 1863, South Africa
	49	Thulare Secondary School	-26.244020	27.877070	3134, Jabavu, Soweto, 1809, South Africa
	50	Tshilidzi Primary School	-26.253604	27.854150	Soweto, Johannesburg, 1868, South Africa
	51	Tlhatlogang Junior Secondary School	-26.245030	27.883242	1349 Mputhi St., Jabavu, Soweto, 1809, South Africa
	52	Moriting Primary School	-26.271111	27.842893	2942 Soma St., Mapetla, Soweto, 6201, South Africa
	53	Tlholohelo Primary School	-26.251371	27.848994	154, Moletsane, Soweto, 1868, South Africa
	54	Forte Secondary School	-26.214449	27.867243	110 Christian Dube St., Mmesi Park, Soweto, 1863, South Africa

PLACE	ID	NAME	LATITUDE	LONGITUDE	ADDRESS
	55	Adelaide Tambo School for the Physically Challenged	-26.249604	27.876056	Diokane St., Jabavu, Soweto, 1809, South Africa
	56	Isipho Lower Primary School	-26.262869	27.873633	144 Inqulube St., Moroka, Soweto, 1818, South Africa
	57	South West College	-26.247705	27.892668	Mncube Dr., Dube, Soweto, 1801, South Africa
	58	Boston City Campus & Business College – Maponya Mall	-26.258154	27.901601	406, Maponya Mall, 2127 Chris-Hani Rd, Klipspruit, Soweto, 2127, South Africa
	59	Pace Community College	-26.240036	27.854647	1340, Bendile St., Soweto, Johannesburg, 1868, South Africa
	60	WO BIBLE COLLEGE	-26.266060	27.873660	02065 Mampona St., Moroka, Soweto, 1818, South Africa
	61	Protea Glen College	-26.276664	27.821564	Crn 104 Red Current & Protea Boulevard Str, Shop 49 Sizwe Shopping Centre, Protea Glen, Soweto, 1819, South Africa
	62	Izipho Zomphakathi Multiskills	-26.276867	27.864800	1378 Ingwayuma St., Senaoane, Soweto, 1818, South Africa
	63	Teacher Development Centre (Central District D14)	-26.266023	27.874296	Vundla St., Moroka, Soweto, 1818, South Africa
	64	Prestige College	-26.271977	27.770656	29 Key St., Protea Glen, Soweto, 1834, South Africa
	65	LechekoPowerYourMind	-26.251995	27.849839	Moliwa street, Soweto, Johannesburg, 1868, South Africa
	66	Chris-Hani Baragwanath Nursing College	-26.263652	27.945111	Diepkloof 319-Iq, Soweto, 1862, South Africa
	67	South West Gauteng College Head Office	-26.264349	27.860417	1822 Molele St., Molapo, Soweto, 1818, South Africa
	68	Lebo Sibi	-26.275714	27.811733	251 12, Absalome Protea Glen Extension 16, Soweto, South Africa
	69	Nurses Home	-26.260072	27.938527	Nurses home Rd, Diepkloof 319-Iq, Soweto, 1862, South Africa
	70	BTC-Soweto	-26.259133	27.885598	752 Elias Motsoaledi Rd, Mofolo South, Soweto, 1801, South Africa
	71	Altmont Technical High School	-26.281236	27.842472	Cnr Alekhine & Stanton Rd, Protea South, Soweto, 1818, South Africa
	72	Nqobile Mhaleni	-26.248538	27.854032	Moletsane, Soweto, 1868, South Africa
	73	Amadoda Ayasebenza (PTY) LTD	-26.254894	27.910138	475 Makhubu St., Klipspruit, Soweto, 1809, South Africa
	74	Melane Academy	-26.242175	27.893682	1083 Sandile St., Dube, Soweto, 1800, South Africa
	75	Makentse	-26.237406	27.807851	2410 Lesedi St., Soweto, 1723 Lesedi St., Doornkop, Soweto, 1723, South Africa
	76	Pq vundla	-26.270657	27.774071	1822, Molapo St., Soweto, 1818, South Africa
	77	Fosta Records	-26.202619	27.876563	218 Masevekela str, Meadowlands, Soweto, 1852, South Africa
	78	Community Matric Learning Centre	-26.233290	27.923300	Orlando West, Soweto, 1804, South Africa
	79	Mooki Memorial College	-26.234656	27.921698	6504 Mooki St., Orlando East, Soweto, 1804, South Africa
	80	Peter Lengene Community Learning Centre	-26.258248	27.916168	Housed at Thaba Jabula secondary school, 1097 Chris-Hani Rd, Soweto, 1809, South Africa
	81	Johannesburg Bible College	-26.256760	27.915900	1032 Mbambisa St., Klipspruit, Soweto, 1809, South Africa
	82	Adelaide Thambo School	-26.248844	27.876419	3132B Diokane St., Soweto, Johannesburg, 1864, South Africa
	83	The Plumbing Academy	-26.271141	27.876735	00617 Ndlovu Street, Dlamini, Soweto, 1818, South Africa
	84	Slovoville Primary School	-26.213820	27.777728	Slovoville, Soweto, 1754, South Africa
	85	Thaba Jabula Secondary School	-26.258323	27.916441	Chris-Hani Rd, Soweto, Johannesburg, 1805, South Africa
	86	HB Technology	-26.248810	27.842580	00229 Bolani Rd, Tladi, Soweto, 1868, South Africa
Khayelitsha	1	Yomelela Primary School	-34.028053	18.674636	Bhemye Cres, Khayelitsha, Cape Town, 7784, South Africa
	2	Academia Primary School	-34.031748	18.694478	Khayelitsha, Cape Town, 7784, South Africa

PLACE	ID	NAME	LATITUDE	LONGITUDE	ADDRESS
	3	Bulumko Secondary School	-34.038810	18.672730	31 Mangezi St., Khayelitsha, Cape Town, 7784, South Africa
	4	Ummangaliso Primary School	-34.047913	18.670508	T Section Bangiso Dve Site B, Khayelitsha, Cape Town, 7784, South Africa
	5	Kukhanyile Publ Primary School	-34.029010	18.671660	13 Lali St., Khayelitsha, Cape Town, 7784, South Africa
	6	Chris-Hani Arts & Culture High School	-34.047218	18.705771	Paul Avenue, Khayelitsha, Cape Town, 7784, South Africa
	7	Vuzamanzi P P School	-34.014135	18.649166	Solomon Tshuku Ave, Khayelitsha, Cape Town, 7784, South Africa
	8	Eluxolweni Primary School	-34.029725	18.670137	Pama &, Mongesi Rd, Khayelitsha, Cape Town, 7784, South Africa
	9	Noxolo Xauka Primary School	-34.042763	18.711244	Nyanda Ave, Khayelitsha, Cape Town, 7784, South Africa
	10	False Bay College	-34.049672	18.654066	Mew Way & Qamba crescent, Khayelitsha, 7785, South Africa
	11	Falsebay Khayelitsha Campus	-34.045269	18.655772	Mew Way, Khayelitsha, Cape Town, 7784, South Africa
	12	False Bay TVET College: Swartklip Campus	-34.032304	18.633812	c/o Swartklip and, Morgenster Rd, Khayelitsha, 7784, South Africa
	13	FALSE BAY TVET COLLEGE, SWARTKLIP CAMPUS	-34.047126	18.641387	Swartklip Rd, Khayelitsha, Cape Town, 7785, South Africa
	14	False Bay College Youth Advisory Centre	-34.045305	18.655789	Mew Way, Khayelitsha, Cape Town, 7784, South Africa
	15	Silulo Ulutho Technologies	-34.027104	18.664722	Nonkqubela Link, Sulani Dr., Khayelitsha, Cape Town, 7784, South Africa
	16	Academia Primary School	-34.031502	18.698764	Khayelitsha, Cape Town, 7784, South Africa
	17	Silulo Ulutho Technologies	-34.027104	18.664722	Nonkqubela Link, Sulani Dr., Khayelitsha, Cape Town, 7784, South Africa
	18	Academia Primary School	-34.031748	18.694478	Khayelitsha, Cape Town, 7784, South Africa
	19	Tree Tech Academy	-34.045547	18.656424	Mew Way /Spine Road, Bandwidth Barn, Khayelitsha, Cape Town, 7784, South Africa
	20	Chris-Hani Arts & Culture High School	-34.047218	18.705771	Paul Avenue, Khayelitsha, Cape Town, 7784, South Africa
	21	VLM Music Academy	-34.037825	18.679890	Khayelitsha, Cape Town, 7784, South Africa
	22	Noxolo Xauka Primary School	-34.042763	18.711244	Nyanda Ave, Khayelitsha, Cape Town, 7784, South Africa
	23	Yomelela Primary School	-34.028053	18.674636	Bhemye Cres, Khayelitsha, Cape Town, 7784, South Africa
Lulekani	1	Lulekani Primary School.	-23.859282	31.076419	Lulekani-A, Phalaborwa, 1392, South Africa
	2	Majeje High School	-23.866728	31.086615	815 Quatro St., Lulekani-B, Phalaborwa, 1392, South Africa
	3	Nwasorini Primary School	-23.861973	31.081610	Lulekani-B, Phalaborwa, 1392, South Africa
	4	Nwa Risenga Primary School	-23.862020	31.089670	124 Park St., Lulekani-B, Phalaborwa, 1392, South Africa
	5	Nkateko High School.	-23.866500	31.072900	Lulekani-A, Phalaborwa, 1392, South Africa
	6	Pondo Combined School	-23.870170	31.071500	764, Lulekani-A, Phalaborwa, 1392, South Africa
	7	Majeje High.	-23.867500	31.081818	437 Bridgeway Street, Lulekani-B, Phalaborwa, 1392, South Africa
	8	Rixile Education Centre	-23.866836	31.083661	373 Bridgeway Street, Lulekani-B, Phalaborwa, 1392, South Africa
	9	Biko Primary School	-23.855748	31.065185	Lulekani, 1392, South Africa
	10	Sumsang	-23.861151	31.077313	217 Nghunghunyani Drive, Lulekani-B, Phalaborwa, 1392, South Africa
	11	Mabakuwa's house	-23.859869	31.082035	91 Tututu Cres, Lulekani-B, Phalaborwa, 1392, South Africa
	12	Khomanani Disabled Project	-23.863688	31.073335	Lulekani-A, Phalaborwa, 1392, South Africa
	13	P Driving School (PDS)	-23.858170	31.076416	Stand NO:1863 Oliver thambo Drive, Lulekani, Phalaborwa,South Africa, 1392, South Africa

PLACE	ID	NAME	LATITUDE	LONGITUDE	ADDRESS
	14	Rixile Education Centre	-23.866836	31.083661	373 Bridgeway Street, Lulekani-B, Phalaborwa, 1392, South Africa
	15	Lulekani Primary School.	-23.859282	31.076419	Lulekani-A, Phalaborwa, 1392, South Africa
	16	Nwa Risenga Primary School	-23.862020	31.089670	124 Park St., Lulekani-B, Phalaborwa, 1392, South Africa
	17	Nwasorini Primary School	-23.861973	31.081610	Lulekani-B, Phalaborwa, 1392, South Africa
Zeerust	1	Zeerust Primary School	-25.544970	26.074007	1 Queen Street, Zeerust, 2865, South Africa
	2	Laerskool Zeerust	-25.539000	26.080220	25 Van Riebeeck St., Zeerust, 2865, South Africa
	3	Hoërskool Zeerust	-25.538170	26.081500	40b Jean St., Zeerust, 2865, South Africa
	4	Ikageleng High School	-25.566170	26.099330	90, Ikageleng, Zeerust, 2865, South Africa
	5	Henryville Primary School	-25.554830	26.093330	Zeerust, 2865, South Africa
	6	Sefatlhane Primary School	-25.565051	26.102598	807 Merementsi Street, Ikageleng, Zeerust, 2865, South Africa
	7	Zeerust Combined	-25.541629	26.075031	Zeerust, 2865, South Africa
	8	Mhapha Public School	-25.560830	26.100170	284, Ikageleng, Zeerust, 2865, South Africa
	9	Zeerust Laerskool	-25.545420	26.085960	19 Van Riebeeck Street, Zeerust, 2865, South Africa
	10	Zeerust Primary School	-25.544934	26.073428	1 Queen St., Zeerust, 2865, South Africa
	11	Sesamotho Primary	-25.526400	26.068810	Zeerust, 2865, South Africa
	12	Mosadikago Training	-25.542250	26.075430	27 Hendrik Potgieter St., Zeerust, 2865, South Africa
	13	Zeerust	-25.552345	26.100489	Zeerust, 2865, South Africa
	14	Computer And Careers Accredited Training Centre	-25.526430	26.069000	16 Forsman street, Zeerust, 2865, South Africa
	15	Henryville Primary	-25.568843	26.090038	Hugo St., Zeerust, 2865, South Africa
	16	MT Learning Academy	-25.541926	26.075437	Hendrik Potgieter St., Zeerust, 2865, South Africa
	17	S A INSTITUTE OF COMMERCE AND TECHNOLOGY	-25.544132	26.076750	Zeerust, 2865, South Africa
	18	Mohapha Primary School	-25.560872	26.100237	322 Maruping St., Ikageleng, Zeerust, 2865, South Africa
	19	Mafikeng	-25.558015	26.065700	Zeerust, South Africa
	20	Koos Driving School	-25.545340	26.075724	Voortrekker St., Zeerust, 2865, South Africa
	21	Correctional Services	-25.541837	26.083460	70 Queen St., Zeerust, 2865, South Africa
	22	Ackermans Zeerust	-25.544917	26.079730	Shop 3 Church St., Zeerust, 2865, South Africa
	23	Taletso Tvet College	-25.481667	25.984875	Zeerust, South Africa
	24	Mosadikago Training	-25.542250	26.075430	27 Hendrik Potgieter St., Zeerust, 2865, South Africa
	25	MT Learning Academy	-25.541926	26.075437	Hendrik Potgieter St., Zeerust, 2865, South Africa
Duduza	1	Duduza Primary School	-26.370216	28.410507	Sobende St., Duduza, Brakpan, 1496, South Africa
	2	Sizwesethu Primary School	-26.372311	28.410294	758 Sibeko St., Duduza, Nigel, 1494, South Africa
	3	Edalinceba Primary School	-26.369450	28.403790	1691, Duduza, Nigel, 1494, South Africa
	4	Nimrod Ndebele Secondary School	-26.376574	28.417474	6970 Flamingo St., Duduza, Nigel, 1494, South Africa
	5	Iphahamiseng Primary School	-26.377569	28.407899	Lekobe St., Duduza, Brakpan, 1496, South Africa
	6	Emzimkhulu Primary School	-26.367717	28.407958	442, Duduza, Nigel, 1494, South Africa
	7	Sibonisiwe Primary School	-26.374537	28.399125	5051 Mothalova Street, Duduza, Johannesburg, 1496, South Africa
	8	Dan Radebe Primary School	-26.381983	28.415084	Duduza, Nigel, 1494, South Africa
	9	Esibonelwesihle High School	-26.370547	28.404309	1689 Jacobs St., Duduza, Nigel, 1496, South Africa

PLACE	ID	NAME	LATITUDE	LONGITUDE	ADDRESS
	10	MMUSO Primary School	-26.380655	28.406830	Lopeng St., Duduza, Brakpan, 1496, South Africa
	11	Zakheni Primary School	-26.373880	28.406727	1525 Nzimande St., Duduza, Nigel, 1496, South Africa
	12	Mom Sebone Secondary School	-26.376815	28.397346	5346 Kau St., Duduza, Nigel, 1494, South Africa
	13	Roseview Primary School	-26.366115	28.404376	Cnr Ndululas & Limu Street, Duduza, Brakpan, 1496, South Africa
	14	Dan Radebe Primary School	-26.382058	28.415063	Kaunda St., Duduza, Brakpan, 1496, South Africa
	15	Thakgalang Primary School	-26.377020	28.411010	3131 Pitzi St., Duduza, Nigel, 1494, South Africa
	16	Edalinceba Primary School	-26.369458	28.403798	Ngubane St., Duduza, Brakpan, 1496, South Africa
	17	M. O. M. Seboni	-26.376260	28.397850	4889 Seboku St., Duduza, Nigel, 1494, South Africa
	18	Inkanyezi Yesizwe Preschool & Creche	-26.373471	28.405698	5514 Nzimande St., Duduza, Nigel, 1496, South Africa
	19	Mbusomusha Nursery & Pre – School	-26.382723	28.415810	4706 Kaunda Street, Duduza, Brakpan, 1496, South Africa
	20	Asser Maloka Secondary School	-26.382489	28.388929	Honeysuckle St., Duduza, Nigel, 1494, South Africa
	21	Duduza prototype early childhood development centre	-26.377779	28.414639	3001 Pooa St., Duduza, Nigel, 1494, South Africa
	22	Mastergucci National Youth Builder Program	-26.374770	28.413679	Resource Centre, 97/2 Nala St., Duduza, Nigel, 1494, South Africa
	23	Sasol	-26.386515	28.400999	131327 Flamingo St., Bluegum View, Duduza, 1499, South Africa
	24	Asser maloka	-26.386515	28.400999	1327 Flamingo St., Bluegum View, Duduza, 1499, South Africa
	25	Nimrod Ndebele Secondary School	-26.376574	28.417474	6970 Flamingo St., Duduza, Nigel, 1494, South Africa
	26	Duduza Primary School	-26.370216	28.410507	Sobende St., Duduza, Brakpan, 1496, South Africa
	27	Sizwesethu PrimarySchool	-26.372311	28.410294	758 Sibeko St., Duduza, Nigel, 1494, South Africa
	28	Edalinceba Primary School	-26.369450	28.403790	1691, Duduza, Nigel, 1494, South Africa
	29	Esibonelwesihle High School	-26.370547	28.404309	1689 Jacobs St., Duduza, Nigel, 1496, South Africa
	30	Mom Sebone Secondary School	-26.376815	28.397346	5346 Kau St., Duduza, Nigel, 1494, South Africa
	31	M. O. M. Seboni	-26.376260	28.397850	4889 Seboku St., Duduza, Nigel, 1494, South Africa
	32	Asser Maloka Secondary School	-26.382489	28.388929	Honeysuckle St., Duduza, Nigel, 1494, South Africa
	33	Nimrod Ndebele Secondary School	-26.376574	28.417474	6970 Flamingo St., Duduza, Nigel, 1494, South Africa
Gon'on'o	1	Kayanene Primary School	-23.275420	30.485270	Gonono, South Africa

(b) *Soweto Health Centres.*

ID	NAME	LATITUDE	LONGITUDE	ADDRESS
1	Marie Stopes Soweto	-26,2580316	27,9430743	Black Chain, Chris Hani Rd, Diepkloof, Soweto, Johannesburg, 2001, South Africa
2	St John's Eye Hospital	-26,259729	27,9332043	M68, Diepkloof 319-Iq, Soweto, 1862, South Africa
3	Freedom Park Clinic	-26,2980878	27,9340324	Jan De Necker Dr., Devland, Soweto, 1811, South Africa
4	Tshepisong Clinic	-26,1901185	27,805446	1754 Unnamed Rd Soweto, Tshepisong, Soweto, 1754, South Africa
5	Slovoville Clinic	-26,2165537	27,7793407	Dobsonville, Johannesburg, 1754, South Africa
6	Zola Gateway Clinic	-26,2480799	27,8576756	Jabulani, Soweto, 1868, South Africa

ID	NAME	LATITUDE	LONGITUDE	ADDRESS
7	Zola Clinic	-26,24356	27,8311599	75/1 765 Buthelezi St., Zola, Soweto, 1878, South Africa
8	Top Care Women's Clinic -Dube, Soweto	-26,238713	27,894722	2223 Mncube Street, Office Number 18, Ekhaya Centre, Dube Village, Soweto, 1800, South Africa
9	Chiawelo Community Healthcare Centre	-26,2792381	27,8653272	Crn Chris Hani Road & Rihlampfu Street, Tshiawelo, Soweto, 1818, South Africa
10	Green Village Clinic	-26,2364778	27,804834	Doornkop, Soweto, 1874, South Africa
11	Jabavu Clinic - T.B Unit	-26,2535012	27,8720234	Jabavu Township, 3123 Tumahole Street, Jabavu, Soweto, 1809, South Africa
12	Tladi Clinic	-26,254116	27,842138	Legwale St., Tladi, Johannesburg, 1868, South Africa
13	Zondi Clinic	-26,232936	27,866257	669 Shomayeli St., Zondi, Johannesburg, 1868, South Africa
14	Chiawelo Community Practice	-26,280623	27,8634017	5203 Maluleke St., Chiawelo, Soweto, 1818, South Africa
15	Moroka Clinic	-26,2616789	27,866185	Soweto, Johannesburg, 1860, South Africa
16	Orlando Clinic	-26,236773	27,919026	Rathebe St., Orlando East, Johannesburg, 1804, South Africa
17	Elias Motsoaledi Clinic	-26,223236	27,917401	Carr St., Soweto, Johannesburg, 1803, South Africa
18	Protea Glen Clinic	-26,273118	27,80539	Wild Chestnut St., Protea Glen, Johannesburg, 1818, South Africa
19	Zone 1 Diepkloof Clinic	-26,2407279	27,947439	Immink St., Diepkloof Zone 1, Soweto, 1802, South Africa
20	Itireleng Community Health Centre	-26,2175319	27,870834	Elias Motsoaledi Rd, Soweto, Johannesburg, 1863, South Africa
21	Mandela Sisulu Clinic	-26,23548	27,9067212	Orlando West, Soweto, 1804, South Africa
22	Protea South Clinic	-26,2856133	27,8404756	1818, Protea South, Soweto, South Africa
23	Prime Cure Dube	-26,237016	27,893973	2413 Mncube Dr., Dube, Johannesburg, 1801, South Africa
24	Senaoane Clinic	-26,27376	27,864571	Khamta Road, Senaoane, Johannesburg, 1818, South Africa
25	Klipspruit West Clinic - T.B Unit	-26,289718	27,881365	Cnr Daisy & Calendula Street, Klipspruit West Ext 1, Soweto, 1811, South Africa
26	Lenasia Travel Clinic	-26,32161	27,86012	229 protea avenue, Extension 7, Lenasia, Johannesburg, 1820, South Africa
27	Noordgesig Municipal Clinic	-26,2251787	27,9360444	1 Collin Drive, Noordgesig, Soweto, 1804, South Africa
28	Eldorado Park Ext 8 Clinic	-26,29015	27,89522	21 Ascot Road, Eldoradopark Ext 8, Soweto, 1811, South Africa
29	Eldorado Park Ext 9 T.B Clinic	-26,2806529	27,891854	Boundary Rd, Eldorado Park, Soweto, 1811, South Africa
30	Pimville Clinic	-26,262257	27,907599	Dlebelendlovo, Pimville Zone 1, Soweto, 1809, South Africa
31	Dr. C.K. Amos	-26,245043	27,878403	3142 Mputhi St., W.C.J., Johannesburg, 1800, South Africa
32	Region D clinics	-26,2427189	27,8306576	75/1 765 Buthelezi St., Zola, Soweto, 1878, South Africa
33	Siphumlile Coj Clinic	-26,2222195	27,8329611	2825 Mohajane, Thulani, Soweto, 1863, South Africa
34	Dr. AD Makhubelas	-26,255364	27,839545	Tamane St., Soweto, Johannesburg, 1868, South Africa
35	Surgery & Optometrist	-26,282151	27,85362	Siaga St., Soweto, Johannesburg, 1818, South Africa
36	Dr B A Hussain	-26,2790949	27,890369	Future Rd, Kliptown, Soweto, 1804, South Africa
37	Skin & Body International	-26,321451	27,863734	Khayam Pl, Lenasia, 1827, South Africa
38	S.A.M.S - Lenz Sick Bay	-26,2363219	27,8062304	Area Military House Unit, 10 Trichardt Avenue, Doornkop, Soweto, 1874, South Africa
39	Meadowlands Zone 11 Portacabin Clinic	-26,223747	27,8869926	Vincent St., Meadowlands West Zone 6, Meadowlands West, 1852, South Africa
40	Eldorado Park Ext 2 Clinic	-26,2899329	27,895764	Arlberg, Eldorado Park, Johannesburg, 1811, South Africa
41	Dr. R. V. Taunyane	-26,2783759	27,848597	Tshithuthune St., Soweto, Johannesburg, 1818, South Africa
42	Eldorado Park Clinic Ext 8	-26,2996139	27,909289	1 Heinkel Rd, Eldorado Park, Johannesburg, 1811, South Africa

ID	NAME	LATITUDE	LONGITUDE	ADDRESS
43	Meadowlands Clinic	-26,219679	27,898588	Hekroodt Cir, Meadowlands, Johannesburg, 1852, South Africa
44	Phenyo's SPATHERAPY &WELLNESSCAFE'	-26,210815	27,884612	2023a, Soweto, Forbes Rd, Meadowlands West Zone 9, Meadowlands West, 1852, South Africa
45	Dr. Latib's Acupuncture and Chinese Medicine Clinic	-26,3184001	27,8440858	11 Mandrill St., Lenasia, 1827, South Africa
46	Lenasia Community Health Centre (Hospital)	-26,3138599	27,8508	Cosmos Street, Lenasia, 1821, South Africa
47	Dr. M.T.D Qobose	-26,245051	27,874495	3939 Mailula St., Jabavu Ext 1, Johannesburg, 1710, South Africa
48	Ringane & Associates Inc	-26,238439	27,8943723	Stand 24/3 Cnr Mahalefele Road &, Mncube Dr., Dube, Soweto, 1801, South Africa
49	Opti Eyewear Optometrist	-26,258849	27,938886	Baragwanath Medical Center, 8103 A Zone 6, Diepkloof, 1862, South Africa
50	Protea Medical Centre	-26,3216485	27,8602512	229 Protea Avenue, Extension 7, Lenasia, Johannesburg, 1820, South Africa
51	Medical Centre	-26,245019	27,879129	Mphuthi St., Soweto, Johannnesburg, 1864, South Africa
52	ZAN Gardens	-26,2645544	27,8776584	01696 Njengele St., Moroka, Soweto, 1818, South Africa
53	Diepkloof Clinic	-26,238733	27,954018	7648 Red Show Drive, Diepkloof Zone 3, Diepkloof, 1862, South Africa
54	Dr. B K C Sithole	-26,268131	27,904478	26B Modjaji St., Pimville, Johannesburg, 1809, South Africa
55	Kliptown Medical & Dental Centre	-26,2790949	27,890369	9 Union Ave, Kliptown, Soweto, 1812, South Africa
56	Slovoville clinic	-26,2157566	27,7795922	Slovoville, Soweto, 1754, South Africa
57	Dr. Haroon Essa	-26,258795	27,9422	Black Chain Centre, Opposite To Baragwanath Hospital, Chris Hani Rd, Diepkloof Zone 6, Johannesburg, 2001, South Africa
58	Lillian Ngoyi Community Health Centre	-26,259999	27,933137	Chris Hani Rd, Diepkloof, Johannesburg, 1862, South Africa
59	Soweto Community Health Centre	-26,2793182	27,8651083	1753 Rihlamvu Street, Chiawelo, Soweto, 1818, South Africa
60	The Roots Health Centre	-26,259674	27,945869	09, Ivan Khoza, Chris Hani Rd, Diepkloof, Johannesburg, 1864, South Africa
61	Quali Health Braamfischer	-26,1978303	27,8557599	Ubunye Dr., Bram Fischerville, Soweto, 1875, South Africa
62	U-Care Medical Centre	-26,2093401	27,8803406	1959, Pimville Zone 9, Meadowlands, Soweto, 1852, South Africa
63	Baragwanath Medical Centre	-26,2587139	27,938152	8103, Bara Mall, Bara Road, Diepkloof, Johannesburg, 1860, South Africa
64	Mofolo Community Health Centre	-26,2474981	27,8840042	Mofolo Central, Soweto, 1801, South Africa
65	Ekhaya Lethu Medical Centre	-26,2304149	27,874988	Koma St., Mofolo, Johannesburg, 1801, South Africa
66	Eldorado Park Medical Centre	-26,2955816	27,9140835	88 Kremetart Ave, Eldorado Park, Soweto, 1811, South Africa
67	CWJ Medical Center	-26,245209	27,868918	Mputhi St., Mofolo Central, Johannesburg, 1864, South Africa
68	Yebohealth Medical Centre	-26,2152783	27,8902091	25510 Vincent St., Meadowlands West Zone 6, Meadowlands West, 1852, South Africa
69	HEALTH CENTRE	-26,3013426	27,8969071	9 Lood St., Eldorado Park, Soweto, 1811, South Africa
70	Medical & Dental Centre	-26,2916399	27,907236	Sirkel Rd, Eldorado Park, Johannesburg, 1811, South Africa
71	My Clinic	-26,283216	27,854739	Chris Hani Rd, Chiawelo, Soweto, 1818, South Africa
72	Dobsonville Medical & Dental Surgery's	-26,2118834	27,8692651	Shop No. 65F, Dobsonville Shopping Centre, Dobsonville Road, Dobsonville, Johannesburg, 1865, South Africa
73	FLEURHOF GOOD HEALTH CENTRE POINT	-26,2001136	27,9130197	WINZE DRIVE, FLEURHOF, Johannesburg, 1709, South Africa
74	Iso Lempilo Health Organization	-26,23778	27,85493	1062 Dlangamandla St., Jabulani, Soweto, 1868, South Africa
75	Vilakazi Healthcare	-26,2381665	27,9020449	7006 Vilakazi St., Orlando West, Soweto, 1804, South Africa
76	Ubuntu HealthCare Clinic	-26,261156	27,9064234	Pimville Zone 1, Pimville, 1809, South Africa

ID	NAME	LATITUDE	LONGITUDE	ADDRESS
77	Tladi Community Health Centre	-26,2548285	27,8493938	Legwale St., Moletsane, Soweto, 1868, South Africa
78	First Care Medical Centre	-26,2637879	27,914987	Modjaji St., Pimville, Johannesburg, 1809, South Africa
79	Glencare Specialist Medical Centre	-26,273511	27,804885	Wild Chestnut St., Protea Glen, Johannesburg, 1818, South Africa
80	Soweto Community Health Centre Pharmacy	-26,2445999	27,82924	780 Obed St., Emdeni South, Soweto, 1861, South Africa
81	Lilian Ngoyi Community Clinic - Medical	-26,2598924	27,9432853	Lilian Ngoyi Community Clinic, Old Potchefstroom Road, Diepkloof Zone 6, Diepkloof, 1862, South Africa
82	Chris Hani Baragwanath Academic Hospital	-26,261231	27,9426395	26 Chris Hani Rd, Diepkloof 319-Iq, Johannesburg, 1864, South Africa
83	Bheki Mlangeni District Hospital	-26,2476789	27,856765	2190, Bolani Rd, Jabulani, Johannesburg, 1868, South Africa
84	Tshepo Themba Private Hospital	-26,2054766	27,8745175	Dobsonville, Soweto, 1863, South Africa
85	Dr. SK Matseke Memorial Hospital	-26,258438	27,9356306	Cnr Immink Drive and, Chris Hani Rd, Diepkloof Zone 6, Diepkloof, 1862, South Africa
86	Chris Hani Baragwanath Hospital - Oncology	-26,266316	27,9479004	Chris Hani Baragwanath Hospital, Chris Hani Road, Diepkloof, 1862, South Africa
87	Total Care Medical Center	-26,25247	27,8852339	350 Elias Motsoaledi Rd, Mofolo South, Johannesburg, 1860, South Africa
88	Dr. Shingange Medical Centre	-26,267722	27,828608	1538 Letsatsi St., Protea North, Johannesburg, 1818, South Africa
89	Advanced Soweto Day Hospital	-26,282958	27,8142533	14475 Isixyxabesha Street Extension 6, Protea Glen, Soweto, 1819, South Africa
90	Dr. TC NGWENYA MEDICAL AND DENTAL CENTRE	-26,2393838	27,9126016	kumalo and, Armitage St., Orlando West, 1804, South Africa
91	Hlophe T	-26,2618304	27,8680149	Kayvee Shopping Centre, 3487 Vundla St., Rockville, Soweto, 1818, South Africa
92	Dr. Michisi S Mbatsana	-26,24294	27,94848	15997 Eben Cuyler Dr., Diepkloof Zone 3, Diepkloof, 1862, South Africa
93	Qengeba Medical Center	-26,2629339	27,911064	11772 Mtangai St., Pimville Zone 1, Johannesburg, 1809, South Africa
94	Medical Surgery	-26,280015	27,822752	Wild Chestnut St., Protea Glen, Johannesburg, 1818, South Africa
95	Drs. Moosajee & Partner	-26,3221509	27,835635	Ext.2, 135 Rose Ave, Lenasia, Johannesburg, 1820, South Africa
96	Dr. D Ngwenya Medical Practice	-26,2073657	27,8878452	479 Maseru Rd, Meadowlands West Zone 7, Soweto, 1852, South Africa
97	Aeroton Medical Centre	-26,25068	27,97193	Shop no 7 at Shell Garage Aeroton, 64 Aerodrome Road, Aeroton, Johannesburg, 2091, South Africa
98	Dr. M.A. Muhammad Medical Practice	-26,2908039	27,8799167	9 Fuschia Rd, Klipspruit West, Johannesburg, 1811, South Africa
99	Goldman Medical Centre	-26,17598	27,92457	109 Goldman St., Florida, Roodepoort, 1709, South Africa
100	Sonar X-Ray	-26,2700089	27,813999	1884 Wild Chestnut St., Protea Glen, Johannesburg, 1819, South Africa
101	Surgery	-26,289682	27,850327	Midway St., Midway, Soweto, 1864, South Africa
102	Life Esidimeni	-26,2006449	27,934992	91 Leader Ave, Robertsville, Johannesburg, 1709, South Africa
103	Catnap Day Care Centre	-26,2441392	27,858001	44 1, Extension, Meadowlands West Zone 10, Soweto, 1868, South Africa
104	Meadowlands Welfare Centre	-26,206778	27,879924	Maseru Rd, Meadowlands, Soweto, 1855, South Africa
105	U-care Walk In Clinic	-26,225791	27,9302943	1959 Soweto Hwy, Orlando East, Meadowlands East, 1804, South Africa
106	LechekoMindPower	-26,2517112	27,8499338	315 Moliwa St., Moletsane, Soweto, 1868, South Africa
107	T & D Medical Health Services	-26,216667	27,866667	3222 Nonhlanhla, Dobsonville, Soweto, 1863, South Africa
108	UPD	-26,190302	27,911574	14 Tamar Ave, Lea Glen, Johannesburg, 1709, South Africa
109	Ebom Consultancy	-26,2428336	27,8819902	01254 Matete St, Mofolo Central, Johannesburg, 1801, South Africa
110	Roman H A and Partners T/a Fresenius Medical Care - Soweto Kidney and Dialysis Centre	-26,2582199	27,93601	Clinix Lesedi Private Hospital, 23967 Chris Hani Road, Diepkloof Zone 6, Diepkloof, 1862, South Africa

ID	NAME	LATITUDE	LONGITUDE	ADDRESS
111	Roodepoort Healthcare Risk Waste Facility	-26,1868972	27,8925591	Rand Leases, Randburg, South Africa
112	Verimark	-26,2791713	27,8628352	1868 Chris Hani Rd, Senaoane, Soweto, 1868, South Africa
113	Clinix Health Group	-26,2055599	27,874453	Rorl, Meadowlands, Johannesburg, 1852, South Africa
114	Kinky world of hair	-26,2582439	27,902267	Maponya Mall, 118 Chris Hani Rd, Soweto, Johannesburg, 1809, South Africa
115	Soweto Independent Living Center	-26,24426	27,88641	Mzilikatse St., Mofolo South, Johannesburg, 1801, South Africa
116	The South African Healthcare Foundation	-26,2471639	28,008324	Robertsham Medical & Dental House, 82 Anson St., Robertsham, Johannesburg, 2175, South Africa
117	OMOLEMO HEALTHCARE PRIVATE CLINIC	-26,1726199	27,91156	28GOLDMAN STREET FLORIDA FLORIDA, Florida, 1709, South Africa
118	Unique Health	-26,150584	27,919778	3rd Floor Mayo Clinic, 7 William Nicol Drive, Constantia Kloof, 1710, South Africa
119	Dr. F. E. Geldenhuys Surgery	-26,2777329	27,838494	35 Ndaba St., Protea Glen, Soweto, 1818, South Africa
120	Naledi Surgery	-26,2535972	27,831502	676 Bona St., Naledi, Soweto, 1861, South Africa
121	Dr TT Muthambi - General Surgeon	-26,2828885	27,8140895	Unnamed Road, Protea Glen, Soweto, 1819, South Africa
122	Dr. A I Jada	-26,2769286	27,8907158	13, Klipspruit Valley Rd, Klipspruit, Soweto, 1809, South Africa
123	Dr. SF Mthembu	-26,258615	27,936672	18, Lesedi Private Hospital, Chris Hani Rd, Soweto, Johannesburg, 1864, South Africa
124	Dr. PR Makaulule - Ear,Nose & Throat	-26,2839193	27,8182448	14475 Isixaxabesha St., Protea Glen, Soweto, 1818, South Africa
125	Dr. L. Mokatedi	-26,274638	27,833427	2945 Botile St., Protea North, Johannesburg, 1818, South Africa
126	Dr. EA Mjuza	-26,2586279	27,936825	Chris Hani Rd, Diepkloof, Johannesburg, 1864, South Africa
127	Dr. Wisani Chauke	-26,2857339	27,849991	Alekhine St., Chiawelo, Johannesburg, 1818, South Africa
128	Moloi Surgery	-26,251171	27,884132	Cross Roads Shopping Center, Phera St., Jabavu, Johannesburg, 1809, South Africa
129	Surgery - Dr. A.N Mmusi	-26,2424289	27,944606	Luaname St., Diepkloof Zone 1, Johannesburg, 1862, South Africa
130	S And S Orthopedic Services	-26,2586409	27,936757	Room 31, Zone 6, Nembula House, Diepkloof, 1864, South Africa
131	Protea Glen Ext 31 Surgery and Accomodation	-26,2765013	27,7843374	17 Umzimkhulu St., Protea Glen, Soweto, 1819, South Africa
132	Dr. NS Mogodi	-26,255443	27,822384	1460 Tshetlo St., Naledi, Johannesburg, 1818, South Africa
133	Dr. M.S. Molefe	-26,2724929	27,861125	Mabalane St., Soweto, Johannesburg, 1818, South Africa
134	Surgery Medicare Centre	-26,2541699	27,854315	Mokwena St., Moletsane, Johannesburg, 1868, South Africa
135	Dr. B.L. Khulu	-26,258615	27,936672	Suite 18, Nembula House, Diepkloof Zone 6, Diepkloof, 1862, South Africa
136	TM Mkhize Dental Surgery	-26,2229162	27,8704822	No. 3 Jabulani St., Dobsonville, Soweto, 1863, South Africa
137	Dr. Mosidi G. Sehume	-26,2586409	27,936757	Lesedi Private Hospital, 30 Nembula House, Diepkloof, Johannesburg, 1862, South Africa
138	Dube Dental Surgery	-26,2376559	27,895021	Mahalefele Rd, Dube, Johannesburg, 1801, South Africa
139	Dr. Charles N. Mujakachi	-26,258308	27,936961	Diepkloof Zone 6, Johannesburg, 1864, South Africa
140	Surgery Dr. Thlabi	-26,2411348	27,9553263	18594 Rustenburg St., Diepkloof Zone 4, Diepkloof, 1862, South Africa
141	Dr. T. E. Ndzeru	-26,258637	27,936741	33, Nembula House, Chris Hani Rd, Diepkloof, Johannesburg, 1862, South Africa
142	Dr. .M. Isabelle	-26,230193	27,837764	Shop 20, Dobsonville Point, Mohajane, Dobsonville, Johannesburg, 1415, South Africa
143	Dr Avhashoni T Mavhungu	-26,2829419	27,854064	4367, Tshiawelo Ext 2, Johannesburg, 1818, South Africa
144	Mkhawana C T	-26,28585	27,84081	Protea South, Soweto, 1818, South Africa
145	Dr. P.S Mabela	-26,202215	27,867528	Amandla Drive, Bram Fischerville, Johannesburg, 1724, South Africa

ID	NAME	LATITUDE	LONGITUDE	ADDRESS
146	Rammutla	-26,2744319	27,7685787	Protea Glen Extension 28, Soweto, 1834, South Africa
147	Dr. T Phefo	-26,271549	27,856044	875 Mabalane St., Phiri, Johannesburg, 1818, South Africa
148	Dr. S Ismail	-26,2410444	27,8617492	540 Dlamini St., Jabulani, Soweto, 1868, South Africa
149	Dr.V.S. Nhlapo Inc.	-26,2697499	27,814535	Glen Health Corner, Opp. BP Garage, Protea Glen, Johannesburg, 8434, South Africa
150	Nkuna L E	-26,2299057	27,900254	Zone 5, 20008 Ndlovu Road, Meadowlands, Roodepoort, 1852, South Africa
151	Dr. Ismail Mia	-26,283441	27,904663	Crystal Place, 6517 George Elliot Ave, Eldorado Park Ext 6, Johannesburg, 1813, South Africa
152	Dr. T.M. Tshabalala	-26,280015	27,822752	Wild Chestnut St., Protea Glen, Johannesburg, 1818, South Africa
153	DR MS MUSHADU	-26,222509	27,900186	Ndofaya Mall Medical Centre, Opposite Meadowlands Police Station), Hekroodt St., Meadowlands, Johannesburg, South Africa
154	Dr. E Nanabhai	-26,2834495	27,8708164	1339 Tshiovhe St., Chiawelo, Soweto, 1817, South Africa
155	Dr. K. Mosalakae	-26,23698	27,929016	1501 B Sofasonke St. & Opp. Baza- Baza Roadhouse, Orlando East, Johannesburg, 1804, South Africa
156	Dr K.M Bopalamo	-26,272278	27,832703	Protea North Family Practise, 2560 Ndaba St., Soweto, Johannnesburg, 1818, South Africa
157	Dr. TC Moloto	-26,211051	27,868967	75, Dobsonville Shopping Centre, Elias Motsoaledi Rd, Soweto, 1863, South Africa
158	Dr. M Machaka	-26,2829189	27,8142108	14475 Isixaxabesha St., Protea Glen, Soweto, 1818, South Africa
159	Dr. David E. Mashigo	-26,2310339	27,839396	10739 Monametsi St., Dobsonville, Soweto, 1863, South Africa
160	Dr. BM Hlatshwayo	-26,257023	27,943011	Toby's Centre, 8122 Patrick Street, Opp. Blackchain Bara, Zone 6, Soweto, Johannesburg, 1864, South Africa
161	Orthopaedic Suppliers	-26,1675115	27,9311269	7 Penelope Ave, Florida North, Johannesburg, 1709, South Africa

BIBLIOGRAPHY

5G-PPP. (2017, December). View on 5G Architecture. *White Paper*. Retrieved August 5, 2019, from 5GPPP: https://5g-ppp.eu/wp-content/uploads/2018/01/5G-PPP-5G-Architecture-White-Paper-Jan-2018-v2.0.pdf

Aamer, B., Chergui, H., Chergui, N., Tourki, K., Benjillali, M., Verikoukis, C., & Debbah, M. (2019). Self-Tuning Spectral Clustering for Adaptive Tracking Areas Design in 5G Ultra-Dense Networks. *arXiv preprint arXiv:1902.01342*.

Abbeel, P., Ganapathi, V., & Ng, A. Y. (2006). Learning vehicular dynamics, with application to modeling helicopters. *Advances in Neural Information Processing Systems , 18*, 1.

AboBakr, A., & Azer, M. A. (2017). IoT ethics challenges and legal issues. *2017 12th International Conference on Computer Engineering and Systems (ICCES)*, (pp. 233-237).

Adam, H. (2019, June 25). *Internal Rate of Return*. Retrieved February 27, 2020, from Investopedia: https://www.investopedia.com/terms/i/irr.asp

Adrianfrith. (2011). *Soweto*. Retrieved February 17, 2020, from Census 2011: https://census2011.adrianfrith.com/place/798026

African Drone. (2018). *South Africa*. Retrieved February 17, 2020, from https://africandrone.org/south-africa

Al-Hourani, A., Kandeepan, S., & Lardner, S. (2014). Optimal LAP altitude for maximum coverage. *IEEE Wireless Communications Letters, 3*, 569-572.

Alliance, N. G. (2015). 5G white paper. *Next generation mobile networks, white paper, 1*.

Al-Namari, M. A., Mansoor, A. M., & Idris, M. Y. (2017). A brief survey on 5G wireless mobile network. *Int. J. Adv. Comput. Sci. Appl., 8*, 52-59.

Alzenad, M., El-Keyi, A., Lagum, F., & Yanikomeroglu, H. (2017). 3-D placement of an unmanned aerial vehicle base station (UAV-BS) for energy-efficient maximal coverage. *IEEE Wireless Communications Letters, 6*, 434–437.

Alzenad, M., El-Keyi, A., Lagum, F., & Yanikomeroglu, H. (2017, 5 3). 3D Placement of an Unmanned Aerial Vehicle Base Station (UAV-BS) for Energy-Efficient Maximal Coverage. *IEEE Wireless Communications Letters*(99).

Alzenad, M., Shakir, M. Z., Yanikomeroglu, H., & Alouini, M.-S. (2018). FSO-based vertical backhaul/fronthaul framework for 5G+ wireless networks. *IEEE Communications Magazine, 56*, 218–224.

Amanda, L., Rich, L., Scott, C., & Kristen, P. (2010, April 10). *Teens and Mobile Phones*. Retrieved February 17, 2020, from Pew Research Center: https://www.pewresearch.org/internet/2010/04/20/teens-and-mobile-phones/

Andersson, O., Wzorek, M., & Doherty, P. (2017). Deep Learning Quadcopter Control via Risk-Aware Active Learning. *AAAI*, (pp. 3812-3818).

Andy, W. (2019, February 26). *Rain, Huawei launch South Africa's 'first commercial 5G network'*. Retrieved January 19, 2020, from Memeburn: https://memeburn.com/2019/02/rain-5g-network-south-africa/

Asadi, A., & Mancuso, V. (2016). Network-assisted outband D2D-clustering in 5G cellular networks: theory and practice. *IEEE Transactions on Mobile Computing, 16*, 2246–2259.

Ateya, A. A., Muthanna, A., Makolkina, M., & Koucheryavy, A. (2018). Study of 5G services standardization: specifications and requirements. *2018 10th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, (pp. 1–6).

Attiah, M. L., Md Isa, A. A., Zakaria, Z., Abdulhameed, M. K., Mohsen, M. K., & Dinar, A. M. (2019). Hybrid multi-independent mmWave MNOs assessment utilising spectrum sharing paradigm for 5G networks. *Telkomnika, 17*.

Au, E. (2018, 3). Spectrum Licensing [Standards]. *IEEE Vehicular Technology Magazine, 13*, 19-20. doi:10.1109/MVT.2017.2783701

Azade, F., Ming, D., & Mahbub, H. (2017, April 5). Dynamic Base Station Repositioning to Improve Spectral Efficiency of Drone Small Cells. *Information Theory*.

Azharuddin, M., Kuila, P., & Jana, P. K. (2015). Energy efficient fault tolerant clustering and routing algorithms for wireless sensor networks. *Computers & Electrical Engineering, 41*, 177–190.

Bae, J., Choi, Y. S., Kim, J. S., & Chung, M. Y. (2014, 10). Architecture and performance evaluation of MmWave based 5G mobile communication system. *2014 International Conference on Information and Communication Technology Convergence (ICTC)*, (pp. 847-851). doi:10.1109/ICTC.2014.6983310

Bagula, A., Abidoye, A., & Zodi, G.-A. (2016). Service-aware clustering: An energy-efficient model for the internet-of-things. *Sensors, 16*, 9.

Bandyopadhyay, S., & Coyle, E. (2003). An energy efficient hierarchical clustering algorithm for wireless sensor networks. *INFOCOM 2003. Twenty-Second Annual Joint Conference of the IEEE Computer and Communications., 00*, 1713-1723. doi:10.1109/INFCOM.2003.1209194

Basta, A., Blenk, A., Hoffmann, K., Morper, H. J., Hoffmann, M., & Kellerer, W. (2017). Towards a cost optimal design for a 5G mobile core network based on SDN and NFV. *IEEE Transactions on Network and Service Management, 14*, 1061-1075.

Bill, S. (2016, September 8). *5G could require cell towers on every street corner*. Retrieved February 27, 2020, from CONSUMER TECH RADAR: https://www.cio.com/article/3117705/5g-could-require-cell-towers-on-every-street-corner.html

Bleiberg, J., & West, D. M. (2014, December 10). *Barriers to Universal Internet Access*. (Brookings) Retrieved August 5, 2019, from Techtank: https://www.brookings.edu/blog/techtank/2014/12/10/barriers-to-universal-internet-access/

Bleicher, A. (2018, 1). 5G goes for the gold. *IEEE Spectrum, 55*, 32-33. doi:10.1109/MSPEC.2018.8241730

BMIT. (2019). *Public and Commercial Wi-Fi in South Africa 2019*. Retrieved January 19, 2020, from http://www.bmit.africa/2017/11/15/public-and-commercial-wi-fi-in-south-africa/

Boccardi, F., Heath Jr, R. W., Lozano, A., Marzetta, T. L., & Popovski, P. (2013). Five disruptive technology directions for 5G. *arXiv preprint arXiv:1312.0229*.

Boccardi, F., Heath, R. W., Lozano, A., Marzetta, T. L., & Popovski, P. (2014). Five disruptive technology directions for 5G. *IEEE communications magazine, 52*, 74–80.

Bor-Yaliniz, I., & Yanikomeroglu, H. (2016). The new frontier in RAN heterogeneity: Multi-tier drone-cells. *IEEE Communications Magazine, 54*, 48-55.

Bosworth, G., & Venhorst, V. (2018). Economic linkages between urban and rural regions–what's in it for the rural? *Regional Studies, 52*, 1075–1085.

Bouras, C., Ntarzanos, P., & Papazois, A. (2016). Cost modeling for SDN/NFV based mobile 5G networks. *2016 8th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*, (pp. 56–61).

Business Tech. (2019, May 28). *Mobile market share 2019: Vodacom vs MTN vs Cell C vs Telkom*. Retrieved February 16, 2020, from Business Tech: https://businesstech.co.za/news/mobile/319378/mobile-market-share-2019-vodacom-vs-mtn-vs-cell-c-vs-telkom/

Buzzi, S., & D'Andrea, C. (2017). Massive MIMO 5G Cellular Networks: mm-wave vs. μ-wave Frequencies.

Chandramouli, D., Liebhart, R., & Pirskanen, J. (2019). Wireless Spectrum for 5G. In *5G for the Connected World* (pp. 35-50). Wiley. doi:10.1002/9781119247111.ch2

Chandrasekharan, S., Kandeepan, S., Evans, R. J., Munari, A., Hermenier, R., Marchitti, M. A., & Gomez, K. (2013). Clustering approach for aerial base-station access with terrestrial cooperation. *2013 IEEE Globecom Workshops, GC Wkshps 2013*, 1397-1402. doi:10.1109/GLOCOMW.2013.6825190

Chen, G., Nocetti, F. G., Gonzalez, J. S., & Stojmenovic, I. (2002). Connectivity based k-hop clustering in wireless networks. *System Sciences, 2002. HICSS. Proceedings of the 35th Annual Hawaii International Conference on*, (pp. 2450-2459).

Chen, J. (2019, May 8). *Business to Business (B2B)*. Retrieved January 28, 2020, from Investopedia: https://www.investopedia.com/terms/b/btob.asp

Cheng, N., Xu, W., Shi, W., Zhou, Y., Lu, N., Zhou, H., & Shen, X. (2018). Air-ground integrated mobile edge networks: Architecture, challenges, and opportunities. *IEEE Communications Magazine, 56*, 26–32.

Chetty, M., Sundaresan, S., Muckaden, S., Feamster, N., & Calandro, E. (2013). Measuring broadband performance in South Africa. *Proceedings of the 4th Annual Symposium on Computing for Development*, (p. 1).

Chiaraviglio, L., Amorosi, L., Blefari-Melazzi, N., Dell'Olmo, P., Natalino, C., & Monti, P. (2018). Optimal design of 5g networks in rural zones with uavs, optical rings, solar panels and batteries. *2018 20th international conference on transparent optical networks (icton)*, (pp. 1–4).

Chiaraviglio, L., Blefari-Melazzi, N., Liu, W., Gutierrez, J. A., Van De Beek, J., Birke, R., . . . others. (2016). 5G in rural and low-income areas: Are we ready? *2016 ITU Kaleidoscope: ICTs for a Sustainable World (ITU WT)*, (pp. 1–8).

Chiaraviglio, L., Blefari-Melazzi, N., Liu, W., Gutiérrez, J. A., van de Beek, J., Birke, R., . . . others. (2017). Bringing 5G into rural and low-income areas: Is it feasible? *IEEE Communications Standards Magazine, 1*, 50–57.

Chiaraviglio, L., Liu, W., Gutierrez, J. A., & Blefari-Melazzi, N. (2017). Optimal pricing strategy for 5g in rural areas with unmanned aerial vehicles and large cells. *2017 27th International Telecommunication Networks and Applications Conference (ITNAC)*, (pp. 1–7).

Chiaraviglio, L., Liu, W., Gutierrez, J. A., Chiaraviglio, L., Liu, W., Gutierrez, J. A., & Blefari-melazzi, N. (2017). Optimal Pricing Strategy for 5G in Rural Areas with Unmanned Aerial Vehicles and Large Cells Optimal Pricing Strategy for 5G in Rural Areas with Unmanned Aerial Vehicles and Large Cells. doi:10.1109/ATNAC.2017.8215406

Choudhary, G., & Sharma, V. (2019). A Survey on the Security and the Evolution of Osmotic and Catalytic Computing for 5G Networks. In *5G Enabled Secure Wireless Networks* (pp. 69–102). Springer.

CISCO. (2019). *What Is SD-WAN?* Retrieved February 27, 2020, from https://www.cisco.com/c/en/us/solutions/enterprise-networks/sd-wan/what-is-sd-wan.html

Clement, J. (2019, February 19). *Digital population in South Africa as of January 2019*. Retrieved February 17, 2020, from Statista: https://www.statista.com/statistics/685134/south-africa-digital-population/#statisticContainer

Coates, A., Abbeel, P., & Ng, A. Y. (2008). Learning for control from multiple demonstrations. In *Proceedings of the 25th international conference on Machine learning* (pp. 144-151). Helsinki, Finland: ACM.

Cosmas, J., Jawad, N., Salih, M., Redana, S., & Bulakci, O. (2019). 5G PPP Architecture Working Group View on 5G Architecture.

Costa-Requena, J., Santos, J. L., Guasch, V. F., Ahokas, K., Premsankar, G., Luukkainen, S., . . . others. (2015). SDN and NFV integration in generalized mobile network architecture. *2015 European conference on networks and communications (EuCNC)*, (pp. 154–158).

Dame, W. H. (2016, June 21). *The future of the Internet is at risk say global web expert*. (University of Southampton) Retrieved January 19, 2020, from http://www.ecs.soton.ac.uk/news/4890

de Villiers, J. (2019, May 06). *Tech*. (Business Insider SA) Retrieved June 6, 2019, from Business Insider SA : https://www.businessinsider.co.za/south-africa-5g-rollout-when-telkom-cell-c-vodacom-mtn-rain-2019-4

Dealna. (2019). *DSLAM and MSAN*. Retrieved February 27, 2020, from https://dealna.com/en/article/post/4404/DSLAM-and-MSAN

Dignan, L. (2016, September 6). *Qualcomm, AT&T to test how drones can use 4G LTE networks*. Retrieved January 23, 2020, from ZDNet: https://www.zdnet.com/article/qualcomm-at-t-to-test-how-drones-can-use-4g-lte-networks/

Eckart, Z. (2018, February 9). *OPINION: The big promise of 5G networks*. Retrieved January 9, 2020, from IOBL usiness Report: https://www.iol.co.za/business-report/technology/opinion-the-big-promise-of-5g-networks-13191795

Eder, T. (2017). Nokia Saving Lives Project Wins the UAE Drones for Good Award 2017 [Humanitarian Technology]. *IEEE Robotics & Automation Magazine, 24*, 91-92.

Elhabyan, R. S., & Yagoub, M. C. (2015). Two-tier particle swarm optimization protocol for clustering and routing in wireless sensor network. *Journal of Network and Computer Applications, 52*, 116-128. doi:10.1016/j.jnca.2015.02.004

Elham, K., Halim, Y., & Abbas, Y. (n.d.). On the Number and 3D Placement of Drone Base Stations in Wireless Cellular Network.

Elham, K., Muhammad, Z. S., Halim, Y., & Abbas, Y. (2017, March 17). Backhaul-aware Robust 3D Drone Placement in 5G+ Wireless Networks.

Ericsson. (2016, August 12). *Ericsson and China Mobile conduct world's first 5G drone prototype field trial*. Retrieved January 23, 2020, from https://www.ericsson.com/en/news/2016/8/ericsson-and-china-mobile-conduct-worlds-first-5g-drone-prototype-field-trial-

Ericsson. (2019, October 2019). *Ericsson at GITEX 2019: 5G is driving innovation in the Middle East & Africa*. Retrieved January 23, 20202, from https://www.ericsson.com/en/press-releases/5/2019/ericsson-at-gitex-2019-5g-is-driving-innovation-in-the-middle-east--africa

Ericsson. (2020). *Internet of Things forecast*. Retrieved February 17, 2020, from Ericson: https://www.ericsson.com/en/mobility-report/internet-of-things-forecast

Erik, D., Stefan, P., & Johan, S. (2014). Chapter 20 - Final Thoughts. In *4G LTE/LTE-Advanced for Mobile Broadband* (pp. 473-484). Waltham: Academic Press. doi:https://doi.org/10.1016/B978-0-12-385489-6.00020-5

Ezreik, A., & Gheryani, A. (2012). Design and simulation of wireless network using NS-2. *Proceedings of 2nd International Conference on Computer Science and Information Technology (ICCSIT'12)*, (pp. 28–29).

Farias, F. S., Monti, P., Västberg, A., Nilson, M., Costa, J. C., & Wosinska, L. (2013). Green backhauling for heterogeneous mobile access networks: What are the challenges? *2013 9th International Conference on Information, Communications & Signal Processing*, (pp. 1–5).

Feijóo, C., Gómez-Barroso, J.-L., & Ramos, S. (2011). An analysis of next generation access networks deployment in rural areas. *2011 50th FITCE Congress-" ICT: Bridging an Ever Shifting Digital Divide"*, (pp. 1–18).

Feng, Q., McGeehan, J., Tameh, E. K., & Nix, A. R. (2006). Path loss models for air-to-ground radio channels in urban environments. *2006 IEEE 63rd Vehicular Technology Conference*, *6*, pp. 2901-2905.

Ferrus, R., Sallent, O., Perez-Romero, J., & Agusti, R. (2018). On 5G radio access network slicing: Radio interface protocol features and configuration. *IEEE Communications Magazine, 56*, 184–192.

Ferry, G., Alexandre, M., Halldor, S., & Nemanja, V. (2018, February). *Network sharing and 5G: A turning point for lone riders*. Retrieved January 20, 2020, from Mckinsey: https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/network-sharing-and-5g-a-turning-point-for-lone-riders

Foukas, X., Patounas, G., Elmokashfi, A., & Marina, M. K. (2017). Network slicing in 5G: Survey and challenges. *IEEE Communications Magazine, 55*, 94–100.

Gandhi, D. (2019, April 12). *Figure of the week: Gap in universal mobile phone and internet access in Afric*. (Brookings) Retrieved August 5, 2019, from Africa in Focus: https://www.brookings.edu/blog/africa-in-focus/2019/04/12/figure-of-the-week-gap-in-universal-mobile-phone-and-internet-access-in-africa/

Giles, T., Markendahl, J., Zander, J., Zetterberg, P., Karlsson, P., Malmgren, G., & Nilsson, J. (2004, 5). Cost drivers and deployment scenarios for future broadband wireless networks - key research problems and directions for research. *2004 IEEE 59th Vehicular Technology Conference. VTC 2004-Spring (IEEE Cat. No.04CH37514)*, *4*, pp. 2042-2046 Vol.4. doi:10.1109/VETECS.2004.1390633

Gonçalves, L. C., Sebastião, P., Souto, N., & Correia, A. (2019). Extending 5G Capacity Planning Through Advanced

Subscriber Behavior-Centric Clustering. *Electronics, 8*, 1385.

Grijpink, F., Ménard, A., Sigurdsson, H., & Vucevic, N. (2018, February). *Network sharing and 5G: A turning point for lone riders*. Retrieved April 13, 2019, from McKinsey & Company: https://www.mckinsey.com/industries/telecommunications/our-insights/network-sharing-and-5g-a-turning-point-for-lone-riders

Gruber, C. G. (2009, 3). CAPEX and OPEX in Aggregation and Core Networks. *2009 Conference on Optical Fiber Communication - incudes post deadline papers*, (pp. 1-3). doi:10.1364/OFC.2009.OThQ1

Gu, Y., Wu, Q., & Rao, N. S. (2010). Optimizing cluster heads for energy efficiency in large-scale heterogeneous wireless sensor networks. *International Journal of Distributed Sensor Networks, 6*, 961591.

Gu, Z., Zhang, J., Ji, Y., Bai, L., & Sun, X. (2018). Network Topology Reconfiguration for FSO-Based Fronthaul/Backhaul in 5G+ Wireless Networks. *IEEE Access, 6*, 69426-69437.

Gummalla, A. C., & Limb, J. O. (2000). Wireless medium access control protocols. *IEEE Communications Surveys Tutorials, 3*, 2-15. doi:10.1109/COMST.2000.5340799

Gupta, A., & Jha, R. K. (2015). A survey of 5G network: Architecture and emerging technologies. *IEEE access, 3*, 1206–1232.

Gupta, L., Jain, R., & Vaszkun, G. (2016). Survey of Important Issues in UAV Communication Networks. *IEEE Communications Surveys and Tutorials, 18*, 1123-1152. doi:10.1109/COMST.2015.2495297

Gusfield, D., & Irving, R. W. (1989). *The stable marriage problem: structure and algorithms.* MIT press.

Hadded, M., Zagrouba, R., Laouiti, A., Muhlethaler, P., & Saidane, L. A. (2015). A multi-objective genetic algorithm-based adaptive weighted clustering protocol in vanet. *2015 IEEE Congress on Evolutionary Computation (CEC)*, (pp. 994–1002).

Hakiri, A., & Berthou, P. (2015, 6 9). Leveraging SDN for The 5G Networks: Trends, Prospects and Challenges.

Han, S.-w., & Ram, M. (2020, 5). Steering connection requests for an access point to a best-serving access point. *Steering connection requests for an access point to a best-serving access point*. Google Patents.

Harris, M. (2016). Project Skybender: Google's secretive 5G internet drone tests revealed. *the Guardian, 29.*

Harrison, J. S., & Do, M. M. (2015). Mobile Network Architecture for 5G Era–New C-RAN Architecture and distributed 5G Core. Netmanias.

Hayajneh, A. M., Zaidi, S. A., Mclernon, D. C., & Ghogho, M. (2017). Performance Analysis of UAV Enabled Disaster Recovery Network : A Stochastic Geometric Framework based on Matern Cluster Processes. *Third Intelligent Signal Processing Conference*. doi:10.1109/ACCESS.2018.2835638

Henkel, D., Engländer, S., Kretschmer, M., & Niephaus, C. (2011, 12). Connecting the unconnected — Economic constraints and technical requirements towards a back-haul network for rural areas. *2011 IEEE GLOBECOM Workshops (GC Wkshps)*, (pp. 1039-1044). doi:10.1109/GLOCOMW.2011.6162335

ICASA. (2019, MArch). *Indepedent Communications Authority of South Africa.* Retrieved February 16, 2020, from https://www.icasa.org.za/uploads/files/state-of-ict-sector-report-2019.pdf

IEEE Standard Definitions of Terms for Radio Wave Propagation. (1998). *IEEE Std 211-1997*, i-. doi:10.1109/IEEESTD.1998.87897

IEEE Standard for Definitions of Terms for Antennas - Redline. (2014, 3). *IEEE Std 145-2013 (Revision of IEEE Std 145-1993) - Redline*, 1-92.

Iellamo, S., Lehtomaki, J. J., & Khan, Z. (2017, 6). Placement of 5G Drone Base Stations by Data Field Clustering. *2017 IEEE 85th Vehicular Technology Conference (VTC Spring)*, (pp. 1-5). doi:10.1109/VTCSpring.2017.8108590

IoL. (2018, November 7). *Telkom, Vodacom agree to share 4G network*. Retrieved January 31, 2020, from Businesss Report: https://www.iol.co.za/business-report/companies/telkom-vodacom-agree-to-share-4g-network-17807735

ITUR, S. (2017). Draft new Report ITU-R M.[IMT-2020. TECH PERF REQ]-Minimum requirements related to technical performance for IMT-2020 radio interface (s). *ITU-R SG05 Contribution, 40*.

Iwama, K., & Miyazaki, S. (2008, 2). A Survey of the Stable Marriage Problem and Its Variants., (pp. 131-136). doi:10.1109/ICKS.2008.7

Jana, P. K. (2016). Particle swarm optimization for maximizing lifetime of wireless sensor networks R. *Computers and Electrical Engineering, 51*, 26-42. doi:10.1016/j.compeleceng.2016.03.002

Ji, Y., Zhang, J., Zhao, Y., Yu, X., Zhang, J., & Chen, X. (2016). Prospects and research issues in multi-dimensional all optical networks. *Science China Information Sciences, 59*, 101301.

Jia, D., Zhu, H., Zou, S., & Hu, P. (2016). Dynamic Cluster Head Selection Method for Wireless Sensor Network. *IEEE Sensors Journal, 16*, 2746-2754. doi:10.1109/JSEN.2015.2512322

Kalantari, E., Shakir, M. Z., Yanikomeroglu, H., & Yongacoglu, A. (2017). Backhaul-aware robust 3D drone placement in 5G+ wireless networks. *2017 IEEE International Conference on Communications Workshops, ICC Workshops 2017*, 109-114. doi:10.1109/ICCW.2017.7962642

Katikala, S. (2014). Google project loon. *InSight: Rivier Academic Journal, 10*, 1-6.

Khalil, M., Qadir, J., Onireti, O., Imran, M. A., & Younis, S. (2017). Feasibility, architecture and cost considerations of using TVWS for rural Internet access in 5G. *2017 20th Conference on Innovations* *in Clouds, Internet and Networks (ICIN)*, (pp. 23–30).

Khaturia, M., Jha, P., & Karandikar, A. (2019). Connecting the Unconnected: Towards Frugal 5G Network Architecture and Standardization. *arXiv preprint arXiv:1902.01367*.

Khediri, S. E., Nasri, N., Wei, A., & Kachouri, A. (2014). A new approach for clustering in wireless sensors networks based on LEACH. *Procedia Computer Science, 32*, 1180-1185. doi:10.1016/j.procs.2014.05.551

Knoll, T. M. (2014). A combined CAPEX and OPEX cost model for LTE networks. *2014 16th International Telecommunications Network Strategy and Planning Symposium (Networks)*, (pp. 1–6).

Krzysztofik, W. J. (2018). Radio Network Planning and Propagation Models for Urban and Indoor Wireless Communication Networks. *Antennas and Wave Propagation*, 77.

Kuila, P., & Jana, P. K. (2014). Energy efficient clustering and routing algorithms for wireless sensor networks: Particle swarm optimization approach. *Engineering Applications of Artificial Intelligence, 33*, 127-140.

Laraqui, K., Tombaz, S., Furuskär, A., Skubic, B., Nazari, A., & Trojer, E. (2017). Fixed wireless access: On a massive scale with 5G. *Ericsson review (English ed.), 94*, 52–65.

Lardinois, F. (2013). Google X Announces Project Loon: Balloon-Powered Internet For Rural, Remote And Underserved Areas [Electronic resource]/Frederic Lardinois. *TechCrunch/AOL Inc.--Jun, 14*.

Larsen, E., Landmark, L., & Kure, Ø. (2017). Optimal UAV relay positions in Multi-Rate networks. In *Wireless Days, 2017* (pp. 8-14). IEEE.

Lawrence, N. P., Ng, B. W.-H., Hansen, H. J., & Abbott, D. (2017, June 7). 5G Terrestrial Networks: Mobility and Coverage-Solution in Three Dimensions. *IEEE Access, 5*, 8064 - 8093. Retrieved August 19, 2017, from http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7902205&isnumber=7859429

Leu, J. S., Chiang, T. H., Yu, M. C., & Su, K. W. (2015). Energy efficient clustering scheme for prolonging the lifetime of wireless sensor network with isolated nodes. *IEEE Communications Letters, 19*, 259-262. doi:10.1109/LCOMM.2014.2379715

Li, Y., Hua, N., & Zheng, X. (2016). CapEx advantages of multi-core fiber networks. *Photonic Network Communications, 31*, 228–238.

Liang, C., & Yu, F. R. (2015). Wireless virtualization for next generation mobile cellular networks. *IEEE wireless communications, 22*, 61–69.

Loni, P. (2018, October 11). *South Africa to start 4G spectrum auction by April 2019, says Cwele*. Retrieved February 27, 2020, from Fin24: https://www.fin24.com/Companies/ICT/south-africa-to-start-4g-spectrum-auction-by-april-2019-says-cwele-20181011

Lu, L., Chen, Y., Guo, W., Yang, H., Wu, Y., & Xing, S. (2015, 12). Prototype for 5G new air interface technology SCMA and performance evaluation. *China Communications, 12*, 38-48. doi:10.1109/CC.2015.7386169

Luca, C., Nicola, B.-M., William, L., Guterrez Jairo, A., Jaap, V. D., Robert, B., . . . Jinsong, W. (2016). 5G in Rural and Low-Income Areas: Are We Ready? ITU.

Luca, C., Nicola, B.-M., William, L., Gutierrez Jairo, A., Beek Jaap, Robert, B., . . . Jinsong, W. (2017). Bringing 5G in Rural and Low-Income Areas: Is it Feasible?

M Mousa, A. (2012, 9). Prospective of Fifth Generation Mobile Communications. *International Journal of Next-Generation Networks, 4*, 11-30. doi:10.5121/ijngn.2012.4302

Maeder, A., Ali, A., Bedekar, A., Cattoni, A. F., Chandramouli, D., Chandrashekar, S., . . . Turtinen, S. (2016, 11). A Scalable and Flexible Radio Access Network Architecture for Fifth Generation Mobile Networks. *IEEE Communications Magazine, 54*, 16-23. doi:10.1109/MCOM.2016.1600140CM

Marcus, M. J. (2018). Spectrum Policy for Radio Technology Experiments. *IEEE Wireless Communications, 25*, 8–9.

Margaret, R. (2007, April). *ATM (asynchronous transfer mode)*. Retrieved February 27, 2020, from https://searchnetworking.techtarget.com/definition/ATM

Margaret, R. (2007, April). *delay-tolerant network*. Retrieved February 27, 2020, from https://searchnetworking.techtarget.com/definition/delay-tolerant-network

Margaret, R. (2009). *Metro Ethernet*. Retrieved February 27, 2020, from https://searchnetworking.techtarget.com/definition/Metro-Ethernet

Market Business News. (2020). *What is B2G or business-to-government? Definition and examples*. Retrieved January 28, 2020, from https://marketbusinessnews.com/financial-glossary/b2g/

Matinmikko-Blue, M., Yrjölä, S., Seppänen, V., Ahokangas, P., Hämmäinen, H., & Latva-aho, M. (2018). Analysis of Spectrum Valuation Approaches: The Viewpoint of Local 5G Networks in Shared Spectrum Bands. *2018 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, (pp. 1–9).

McKinsey & Company. (2014, September). *Offline and falling behind: Barriers to Internet adoption | McKinsey*. Retrieved August 05, 2019, from http://www.mckinsey.com/insights/high_tech_telecoms_internet/offline_and_falling_behind_barriers_to_internet_adoption

Mohammad, M., Walid, S., Bennis, M., & Merouane, D. (2016, 6 6). Efficient Deployment of Multiple Unmanned Aerial Vehicles for Optimal Wireless Coverage.

Mothobi, O., Gillwald, A., & Rademan, B. (2018). Dominant Operators' Data Prices Remain Static while SA Struggles to Get and Stay Online.

Motlagh, N. H., Bagaa, M., & Taleb, T. (2017). UAV-based IoT platform: A crowd surveillance use case. *IEEE Communications Magazine, 55*, 128-134.

Motlagh, N. H., Taleb, T., & Arouk, O. (2016). Low-altitude unmanned aerial vehicles-based internet of things services: Comprehensive survey and future perspectives. *IEEE Internet of Things Journal, 3*, 899-922.

Mouradian, C. a., Glitho, R. H., Morrow, M. J., & Polakos, P. A. (2017). A Coalition Formation Algorithm for Multi-Robot Task Allocation in Large-Scale Natural Disasters. *arXiv preprint arXiv:1704.05905* .

Mousa, A. M. (2012). Prospective of fifth generation mobile communications. *International Journal of Next-Generation Networks (IJNGN), 4*, 1–30.

Mozaffari, M., Kasgari, A. T., Saad, W., Bennis, M., & Debbah, M. (2018). 3D cellular network architecture with drones for beyond 5G. *2018 IEEE Global Communications Conference (GLOBECOM)*, (pp. 1–6).

Mozaffari, M., Saad, W., Bennis, M., & Debbah, M. (2015). Drone small cells in the clouds: Design, deployment and performance analysis. *2015 IEEE Global Communications Conference (GLOBECOM)*, (pp. 1-6).

Mozaffari, M., Saad, W., Bennis, M., Nam, Y.-H., & Debbah, M. (2018). A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems. Retrieved from http://arxiv.org/abs/1803.00680

Mudiwa, G. (2019, November 18). *Cell C and MTN sign expanded roaming deal*. Retrieved January 31, 2020, from Business Live: https://www.businesslive.co.za/bd/companies/telecoms-and-technology/2019-11-18-cell-c-and-mtn-sign-expanded-roaming-deal/

MUTLU, M. (2014). Application of Rayleigh probability density function in electromagnetic wave propagation. *Journal of Electrical and Electronic Engineering, 2*, 17–21.

Mutlu, M., & Çavdar, İ. H. (2010). Adaptation of COST-231 Walfisch-Ikegami method to Ordu city in GSM 900 frequency band. *National Conference on Electrical, Electronics and Computer Engineering*, (pp. 447–453).

MyBroadband. (2019). *MTN's huge 900MHz LTE network rollout*. Retrieved January 19, 2020, from https://mybroadband.co.za/news/cellular/277517-mtns-huge-900mhz-lte-network-rollout.html/amp

Naqvi, S. A., Hassan, S. A., Pervaiz, H., & Ni, Q. (2018). Drone-aided communication as a key enabler for 5G and resilient public safety networks. *IEEE Communications Magazine, 56*, 36-42.

Narang, M., Xiang, S., Liu, W., Gutierrez, J., Chiaraviglio, L., Sathiaseelan, A., & Merwaday, A. (2017). UAV-assisted edge infrastructure for challenged networks. *2017 IEEE Conference on Computer Communications Workshops, INFOCOM WKSHPS 2017*. doi:10.1109/INFCOMW.2017.8116353

Narang, M., Xiang, S., Liu, W., Gutierrez, J., Chiaraviglio, L., Sathiaseelan, A., & Merwaday, A. (2017). UAV-assisted Edge Infrastructure for Challenged Networks. *IEEE Infocom Workshop on Wireless Communications and Networking in Extreme Environments (WCNEE 2017).*

Nayak, P., & Devulapalli, A. (2016). A Fuzzy Logic-Based Clustering Algorithm for WSN to Extend the Network Lifetime. *IEEE Sensors Journal, 16*, 137-144. doi:10.1109/JSEN.2015.2472970

Nekovee, M. (2018). Opportunities and Enabling Technologies for 5G and Beyond-5G Spectrum Sharing. *Handbook of Cognitive Radio*, 1–15.

Niemi, O. (2017, June 12). *Nokia Saving Lives put to work in live rescue missions*. Retrieved January 23, 2020, from Nokia: https://www.nokia.com/blog/nokia-saving-lives-put-work-live-rescue-missions/

Nikolikj, V., & Janevski, T. (2014). A cost modeling of high-capacity LTE-advanced and IEEE 802.11 ac based heterogeneous networks, deployed in the 700 MHz, 2.6 GHz and 5 GHz Bands. *Procedia Computer Science, 40*, 49–56.

Nimisha, T. S., & Ramalakshmi, R. (2015). Energy efficient connected dominating set construction using ant colony optimization technique in wireless sensor network. *2015 International Conference on Innovations in Information, Embedded and Communication Systems (ICIIECS)*, (pp. 1–5).

Onireti, O., Qadir, J., Imran, M. A., & Sathiaseelan, A. (2016). Will 5G See its Blind Side? Evolving 5G for Universal Internet Access. In *Proceedings of the 2016 workshop on Global Access to the Internet for All* (pp. 1-6). ACM.

Oughton, E. J., & Frias, Z. (2018). The cost, coverage and rollout implications of 5G infrastructure in Britain. *Telecommunications Policy, 42*, 636–652.

Palmer, G. (2019). Breaking down the barrier of business start-up costs. *TAXtalk, 2019*, 24–25.

Panov, A. I., & Yakovlev, K. (2017). Behavior and path planning for the coalition of cognitive robots in smart relocation tasks. In *Robot Intelligence Technology and Applications 4* (pp. 3-20). Springer.

Panwar, N., Sharma, S., & Singh, A. K. (2016). A survey on 5G: The next generation of mobile communication. *Physical Communication, 18*, 64-84.

Parkvall, S., Dahlman, E., Furuskar, A., & Frenne, M. (2017, 12). NR: The New 5G Radio Access Technology. *IEEE Communications Standards Magazine, 1*, 24-30. doi:10.1109/MCOMSTD.2017.1700042

Parvez, I., Rahmati, A., Guvenc, I., Sarwat, A. I., & Dai, H. (2018). A survey on low latency towards 5G: RAN, core network and caching solutions. *IEEE Communications Surveys & Tutorials, 20*, 3098–3130.

Qualcomm. (2020). *QTM052 mmWave antenna modules*. Retrieved February 27, 2020, from Qualcomm: https://www.qualcomm.com/products/qtm052-mmwave-antenna-modules

R, I. T. (2003). Rec. P1410-2 Propagation data and prediction models for the design of terrestrial boradband millimnetric radio access systems. *P series, Radiowave Propagation*.

Rappaport, T. S., Sun, S., Mayzus, R., Zhao, H., Azar, Y., Wang, K., . . . Gutierrez, F. (2013). Millimeter wave mobile communications for 5G cellular: It will work! *IEEE access, 1*, 335-349.

Roessler, A. (2018). Pre-5G and 5G: Will The mmWave Link Work? *5G Semiconductor Solutions-Infrastructure and Fixed Wireless Access*, 29.

Rost, P., Berberana, I., Mäder, A., Paul, H., Suryaprakash, V., Valenti, M., . . . Fettweis, G. (2015, 12). Benefits and challenges of virtualization in 5G radio access networks. *IEEE Communications Magazine, 53*, 75-82. doi:10.1109/MCOM.2015.7355588

Rostami, A., Ohlen, P., Wang, K., Ghebretensae, Z., Skubic, B., Santos, M., & Vidal, A. (2017, 4). Orchestration of RAN and Transport Networks for 5G: An SDN Approach. *IEEE Communications Magazine, 55*, 64-70. doi:10.1109/MCOM.2017.1600119

SA Venues. (2019). *SOUTH AFRICA WEATHER AND CLIMATE*. Retrieved February 27, 2020, from SOUTH AFRICAN WEATHER: https://www.sa-venues.com/no/weather.htm

Sabet, M., & Naji, H. R. (2015). International Journal of Electronics and Communications (AEÜ) A decentralized energy efficient hierarchical cluster-based routing algorithm for wireless sensor networks. *AEUE - International Journal of Electronics and Communications, 69*, 790-799. doi:10.1016/j.aeue.2015.01.002

Saska, M., Vonásek, V., Chudoba, J., Thomas, J., Loianno, G., & Kumar, V. (2016, June 12). Swarm distribution and deployment for cooperative surveillance by micro-aerial vehicles. *Journal of Intelligent \& Robotic Systems, 84*(1-4), 469-492.

Schoentgen, A., & Gille, L. (2017). Valuation of telecom investments in sub-Saharan Africa. *Telecommunications Policy, 41*, 537–554.

Sekander, S., Tabassum, H., & Hossain, E. (2018). Multi-tier drone architecture for 5G/B5G cellular networks: Challenges, trends, and prospects. *IEEE Communications Magazine, 56*, 96–103.

Series, M. (2009). Guidelines for evaluation of radio interface technologies for IMT-Advanced. *Report ITU, 638*.

Seybold, J. S. (2005). *Introduction to RF propagation.* John Wiley & Sons.

Shafi, M., Molisch, A. F., Smith, P. J., Haustein, T., Zhu, P., Silva, P. D., . . . Wunder, G. (2017, 6). 5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice. *IEEE Journal on Selected Areas in Communications, 35*, 1201-1221. doi:10.1109/JSAC.2017.2692307

Shah, S. A., Khattab, T., Shakir, M. Z., & Hasna, M. O. (2017). A distributed approach for networked flying platform association with small cells in 5G+ networks. *GLOBECOM 2017-2017 IEEE Global Communications Conference*, (pp. 1-7).

Shah, S. A., Khattab, T., Shakir, M. Z., & Hasna, M. O. (2017, April 21). A Distributed Approach for Networked Flying Platform Association with Small Cells in 5G+ Networks. *Networking and Internet Architecture (cs.NI); Machine Learning (stat.ML)*.

Shah, S. A., Khattab, T., Shakir, M. Z., & Hasna, M. O. (2017, April 21). A Distributed Approach for Networked Flying Platform Association with Small Cells in 5G+ Networks. *arXiv preprint arXiv:1705.03304*.

Sharma, V., You, I., Andersson, K., Palmieri, F., & Rehmani, M. H. (2019). Security, Privacy and Trust for Smart Mobile-Internet of Things (M-IoT): A Survey. *arXiv preprint arXiv:1903.05362*.

Sharon, S. (2018, January 16). *Reaching rural America with broadband internet service*. Retrieved January 16, 2020, from The Conversation: http://theconversation.com/reaching-rural-america-with-broadband-internet-service-82488

Sibanda, M. (2019). *South Africa's first 5G commercial network launched*. Retrieved January 19, 2020, from CAJ News Africa: http://cajnewsafrica.com/2019/02/26/south-africas-first-5g-commercial-network-launched/

Siriwardhana, Y., Porambage, P., Liyanage, M., Walia, J. S., Matinmikko-Blue, M., & Ylianttila, M. (2018). Micro-operator driven local 5G network architecture for industrial internet. *arXiv preprint arXiv:1811.04299*.

Smail, G., & Weijia, J. (2017). Techno-economic analysis and prediction for the deployment of 5G mobile network. *2017 20th Conference on innovations in clouds, internet and networks (ICIN)*, (pp. 9–16).

Stats SA. (2019). *Hlankomo*. Retrieved January 27, 2020, from http://www.statssa.gov.za/?page_id=4286&id=6598

Stats SA. (2020). *Indicators*. Retrieved February 27, 2020, from http://www.statssa.gov.za/?page_id=593

Stefano, R., Karol, K., Gregoire, H., Dario, F., & Bixio, R. (2015, 3 26). Dynamic Routing for Flying Ad Hoc Networks. *IEEE Transactions on Vehicular Technology, 65*(3), 1690-1700.

Stefano, R., Karol, K., Gregoire, H., Dario, F., & Bixio, R. (2015, March 26). Dynamic Routing for Flying Ad Hoc Networks. *IEEE Transactions on Vehicular Technology, 65*(3), 1690-1700.

Stefano, R., Karol, K., Gregoire, H., Dario, F., & Bixio, R. (2015, 3 26). Dynamic Routing for Flying Ad Hoc Networks. *IEEE Transactions on Vehicular Technology, 65*(3), 1690-1700.

Study Tonight. (2020). *Types of Network Topology*. Retrieved February 27, 2020, from https://www.studytonight.com/computer-networks/network-topology-types

Sukesh, M. (2018, September 10). *Network topology guide: Why it's cucial you build the right structure*. Retrieved February 27, 2020, from TechGenix: http://techgenix.com/network-topology/

Sun, S., Rappaport, T. S., Thomas, T. A., Ghosh, A., Nguyen, H. C., Kovács, I. Z., . . . Partyka, A. (2016). Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications. *IEEE Transactions on Vehicular Technology, 65*, 2843–2860.

Sunitha, C., G Krishnan, D., & Dhanya, V. A. (2017, 1). Overview of Fifth Generation Networking. *International Journal of Computer Trends and Technology, 43*, 49-55. doi:10.14445/22312803/IJCTT-V43P107

Taniuchi, K., Ohba, Y., Fajardo, V., Das, S., Tauil, M., Cheng, Y.-H., . . . Famolari, D. (2009). IEEE 802.21: Media independent handover: Features, applicability, and realization. *IEEE Communications Magazine, 47*, 112–120.

Tazibt, C. Y., Bekhti, M., Djamah, T., Achir, N., & Boussetta, K. (2017). Wireless sensor network clustering for UAV-based data gathering. *2017 Wireless Days*, 245-247. doi:10.1109/WD.2017.7918154

Tech Terms. (2020). *DSLAM Definition*. Retrieved February 27, 2020, from https://techterms.com/definition/dslam

The Ericsson Blog. (2016, August 12). *Ericsson and China Mobile conduct world's first 5G drone prototype field trial*. Retrieved January 19, 2020, from Ericsson: https://www.ericsson.com/en/news/2016/8/ericsson-and-china-mobile-conduct-worlds-first-5g-drone-prototype-field-trial-

The NPD Group. (2018). *Drone Sales – Looking Up!* Retrieved January 19, 2020, from NPD: https://www.npd.com/wps/portal/npd/us/news/infographics/2019/drone-sales/

Trading Economics. (2020, February). *South Africa Average Monthly Gross Wage*. Retrieved February 27, 2020, from https://tradingeconomics.com/south-africa/wages

Tripathi, P. S., & Prasad, R. (2018, 5 01). Spectrum for 5G Services. *Wireless Personal Communications, 100*, 539–555. doi:10.1007/s11277-017-5217-9

Tshwane Capital. (2018, July 24). *Was project isizwe Wi-Fi project a success?* Retrieved February 17, 2020, from Tshwane Capital: http://tshwanecapitall.co.za/was-project-isizwe-wi-fi-project-a-success/

Tucker, K., Bulim, J., Koch, G., & North, M. M. (2018). Internet Industry: A Perspective Review Through Internet of Things and Internet of Everything. *International Management Review, 14*, 26.

Tuyishimire, E., Bagula, A., Rekhis, S., & Boudriga, N. (2016). Cooperative Data Mulling from Ground Sensors to Base Station Using UAVs.

Tuyishimire, E., Bagula, B. A., & Ismail, A. (2018). Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion Optimal Clustering for Efficient Data Muling in the Internet-of-Things in Motion.

Verbrugge, S., Colle, D., Pickavet, M., Demeester, P., Pasqualini, S., Iselt, A., . . . Jäger, M. (2006). Methodology and input availability parameters for calculating OpEx and CapEx costs for realistic network scenarios. *Journal of Optical Networking, 5*, 509–520.

Verizon Wireless. (2020). *LTE Internet (Installed) Data Calculator*. Retrieved February 27, 2020, from Verizon Wireless: https://www.verizonwireless.com/freedom/datacalculator.html

Vimalarani, C., Subramanian, R., & Sivanandam, S. N. (2016). An Enhanced PSO-Based Clustering Energy Optimization Algorithm for Wireless Sensor Network. *2016*.

Vishal, S., Kathirava, S., Han-Chieh, C., Kai-Lung, H., & Wen-Huang, C. (2016, 12 2). Intelligent deployment of UAVs in 5G heterogeneous communication environment for improved coverage. *Journal of Network and Computer Applications*.

Vishal, S., Roberto, S., & Subramanian, R. (2016, Decemember). UAVs Assisted Delay Optimization in Heterogeneous Wireless Networks. *IEEE Communications Letters, 20*(12), 2526-2529.

Vodacom. (2016, June 24). *Vodacom behind education in Gauteng*. Retrieved January 31, 2020, from Vodacom: https://now.vodacom.co.za/article/vodacom-behind-education-in-gauteng

Wang, C.-X., Haider, F., Gao, X., You, X.-H., Yang, Y., Yuan, D., . . . Hepsaydir, E. (2014). Cellular architecture and key technologies for 5G wireless communication networks. *IEEE communications magazine, 52*, 122–130.

Wang, L.-C., Wang, C.-W., & Liu, C.-M. (2009). Optimal number of clusters in dense wireless sensor networks: a cross-layer approach. *IEEE Transactions on Vehicular Technology, 58*, 966-976.

Wang, S., & Ran, C. (2016, 4). Rethinking cellular network planning and optimization. *IEEE Wireless Communications, 23*, 118-125. doi:10.1109/MWC.2016.7462493

Wang, S., Cao, Q., Wang, X., Li, B., Tang, M., Yuan, W., . . . Zhang, W. (2013). PAI-1 4G/5G Polymorphism Contributes to Cancer Susceptibility: Evidence from Meta-Analysis. *PLOS ONE, 8*(2). Retrieved 4 13, 2019, from http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0056797

Weisstein, E. W. (2004). Gamma distribution. *https://mathworld. wolfram. com/*.

Werner, R. (2017, January 27). Living Conditions of Households in South Africa. Pretoria. Retrieved February 27, 2020, from http://www.statssa.gov.za/publications/P0310/P03102014.pdf

Whatsag. (2019). *What Is a Cell Tower?* Retrieved February 27, 2020, from Whatsag: https://whatsag.com/g/what-is-a-cell-tower.php

White Papers. (n.d.). (The 5G Infrastructure Public Private Partnership) Retrieved August 5, 2019, from 5GPPP: https://5g-ppp.eu/white-papers

White, K., Denney, E., Knudson, M. D., Marnerides, A., & Pezaros, D. (2016). A programmable SDN+ NFV-based architecture for UAV telemetry monitoring.

Will, K. (2019, May 20). *Business-to-Consumer (B2C)*. Retrieved January 28, 2020, from Investopedia: https://www.investopedia.com/terms/b/btoc.asp

Willems, W. (2016). Beyond Free Basics: Facebook, data bundles and Zambia's social media internet. *Africa at LSE*.

Xilouris, G. K., Batistatos, M. C., Athanasiadou, G. E., Tsoulos, G., Pervaiz, H. B., & Zarakovitis, C. C. (2018). UAV-Assisted 5G Network Architecture with Slicing and Virtualization. *2018 IEEE Globecom Workshops (GC Wkshps)*, (pp. 1–7).

Xu, L., Collier, R., & O'Hare, G. M. (2017). A survey of clustering techniques in WSNs and consideration of the challenges of applying such to 5G IoT scenarios. *IEEE Internet of Things Journal, 4*, 1229–1249.

Yaliniz, R. I., El-Keyi, A., & Halim, Y. (2016, 2 26). Effecient 3-D Placement of an Aerial Base Station in Next Generation Cellular Networks.

Yang, H., & Sikdar, B. (2007). Optimal cluster head selection in the LEACH architecture. *Performance, Computing, and Communications Conference, 2007. IPCCC 2007. IEEE Internationa*, (pp. 93-100).

Yang, Y., Qiu, X., Meng, L., & Long, K. (2014). Task coalition formation and self-adjustment in the wireless sensor networks. *International Journal of Communication Systems, 27*, 2241–2254.

Yassen, M. B., Aljawaerneh, S., & Abdulraziq, R. (2016). Secure low energy adaptive clustering hierarchal based on internet of things for wireless sensor network (WSN): Survey. *Engineering & MIS (ICEMIS), International Conference on*, (pp. 1-9).

Yin, X., Dai, W., Li, B., Chang, L., & Li, C. (2017). Cooperative task allocation in heterogeneous wireless sensor networks. *International Journal of Distributed Sensor Networks, 13*, 1550147717735747.

Younis, O., Krunz, M., & Ramasubramanian, S. (2006). Node clustering in wireless sensor networks: recent developments and deployment challenges. *IEEE network, 20*, 20–25.

Yu, J. Y., & Chong, P. H. (2005). A survey of clustering schemes for mobile ad hoc networks. *IEEE Communications Surveys & Tutorials, 7*, 32-48.

Yu, J., Li, W., Cheng, X., Atiquzzaman, M., Wang, H., & Feng, L. (2016). Connected dominating set construction in cognitive radio networks. *Personal and Ubiquitous Computing, 20*, 757–769.

Zeng, Y., Lyu, J., & Zhang, R. (2018). Cellular-connected UAV: Potential, challenges, and promising technologies. *IEEE Wireless Communications, 26*, 120–127.

Zeng, Y., Zhang, R., & Lim, T. J. (2016). Wireless communications with unmanned aerial vehicles: Opportunities and challenges. *IEEE Communications Magazine, 54*, 36-42.

Zhang, H., Zhang, S., & Bu, W. (2014). A clustering routing protocol for energy balance of wireless sensor network based on simulated annealing and genetic algorithm. *International Journal of Hybrid Information Technology, 7*, 71-82.

Zhang, Y., Meo, M., Gerboni, R., & Marsan, M. A. (2017). Minimum cost solar power systems for LTE macro base stations. *Computer Networks, 112*, 12-23.