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Mobility management for Wi-Fi infrastructure and mesh networks

by

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Declaration of Authorship

I, Zimani Chitedze, declare that *Mobility management for Wi-Fi infrastructure and mesh networks* is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

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Abstract

This thesis shows that mobility management protocols for infrastructure Internet may be used in a wireless mesh network environment. In this research Mobile IPv6 and Fast Handover for Hierarchical Mobile IPv6 are successfully implemented in a wireless mesh network environment. Two experiments were carried out: vertical and horizontal handover simulations. Vertical handover simulation involved a heterogeneous wireless environment comprising both wireless local area and wireless mesh networks. An OPNET Mobile IPv6 model was used to simulate the vertical handover experiment. Horizontal handover simulation involved Mobile IPv6 and Fast Handover for Hierarchical Mobile IPv6 applied in ns2 wireless mesh network. The vertical handover results show that MIPv6 is able to manage vertical handover between wireless local area and wireless mesh network. The horizontal handover results illustrate that in mesh networks, Fast Handover for Hierarchical Mobile IPv6's performance is superior to Mobile IPv6. Fast Handover for Hierarchical Mobile IPv6 generates more throughput and less delay than Mobile IPv6. Furthermore, Fast Handover for Hierarchical Mobile IPv6 drops less data packets than Mobile IPv6. The simulations indicate that even though there are multi-hop communications in wireless mesh networks, the performance of the multi-hop routing may not play a big role in the handover performance. This is so because the mesh routers are mostly static and the multi-hop routes are readily available. Thus, the total handover delay is not affected too much by the WMN hops in the paths for signaling message transmission.

Association of Computer Machinery (ACM) Classification Keywords

C.2.2 [**Computer Systems Organization**]: Computer-communication networks - Routing protocols; C.2.1 [**Network Architecture and Design**]: Wireless Communication / Network Communication

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List of Abbreviations

4G	Fourth Generation
ACK	Acknowledgement
ACM	Association of Computer Machinery
AHRA	Ad Hoc Routing Agent
AN	Anchor Node
AODV	Ad Hoc on Demand Vector
AP	Access Point
AR	Access Router
BAck	Binding Acknowledgement
BDT	Bi-Directional Tunneling
BSS	Basic Service Set
BU	Binding Update
CAGR	Compound Annual Growth Rate
CBR	Constant Bit Rate
CCG	Client Control Group
CDG	Client Data Group
CN	Corresponding Node
CoA	Care-of-Address
DAD	Duplication Address Detection
DHCP	Dynamic Host Configuration Protocol
DS	Distribution System

DV Dependent Variable

FA Foreign Agent

FBAck Fast Binding Acknowledgement

FBU Fast Binding Update

FHMIPv6 Fast handover for Hierarchical Mobile IPv6

FMIPv6 Fast Mobile IPv6

FNA Fast Neighbor Advertisement

GPRS General Packet Radio Service

HA Home Agent

HAck Handover Acknowledgement

HAWAII Hando-Aware Wireless Access Internet Infrastructure

HI Handover Initiation

HI-HAck Handover Initiation handover acknowledgment

HMIPv6 Hierarchical Mobile IPv6

IBSG Internet Business Solutions Group

IBSS Independent Basic Service Set

ICANN Internet Corporation for Assigned Names and Numbers

IEEE Institute of Electrical and Electronics Engineers

IETF Internet Engineering Task Force

IMS IP multimedia subsystem

IP Internet Protocol

IPv4 Internet Protocol version 4

IPv6 Internet Protocol version 6

IV Independent Variables

kbps Kilobit Per Second

LBAck Local Binding Acknowledgment

LCoA Local Care-of-Address

LTE Long Term Evolution

M2M Machine-to-Machine

MAC Media Access Control

MANET Mobile Ad Hoc Network

MAP Mobility Anchor Point

Mbps megabit per second

MIPv4 Mobile Internet Protocol version 4

MIPv6 Mobile IPv6

MN Mobile Node

NAM Network Animator

NAR New Access Router

NAT Network Address Translation

NLCoA Next Link Care-of-Address

NOAH No Ad Hoc routing Agent

ns2 network simulator 2

OLSR Optimized Link State Routing

OPNET Optimized Network Engineering Tool

OSI Open Systems Interconnection

oTCL Object-oriented Tool Command Language

pAR Previous Access Router

PLCoA Previous Link Care-of-Address

PPP Point to Point Protocol

PRD Pre-handover Route Discovery

PrRtAdv Proxy Router Advertisement

QoS Quality of Service

RCoA Regional Care-of-Address

RFC Request for Comments

RIPng Router Information Protocol next generation

RO Route Optimization

RtSolPr Router Solicitation for Proxy

SMIP Seamless Mobile Internet Protocol

SSID Service Set Identification

TCP Transfer Control Protocol

UMTS Universal Mobile Telecommunications System

VNI Visual Networking Index

VoIP Voice over Internet Protocol

WDS Wireless Distribution System

Wi-Fi Wireless Fidelity

WiMAX Worldwide interoperability Microvave Access

WLAN Wireless Local Area Network

WMN Wireless Mesh Network

Chapter 1

Introduction

This thesis shows that mobility management protocols for infrastructure-based wireless fidelity (Wi-Fi) may be applied to a wireless mesh network (WMN) environment. Mesh topology tends to be an unplanned graph and routes change dynamically. This thesis describes how Mobile IPv6 (MIPv6) and Fast Handover for Hierarchical Mobile IPv6 (FHMIPv6) were successfully implemented in a WMN environment. Mobility management in WMNs has still not been researched thoroughly, although a significant amount of research on infrastructure Wi-Fi and cellular networks mobility management has been conducted [53]. Fourth generation (4G) networks will include all-IP (Internet Protocol) wired and wireless networks interworking together as heterogeneous networks (see Figure 1.1) and promise to provide data rates up to a hundred times faster than current networks [53]. Its high capacity will be beneficial as it is projected that by 2015 overall global data traffic will grow up to 6.3 exabytes per month [11].

It is suggested that operators may be able to offload this traffic onto other IP networks such as WMNs by offering subscribers dual-mode mobile phones [11]. WMNs are attracting attention because of characteristics such as ease of installation and scalability, low cost network deployment, ease of network reconfiguration, reduction in wired links, robust communication, spectrum reuse efficiency and network capacity improvement [1]. Even though WMNs have turned out to be attractive and hold a great potential for 4G networks due to their capability to integrate with other wireless networks, there are still challenges that need to be addressed, particularly, MIPv6-based mobility management in a mesh environment [53]. Section 1.1 introduces mobility management and wireless mesh networks. Section 1.2 discusses the motivation for addressing these topics. Section 1.3 presents the research question and the overall approach of this investigation. Section 1.4 lays out the structure for the rest of the thesis.

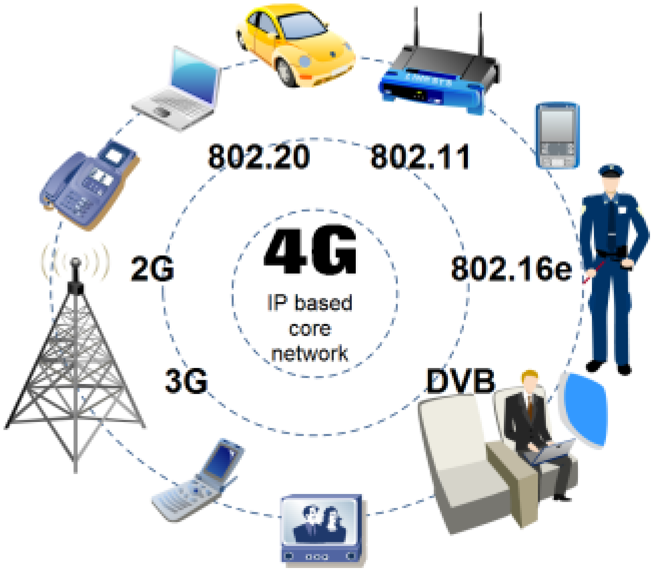

Figure 1.1: *4G network - is projected to offer an all-IP network with facilities such as Internet, voice over IP and video at a high speed. Mobile devices such as laptops, smartphones and tablets are expected to be supported. It is being developed to accommodate existing technologies as well as new ones.*

1.1 Background

The popularity of portable devices that support real-time data services, such as smartphones, laptops and tablets has caused the need for the convergence of different wireless access networks. Section 1.1.1 introduces mobility management and Section 1.1.2 presents wireless mesh networks.

1.1.1 Mobility management

Mobility management has become the most important ingredient in ubiquitous networks since the progress towards All-IP next generation heterogeneous networks. It provides seamless support of real-time and non-real-time services for mobile subscribers and facilitates connection maintenance for subscribers on the move when they change points of attachment. Futhermore, mobility management involves location management and handover management (see Figure 1.2)[2].

Location management allows the network to keep track of the location of the mobile clients and it involves two procedures: location registration and paging. In a location registration procedure,

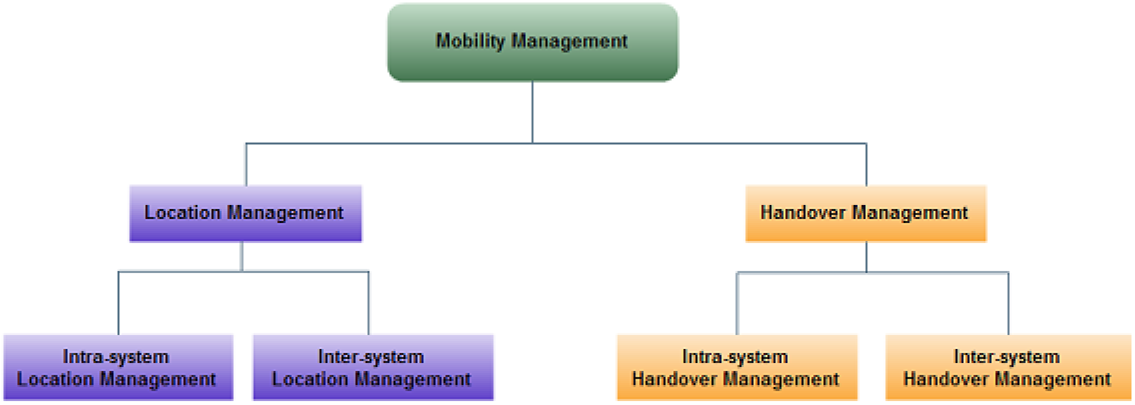

Figure 1.2: *Mobility managment - contains two components: location management and handover management, and there are two types of roaming for mobile nodes (intra-system and inter-system)*

the network is informed periodically by the mobile node communicating its current location which the network updates in the location database. After location management takes place, paging procedure requests the network to get information about the specific location of a mobile client so that data is delivered successfully [53].

Handover management is the procedure by which a mobile node (MN) keeps its connection active when it moves from one point of attachment to another. The handover procedure involves three stages:

1. Either the MN or the network triggers the initiation of handover.
2. Then the network finds new resources for the handover connection.
3. Finally, data flow control maintains the delivery of data from the old point of attachment to the new point of attachment with quality of service (QoS) [2].

Several protocols and mechanisms have been developed to support handover for multimedia services. Depending on the movement of the MN, the handover can be classified as horizontal or vertical. Horizontal handover refers to the ability to handover from one access point to the other within a homogeneous technology, for example handover from 802.11 to another 802.11 Wi-Fi subnet (see Figure 1.3).

Figure 1.3: *Horizontal handover - handover between homogeneous access technology. For example, the MN moves from WLAN subnet to the other WLAN subnet.*

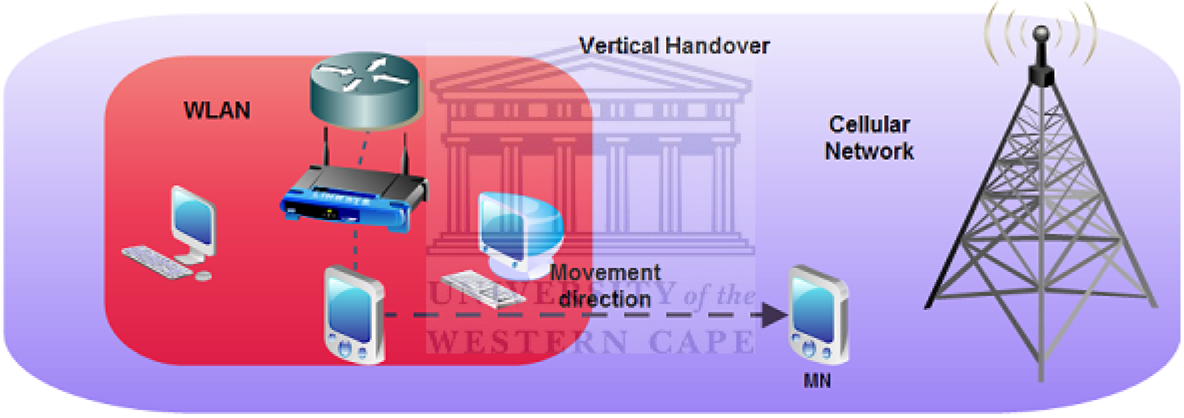

Figure 1.4: *Vertical handover - handover across heterogeneous access technologies. For example, the MN moves from WLAN to cellular network.*

On the other hand, vertical handover (see Figure 1.4) refers to the ability to handover across heterogeneous wireless technologies, for example, handover from any wireless local area network (WLAN) technology to General Packet Radio Service/Universal Mobile Telecommunication System (GPRS/UMTS). Handover in heterogeneous networks is a much more complex matter. That is why it has been researched on different levels of the Open System Interconnection (OSI) reference model protocol stack. Mobility protocols will be addressed in more detail in Section 2.1.

1.1.2 Wireless mesh networks

As the wireless communication technologies go through swift progression, there has been growing research in the area of WMNs [17]. WMNs are attracting attention because of their characteristics such as ease of and low cost network deployment, ease of network reconfiguration, reduction in wired links, robust communication, spectrum reuse efficiency and network capacity improvement [31].

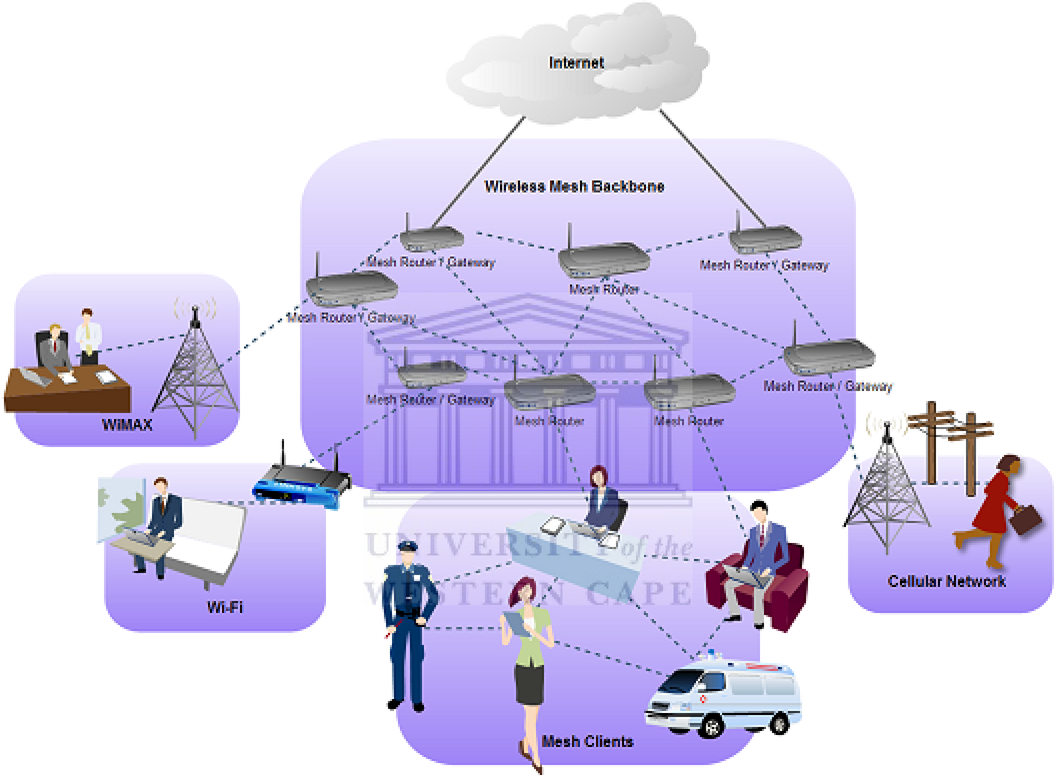

Figure 1.5: *Hybrid WMN - combines infrastructure and client meshing. Mesh clients are able to access the mesh network through the mesh routers or through peer-to-peer communication with other mesh clients.*

A basic WMN consists of mesh routers and mesh clients. There are three main types of WMNs determined by their structural design and deployment configuration: infrastructure mesh, client mesh and hybrid mesh. Infrastructure WMN architecture comprises mesh routers creating an infrastructure for clients. The mesh routers create links which configure and heal themselves, and some mesh routers with gateway functionalities connect to the Internet through access routers (ARs). Client WMN architecture is a peer-to-peer mesh networking among clients. Mesh routers are not required in this architecture because mesh clients do all the routing and configurations themselves. Hybrid WMN (see Figure 1.5) architecture combines infrastructure and client meshing. Mesh clients are able to access the mesh network through the mesh routers or through peer-to-peer communication with other mesh clients.

WMNs can be connected to other wireless communication networks such as Wi-Fi, worldwide interoperability microwave access (WiMAX) and cellular and networks (see Figure 1.5). Even though WMNs are attractive and hold great promise for 4G networks because of their integration with other wireless networks, there are still challenges that need to be addressed. One well known challenge is mobile IP-based mobility management in a WMN environment.

1.2 Motivation

According to CISCO Visual Networking Index (VNI) forecast, total mobile data traffic is projected to grow to 6.3 exabytes per month by 2015 (see Figure 1.6). Mobile data traffic will grow at a compound annual growth rate (CAGR) of 92 percent from 2010 to 2015. The introduction of laptops, tablets and high-end handsets onto mobile wireless networks has caused the increase of traffic. These devices generate high traffic because of consumer content and applications offered, which were not supported by the previous generation of mobile devices. For example, a laptop can generate traffic equivalent to 515 basic-feature phones and a smartphone can produce as much traffic as 24 basic-feature phones. These devices will carry on generating high amount of traffic especially video, but new devices such as tablets and Machine-to-Machine (M2M) will begin to account for a large portion of traffic by 2015 (see Figure 1.6). Mobile video content will be the main cause of traffic growth through 2015 because it has higher bit rates than other content type. Video content will generate 4.2 exabytes of the 6.3 exabytes per month [11].

A survey conducted by Cisco's Internet Business Solutions Group (IBSG) confirms that on average approximately 40 percent of total mobile data use is spent at home and approximately 35 percent of mobile Internet is used on the move, while the remaining 25 percent of mobile Internet use happens at work. The high percentage of using mobile Internet at home opens an

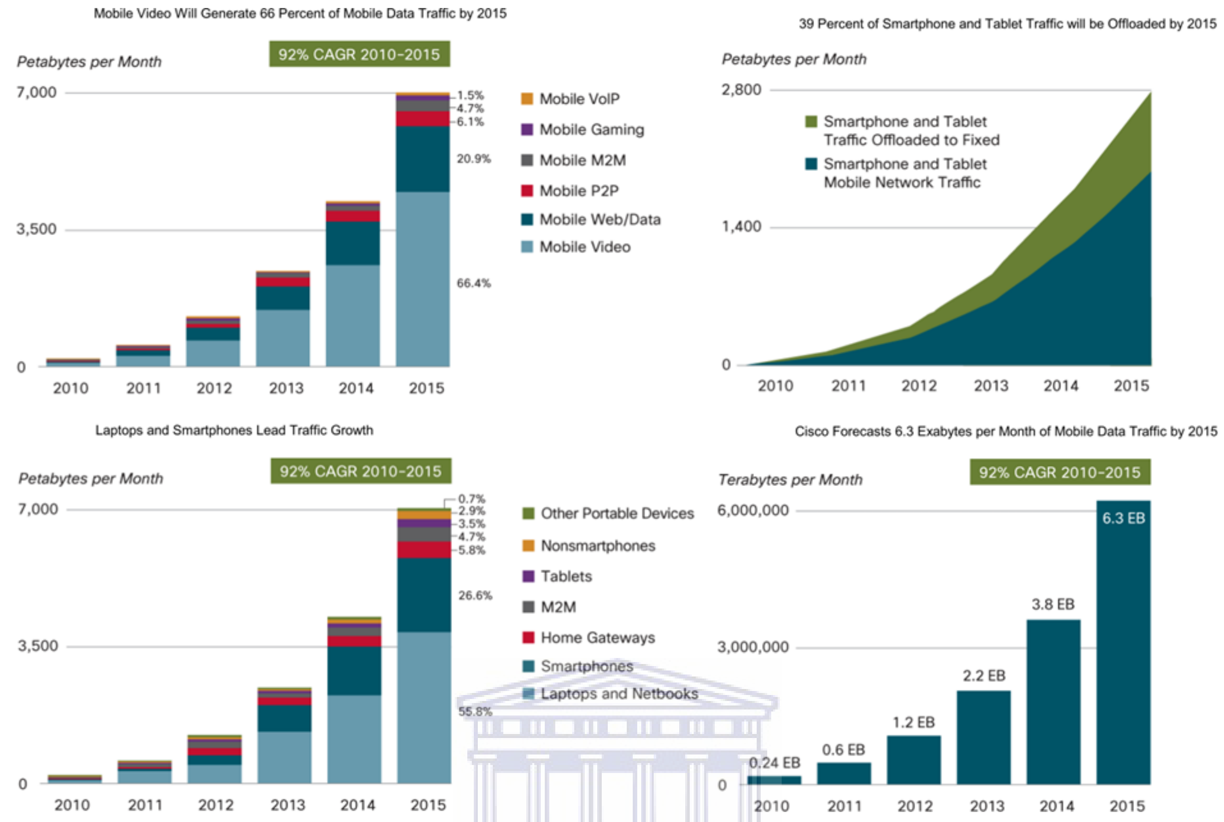

Figure 1.6: *CISCO Visual Networking Index forecast - Cisco forecasts 6.3 exabytes per month of mobile data traffic by 2015. 39 percent of smartphone and tablet traffic will be offloaded by 2015. Mobile video will generate 66 percent of mobile data traffic by 2015. Laptops and smartphones lead traffic growth [11].*

opportunity for operators to offload high mobile Internet traffic to other networks such as WLAN and WMNs. The operators may offer dual-mode mobile phones or mobile devices that support different wireless access networks, which can be used to roam across various wireless networks. For example, mobile data traffic may be offloaded to Wi-Fi when the subscriber is at home and roams to WMN when on the move. Without offloading the traffic, the combined amount of tablet and smartphone traffic would be 2.7 exabytes per month in 2015. While with offload, smartphone and tablet traffic will amount to 1.9 exabytes per month in 2015. [11].

1.3 Research Question

Mobility management is crucial for 4G network support and integrating all-IP based wireless networks. Mobility support can be provided using MIPv6 and its extensions. The objective of this research is to study MIPv6 mobility management schemes for WMN support in next generation heterogeneous all-IP based wireless networks. MIPv6 protocols for non-mesh IP networks provide a starting point for the invesigation. Handover management is investigated and since handover management consists of both vertical and horizontal handover, these two types of handover are explored in a WMN environment. Two simulations are developed: a WMN and a WLAN for the vertical handover prototype, while the horizontal handover prototype comprise WMNs only. This thesis addresses the following question: **How do mobility managment protocols such as MIPv6 and FHMIPv6 behave for handover with mesh networks?** Furthermore, because mobility management is affected by different variables, other sub-questions concerning handover for mesh networks include:

- **How is throughput affected during handover?**
- **How much delay occurs during handover?**
- **How much packet loss is there during handover?**

This research effort is concerned with MIPv6 based mobility management mechanisms including identifying the strengths and shortcomings of MIPv6. The handover performance shortcomings of MIPv6 for WMNs are identified and validated through experimentation. A MIPv6 extension, FHMIPv6, addresses the deficiency of MIPv6 handover performance. This thesis evaluates both protocols by means of discrete event simulations. The research is scoped to MIPv6 with particular focus over IEEE 802.11 WMNs. The reason for such focus is the excessive loss of performance experienced by MIPv6 when implemented in ad hoc networks. We can characterize the performance by answering the sub-questions for each protocol.

1.4 Thesis outline

The rest of the thesis is structured as follows:

Chapter 2 presents related work concerning attaining low latency and packet loss during handover for WLANs and WMNs. The literature survey provides insight into mobility management in wireless networks using MIPv6 and its extensions. A section on IPv6 mobility protocols examines mobile IPv6 mobility management protocols for WLANs. WMN client side transparency mobility management protocols are also summarized.

Chapter 3 identifies challenges and research gaps associated with mobility management. It also frames the research question and discusses the research method used to answer this research question. Furthermore, it presents the experimental design of this investigation, and introduces vertical and horizontal handover prototypes.

Chapter 4 presents and discusses handover results. Both vertical and horizontal handover prototypes are presented. The following performance metrics are addressed: throughput, delay and packet loss during handover.

Chapter 5 concludes the thesis and clarifies the limitations of this research effort. It also recommends what can be done to overcome the limitations. Finally, future research directions that could provide the next steps along the path to a practical and usable 4G heterogeneous network are suggested.

Appendices include published papers arising from this research. Final findings of this research were presented and published in Southern Africa Telecommunication Networks and Applications Conference (SATNAC) 2012 (see Appendix A). Preliminary results of this research were presented and published in Southern Africa Telecommunication Networks and Applications Conference (SATNAC) 2011 (see Appendix B). The research proposal report was accepted for poster presentation at the same conference in 2010 (see Appendix C). All the papers in appendices are co-authored with the supervisor but this thesis is written exclusively by the author.

Chapter 2

Related Work

One of the objectives of mobility management is seamless support for real-time communication. This seamless support refers to achieving a sufficiently low latency and packet loss during handover. This chapter presents related work toward attaining these objectives for WMNs and WLANs. The literature survey is conducted to provide insight into mobility management in wireless networks using MIPv6 and its extensions. The existing work focuses on mobile IP-based mobility in wireless networks such as WLAN and Cellular. Section 2.1 examines mobile IPv6 mobility management protocols for WLANs. There is little research on mobile IP-based mobility in ad hoc networks such as WMNs. Section 2.2 looks at WMN client side transparency mobility management protocols.

2.1 IPv6 mobility protocols

Several mobility protocols have been proposed for managing IPv6 [1]. These protocols can be categorized as micro-mobility and macro-mobility protocols. In micro-mobility, an MN moves within a given domain between subnets and engages in intra domain handovers [43]. Micro-mobility solutions include cellular IP [5] and handoff-aware wireless access Internet infrastructure (HAWAII) [42]. Cellular IP, from Columbia University and Ericsson Research supports paging and several handover techniques and optimization. Host location information is updated regularly using packets, to minimize signaling. However, cellular IP relies on MIP to support global mobility, and has a limitation to support heterogeneous mobility between different domains [49]. HAWAII, from Lucent Technologies, also relies on MIP for inter-domain mobility. HAWAII is not a standalone solution but extends MIP to provide intra-domain mobility with QoS support. HAWAII leverages MIP to enable QoS mobility [41].

In macro-mobility, an MN moves from one administrative domain to another administrative domain, and engages in inter domain handovers. Mobile IP is the most widely used protocol for macro-mobility management.

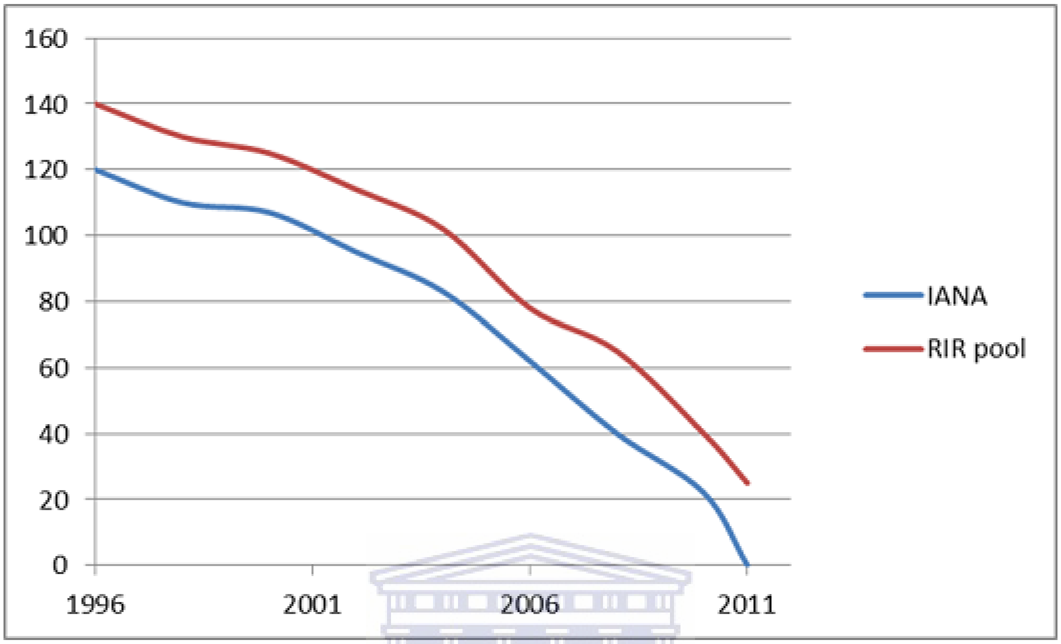

Figure 2.1: *IPv4 lifetime projection - The graph shows the decline of available IPv4 spaces in /8s. ICANN (Internet Corporation for Assigned Names and Numbers) gave out the last block of IPv4 addresses and the remaining addresses will be assigned as early as 2012 (http://www.icann.org/).*

Mobile IP [38] (RFC 2002) has made it possible for MNs to have roaming capabilities. MNs can change their point-of-attachment without changing their IP addresses. This permits seamless mobility of MNs from one network to another while maintaining the existing connection. There are two versions of MIP; MIP version 4 (MIPv4) [38], which enables roaming capabilities of MNs in IPv4 networks and MIP version 6 (MIPv6) [39], which allows mobility in IPv6 networks. Although MIPv4 has been a standard for the past few years, MIPv6 is becoming more popular [2]. MIP was originally designed for IPv4 but IPv4 has a lot of limitations:

- The shortage of globally routable IPv4 addresses. IPv4 has a 32-bit addressing scheme that adds up to 4.3 billion unique address spaces. When IPv4 was first introduced, that address space looked like a lot of addresses but now as the world progress towards all-

IP next generation networks, IPv4 addresses have quickly run out (see Figure 2.1), as a result of the popularity of IP based data applications on handheld devices such as mobile phones, laptops, tablets and the like. With IPv6's 128-bit addressing scheme, that is 2 to the 128th power, equivalent to 340,282,366,920,938,000,000,000,000,000,000,000,000 address spaces, IPv6 appears safe from running out of unique addresses [8]. IPv6 addresses consist of 8 groups of 4 hexadecimal numbers, for example, 2005::0002.

- The use of private addresses with network address translation (NAT) may give reachability problems when packet-based data applications such as voice over IP (VoIP), video conference and the like are used. A router may no be able to correctly re-direct data it has received from the outside world to the computer in the network. In IPv6 there is no need for developers and network administrators to spend a lot of time trying to get applications work around NAT [26].
- Configuration is complex in IPv4, thus, addresses are either set up manually or dynamic host configuration protocol (DHCP) is used for a stateful address configuration [29].

Like IPv4, MIPv4 has issues of its own, particularly with real-time multimedia applications [39]. Triangular routing is the main problem in MIPv4 as illustrated in Figure 2.2, where the MN is able to deliver packets destined for the corresponding node (CN) using a path through the foreign agent (FA). The CN delivers packets destined for the MN to the home agent (HA) in the home network and the HA routes them to the MN. This kind of routing is not ideal because the packets from the CN to the MN take the long path by passing through the home network of the MN instead of direct communication between the MN and the CN [39]. A new protocol and standard was needed to address these limitations.

Section 2.1.1 introduces MIPv6 protocol implemented in WLANs. Section 2.1.2 presents the hierarchical extension of MIPv6. Section 2.1.3 introduces another extension of MIPv6 that utilizes the fast handover scheme. Section 2.1.4 discusses the protocol that combines hierarchical scheme of HMIPv6 and fast handover scheme of FMIPv6. Section 2.1.5 introduces a non-standard MIPv6 extension that uses a node called *Decision Engine* to observe the MN.

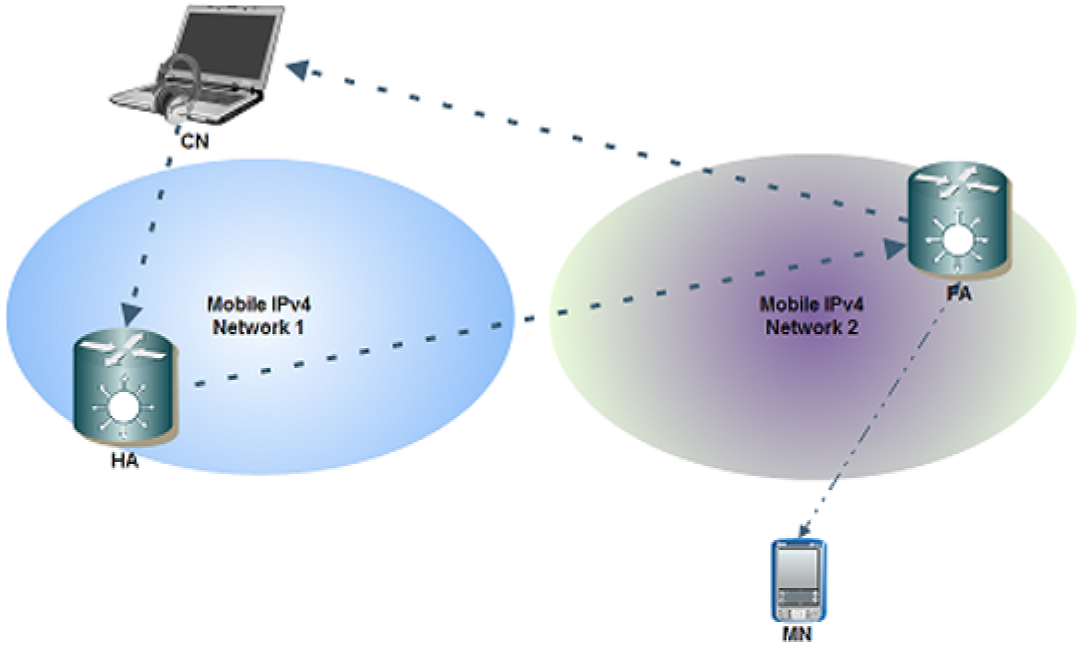

Figure 2.2: *Mobile IPv4 overview - the MN delivers packets destined for the CN through the FA, which causes triangular routing.*

2.1.1 Mobile IPv6

MIPv6 [39] is intended to deal with MNs in motion between IPv6 networks (see Figure 2.3). When a MN is on the move and connects to a new AR in another subnet, its home address is not valid any longer, therefore it requires a new address in the visiting subnet. The MN obtains a new address called care-of-address (CoA) to register with its HA and the CN whilst the MN is away from home network. The mapping of the home address and CoA of the MN so that the HA can at all times recognize the communication of the MN is called *Binding*[30].

In MIPv6, the handover procedure occurs when the MN examines router advertisements sent by the AR or the MN requests the AR to send router advertisements (router solicitation) and realizes that it is no longer in the home network. The CoA is created using information in the router advertisements. Firstly, the MN confirms that the link-local address is unique, then creates the new CoA by auto-configuring a stateful or stateless address. The process of verifying the address is unique is called duplication address detection (DAD) and it involves sending neighbor

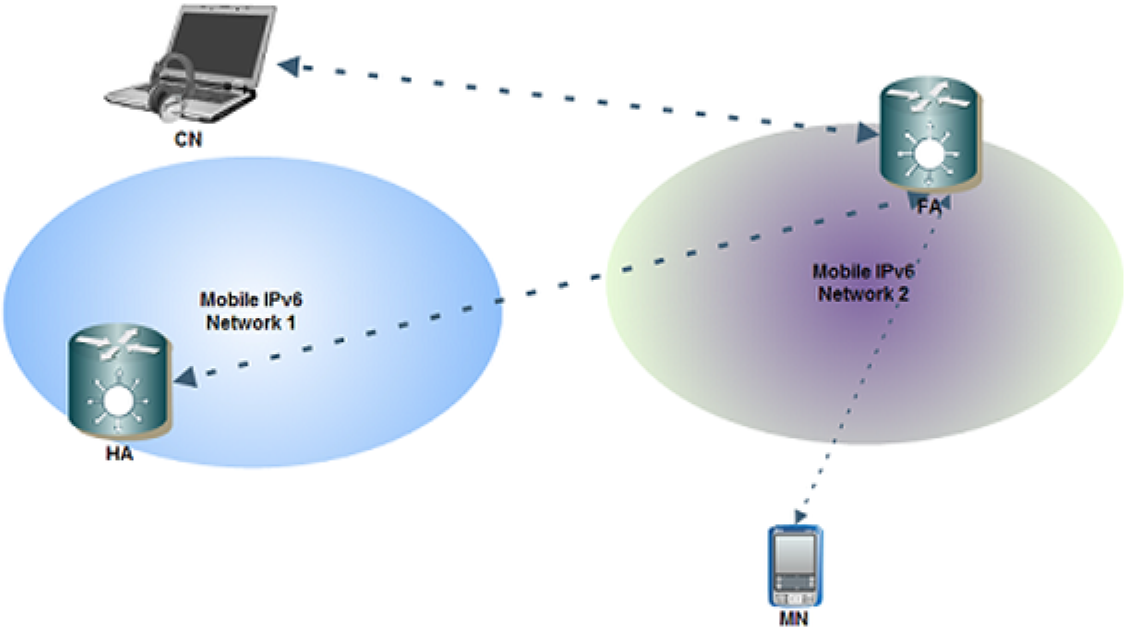

Figure 2.3: *Mobile IPv6 overview - MIPv6 is able to support seamless mobility more efficiently than MIPv4 because of its robustness, easiness and reliability. MIPv6 also supports route optimization which results in effective route creation between the MN and the CN.*

solicitation to the new address. DAD takes some time which increases handover latency. To deal with the DAD's additional time during handover, the MN carries out DAD at the same time of its communications. The MN sends binding updates (BUs) to the HA and the CN when the assembling of CoA is finalized [32].

MIPv6 is able to support seamless mobility more efficiently than MIPv4 because of its robustness, easiness and reliability. MIPv6 also supports route optimization which results in effective route creation between the MN and the CN. Nevertheless, sometimes it takes too long to send BUs after handover, which results in packets destined for the MN being dropped [32]. Hierarchical handover for Mobile IPv6 (HMIPv6) and Fast handover for Mobile IPv6 (FMIPv6) were proposed by Internet engineering task force (IETF) as extensions of MIPv6 to enhance its benefits [15]. HMIPv6 concentrates on localizing the mobility management by minimizing signaling load within a network. FMIPv6 offers anticipated handovers by using Layer 2 triggers to initiate the handover process beforehand [15]. HMIPv6 and FMIPv6 mobility management protocols will be explained in detail in the following sub-sections. Furthermore, FHMIPv6 and Seamless MIP (SMIP) protocols are introduced later on.

2.1.2 Hierarchical Mobile IPv6

HMIPv6 (RFC 4041) [45] has been proposed by IETF to reduce the amount of signaling load to the CN and the HA by allowing the MN to register in a domain locally (see Figure 2.4). The MN does not require sending BUs to the CN and the HA like in flat MIPv6 [6].

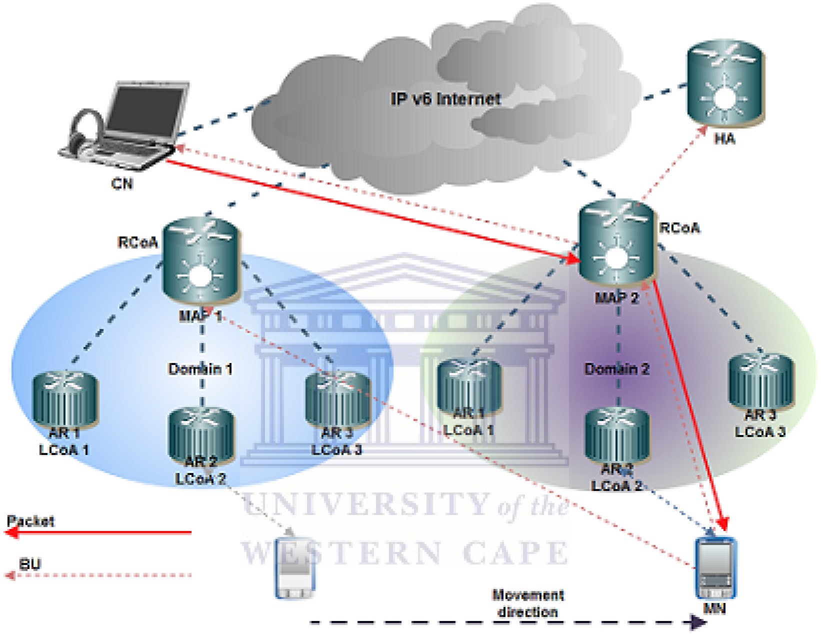

Figure 2.4: *HMIPv6 overview - The MN does not require sending BUs to the CN and the HA like in flat MIPv6. The MAP in HMIPv6 provides support for the hierarchical arrangement and manages the binding process for the MN present in its domain.*

Mobility anchor point (MAP), a conceptual entity provides support for the hierarchical arrangement [6]. MAP is a router that manages the binding process with the MNs present in its domain and it is normally located at the edge of the network. It controls ARs and receives packets destined for the MNs inside its domain. When handover takes place, the MN must register with the new MAP serving that network domain. The MAP serves as a HA for the MN in that it interrupts the packets destined for the MN's address and tunnels them to the CoA of the MN in the foreign network. Once the MN changes its CoA in the MAP domain, it registers the new CoA with the MAP; this is labeled local CoA (LCoA) [6]. To communicate with nodes outside the domain, the MN obtains a regional CoA (RCoA), which is the address of the current MAP. The MAP binds the MNs RCoA and the LCoA after the MN sends BUs and the MAP sends back the BAck to the MN notifying the successful registration. Every time the MN changes its RCoA, a binding update is sent to the HA of the MN [45]. The hierarchical arrangement contributes to minimizing the location update signaling since the regularity of the HA registration is reduced. When using HMIPv6, the MN only executes HA registration when it moves to another MAP domain. If the MN moves within the MAP domain, then there is no need for HA registration. This technique helps to minimize the total handover delay by decreasing the HA registration delay [46].

2.1.3 Fast Handover for Mobile IPv6

MIPv6 defines procedures which include movement detection, IP address configuration, and location update for the MN to retain connectivity during handover. Real-time applications such as VoIP and video conferencing are affected as a result of the combined handover latency. These real-time applications can benefit from reduction of this latency [30].

FMIPv6 (RFC 4068) [23] has been proposed as a remedy to reduce the disturbance of communication on the MN as it moves from one point of attachment to the other. This mechanism enables the MN to send or receive packets from the period of time it de-associates with one point of attachment in a subnet to the period of time it associates with a new CoA from the new point of attachment in a new subnet. The main objective of FMIPv6 is to leverage information from Layer 2 to either anticipate or promptly react to a handover incident. This permits the MN to associate with the new point of attachment more quickly [32].

FMIPv6 uses bi-direction tunnels (BDT) between the previous access router (pAR) and the new access router (nAR) to transfer data packets during handover (see Figure 2.5). The pAR is the router that the MN is currently connected to, whereas, the nAR is the router that the MN is about to connect to. FMIPv6 technique decreases the handover delay by decreasing the address resolution delay. The new CoA of the MN is pre-configured before the MN connects to the nAR [32].

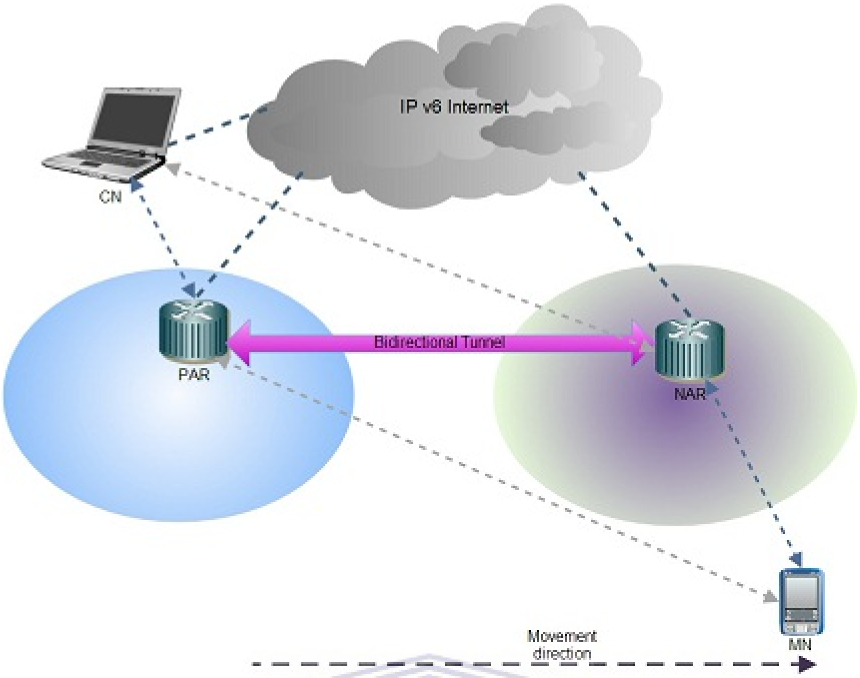

Figure 2.5: *FMIPv6 overview - FMIPv6 uses bi-direction tunnels between the pAR and the nAR to transfer data packets during handover. The pAR is the router that the MN is currently connected to, whereas, the nAR is the router that the MN is about to connect to.*

FMIPv6 differentiates between two forms of handover, reactive and anticipated, which are both tunnel-based. A reactive handover denotes a situation where the MN breaks its association with the pAR before it can make an association with the nAR, and it is referred as a break-before-make handover. An anticipated handover denotes to a situation where the MN makes an association with the nAR before it breaks its existing association with the pAR, and it is referred as make-before-break handover. In both situations, whether reactive or anticipated, the MN may configure an IPv6 address in advance before the handover takes place, by utilizing FMIPv6 messaging information [23].

The FMIPv6 messaging (see Figure 2.6) includes;

- Router Solicitation for Proxy (RtSolPr) message, from the MN to the pAR.
- the Proxy Router Advertisement (PrRtAdv) message, from the pAR to the MN,

- Handover Initiation (HI) message, from pAR to nAR and
- Handover Acknowledgement (HAck) message, from nAR to pAR.

Furthermore, there are more messages involved such as fast binding update (FBU), fast binding acknowledgement (FBAck) and fast neighbor advertisement (FNA).

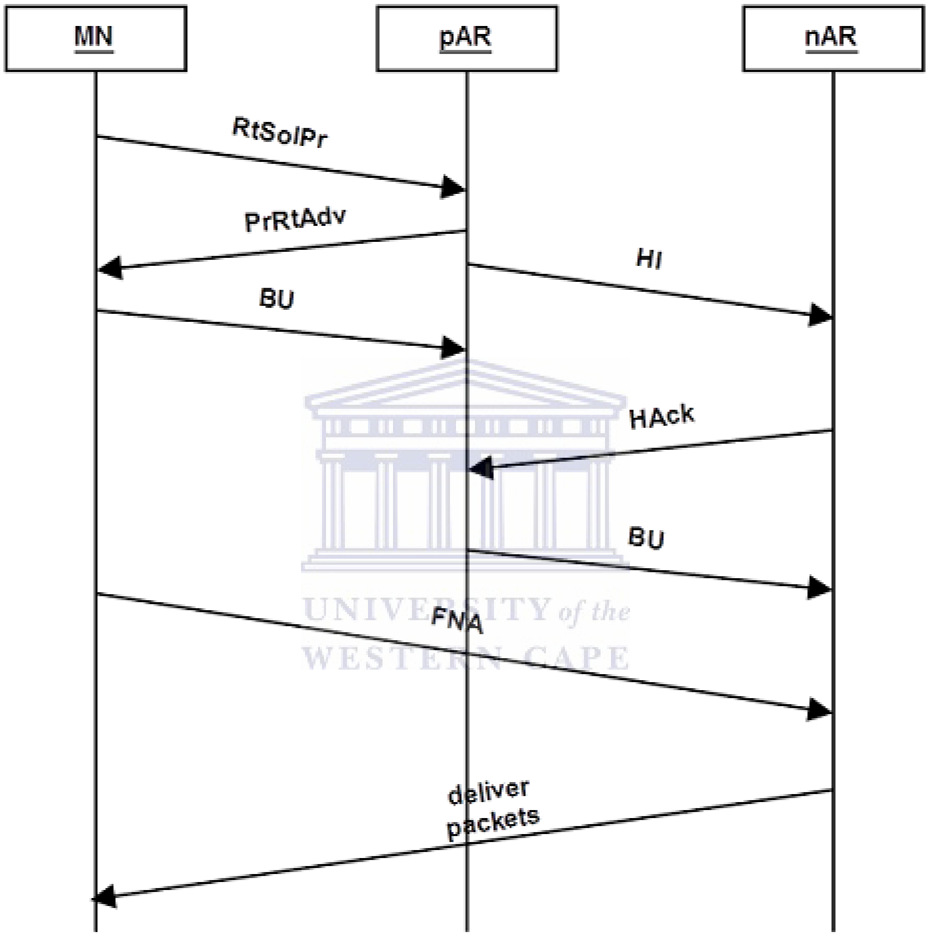

Figure 2.6: *FMIPv6 messaging enables fast and lossless handovers of the MN from the pAR to the nAR.*

A fast handover procedure is instigated once the MN sends a router solicitation proxy (RtSolPr) message to the pAR after it detects a handover is necessary. The MN also sends the RtSolPr message to the next AR. The pAR responds by sending a proxy router advertisement (PrRtAdv) message to the MN, which holds the information of the nAR whether it is known, unknown or linked to the same AR. If the nAR is known then the PrRtAdv will contain a network prefix that will be used to create a new CoA. After the new CoA is created using stateless address configuration, the MN sends an FBU to the pAR before the actual handover starts and the pAR or the nAR responds by sending an FBAck to make sure the binding is a success. FNA is sent by the MN if it moves to a new network to trigger the packet forwarding from the nAR [23].

The pAR and the nAR exchange messages between them to enable sending of packets that result in decrease of BU latency. The pAR sends an HI message to the nAR demanding a new CoA registration for the MN and it also holds the previous CoA of the MN. The nAR will then send HAck message to state whether it accepts or rejects the new CoA. If the new CoA is accepted, the pAR sets up a tunnel to the nAR. To create this tunnel, the MN sends a FBU message to its pAR and the pAR starts to tunnel the packets destined for the previous CoA to the new CoA and the tunnel is up until the MN finishes the BU [23].

2.1.4 Fast Handover for Hierarchical Mobile IPv6

Jung et al. [20] proposed combining HMIPv6 and FMIPv6 extensions to MIPv6 (see Figure 2.7). Fast handover for hierarchical mobile IPv6 allows signaling overhead and BU delay during handover to be reduced by using HMIPv6 procedures. Furthermore, movement detection latency and new CoA configuration delay during handover are reduced by utilizing FMIPv6 processes. When the MN associates with a new MAP domain, HMIPv6 procedures are performed with the HA and the MAP. If the MN moves from a pAR to a nAR within the domain, it follows the local BU process of FHMIPv6. Packets sent to the MN by the CN during handover are tunneled by the MAP en route for the nAR [20].

FHMIPv6 supports both network-initiated and mobile-initiated handovers. Network-initiated handover involves Layer 2 triggers from the pAR or nAR notifying that the MN is on the move. The following steps are involved in FHMIPv6 procedure [21]:

- The MN sends the RtSolPr message to the MAP, based on Layer 2 handover anticipation. The RtSolPr includes information about the Layer 2 address or identifier of the involved nAR.
- The MAP sends the PrRtAdv message to the MN in response to the RtSolPr message. The

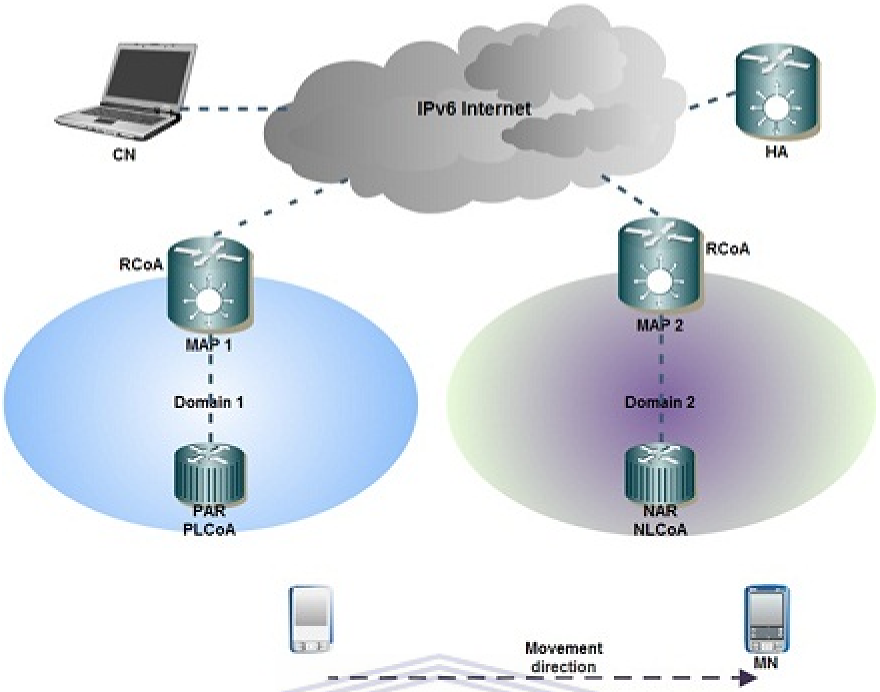

Figure 2.7: *FHMIPv6 overview - A handover tunnel is established between the MAP and the nAR, rather than between the pAR and the nAR, and the MN exchanges signaling messages with the MAP, rather than the pAR.*

PrRtAdv has information about the Layer 2 address or identifier of the involved nAR.

- The MN sends a FBU message containing PLCoA and IP address of the nAR to the MAP.
- The MAP sends a HI message to the nAR after receiving the FBU message. A BDT between the MAP and the nAR is established as a result.
- The MAP sends FBACK messages towards the MN over PLCoA and NLCoA. The MAP starts sending packets to the nAR destined for the MN by using the tunnel.
- When the MN detects that it is moved in the Layer 2, it sends FNA messages to nAR. Then the nAR delivers the buffered data packets to the MN over the PLCoA.
- The MN then follows the normal HMIPv6 operations.

- Finally, the MAP sends local binding acknowledgement (LBACK) in response to the LBU and the HMIPv6 procedures will be followed again.

2.1.5 Seamless Mobile IPv6

S-MIP was proposed by Hsieh et al. [16]. Even though S-MIP has not been standardized by the IETF, its processes are similar to FHMIPv6 and it is considered as a further extension of FHMIPv6. S-MIP is a seamless handover protocol for hierarchical MIP architectures that enables the reduction of time period the MN fails to send and receive data packets during handover. As a result, communication disruption during Layer 3 handover is reduced. Data packets are delivered to the MN while it is still connected to the pAR. A new node called *Decision Engine* (see Figure 2.8) is used to observe movements of the MN and decides how to handle the handover [16].

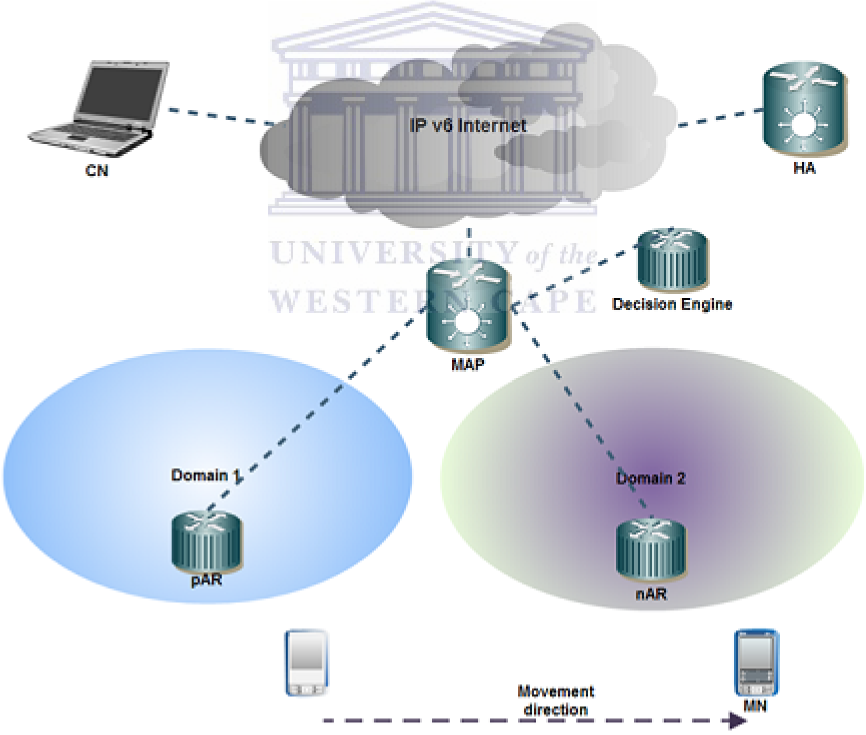

Figure 2.8: *S-MIP overview - S-MIP Architecture builds on the fast handover and hierarchical schemes and introduces the use of an intelligent handover mechanism utilizing a decision engine [16].*

When handover is initiated, data packets received by the MAP from the CN are replicated and sent to both the pAR and the nAR concurrently and are marked with a *Simulcast (Scast) bit* in the IP header. A BDT is created between the pAR and the nAR whereas in FHMIPv6 the tunnel is created between the MAP and the nAR [16].

As in HMIPv6, FMIPv6 and FHMIPv6, Layer 3 handovers are initiated by the Layer 2 triggers that can be initiated by the MN or the network. The only difference is the initial messages. Mobile-initiated predictive S-MIP handover procedure activates when a Layer 2 trigger is initiated by the MN. It sends the RtSolPr message to pAR, which comprises the information to identify the nAR. Then Handover Initiation- handover acknowledgment (HI-HACK) messages are exchanged between pAR and nAR to initiate a BDT and agree on the MN's next link CoA (NLCoA). Then the PrRtAdv message containing information about the MN's NLCoA is sent to the MN by the pAR. The Layer 3 handover is initiated by the MN by sending the FBU message to the pAR. The MAP receives a *Simulcast* message from the pAR informing the MAP to set the *Sbit* in packets. The pAR sends the FBACK message to NLCoA and previous link CoA (PLCoA) [16].

Table 2.1: *Handover performance comparison of IPv6 mobility protocols.*

	Classification	**Delay**	**Packet loss rate**	**Signal load**
MIPv6	Standard Mobile IP	Poor	Poor	Poor
HMIPv6	Hierarchical management scheme	Acceptable	Acceptable	Good
FMIPv6	Fast switching scheme	Good	Good	Very poor
FHMIPv6	Fast hierarchical management scheme	Good	Good	Good
S-MIP	Similar to FHMIPv6 scheme	Good	Good	Good

2.1.6 Related work

After studying the five mobility protocols, it is clear that they all manage the handover in different ways. Table 2.1 compares these protocols qualifying to how they manage delay, packet loss and signaling load during handover. Literature study indicates that handover latency experienced by MIP and its extensions has been studied in numerous publications [10] [13] [15] [24] [50] [55].

Gwon *et al.* [13] investigated a handover performance of MIP and its extensions (see Table 2.2). The investigation involved simulating 100,000 mobile subscribers across a large scale experimental network consisting of WLANs. The results indicated that HMIPv6 suffers considerably less handover signaling overhead than FMIPv6. FMIPv6 achieves the best handover performance exhibiting the lowest latency and data loss. FHMIPv6 achieves similar handover performance to that of FMIPv6 but with improved handover signaling overhead. FHMIPv6 is also more robust to AR and HA failures.

Table 2.2: *Handover latency presented in [13].*

Protocol	**Handover latency in milliseconds (ms)**
MIPv6	1300
HMIPv6	300 - 500
FMIPv6	200
FHMIPv6	200 - 400

Hsieh and Seneviratne [15] compare the five IPv6 handover protocols discussed in Section 2.1 (see Table 2.3). The authors use the topology and link delays shown in Figure 2.9.The results show that S-MIP performs best under both ping-pong and linear movement during handover. All other protocols suffer from packet loss and performance degradation. Optimization of S-MIP is proposed to improve its performance. Chow *et al.* [10] propose a protocol for both macro and micro mobility management in mobile broadband wireless access networks. The mobile-initiated handovers are based on Signal-to-Noise-and-Interference-Ratio (SNIR). The proposed protocol is similar to FHMIPv6, although the terminology used is different, for example, the MAP is replaced by a domain AR. The experiments are conducted in OPNET simulator. The topology used is similar to Figure 2.9 but uses 802.16e standard. In the results, the handover latency is defined as the delay incurred for obtaining a new CoA. It is not the communication between the MN and the CN. The proposed scheme experiences 128 ms delay while obtaining a new CoA.

2.2 Mobility management protocols in Wireless Mesh Networks

A literature review of mobility management protocols in WMNs was conducted and is reported in this section. WMN mobility protocols tend to focus on *client-side transparency*, as reported in Section 2.2.1. In addition, other WMN protocols are highlighted briefly concentrating on *intra-*

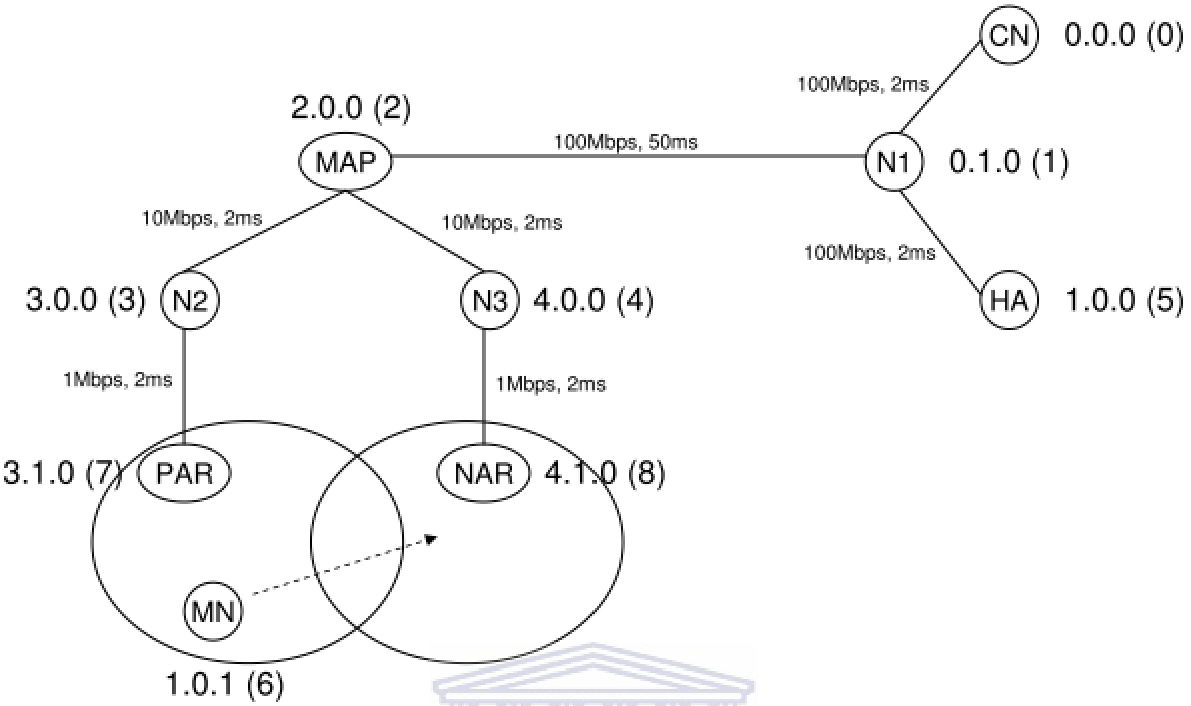

Figure 2.9: *Topology used in [15] and [10]. Both CN and HA are connected to an intermediate node (N1) with 2ms link delay and 100 Mbps links. The link between N1 and the MAP is a 100 Mbps link with 50 ms link delay. The MAP is further connected to the intermediate nodes N2 and N3 with 2ms link delay over 10 Mbps links. N1 and N2 are connected to PAR and NAR with 2ms link delay over 1 Mbps links.*

Table 2.3: *Handover latency presented in [15].*

Protocol	**Handover latency in milliseconds (ms)**
MIPv6	814
HMIPv6	326
FMIPv6	358
FHMIPv6	270
S-MIP	100

domain mobility support in Section 2.2.2 and *inter-domain* mobility support in Section 2.2.3.

2.2.1 Client-side transparency

Client-side transparency refers to when the MN is unaware of the mesh networking backbone. The MN views the network as one big network and associates with an AP using a traditional association mechanism in WLANs. This sub-section presents the following *client-side transparency* schemes: *SMesh* [3], *iMesh* [33] and *Ant* [51] mobility protocols for WMNs [31].

SMesh [3] is a scheme developed at John Hopkins University by the Distributed System and Networks Lab. *SMesh* provides seamless mobility and fast handover without the clients pre-installing anything (see Figure 2.10). Any 802.11 mobile device which supports dynamic host configurationl protocol (DHCP) will be able to connect to *SMesh* network. *SMesh* is a wireless mesh network that allows unmodified clients to connect and roam freely between access points on a wireless coverage area. The wireless clients perceive the wireless mesh as a single omni-present access point. All nodes have the same service set identification (SSID) using independent basic service set (IBSS) in ad-hoc mode. Some nodes are connected to the Internet (mesh Internet gateways). As the client moves, the mesh nodes continuously monitor the mobile client connectivity to decide the best access point that should service the client [3].

SMesh uses a DHCP server to allow mesh routers to rapidly locate and manage mobile client's connectivity. *SMesh* client is associated with a client control group (CCG) and a client data group (CDG) which are multicast groups. CCG consists of a group of access points which communicate among each other to determine the best set of access points to serve a client. A CDG consists of a group of access points from CCG which have the best connectivity to the client. For example (see Figure 2.11) IP address of Client A is 10.1.2.3 and its CCG IP address is 224.1.2.3. Each AP calculates the distance to the client and compares the results with other members of the group. APs with the best results form a new CDG multicast group. After extracting IP address from the client, CDG IP address is created, as in this example (see Figure 2.11) 255.1.2.3 is the CDG IP address. Although, handover performance is improved using this multicasting concept, bandwidth use is rapidly increased [3].

iMesh [33] is another WMN architecture used for community networking applications. *iMesh* uses 802.11b technology for its access mesh routers and aims to provide seamless network services to mobile clients. Like *SMesh*, client side transparency is an essential objective of the design of

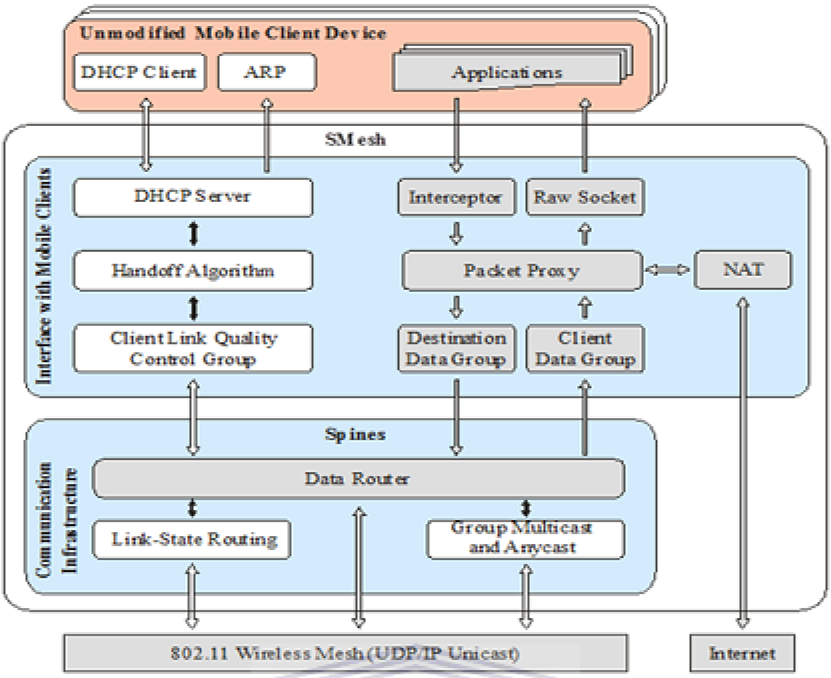

Figure 2.10: *SMesh architecture - SMesh is based on Spines messaging system that provide transparent multi-hop unicast, multicast and anycast communication between the mesh nodes. SMesh provides the illusion of a single distributed AP to MNs. This is accomplished by providing connectivity information to mesh clients through DHCP.*

this architecture. Mesh clients are not aware of the mesh backbone. Hence they view they whole network as a single AP. When a mesh client is on the move and associates with a different AP (see Figure 2.12), a Layer 2 handover mechanism initiates routing updates in the mesh backbone. The handover procedure involves both Layer 2 and Layer 3 mechanisms. When implementing *iMesh*, [33] used two solutions: transparent mobile IP, which is similar to MIP and a flat routing scheme, which according to [33] is much better than a traditional Layer 3 handover technique.

The architecture of *iMesh* uses 802.11-based APs in infrastructure mode that provides complete client-side transparency as opposed to operating in ad hoc mode. This way, the system is able to operate without any specialized software on the MNs. The MNs understand the network is wireless LAN but the APs are connected by the distribution system (DS) that are made of wireless backbone network usually called wireless distribution system (WDS) (see Figure 2.13).

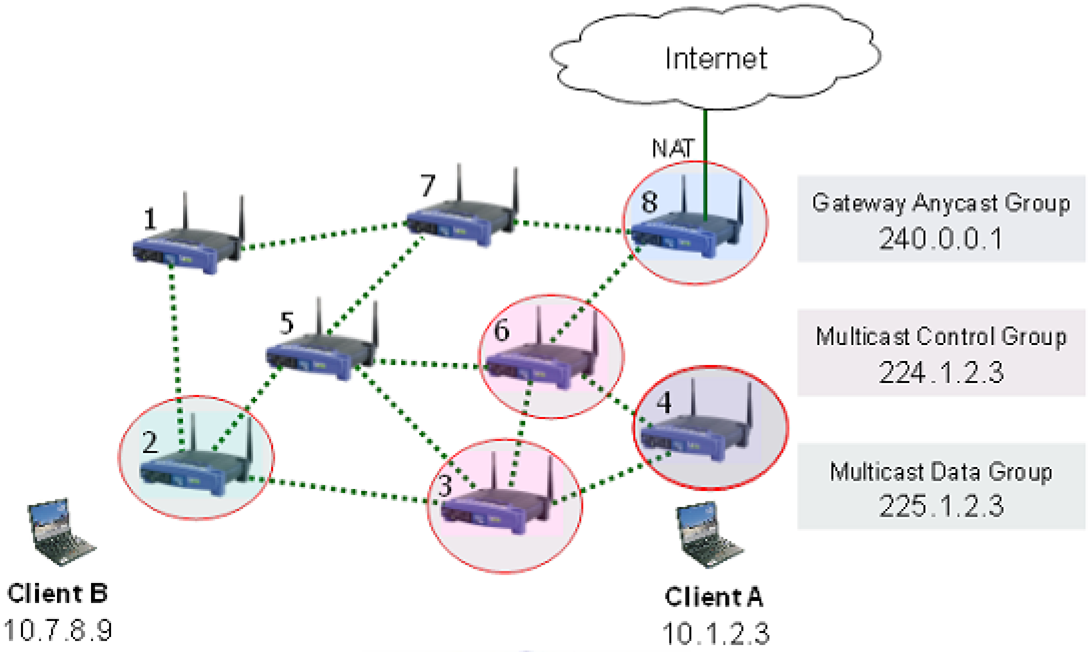

Figure 2.11: *SMesh example - Client A communicates with Client B. While Client A is on the move, mesh nodes 3, 4 and 6 receive DHCP request and calculate the power of the request. In this case, mesh node 4 indicates being the nearest, as a result, mesh node 4 joins the multicast data group 225.1.2.3.*

WDS links are used to communicate between neighboring APs. The WDS links are configured to the neighboring APs by emitting Layer 2 beacon messages that are eavesdropped by neighbor discovery protocol in infrastructure mode. When a MN moves to another network and associates with a new AP, the association triggers a routing update in the network and data packets destined for the MN are sent to the new AP, which is usually not mobile and is powered by a power outlet. The power outlets enable the researchers to get rid of power optimization issues when designing the mesh network architecture. Proactive routing protocols, which are based on approaches such as link state and distance vector, are used instead of on demand routing approaches associated with mobile ad hoc networks (MANETs). This enables the mesh network to be steady for a long period of time [33].

Ant [51] is a another WMN mobility management scheme which also employs client side transparency like *SMesh* and *iMesh*. It creates bi-directional tunnels between previous mesh

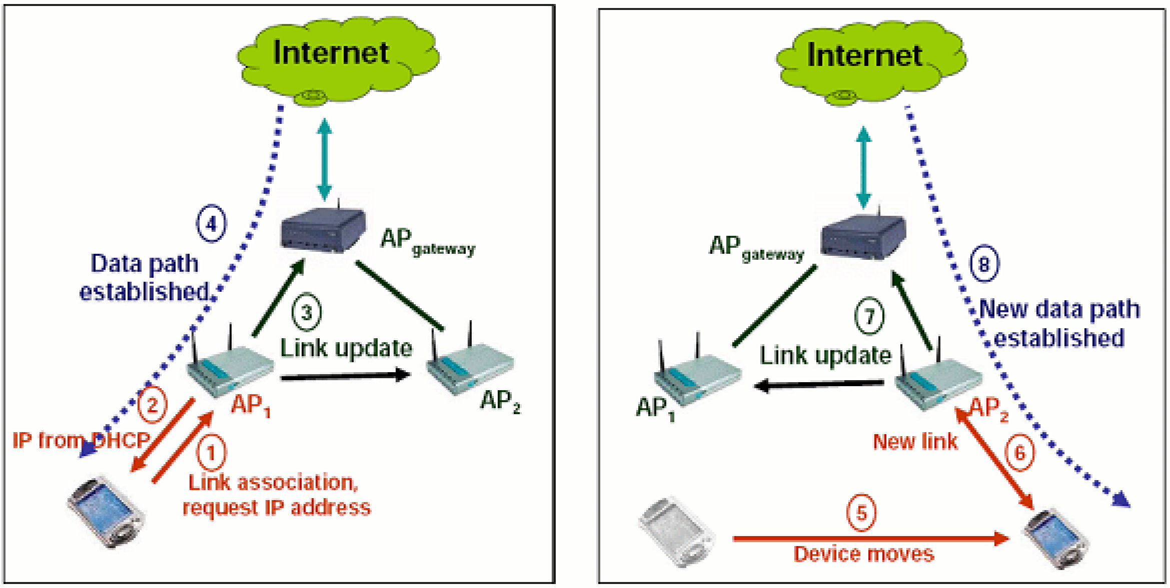

Figure 2.12: *iMesh overview - When a MN moves to another network and associates with a new AP, the association triggers routing update in the network and data packets destined for the MN are sent to the new AP. This handover process involves both Layer 2 and Layer 3 procedures.*

nodes and a new mesh node during handover, similar to fast handoff [RFC 4068] [23]. This scheme is used to reduce handover latency and packet loss. A location server on a neighborhood mesh node is used by the new mesh node to determine the previous mesh nodes IP address. The previous node decreases packet loss by buffering the packets when the media access control (MAC) layer de-association event is triggered [51].

Even though *SMesh*, *iMesh* and *Ant* WMN mobility management protocols are implemented differently, they all use a client side transparency scheme. This transparency feature enables mesh nodes to support mobility in any heterogeneous network because the mobility management protocol is not incorporated into a mesh node's stack. However there will be limitations to the MN trying to roam between a 4G network and these client side transparency networks. This is so because these networks will be using different mobility management mechanisms, which will be difficult to manage. 4G networks will be a combination of wired and wireless networks interworking together. Therefore, mobility management protocols such as MIPv6, HMIPv6 and

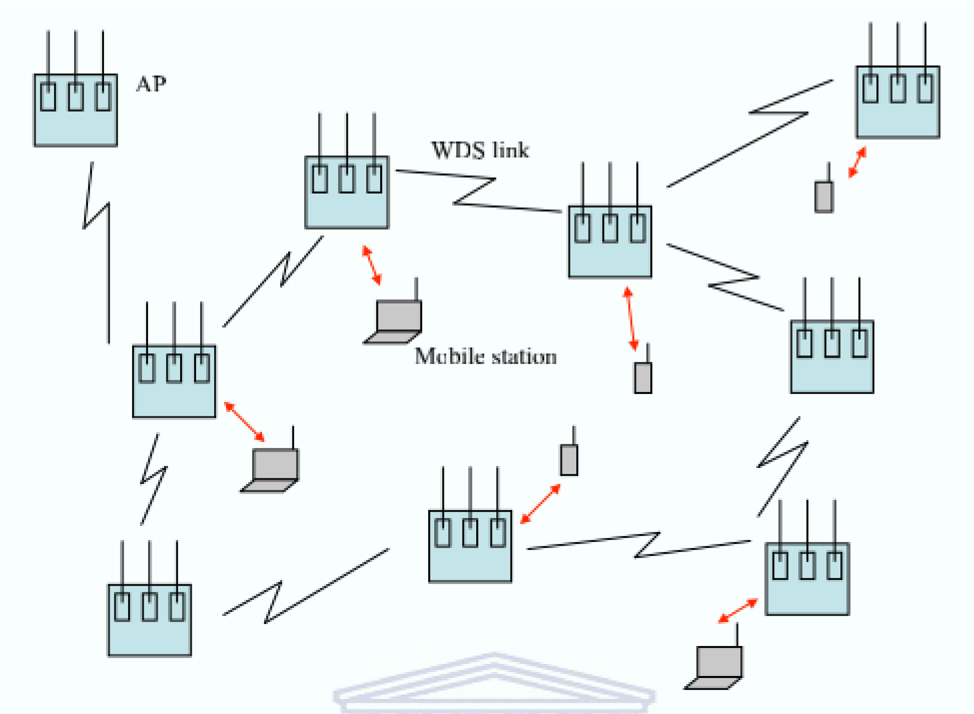

Figure 2.13: *iMesh architecture - WDS links are used to communicate between neighboring APs. The WDS links are configured to the neighboring APs by emitting Layer 2 beacon messages that are eavesdropped by neighbor discovery protocol in the infrastructure mode.*

FMIPv6 will be essential for future seamless mobility in 4G networks [31].

2.2.2 Intra-domain mobility support

Intra-domain [14] handovers occurs when the MN moves within a confined administrative domain. A domain is defined as a set of network resources managed by a single administrative entity that authenticates and authorizes access for the MNs. An administrative entity may be a service provider or an enterprise. Mobility management protocols such as MobileNAT [4], DHCP and ad hoc on demand vector (AODV) [40], and Mobile Party [44] support intra-domain mobility.

MobileNAT [4] is a WMN mobility management protocol that combines NAT procedures with mobility management processes. MobileNAT lets a gateway mesh router NAT all the traffic destined for Internet nodes using the public IP address of the gateway, which is referred to as an anchor node (AN). Each MN associates itself to one mesh router when it first boots up.

Intra-domain mobility enables the MN to roam in the AN's domain [4].

DHCP and AODV [40] can also be used as a mobility solution similar to MobileNAT. Each MN obtains an IP address dynamically that it retains when it is moving from one mesh router to the other. When a MN associates with a mesh router, the mobility agent (MA) in the mesh router broadcasts corresponding IP address routes in the AODV mesh network. Proactive updates are enabled by the MA in the other mesh routers when the MN is detected or lost. These proactive updates increase the handover performance.

Mobile Party is another WMN mobility management protocol that uses address management for mobility support [40]. In Mobile Party [44], an address tree is used to allocate new addresses for the mesh nodes. These addresses are unique and assigned dynamically after considering the location of the MN in the mesh network. Association of neighboring mesh nodes is determined by the levels of node addresses in the address tree. The new neighbor sends a newly configured address to the MN and it also becomes the new parent of the MN in the address tree. Routing is simplified and the handover delay is reduced by this tree-based address management mechanism [44].

2.2.3 Inter-domain mobility support

Inter-domain [52] handovers occur when the MN changes its point of attachment from one administrative domain to another administrative domain. AODV pre-handover route discovery (AODV-PRD) [48], OLSR-FastSync [47] and *iMesh* [33] are some existing mobility management protocols that support both intra-domain and inter-domain mobility.

AODV-PRD[48] aims to reduce Layer 3 handover latency in WMNs that are using AODV ad hoc routing protocol. Multi-hop routes are created in the handover target subnet just before the actual handover. These routes are created to evade route re-discovery delays after handover has occurred [48].

Unlike AODV-PRD, which focuses on AODV-based WMNs, OLSR-FastSync [47] focuses on WMNs using optimized link state routing (OLSR) protocol. In the OLSR-FastSync scheme, the routes to the MN can be calculated straightaway after a handover occurs by enabling the MN to discover, select and declare multipoint relays in the handover target network quickly. These fixed relays of the handover target network also enable the MN to acquire the network topology and

Table 2.4: *WMN mobility management protocols summary [53]*

	Mobility domain	**Address allocation**	**Address management**	**Routing**
MobileNAT	Intra	Unique IP address in mesh backbone, public IP address in internet	No address change inside domain	AODV-Spanning Tree (AODV-ST)
DHCPandAODV	Intra	Dynamic IP address	No addr. change inside domain	AODV-ST and tunneling
Mobile Party	Intra	Tree-based	Address change when moving	Tree-based
AODV-PRD	Intra and Inter	Unique IP address	Address change when moving	AODV
OLSR-FastSync	Intra and Inter	Unique IP address	Address change when moving	OLSR
iMesh	Intra and Inter	Unique IP address	Address change when moving	OLSR
SMesh	Intra	MAC address	No address change inside domain	Link state
Ant	Intra	Unique IP address	No address change inside domain	Non-std IP routing

gateway information immediately after the handover [47].

AODV-PRD[48], OLSR-FastSync [47], and Mobile Party[44] schemes depend on MIP to manage the inter-domain mobility support. These Layer 3 mobility management schemes for WMNs just manage mobility within an administrative domain and let MIP handle mobility between two different administrative domains [53]. Table 2.4 illustrates a summary of the mobility management protocols in WMN that were discussed in this section.

2.3 Summary

This chapter presented work related to mobility management for both WLANs and WMNs. We examined IPv6 mobility management protocols in WLANs such as MIPv6, HMIPv6, FMIPv6, FHMIPv6 and S-MIP. Mobility management protocols in WMNs were also discussed. These WMN protocols that were discussed focused mainly on client-side transparency, *intra-domain* and *inter-domain* mobility support. Client-side transparency schemes such as *SMesh*, *iMesh* and

Ant mobility protocols for WMN were presented. This transparency feature enables mesh nodes to support mobility in any heterogeneous network because the mobility management protocol is not incorporated into a mesh node's stack. However it was noted that there will be issues with the MN trying to roam between a 4G network and these client side transparency networks. This is so because these networks will be incompatible with each other and difficult to manage.

After studying the five mobility protocols for WLANs, it is clear that they all manage the handover in a different way. That is why they all have advantages and disadvantages when compared according to how they manage delay, packet loss and signaling load during handover. These parameters are discussed in detail in Section 3.4.1. These traditional mobility management schemes can trigger major performance degradation when directly implemented to WMNs because of the multi-hop feature in WMNs. The traditional mobility management schemes rely on infrastructure networks to guarantee good performance. The next chapter is on this challenge with a research question and describes a method used to answer this question.

Chapter 3

Methods and experimental design

This chapter details the research questions and research method. There are many challenges and research gaps associated with mobility management. Section 3.1 introduces these challenges and gaps. Section 3.2 presents the research question and Section 3.3 discusses the research method used to answer this research question. Section 3.4 presents an experimental design to measure handover performance with two simulations. The first simulation has a vertical handover configuration. The second simulation has a horizontal handover setup. Results from conducting experiments with the two simulation setups are presented in chapter 4.

3.1 Gaps and challenges

Mobility management in WMNs has still not been researched thoroughly, although a significant amount of research on Wi-Fi, cellular and mobile ad hoc mobility management has been addressed. Networks such as Wi-Fi and cellular depend on infrastructure-based architecture to manage traffic delivery between a MN and a CN, while ad hoc networks depend on multi-hop routing, route maintenance and recovery. The emphasis of handover in an ad hoc network is discovering a multi-hop route rapidly to make sure packets are delivered through the new path as soon as a link goes down. Traditional mobility management schemes cannot be simply extended for multi-hop ad hoc networks because mobility management protocols for infrastructure-based networks with wireless nodes at the edge rely on the good performance of the infrastructure-based network infrastructure. When the traditional mobility management protocols are applied to WMNs, there is no longer assurance for the good performance of delivering signaling traffic [53].

Traditional mobility management protocols for infrastructure-based networks described in Chapter 2 have drawbacks when implemented in WMN environment. For example:

- Hierarchical trees are created when implementing HMIPv6, which make it difficult in WMN, since the network topology is always changing and it is a challenge placing MAPs during network deployment in this environment. However, non-mesh networks have unchanging fixed links [31].
- The period of time of transferring BUs can be compromised in WMNs as a result of its dynamic characteristic nature. Transferring of BUs to the MAP would vary because of the route changes that would result in degradation of performance of real-time applications such as VoIP and video conferencing during handover [31].

Some other major challenges with WMNs include scalability and security. As the amount of mesh nodes increase in the mesh network, routing overhead also increases. Similarly, as the number of hops increase, the performance of the network degrades significantly. Ad hoc networks also lack rigid security solutions as a result of the WMN topology, which tends to be an unplanned graph where routes change dynamically[1].

3.2 Research questions

This thesis answers the following question:

> **How do mobility management protocols such as MIPv6 and FHMIPv6 behave for handover with mesh networks?**

Several performance metrics are available for evaluating handover management. These metrics demonstrate different behaviours of the overall network or the individual nodes. QoS parameters are studied in this experiment to evaluate the performance of the network during handover. QoS is a common concern in wireless access networks because of the convergence of the broadband Internet and mobile communications, which has resulted in the increase in use of applications such as VoIP and video conferencing [28]. These applications require minimum disruption during communication. The main QoS parameters in handover management are throughput, delay and packet loss. Real-time applications require an acceptable level of these QoS parameters for optimum performance. Below is a brief definition of each metric:

- **Throughput** is the total amount of data that is transmitted at a certain period of time. Unlike the other QoS parameters, throughput is primarily useful for non-real time applications, although it may be useful for measuring total data traffic for applications that are sensitive to packet loss [25]. For example, if the throughput is 85 Mbit/s in a 100 Mbit/s connection, the channel efficiency is 85%.
- **Delay (Latency)** is the time period that passes between the last data packet received by the MN through the previous point of attachment and the first data packet received by the MN through the new point of attachment during handover. Latency is important for delay sensitive applications because it can result in interruption or poor quality of communication service if there is too much delay [37].
- **Packet loss** is defined as the number of data packets dropped during handover. Higher layer data traffic dropped by Layer 2 can be due to consistently failing retransmissions. This statistic reports the number of the higher layer packets that are dropped because the Layer 2 could not receive any ACKs for the retransmissions of those packets or their fragments, and the packets' short or long retry counts reached the Layer 2's short retry limit or long retry limit, respectively [37].

Because mobility management is affected by different variables, other sub-questions that will be addressed are:

- **How is thoughput affected during handover?**
- **How much delay occurs during handover?**
- **How much packet loss is there during handover?**

Mobility management in mesh is not a simple extension of MIPv6 to multihop wireless networks. MIPv6 and its extensions' performance is based on the good performance of mobility-related and signalling traffic delivery in infrastructure networks. However, when these protocols are applied to mesh, the good performance no longer guaranteed. In mesh, signalling messages go through multiple wireless hops. Hence, this increases delay of signal messages. Also, these protocols are designed with a goal of improving throughput but at a cost of signalling overhead.

These additional signalling messages and mobility management signalling messages compete for limited resources. Even low rate signalling traffic can create a negative impact on mesh networks' performance.

3.3 Research method

The study is designed as an exploratory initiative seeking to establish how MIPv6 and its extensions can be used for WMNs mobility management. The study uses only one research method, quantitative research, which is used to gather information in order to answer the research questions and achieve the research objectives. Section 3.3.1 discusses quantitative research method, while Section 3.3.2 addresses experimental quantitative research.

3.3.1 Quantitative research

Quantitative research is one of the most widely used research methods and it involves analyzing objects through numeric representations and statistical analysis. Quantitative research is an empirical research method that uses numbers and quantifiable data. It is typically done by collecting statistical data via questionnaires, interviews, surveys and experiments. This statistical data is intended to define views of people or some tendencies or developments in the society [34]. Quantitative research fits in a *positivist paradigm*, which states that real knowledge is founded on experience of senses and can be acquired by observation and experiment. Positivistic thinkers adopt the French philosopher August Comte's scientific approach as a means of knowledge generation. The outcome of the research represents characteristics used to describe the total population rather than just part of it. The researchers are able to gather useful information from the data being collected from different sources. Unlike qualitative research, quantitative research usually uses standardized methods that afford greater objectivity and the results are more accurate. Recommended actions are deployed to make sure validity and reliability are in place because quantitative research usually involves few variables and many cases. The research is frequently repetitive because of high level of reliability it possesses and it is relies on deductive methods and theories that are examined in a *cause effect order* [34]. Quantitative research advantages include:

- Reliability, thus it is an outstanding way of concluding outcomes and (dis)proving a hypothesis.

- Results are accepted as real and unbiased because external factors are filtered out.
- Quantitative research can be used for testing results attained by qualitative experiments, which can lead to the final conclusion.

3.3.2 Experimental quantitative research

Experimental quantitative research involves studying the causes and effects of correlations, and relies on the use of manipulation of *independent variables* (IV). The main objective of experimental research is to deliver solid evidence for cause-and-effect relationships. This is achieved by producing different outcomes after manipulating one or more variables. The manipulated variable is called the *independent variable*, while the affected variable is called the *dependent variable* (DV) (see Figure 3.1).

Figure 3.1: *Experimental quantitative research involves two types of variables, the manipulated variable is called the independent variable, and the affected variable is called the dependent variable [19]*

The experimental groups begin with equal attributes but the treatment condition can differ, which result to different outcomes. This way, the researcher is certain that the outcome differences are due to the independent variable under investigation. The next section discusses how experimental quantitative method is used to analyse QoS metrics during horizontal and vertical handover with WMNs.

3.4 Experimental design

The experiments are conducted in three main phases of modeling and simulation: *model specification*, *data collection and simulation*, and *analysis* [22]. They are performed in sequence and generally form a cycle, with a return to *specification* following *analysis*. *Specification* is actually devided into two parts: *initial specification* and *re-specification*, with only the latter belonging to the cycle, as shown in Figure 3.2. Specification involves setting up network configurations and parameters. Data collection and simulation phase consist of running the actual simulation and assembling the results. The results are examined in the analysis phase. If adjustments or more simulations are needed, the study goes back to specification phase.

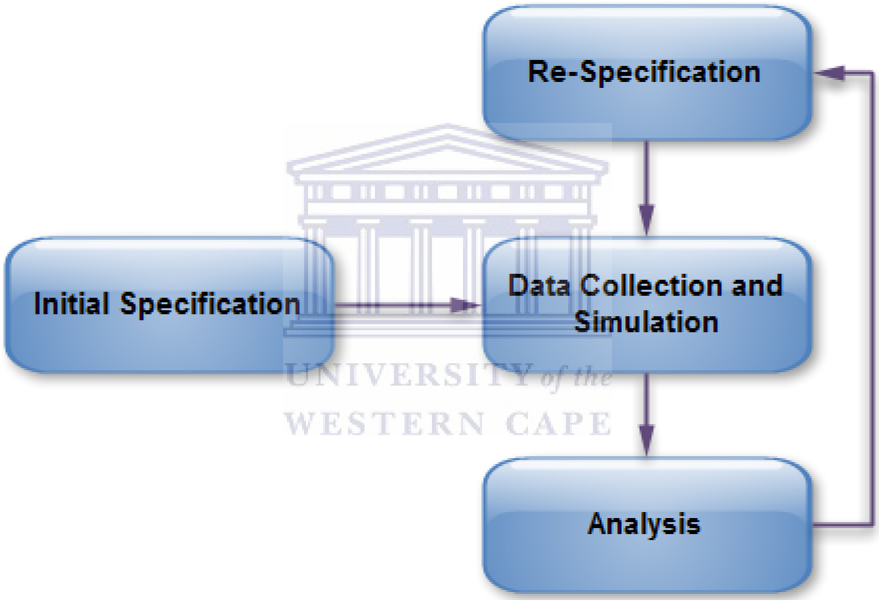

Figure 3.2: *Experimental Design - the experiments are conducted in three main phases of modeling and simulation that includes model specification (initial specification and re-specification), data collection and simulation, and analysis [22].*

The wireless networks that are studied are represented by model specification. The objectives of this research effort are to obtain measures of handover performance and also to make observations concerning the behavior of the models. Simulations are satisfactorily representative of the actual wireless networks and they allow realistic approximations of performance and behavior to be achieved by prototypes. Data is collected in two different forms: *output vector* and *scalar statistics*.

Output vector is a collection of pairs of real values, which contains a list of entries collected during one simulation run and it is the most common form extracted from a simulation. The entries contain two values: IV and DV, which are referred to as *abscissa* and *ordinate*, respectively. Most of the times, the IV of a vector is the *time* and increases as the simulation progresses [22].

On the other hand, *scalar statistics* contain individual values such as averages or probabilities. Scalars are statistics of the set of entries acquired in an output vector. They are created after computing values in an output vector and are of limited use when taken as individual data points. Furthermore, scalars are usually combined to form a graph to show the impact of a variable on other parameters. To produce such a graph, both the DV and IV are recorded as scalars. For example, a graph produced in handover performance analysis might be throughput vs. signaling load, which illustrates performance of the network in delivering packets during handover, as the BUs increase. In this case, the throughput scalar is a DV, while the signaling load scalar is an IV [22].

Finally, the results collected during the simulation are analysed. Where ever necessary, the specifications are re-visited and amendments are made accordingly. Two prototypes are run in simulations to collect data. Section 3.4.1 describes a simulation for vertical handover. Section 3.4.2 describes a simulation for horizontal handover.

3.4.1 Vertical handover simulation

Based on how MIPv6 operates in general, MIPv6 is applied in a wireless environment comprising WLAN and WMN using a simulator model. The objective is to learn how MIPv6 functions in a heterogeneous wireless network. This subsection introduces the simulation environment used for the experiment and also presents the simulation setup that involves the MN moving from one network to the other in order to measure vertical handover performance. Lastly, it discusses the performance metrics used to evaluate handover management performance of MIPv6.

OPtimized Network Engineering Tool version 16.1 (OPNET 16.1) [7] is used in this experiment. OPNET is a commercial network simulation tool that models various IP networks such as Wi-Fi, MANET, WiMAX and UMTS. OPNET simulation involves four steps: *creating models*, *apply* *statistics*, *simulation* and *view results* (see Figure 3.3).

The MIPv6 model in OPNET has been designed and developed with standard MIPv6 features. The OPNET MIPv6 model supports features such as router optimization, BDT between the MN and the HA, IP extension headers which include mobility, routing and destination option extension headers. It also supports neighbor discovery, duplicate address destination modeled as a delay and router advertisements for movement detection, address auto-configuration (stateless) and home agent address detection [9].

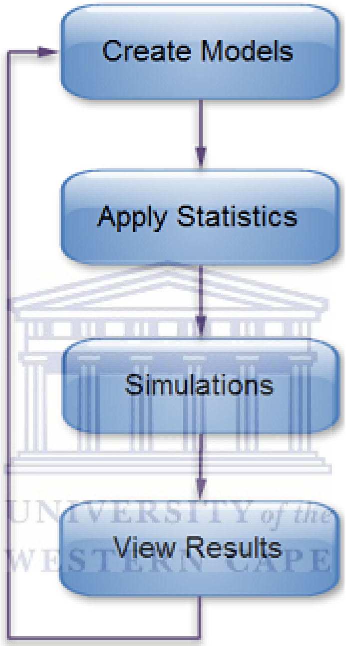

Figure 3.3: *OPNET Flowchart - OPNET simulation involves four steps - creating models, apply statistics, simulation and view results [7].*

In OPNET, a WLAN workstation or server node can be configured as MIPv6 MN or CN with route optimization either enabled or disabled. All regular workstation nodes behave as CNs with no route optimization support. If the MN is initially away from home, and more than one AP exist, the HA needs to be specified. Otherwise, this can be learned from the HA's router advertisements when the MN is at home. Furthermore, the global address of the MN should also be specified and use the same network prefix as the HA [9].

WLAN roaming capability should be enabled on the node to allow the MN to scan and switch to other APs when the signal from the connected AP becomes weak. A router can have many wired or wireless interfaces that act as HAs but each interface needs to be configured individually. HAs and FAs also need to have router advertisements enabled so that MNs can learn of the closest HA [9].

The purpose of this experiment is to quantitatively evaluate the performance of MIPv6 during handover using the OPNET MIPv6 module comparing MIPv6 routing mechanisms: Route optimization (RO) and bi-directional tunnelling. The simulation topology was designed to produce realistic results in the OPNET simulator. The topology (see Figure 3.4) has a WMN (BSS 2) that is connected to the Internet (depicted as a cloud) via a gateway using a point to point (PPP) duplex link. The gateway has two interfaces, one running Router Information Protocol next generation (RIPng) and the other running AODV. The interface running RIPng is connected to the Internet while the interface running AODV communicates with the rest of the WMN. AODV is the ad-hoc routing protocol in the WMN.

WLAN subnets (BSS 0, BSS 1 and BSS 3) are each connected to the Internet via a router in their BSS running RIPng routing protocol. BSS 0 is the home network of the MN and BSS 3 is the home network of the CN. The nodes in the simulation are positioned in a way to provide a total coverage to an area of approximately 200 square meters after considering a transmission range of the 802.11b standard which is being used by all nodes in the scenario. A node's transmission power is set to 0.005 watts and the data rate is set to 11Mbps. This is the data rate that will be used by the MAC for transmission of data frames via the physical layer. The routers also act as APs for the BSSs. Table 3.1 illustrates the summary of the simulation setup settings for this experiment.

OPNET nodes used in this handover experiment are:

- *Mobile/Fixed workstation* is the node model that represents a workstation with client-server applications running over TCP/IP and UDP/IP. The workstation supports one underlying WLAN connection at 1 megabits per second (Mbps), 2 Mbps, 5.5 Mbps and 11 Mbps. It requires a fixed amount of time to route each packet as determined by the IP forwarding rate attribute of the node. Packets are routed on a first-come-first-serve basis and may encounter queuing at lower protocol layers, depending on the transmission rates of the corresponding output interface.

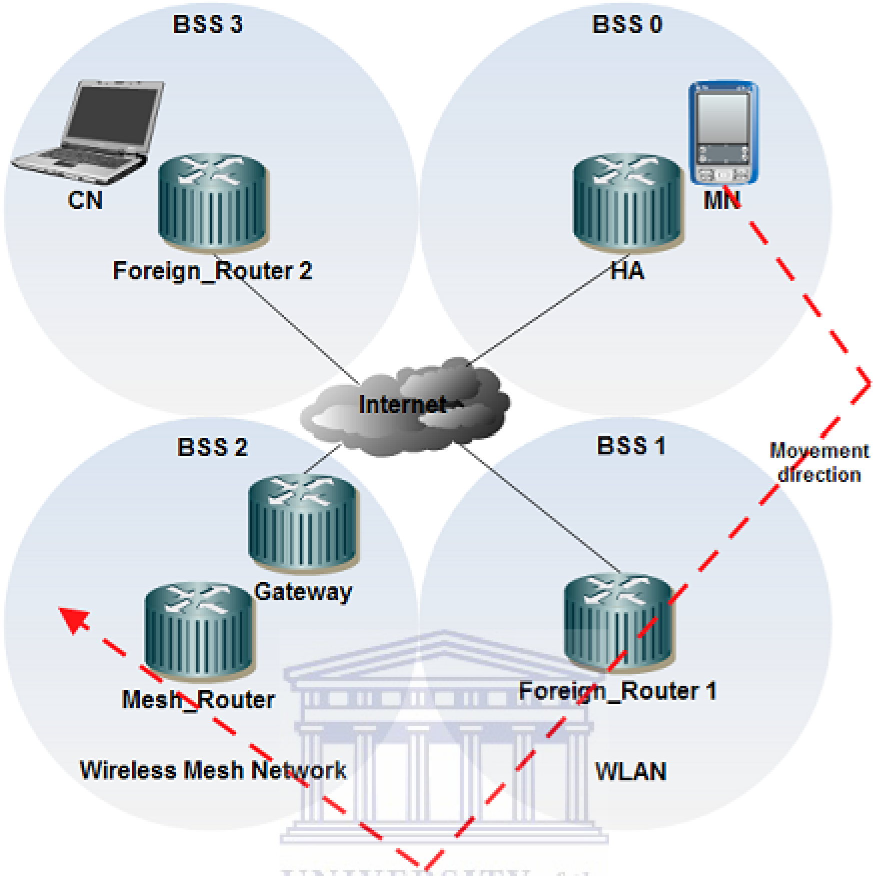

Figure 3.4: *Simulation topology - is composed of WMN (BSS 2) that is connected to the Internet (depicted as a cloud) via a MANET gateway and WLAN subnets (BSS 0, BSS 1 and BSS 3) are each connected to the internet via a router in their basic service sets (BSS).*

- *WLAN Router* supports 802.11 technologies and has two interfaces that allow the router to operate in two separate channels.
- *MANET gateway/router* functions as an AP in the WMN and can also connect mesh nodes to other IP networks or the Internet. It connects the Internet through the Ethernet port and connects to wireless networks by using its three separate interfaces.
- *IP cloud* is a backbone of the Internet and it supports up to 8 serial line interfaces at a selectable data rate through which IP traffic can be modelled. IP packets arriving on any

cloud interface are routed to the appropriate output interface based on the destination IP address.

In OPNET, the process models of MIPv6 and ad hoc wireless network cannot be activated at the same time. Hence, nodes mentioned above are modified to support the deigned MIPv6-based vertical handover prototype. These modified models are developed and incorporated in the existing ad hoc process model. Four new signalling messages are introduced for WLAN-WMN handover support. These four messages are *Gateway Request, Gateway Reply, Registration and Registration Acknowledgement*. The MN sends a *Gateway Request* to request a CoA when it associates with a new point of attachment. The *Gateway Request* message format is similar to *Router Solicitation* in MIPv6. The gateway replies with a *Gateway Reply* containing the CoA. The MN sends a *Registration* message to the gateway to update its new CoA. The message is forwarded to the HA by the mesh gateway. The message contains the home address of the MN, the IP address of the MN's point of attachment and the CoA. The gateway functions as the FA in the WMN. and it is responsible for assigning new CoA to the MN during WLAN-WMN vertical handover. The gateway gives the MN its new CoA with a similar network prefix. A new lookup table is also implemented at the mesh gateway. The lookup table contains information about the MN's point of attachment, the home address of the MN and the CoA. When the handover occurs, the point of attachment column is updated with the new associated mesh router.

We analyze the degradation of the performance metrics from the point of view of a single MN that follows a deterministic path, roaming through two WLAN subnets (BSS 0 and BSS 1) to the WMN (BSS 2).All simulations have a duration of 33 minutes. The studied MN performs two handovers during the simulation run roaming at 2.7m/s from BSS 0 to BSS 1, then to BSS 2. The first handover is between two WLAN subnets; the second handover is from WLAN to WMN; the second being vertical handover. The MN communicates with the CN via a video conferencing application throughout the simulation run. Parameters for the video conferencing application consist of low resolution video with 128 x 120 pixels, 9 bits per pixel and 10 frames per second. The application starts after 60 seconds into the simulation, at a constant rate.

There are two simulation scenarios in this setup (see Table 3.2). The first scenario uses the RO signaling mechanism of MIPv6 while the second scenario has the RO signaling mechanism disabled and uses the BDT signaling mechanism only. RO allows the MN to communicate directly

Table 3.1: *Simulation parameters summary*

Coverage area	200 square meters
Transmission power	0.005
Data rate	11 Mbps
Simulation time	25 minutes
Application	Video conferencing
WMN routing protocol	AdnHoc on Demand Vector (AODV)
WLAN routing protocol	Router Information Protocol next generation (RIPng)

with its CN instead of tunneling the traffic via the HA node. If enabled, the MN tries to establish an optimized route with the CN it is communicating with (see Figure 3.5(a)). On the other side, the CN accepts the request from MN to establish route optimization only if it is also enabled for this attribute. When disabled, the MN will not try to start the RO procedure at any time. The alternative mechanism used instead of RO will be BDT traffic via a HA (see Figure 3.5(b)).

Table 3.2: *Vertical handover scenarios summary*

Scenario number	**Independent Variables**	**Dependent Variables**
1	Route optimization	Throughput Delay Packet loss
2	Bi-directional tunneling	Throughput Delay Packet loss

Initially, we began building an FHMIPv6 model using the MIPv6 model. The problem was that no MIPv6 traffic was being generated. The network was operational in the simulation but the MN was not able to contact the HA. The MN was able to receive MAP advertisements and send MAP registration packets to the MAP. However, when the AR received the MAP registration packets over the wireless interface, it destroyed the packets. The ARP module seemed to think that IPv6 was not enabled on that interface. For this experiment, the IV being manipulated is the MIPv6 routing scheme, while the DVs being measured are throughput, delay and packet loss (see Table 3.2). Futhermore, traffic received and sent by the MN, and signaling load are also

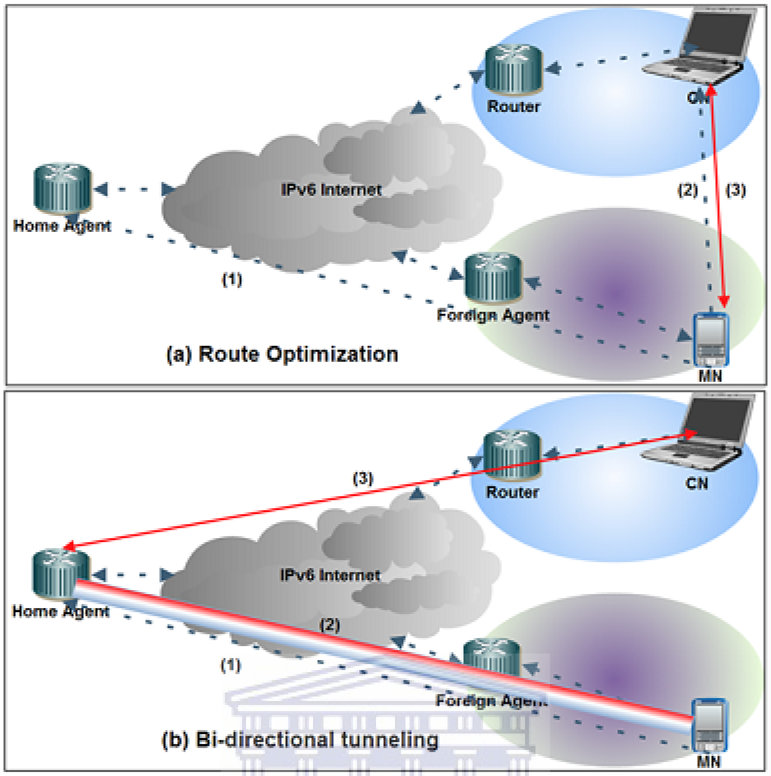

Figure 3.5: *MIPv6 routing mechanisms - Figure (a) shows RO - (1) Home registration, (2) CN registration and (3) Data exchange; Figure (b) shows BDT - (1) Register the CoA, (2) BDT between the HA and the MN and (3) Data forwarding between the HA and the CN.*

studied to help evaluate the handover performance of MIPv6 protocol.

3.4.2 Horizontal handover simulation

Next a homogeneous wireless network is constructed in which MIPv6 and FHMIPv6 are applied within a WMN. MIPv6 is used as a baseline to study the performance of FHMIPv6 in WMNs. The FHMIPv6 was chosen to be compared with MIPv6 because it performs best in related work's results (see Table 2.2 and Table 2.3). It is a combination of HMIPv6 and FMIPv6, which adds up the advantages of the two protocols and provides additional improvements. FHMIPv6 utilizes HMIPv6's mechanisms to reduce signalling overhead and BU delay. It also uses FMIPv6's processes to reduce handover latency. This experiment uses FHMIPv6 to experience the benefits of combining HMIPv6 and FMIPv6. The simulation experiment for this prototype is carried out in network simulator 2 (ns2) [18] version 2.32. OPNET simulator was swapped for ns2 because we failed to extend OPNET MIPv6 model to FHMIPv6 and ns2 simulator supports this MIPv6 extension.

ns2 [18] is a network simulator that simulates different types of IP networks. It is an event driven simulator developed at UC Berkeley. It supports protocols such as transfer control (TCP), file transfer protocol (FTP), telnet, constant bit rate (CBR) and router queue management mechanisms. It also supports multicasting and Layer 2 protocols. ns2 is written in C++ and object-oriented Tool Command Language (oTcl), which triggers an event scheduler and arranges the network topology. ns2 uses an event scheduler to keep track of simulation time and puts all the events in a queue. After the simulation is complete, ns2 generates a text file that stores the simulation results. The simulation data can be used to produce graphs using plotting programs such as MS Excel, Xgraph or Gnuplot (see Figure 3.6). The data can also be used as input to network animator (NAM), which is a graphical simulation display tool [12].

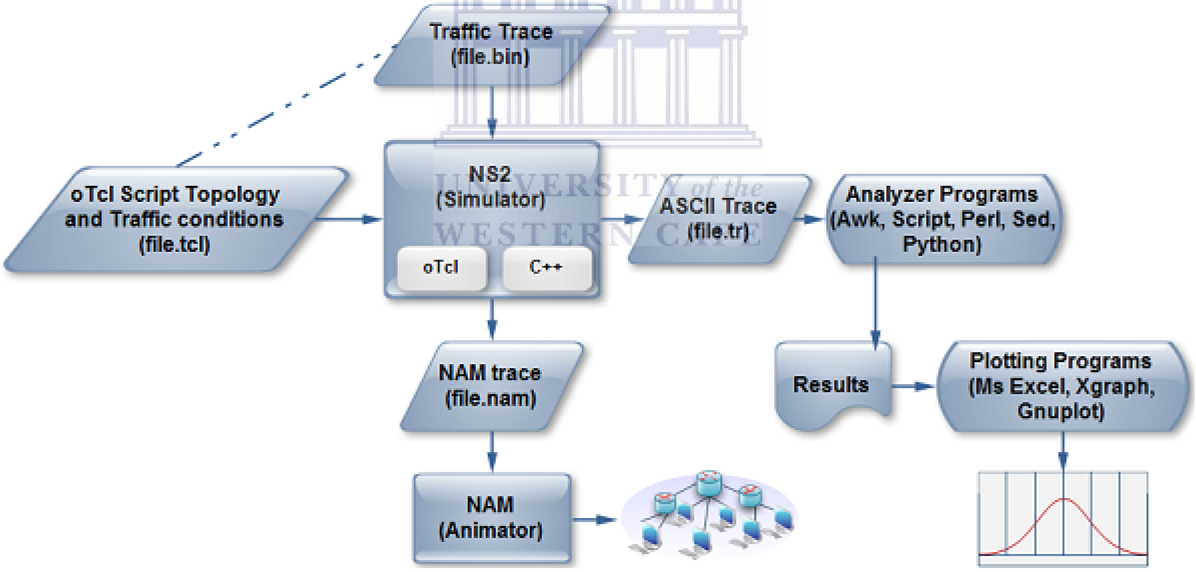

Figure 3.6: *ns2 flowchart - ns2 generates a text file that comprises of the simulation results, which can be used to produce graphs and can also be used as input to NAM, a graphical simulation display tool.*

The FHMIPv6 extension in ns2 offers IPv6 handover management protocols models discussed in Section 2.1. It was developed by Hsieh *et al.* and supports MIPv6, HMIPv6, FMIPv6 and FHMIPv6. S-MIP is not supported although it was proposed by the same people who developed this extension [16]. The FHMIPv6 extension was developed by extending a special *MAP Agent* and fast handover functionality to the standard mobile IP and NOAH (no ad hoc routing agent) [27] extensions. *The MAP Agent* is attached to a wired node to make a MAP, which behaves as a hop between the HA and the pAR. The packets destined for the MN are encapsulated by the HA and tunnels them to the MAP. The MAP decapsulates packets and encapsulates them again, by using the address of the FA. Finally the FA decapsulates the packets and delivers them to the MN [54].

Originally, the FHMIPv6 patch did not support ad hoc routing. To handle this problem, a new routing agent called Ad Hoc Routing Agent (AHRA) [35] is introduced in the prototype. AHRA enables FHMIPv6 patch in ns2 to support ad hoc multi-hop routing and this is made possible by making modifications to the NOAH routing agent as in [35]. The NOAH routing agent does not support multi-hop routing but only direct communication between wireless nodes or MNs and base stations, although static multi-hop routing can be set up. NOAH routing agent is only essential for the simulations of scenarios that do not involve multi-hop wireless routing [27].

FHMIPv6 with AHRA (FHAMIPv6) was proposed by Ortiz *et al.* at the University of Castilla La-Mancha in Spain [35]. This FHAMIPv6 [36] is an extension of a FHMIPv6 patch and it was developed for mobile IP-based mobility management in ad hoc networks in ns2. AHRA involves two operational stages. The first *Routing discovery* takes place during registration process where the modified NOAH learns about the available routes by taking each mesh nodes registered messages address. MIP agents exchange registration messages and the NOAH agent takes the information. The second stage is, *Sending of data through defined routes*, which happens after establishing the TCP connection. The modified NOAH uses the captured information and forwards the TCP packets until they arrive at their destination. The MIP agents are implemented according to Hsieh *et al.*'s proposals and they allocate roles to the base stations, the MAP and the MNs. In addition to the messages defined by Hsieh *et al.* [16], Ortiz *et al.* [35] added supporting messages in the registration process.

This experiment was planned to produce realistic results and at the same time make sure ns2 is able to handle the simulation resourcefully. The simulation setup consists of nodes in a wireless mesh network. The mesh nodes include the MN, within the vicinity of the HA in the home network. It also includes the CN, intermediate routers (N1, N2 and N3), the pAR, the nAR and the MAP. All mesh nodes possess a hierarchical address and the nodes are distributed in 5 domains.

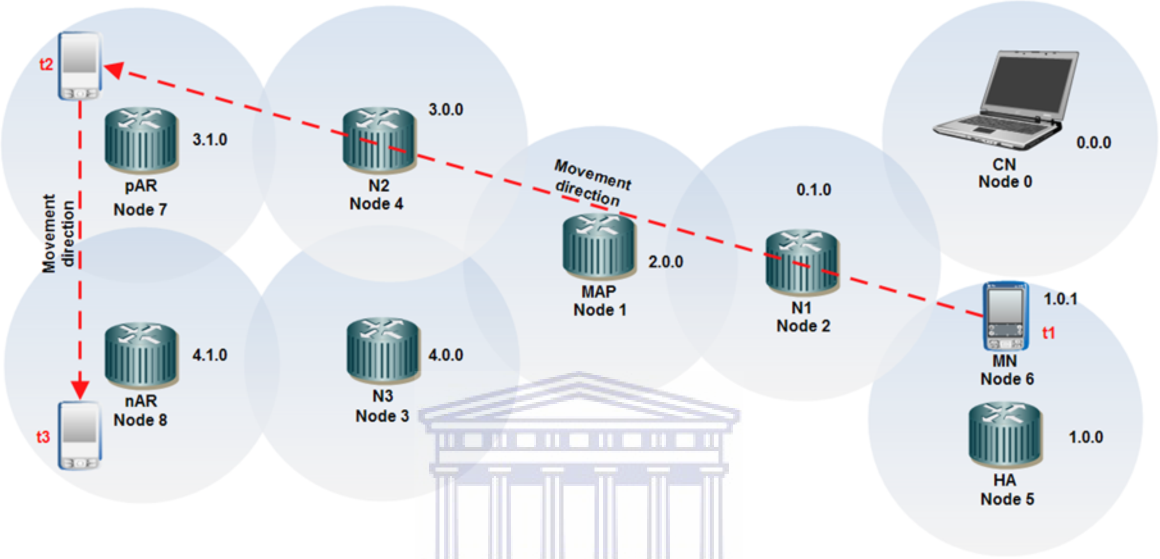

Figure 3.7: *Horizontal handover topology - consists of nodes in a WMN. The MN follows a pre-determined path from position t1 to position t2, then to position t3.*

In the simulations, the performance metrics are studied as observed by the MN, which is communicating with the CN. The MN follows a pre-determined path from position t1 to position t2, then to position t3 (see Figure 3.7). The simulation duration is 30 seconds. This setup permits full control of the MN and the handover while the interruption from the other mesh nodes is still realistic as a result of the mesh nodes fighting for resources. When the MN moves towards the vicinity of the nAR (see Figure 3.7), different handover scenarios behave in different ways:

1. **MIPv6 scenario**: The MN does not respond to advertisements from the nAR when it is receiving advertisements from the pAR. As soon as the MN loses its connection to the pAR, that is when it sends a registration request to the nAR and changes its CoA. In the scenario of MIPv6 with priority handover, priorities are allocated to the base stations (pAR and

nAR). If the nAR possess a higher priority than the pAR, then the handover is triggered right away [54].

2. **FHMIPv6 scenario**: combines FMIPv6 functionality of the extension and the FHMIPv6 draft (as described in Chapter 2). The MN sends RtSolPr message to the pAR once receiving an advertisement from the nAR. Instead of sending the message to the MAP (to imitate FHMIPv6), pAR and nAR construct a HI-HACK conversation like in FMPv6. The MN receives the PrRtAdv message from the pAR and sends a request to register with the nAR. The MAP receives a request from the nAR and the MAP begins sending packets to nAR. This does not really create a bi-directional tunnel that minimizes packet loss since packets are sent after the registration is completed [54].

UDP CBR source is used in the simulations and this source offers constant traffic where acknowledgement is not compulsory. Real-time applications generally produce this sort of traffic. It is easy to study and compare the protocols using this traffic because of its deterministic features and it has no recovery mechanisms. Table 3.3 illustrates the summary of the simulation setup settings for this experiment.

Table 3.3: *Horizontal handover simulation parameters summary.*

Coverage area	500 square meters
Sampling time	0.5
Data rate	11 Mbps
Simulation time	30 seconds
Traffic source	UDP-CBR
WMN routing protocol	Ad Hoc Routing Agent (AHRA) (modified-NOAH)

When the simulation starts, the MN is positioned at t1 in the home network and begins to communicate with the CN right away. At 3 seconds into the simulation, the MN starts moving towards the pAR passing nodes N1, the MAP and N2 on its way, until it reaches position t2 in the network of the pAR. 15 seconds into the simulation the MN starts to move towards the nAR. At this point in time the registration process is complete and the MN has already registered its CoA with the HA.

Table 3.4: *Horizontal handover scenarios summary*

Scenario number	**Independent Variables**	**Dependent Variables**
1	MIPv6	Throughput Delay Packet loss
2	FHMIPv6	Throughput Delay Packet loss

The main objective of this simulation experiment is to observe and compare the effects of FHMIPv6 in the WMN on the QoS parameters described in the previous section. There are two different scenarios simulated using the same simulation setup (see Figure 3.7). The first scenario uses MIPv6 protocol, which is a baseline for this experiment, and the second scenario uses FHMIPv6 protocol. For this experiment, the IVs that are protocols (MIPv6 and FHMIPv6), while the DVs that are measured are throughput, delay and packet loss (see Table 3.4).

3.5 Summary

This research attempts to answer the following question: ***How do mobility management protocols such as MIPv6 and FHMIPv6 behave for handover with mesh networks?*** Experimental quantitative research method was used to answer this question. MIPv6 was applied in a wireless environment comprising WLAN and WMN using an OPNET MIPv6 model. The objective was to learn how MIPv6 functions in a heterogeneous wireless network. The purpose of this experiment was to quantitatively evaluate the performance of MIPv6 during handover using OPNET MIPv6 module comparing MIPv6 routing mechanisms: RO and BDT. The MIPv6 routing schemes were used as IVs, while throughput, delay and packet loss were measured as DVs. The MN communicated with the CN via a video conferencing application. The MN moved from two WLAN subnets to a WMN. During this movement, the MN was involved in two handovers: WLAN - WLAN (horizontal) and WLAN - WMN (vertical). A homogeneous wireless network was then constructed in which MIPv6 and FHMIPv6 were applied within a WMN. MIPv6 was used as a baseline to study the performance of FHMIPv6 in WMNs. The FHMIPv6 was chosen to be compared with MIPv6 because it performed best in related work's results. FHMIPv6 is a combination of HMIPv6 and FMIPv6, which combines the advantages of the two protocols and provides additional improvements. This experiment was carried out in ns2 because OPNET does not include FHMIPv6 model yet. Efforts to build the FHMIPv6 model using MIPv6 model in OPNET failed because MIPv6 traffic was not being generated. A new routing agent called AHRA was introduced in the ns2's FHMIPv6 patch to enable ad hoc routing. The main variables that were measured are throughput, delay and packet loss.

Chapter 4

Results

This chapter presents simulation results of both vertical and horizontal handover experiments based on the experimental design. Vertical handover simulation uses MIPv6 and horizontal handover simulation applies MIPv6 and FHMIPv6. The following performance metrics were measured for each scenario: throughput, delay and packet loss. Section 4.1 reflects on vertical handover results. Section 4.2 discusses horizontal handover results.

4.1 Vertical handover

The results of the vertical handover simulation (see Figure 3.4) are presented in this section focusing on the following parameters: packet loss, delay and throughput. Figure 4.1 shows traffic sent and received during the simulation. Traffic sent is the average traffic in bytes per second submitted to the transport layers as a result of video conferencing between the MN and the CN. Traffic received is the average traffic in bytes per second forwarded to all video conferencing applications by the transport layers in the network. Figure 4.1 illustrates that traffic was sent at about 699 bytes per second after 60 seconds into the simulation up until the end of the simulation. It also indicates that traffic that was received is identical to the traffic that was sent, however, there are communication gaps visible at *point 1* and *point 2* in Figure 4.1(b).

Figures 4.1(a) and 4.1(b) are graphs of RO and BDT scenarios. RO scenario is represented by a blue line, whereas, BDT scenario is represented by a red line. In Figure 4.1(a), only the blue line is visible because the statistics are identical that the blue line is on top of the red line. In Figure 4.1(b), RO and BDT scenarios are slightly different at *point 1* on the second gap.

Section 4.1.1 discusses throughput experienced throughout the simulation. Section 4.1.2 presents the amount of delay incurred during handover. Section 4.1.3 presents results on packet loss during handover. Section 4.1.4 discusses the vertical handover simulation results.

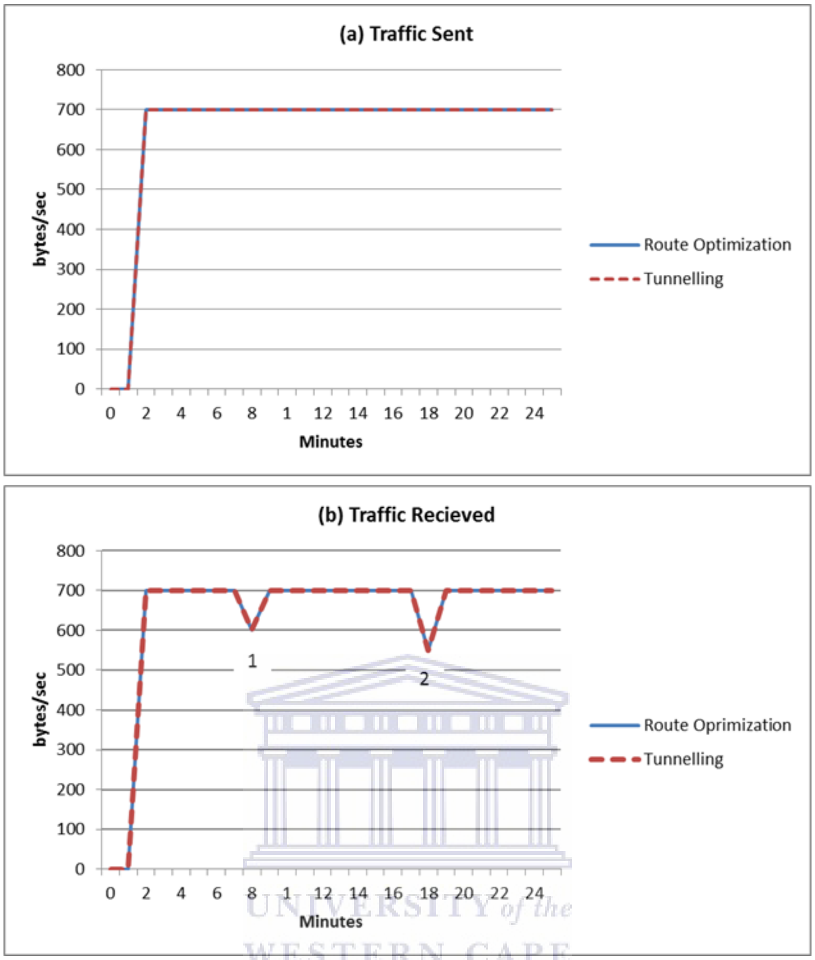

Figure 4.1: *(a) and (b) are overlaid graphs of RO and BDT scenarios. The traffic that was received is identical to the traffic that was sent, however, there are communication gaps visible at point 1 and point 2 in Figure 4.1(b).*

4.1.1 Throughput

Throughput statistics represents the total number of bits in bits/sec forwarded from WLAN layers to the higher layers in all WLAN nodes of the network. Figure 4.2 shows throughput for MIPv6 using BDT in red and throughput for MIPv6 using RO blue. Figure 4.2 illustrates BDT's throughput of up to 17,000 bits/sec, although there are two small communication fluctuations. Before the first fluctuation, throughput is just over 16,000 bit/sec, and then it goes up to 17, 000 bits/sec until the end of the simulation. Similarly, the RO scenario demonstrates fluctuations at around *point 1* and *point 2* in the simulation. RO scenario shows throughput of 16,000 bits/sec after 1 min into the simulation,then later it goes up to 18,000 bits/sec. Comparing BDT scenario to RO scenario, it is clear that RO scenario is sending more data than BDT scenario after the second fluctuation. These fluctuations are caused by the delay of communication between the MN and the CN.

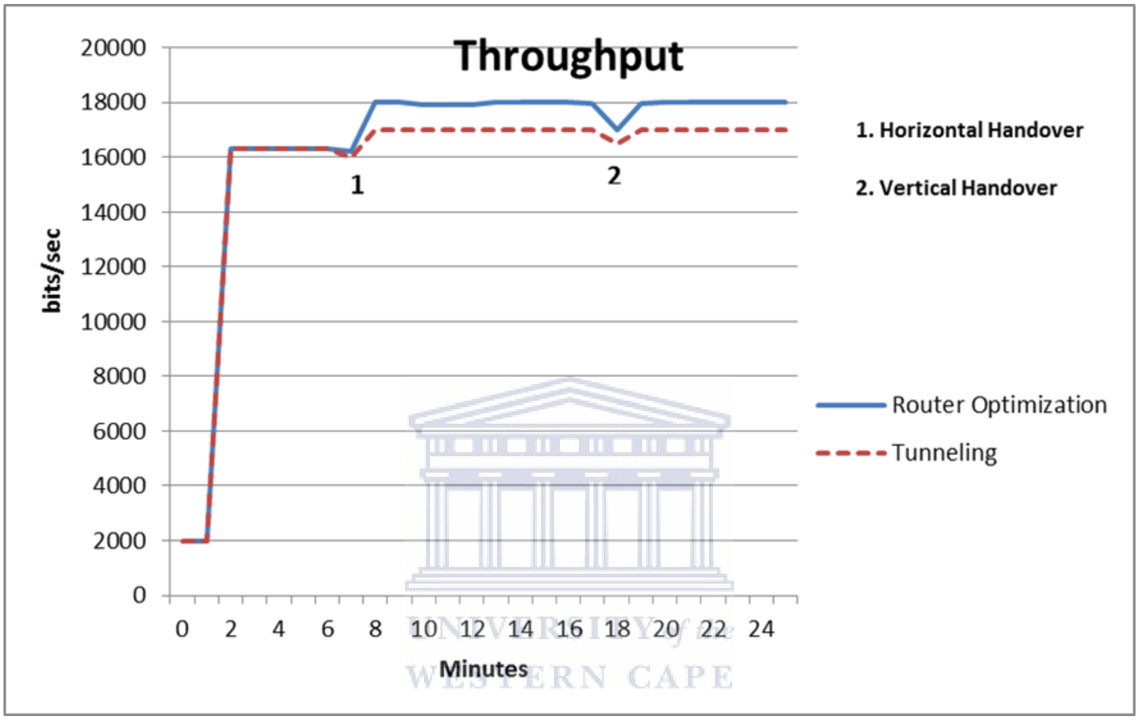

Figure 4.2: *shows throughput generated during the simulations. Point 1 shows where horizontal handover occurs and point 2 is there vertical handover happens.*

4.1.2 Delay

Delay statistics represent the end to end delay of all the packets received by the wireless LAN MACs of all WLAN nodes in the network and forwarded to the higher layer. This delay includes medium access delay at the source MAC, reception of all the fragments individually, and transfers of the frames via the AP.

Figure 4.3 shows the handover delay for MIPv6 using BDT (in red) and the handover delay

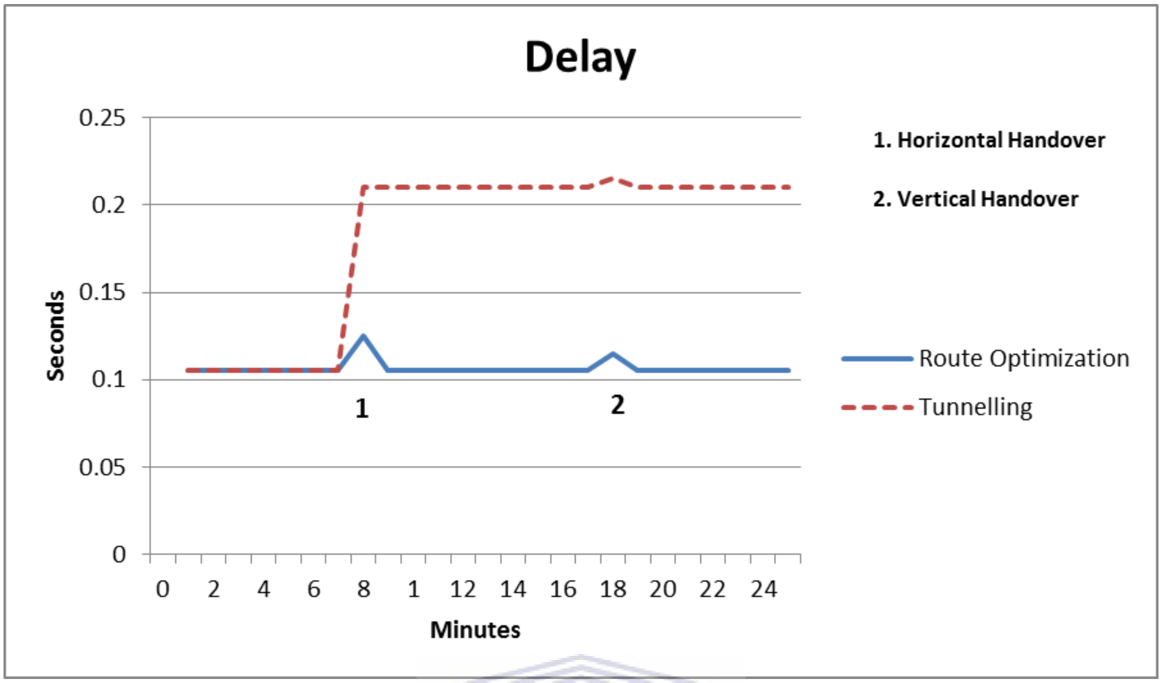

Figure 4.3: *shows delay incurred during the simulation. The delay is triggered by handovers on point 1 and point 2. Both delays last for about 1 minute.*

for MIPv6 using RO (in blue). The BDT scenario illustrates that after 60 sec into the simulation, up to 0.011 sec delay occurs and at *point 1* it goes up to 0.21 sec. From there onwards, the it stays at 0.21 sec delay until at *point 2* when it goes a little bit up. Similarly, the RO scenario demonstrates that at *point 1* handover delay takes place, going up to 0.125 sec for about a minute. It stays on about 0.11 sec until at *17 min 30sec* where it goes up to 0.135 sec.

From the gaps in the figures, there are two handover processes during the simulation time. The first handover starts at *point 1* and the second handover starts at *point 2* into the simulation, which is triggered by the delay. The first handover happens when the MN moves from the HA, which is BSS 0 to the other WLAN subnet on BSS 1 and the second handover takes place when the MN roams from the visited WLAN (BSS 1) to the WMN.

Figure 4.3 presents a clear view of the effects of MIPv6 routing mechanisms during video conferencing. The delay becomes clearer when comparing the gap after the first delay of BDT and RO, it is observed that BDT scenario has a higher delay compared to RO scenario.In RO, the MN and the CN communicate directly but in BDT, all communication goes through the HA. Packets travel twice the distance in BDT than in RO.

4.1.3 Packet loss

Packet loss represents the total higher layer data traffic in bits per second (bits/sec) dropped by wireless nodes in the network as a result of consistently failing retransmissions. Figure 4.4 illustrates the number of higher layer packets that are dropped because the MAC Layer could not receive any ACKs for the (re)transmissions of those packets and their fragments.

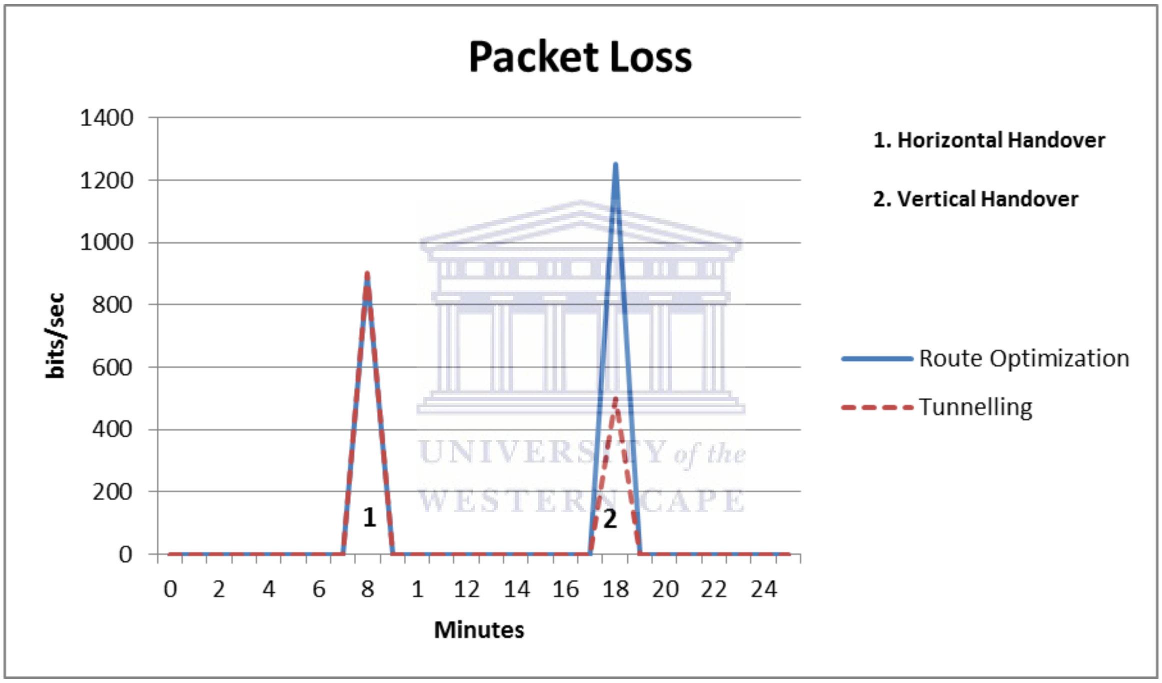

Figure 4.4: *Point 1 indicates that 900 bits of data are dropped during handover and point 2 shows 1300 bits dropped in RO scenario while 500 bits are lost during handover in BDT scenario.*

BDT scenario illustrates that at around *point 1* into the simulation, data is dropped up to 900 bits/sec maximum. Packets are lost again at *point 2* into the simulation. Maximum of 500 bits of data is dropped per sec in this second gap. RO scenario shows two communication gaps at the same time as BDT. The first gap shows 900 bits/sec loss of packet for one minutes at *point 1*, indistinguishable to BDT. Even though the second gap occurs at *point 2* into the simulation similarly to BDT, more data is dropped with the highest drop reaching of 1300 bits per second.

4.1.4 Discussion

Comparing packet loss (see Figure 4.4) with delay (see Figure 4.3), it can be seen that they are directly proportional. In this case, packets are lost in two separate occasions and so is delay. This is triggered by the two handover occurrences at point 1 and point 2 during the simulation. Figure 4.2 illustrates the throughput produced during the simulation run. Two gaps in communication can also be observed. Each gap is produced every time the MN changes its current point of attachment, which is triggered by MIPv6 registration/binding procedures to notify the HA and the CN of the new CoA. While the registration/binding procedures update the HA and the CN, all applications traffic that are directed to the MN are interrupted. The throughput is directly affected by the handover since communication is interrupted.

Comparing *point 1* with *point 2*, it can be seen that the throughput fluctuations are similar, althought after *point 1* the thoughput goes higher. After horizontal handover at *point 1* and vertical handover at *point 2*, the throughput is the same and consistent. Vertical handover is a bit less that that of horizontal handover. This might be the case because the mesh routers in WMN are static. The muilti-hop route between the mesh router and the gateway is always readly available all the time. Since the routers are not moving, the signaling messages are mostly sent on one path. Thus, the WMN has one routing path. Comparing Horizontal handover packet loss with vertical handover packet loss, horizontal handover scenario drops more packets while using RO and drops less packets with BDT.

The WMN uses AODV, a reactive routing protocol, which reduces handover delay because there is minimum signaling load. With AODV, the routes are established on demand. Thus, when the source node has data to send, it initiates a route discovery procedure, and once the node acquires the desired routing information from the route dicovery procedure, it forwards the data using the acquired route.

The video application response time is directly affected by the handover as well as the MIPv6 routing mechanisms used by the MN to communicate with the CN. Figure 4.3 shows the responses time with BDT and RO. From the graph, delay with RO is reduced compared to the case using BDT. When using RO, the IPv6 extension headers including Routing Extension header and

Destination Extension header will be used to transport the data traffic directly between the MN and the CN. In this case, the application response time will be mainly produced one occasion when the data traffic passes through HA. When using BDT, the tunnels will be needed for the communication between the MN and the HA. In this case the application response time will be mainly produced on two occasions the data traffic passes through the HA. The HA registration is the main factor of handover delay in MIPv6. The HA registration delay is the time it takes to transmit the registration messages between the MN and the HA. It also includes the time between when the MN transmits a BU to the HA and the time the MN receives a BAck in response from the HA. That is why BDT delay is twice higher than RO. RO WLAN-WMN handover delay is lower than WLAN-WLAN handover delay because of the distance between the MN and the CN. The first handover occurs when the two nodes are far apart but during the second handover they are near each other. Distance between the communicating nodes influences the delay. Same with BDT handover delay, the first delay is lower than the second because of the distance of tunnelling between the MN and the CN through the HA. The second handover occurs while there is a longer tunnel than the first handover.

The packet loss (see Figure 4.4) is caused by handover. The main reason for the packet loss caused by handover is the fact that packets are routed to the pAR while the link to the pAR is already broken. These packets are dropped by the pAR. The number of lost packets is an indicator of the service quality the application is receiving. Real-time applications that realize a two-way communication require a small end-to-end delay, and therefore, cannot retransmit lost packets. Other applications that require a certain degree of reliability retransmit packets. Retransmissions, in turn, increase the delay and consume bandwidth. Additionally, flow control mechanisms triggered by loss reduce the transmission rate of the sender. Figure 4.4 shows packets are lost up to 900 bits/sec during the WLAN-WLAN handover. As expected RO handover experience over 1200 bits/sec packet loss that is higher than the WLAN-WLAN handover. However, BDT experiences about 500 bits/sec packet loss, which is lower than WLAN-WLAN handover. This is because in RO, the MN send packets using a Type 2 router header, corresponding packets from the MN use a Home Address option with Destination Extension header, which incurs the overhead cost of both Routing Header and Home Address options in each direction. Each extension header length is 24 bytes, therefore a total header length of 48 bytes is essentially needed for RO. In BDT, IPv6 encapsulation header length is 40 bytes, so the mechanism reduces 8 bytes for the data packets.

4.2 Horizontal handover

The results of the horizontal handover prototype are presented in this section and focuses on throughput, delay and packet loss during the simulations. The studied MN performs horizontal handovers within the WMN roaming from the home network moving towards the pAR and then to the nAR during the 30 sec of the simulation (see Figure 3.7). The MN starts moving towards the pAR 3 sec into the simulation, then at 20 sec, it moves towards the nAR. The MN communicates with the CN using UDP-CBR throughout the simulation. The CN is connected to the UDP-CBR agent and the MN acts as a sink of the UDP-CBR agent. After the simulation, a trace file (*.tr file) and an animation file (*.nam file) are produced. The trace file is used to trace the performance metrics being studied. AWK is used to filter the trace file to construct a graph in Microsoft Excel. The animation file is used to show the graphical representation of the network topology.

Section 4.2.1 discusses throughput experienced throughout the simulation. Section 4.2.2 presents delay experienced during handover. Section 4.2.3 presents results on packet loss during handover. Section 4.2.4 discusses the horizontal handover simulation results.

4.2.1 Throughput

The throughput is measured in kilobit per second (kbps) and corresponds to the amount of data that is transmitted between the MN and the CN per period of time. CBR packets are the only data considered, the rest are filtered out including the overhead in the network.

Figure 4.5 shows throughput incurred during this experiment. MIPv6's throughput is indicated in blue and FHMIPv6's throughput is shown in red in the graph. MIPv6's throughput shows that as soon as the MN starts moving, the throughput begins to go down until 5 sec into the simulation and it stabilizes at 0.5 kbps. The throughput goes up briefly when the MN starts moving from the pAR to the nAR and goes down back to 0.5 kbps up to the end of the simulation. In contrast, FHMIPv6's throughput begins to rise up to 3.1 kbps when the MN starts

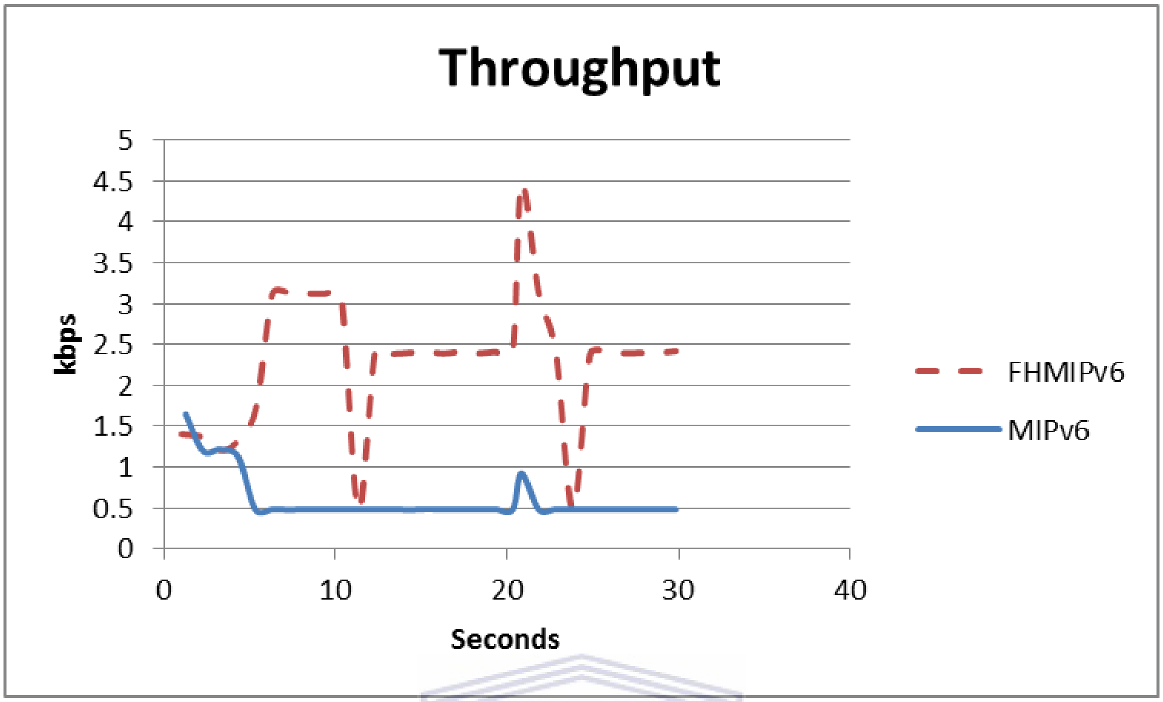

Figure 4.5: *compares throughput of MIPv6 and FHMIPv6 scenarios. FHMIPv6 generates more throughput than MIPv6.*

moving towards the pAR. As soon as the MN reaches the pAR and begins to associate with it, the throughput drops to 0.5 kbps. After finalizing pAR association, the throughput goes up again to 2.4 kbps. The MN starts moving from the pAR to the nAR at 20 sec into the simulation, which causes throughput to shoot up to 4.5 kbps then begins to drop to 0.5 kbps. After association with the nAR completes, the throughput goes back to 2.4 kbps.

4.2.2 Delay

Delay (Latency) is the time period that passes between the last data packet received by the MN through the previous point of attachment and the first data packet received by the MN through the new point of attachment during handover.

Figure 4.6 shows the delay for MIPv6 scenario as well as FHMIPv6 scenario incurred during the experiment. The blue line in the graph indicates delay for MIPv6 and the red line indicates delay produced with FHMIPv6. 3 seconds into the simulation, when the MN starts moving,

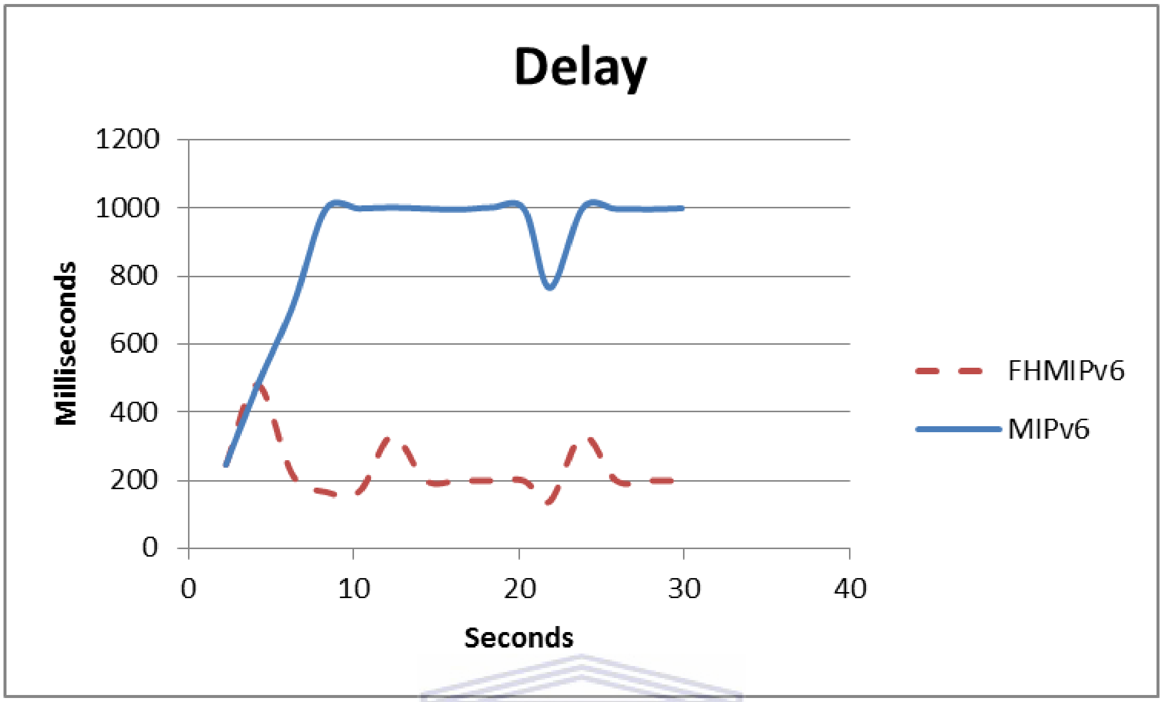

Figure 4.6: *compares delay incurred during MIPv6 and FHMIPv6 scenarios. MIPv6 suffers more delay than FHMIPv6.*

MIPv6s delay begins to increase peaking at 8 seconds 1000 ms. The delay remains at 1000 ms up to the end of the simulation except at 21 sec delay decreases to 790 ms. In contrast, FHMIPv6's delay is at its peak (500 ms) at 5 sec into the simulation. Throughout the simulation delay stays at around 200 ms. The only time delay is at 350 ms is when horizontal handover occurs.

Figure illustrates that FHMIPv6 experience less latency than MIPv6. Less latency shows that communication between the MN and the CN will have a better quality than communication with higher latency.

4.2.3 Packet loss

Packet loss represents a ratio of the number of packets lost to the total number of packets transmitted between the MN and the CN. Packet loss is a consequence of packets that are sent by the nodes but not received by the final destination.

712 UDP data packets are sent by the CN during the simulations, but in MIPv6 scenario,

Table 4.1: *Packet loss statistics of horizontal handover simulation.*

Mobility management protocol	**Sent data**	**Received data**	**Packet loss percentage**
MIPv6	712	638	10.39
FHMIPv6	712	686	3.65

only 638 packets are received by the MN and in FHMIPv6, the MN receives 686 packets. MIPv6 incurs 10.39 percent packet loss while FHMIPv6 experiences 3.65 percent packet loss (see Table 4.1).

4.2.4 Discussion

Comparing throughput of MIPv6 with throughput of FHMIPv6, it can be seen that FHMIPv6 scenario has higher throughput than MIPv6 scenario. Even though FHMIPv6's throughput drops twice during the simulation, its throughput is still better than MIPv6's throughput, which remains mostly at 0.5 bits/sec. FHMIPv6's throughput also illustrates the drop of throughput when the MN is on the move and associates with a new mesh router. For example, when the MN is associating with the pAR, throughput drops. Another drop occurs when the MN moves from the pAR to the nAR at 20 sec into the simulation. Figure 4.5 clearly shows that FHMIPv6 is better than MIPv6 at handling throughput in a WMN.

Figure 4.5 shows that FHMIPv6 has higher average rate of successful messages delivery than MIPv6 during simulation. FHMIPv6 produces 2.3 average throughput, compared to MIPv6 with 0.61. This is so because FHMIPv6 experiences lower latency than MIPv6. FHMIPv6's latency outperforms MIPv6's latency since the distance in order to update the node that is forwarding packets to the MN is always shorter. MAP is used to send updates locally, which reduces latency. FHMIPv6 also uses the FMIPv6 mechanisms by preparing the handover in advance. After handover, theres no wait for the old AR to be updated to start receiving packets again. When the MN receives the FBAck from the MAP indicating that the handover should be performed, the re-directed packets are already waiting in the nAR. When packets are experiencing delay during handover, the FBAck acts as a synchronization packet informing the mechanism that new packets are already waiting or about to arrive to the nAR. This way handover latency is reduced or removed. FHMIPv6 waits as long as possible for the FBAck at the old point of attachment to start handover. If the MN performs the handover right after sending theFBU, it will not immediately receive any redirected packets, which increases the handover latency and packet loss. FHMIPv6 assures that when FBAck is received, no packets lost sent to the old CoA and the packets redirected to the new CoA are buffered. This result in reduced or no packet loss at all. Table 4.2 summarizes the performance of the two protocols. FHMIPv6 achieves better results than MIPv6 in all three performance metrics that are studied.

Table 4.2: *Average statistics of horizontal handover simulation.*

Handover protocol	**Average throughput**	**Average delay**	**Packet loss rate percentage**
MIPv6	0.61	880.26	10.39
FHMIPv6	2.3	231.92	3.65

Table 4.3 illustrates handover latency comparison of mesh and non-mesh experiments. Gwon *et al.* and Hsieh and Seneviratne experiments involve non-mesh network infrastructure (see Section 2.1.6). This research is mesh-based experiment. The mesh handover delay results show a better performance against Gwon *et al.*'s results, in both MIPv6 and FHMIPv6. It also achieves better against Hsieh and Seneviratne's FHMIPv6 handover delay. But Hsieh and Seneviratne's MIPv6 delay is lower.

Table 4.3: *Handover latency - mesh vs non-mesh.*

Handover protocol	**Non-mesh**	**Non-mesh**	**Mesh**
	Gwon *et. al*	**Hsieh and Seneviratne**	**Our experiment**
MIPv6	1300	814	880.26
FHMIPv6	200 - 400	270	231.92

4.3 Summary

In this Chapter, simulation results of both vertical and horizontal handover prototypes are presented. Both simulations results are presented focusing on throughput, packet loss and delay. In vertical handover simulation results, it can be seen that packet loss is directly proportional with delay. In this case, packets are lost in two separate occasions and so is delay. This is triggered by the two handover occurrences at *point 1* and *point 2* during the simulation. Two gaps in communication can also be observed. Each gap is produced every time the MN changes its current point of attachment, which is triggered by MIPv6 registration/binding procedures to notify the HA and the CN of the new CoA. Comparing throughput of MIPv6 with throughput of FHMIPv6 in horizontal handover simulation, it can be seen that FHMIPv6 scenario has higher throughput than MIPv6 scenario. FHMIPv6 has higher average rate of successful messages delivery than MIPv6 during the simulation. This is so because FHMIPv6 uses fast handover procedures and utilizes the MAP for local messaging, which result in lower latency than MIPv6. Latency is the main factor that affects how much throughput is delivered and how much packet loss is experienced. Low latency means better performance. The mesh handover delay results show a better performance against some non-mesh related work results in both MIPv6 and FHMIPv6. In one case, it achieves better in FHMIPv6 but it is outperformed in MIPv6. The simulations indicate that even though there is multi-hop communications in the WMN, the performance of the multi-hop routing might not play an important role in the handover performance. Especially when the mesh routers are mostly static and the multi-hop routes are readily available at any time without the need of route discovery.

Chapter 5

Conclusion and future work

This chapter presents the conclusion of the study. The limitations of the study, recommendations and future work are also discussed. Section 5.1 presents conclusions based on the vertical and horizontal handover simulation results potrayed in Chapter 4. Section 5.2 identifies forward the limitations of this research effort. Section 5.3 recommends what can be done to overcome limitations in Section 5.2. Section 5.4 suggests some future research directions that could provide the next steps along the path towards integration of WMNs into 4G.

5.1 Conclusion

This thesis addressed how mobility management protocols such as MIPv6 and FHMIPv6 behave for handover with wireless mesh networks. The research presented results from two handover simulations: vertical and horizontal. Both prototypes use MIPv6 to manage mobility in a WMN environment. The study evaluated the handover impact on throughput, delay and packet loss. MIPv6 was applied in a wireless environment comprising WLAN and WMN using OPNET MIPv6 model. The objective of this experiment was to learn how MIPv6 functions in a heterogeneous wireless network. This experiment involved two handover incidences, the first occurred between WLAN and other WLAN subnet, and then between WLAN and WMN, and the main focus was the latter, vertical handover. Performance of MIPv6 was evaluated comparing the two MIPv6 routing mechanisms: route optimization and tunnelling. On throughput, RO performed better than BDT. RO produced higher throughput than BDT even though the difference was not huge. 7 minutes into the simulation RO produced 1000 bits/sec more data than BDT. BDT experienced twice the delay produced by RO. In RO, the MN and the CN communicate directly, which lessens the delay but in BDT, all communications have to go through the HA. The communication delays between the communicating nodes also depend on the geographical positions. For example, when the MN is located in the home network close to the HA, but far from the CN suggests a short communication delay between the MN and the HA but a longer delay between the MN and the CN. As experienced in WLAN-WLAN handover (see Figure 3.4). When the MN is close to the CN, but far from the HA, the delay between the MN and the CN will be short. While the delay between the MN and the HA will be long. From these results, it shows that MIPv6 behaves the same way when applied in mesh network. Whether it is non-mesh or mesh network, RO performs better than BDT. However, in our opinion, MIPv6 performance in both mesh and infrastructure is not effective enough. It suffers from handover latency and packet loss, which can combine to compromise delay-sensitive applications such as video conferencing. The route advertisement interval in MIPv6 is not short enough and route solicitation during handover is not timed properly that it impacts the movement detection process significantly. Section 2.1.6 presented work that shows MIPv6 is outperformed by its extensions in infrastructure networks.

After studying MIPv6 in a vertical handover scenario, a homogeneous wireless network was constructed in ns2 simulator in which MIPv6 and FHMIPv6 were applied within a WMN. We decided to experiment with FHMIPv6, which performs better than all MIPv6 extensions discussed in Chapter 2 because it combines HMIPv6 procedures and FMIPv6 processes to reduce signalling overhead and delay during handover. As expected, FHMIPv6 performed better than MIPv6 in all three focus areas of throughput, delay and packet loss. FHMIPv6 experienced higher throughput, less delay and less packet loss than MIPv6. From the above experimental evidence we can assume that FHMIPv6 handover performance is in line with performance claims made by FHMIPv6 specification [20]. In particular, FHMIPv6 can guarantee a good handover performance compared to MIPv6. This arises from the demonstration that an FHMIPv6 handover away to a foreign router with the help of HMIPv6 procedures and FMIPv6 processes. HMIPv6 procedures in FHMIPv6 allows the MN to register locally, which reduces network overhead because the MN does not require sending BUs to the CN and the HA like in MIPv6. FMIPv6 mechanism in FHMIPv6 enables the MN to send or receive packets from the period of time the MN de-associates with one point of attachment in a subnet to the period of time the MN associates with a new CoA from the new point of attachment. These extensions help to reduce handover delay and packet loss while maximizing throughput. After comparing mesh's MIPv6 and FHMIPv6 with non-mesh handover delays, it is clear that MIPv6 and its extensions can behave the same way whether in mesh or non-mesh environment. Table 4.3 shows the comparison of this research's mesh experiment with related work non-mesh results. Gwon *et al.* experienced 1300 ms MIPv6 handover delay and 200-400 ms for FHMIPv6. Hsieh and Seneviratne study generates 814 ms handover delay with MIPv6 and 270 ms with FHMIPv6. Our experiment produces 880.26 ms handover delay with MIPv6 and 231.92 ms when applying FHMIPv6. Considering that these protocols are meant for infrastructure-based networks with wireless nodes at the edge and rely on the good performance of the network infrastructure, but our mesh prototype produces similar results of non-mesh prototypes. MIPv6 and its extensions can be used effectively in mesh networks.

The WMN simulations indicate that even though there are multi-hop communications, the performance of the multi-hop routing did not play a big role in the handover performance. Unlike in infrastructure network where handover signaling messages are transmitted along the wired routes, in the WMN network, the wireless multi-hop routes are used. But the mesh routers are mostly static and the multi-hop routes are readily available at any time after utilizing the route cache. Thus, the total handover delay is not affected too much by the WMN hops in the routes for signing message transmission. If the WMN scenario included both mesh clients and mesh routers moving frequently, route discovery would be needed whenever the current multi-hop route is broken, which would result to long delay for trying to find a new route. Using AODV, a reactive routing protocol also helped reduce signaling overhead. AODV creates no extra signaling messages for communication and this result to lower handover delay. However, reactive routing protocols sometime require more time to establish communication. Therefore, a hybrid routing protocol may be a feasible way to balance the tradeoffs between handover delay and signaling overhead. A hybrid routing protocol that combines the tree-based routing strategy with the reactive routing strategy.

5.2 Limitations

OPNET MIPv6 extensions: in the preliminary study, OPNET was selected as a simulator to be used for the experiments. We began building an FHMIPv6 model using the OPNET MIPv6 model. The problem was that no MIPv6 traffic was being generated. The network was operational in the simulation but the MN was not able to contact the HA. The MN was able to receive MAP advertisements and send MAP registration packets to the MAP. However, when the AR received the MAP registration packets over the wireless interface, it destroyed the packets. The ARP module seemed to think that IPv6 was not enabled on that interface.

Results comparison: even though the numerical results are available for comparison, they do not really show all the main factors affecting the handover performance. Mostly, the handover performance experiments are based on different assumptions about the simulation environment, the network topology, delays in the links and the definition of the performance metrics.

5.3 Recommendations

It is recommended to combine the two simulations into one and implementing it all in ns2. As demonstrated in horizontal handover prototype, ns2 supports MIPv6, HMIPv6, FMIPv6 and FHMIPv6. It also supports both horizontal and vertical handover. A heterogeneous wireless network comprising WLAN, WMN and possibly other access networks such as WiMAX or LTE can be deployed. The MN would move from the home network to the WLAN and roam through WMNs multi-hop route then back to home network.

5.4 Future Work

Mobility management is unquestionably on its way to becoming a necessity in wireless networks. Mobile users are increasing rapidly and the demand of voice over IP and video is increasing. Deploying 4G all-IP heterogeneous networks will require data communication manageability and interoperability. Networks will need to support different kind of mobile devices and provide high performance service. The growth of wireless networks will increase the number of users who access and depend on on these networks [11]. The following are suggestions for future work:

- **All five variations**: section 2.1 presented MIPv6 and its three extensions (HMIPv6, FMIPv6 and FHMIPv6) as well as S-MIP. It will be good to simulate and compare all these five protocols to see their performance in mesh networks. Even though FHMIPv6 is a hybrid of HMIPv6 and FMIPv6, it will be interesting to see individual performance of the two in mesh networks.

- **Scalability**: one of the main critical design factors that influence the performance of WMNs. Scalability allows the network performance not to degrade when the network size increases. It is expected that future all-IP 4G networks will need to support an increase in nodes in the network as many as the subscribers the cellular networks can handle. Therefore, mobility management schemes must support scalability. To evaluate the impact of number of nodes in the network on handover performance, total number of nodes in the network could be increased.

- **MN random movement**: instead of following pre-deterministic path, the MN can move randomly unaware of overlying areas where handover decisions are taken. These unanticipated movements can have an undesirable influence on packet loss.

- **Mesh multiple path topology**: in WMN, the simulation topology should include multiple mesh routers or clients moving frequently creating different paths. These dynamic movements will challenge the mobile IPv6 handover procedures.

- **Traffic sources**: instead of using one traffic source, different sources of traffic such as VoIP, video and TCP can be considered. This way, different performance improvements or loss of performance are observed.

- **Other technologies**: since several technologies that facilitate vertical and horizontal handovers exist, it would be interesting to see how they perform in a wireless mesh network environment. For example, IP multimedia subsystem (IMS) supports MIPv6, however there is no research about it facilitating MIPv6-based wireless mesh network handovers.

- **Ad Hoc routing protocols**: since we applied modified routing protocol that is exclusive for ns2. For future work, a hybrid ad hoc routing protocol might be modified and applied. This might produce better handover performance. The mesh protocols described in Chapter 2 might also be examined to see their handover performance.

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Appendix A

SATNAC 2012 full paper

FHMIPv6-based Handover for Wireless Mesh Networks

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Abstract- This paper shows that mobility management protocols for infrastructure Internet may be used in a wireless mesh network environment. Mesh topology tends to be an unplanned graph and routes change dynamically and in this research Mobile IPv6 and Fast Handover for Hierarchical Mobile IPv6 are successfully implemented in a wireless mesh network environment. Horizontal handover simulation with ns2 involved Mobile IPv6 and Fast Handover for Hierarchical Mobile IPv6 applied to wireless mesh networks. Mobile IPv6 was used as a baseline to compare the performance of the two protocols. The results show that in mesh networks, Fast Handover for Hierarchical Mobile IPv6's performance is superior to Mobile IPv6. Fast Handover for Hierarchical Mobile IPv6 generates more throughput and less delay than Mobile IPv6. Furthermore, Fast Handover for Hierarchical Mobile IPv6 drops fewer data packets than Mobile IPv6. Even though MIPv6 and its extensions are for infrastructure networks, they can be used effectively in mesh networks.

Index Terms—Mobility, handover, MIPv6, FHMIPv6, wireless mesh networks.

I. INTRODUCTION

This paper demonstrates that mobility management protocols for infrastructure Internet such as Mobile IPv6 (MIPv6) and Fast handover for Hierarchical Mobile IPv6 (FHMIPv6) can be used in a wireless mesh network (WMN) environment. Mobility management in WMNs has still not been researched thoroughly, although a significant amount of research on wireless and cellular network mobility management has been addressed [1]. Fourth generation (4G) networks will include all-IP (Internet Protocol) wired and wireless networks interworking together as heterogeneous networks [2]. WMNs can be connected to other wireless communication networks such as generic wireless fidelity (Wi-Fi), worldwide interoperability microwave access (WiMAX), cellular and sensor networks but the challenge is MIPv6-based mobility management. MIPv6 and its extensions rely on the good performance of an infrastructure-based network but a typical WMN topology tends to be an unplanned graph and routes change dynamically [3].

Mobility management provides seamless support of real-time and non-real-time services for mobile subscribers and facilitates the maintenance of connections for subscribers on the move when they change points of attachment. Mobility management involves location management and handover management [4]. Location management allows the network to keep track of the location of a mobile client and handover management is the procedure by which a mobile node keeps its connection active when it moves from one point of attachment to another. Handover can be classified as horizontal or vertical. Horizontal handover refers to the move from one access point to the other within the same technology. Vertical handover refers to the ability to roam between heterogeneous wireless technologies.

MIPv6 [5] is intended to deal with mobile nodes (MNs) in motion between IPv6 networks. When an MN is on the move and connects to a new access router (AR) in another subnet, its home address is not valid any longer; therefore it requires a new address in the visiting subnet. The MN obtains a new address called care-of-address (CoA) to register with its home agent (HA) and the corresponding node (CN) whilst the MN is away from its home network. MIPv6 supports Route Optimization which results in an effective route formation between the MN and the CN. Nevertheless, sometimes it takes too long to send binding updates (BUs) after handover in MIPv6 which results in packets destined for the MN being dropped [6].

FHMIPv6 [7] is a proposal that combines Hierarchical MIPv6 (HMIPv6) and Fast handover for MIPv6 (FMIPv6) extensions to MIPv6. Fast handover for hierarchical mobile IPv6 reduces signaling overhead and BU delay during handover by using HMIPv6 procedures. Furthermore, movement detection latency and new CoA configuration delay during handover are reduced by utilizing FMIPv6 processes. When the MN associates with a new MAP domain, HMIPv6 procedures are performed with the HA and the Mobility Anchor Point (MAP). If the MN moves from a previous AR (pAR) to a new AR (nAR) within the domain, it follows the local BU process of HMIPv6. Packets sent to the MN by the CN during handover are tunneled by the MAP en route for the nAR [8]. However, when FHMIPv6 is applied in WMN, the good performance is no longer guaranteed. Multiple wireless hops in WMN makes it difficult for a protocol designed for infrastructure networks.

The remainder of this paper is arranged as follows. Section II presents work related to handover. Section III details the experimental design to learn how MIPv6 and FHMIPv6 perform for handover between mesh networks. Section IV presents and discusses handover results. Section V concludes the paper and also points toward future work.

II. RELATED WORK

MIPv6 and its extensions have been studied in numerous publications, all for infrastructure rather than ad-hoc networks [9] [10] [11] [12] [13]. Gwon *et al.* [10] investigated handover performance of MIP and its extensions (see Table 1). The investigation involved simulating 100,000 mobile subscribers across a large scale experimental network consisting of WLANs. The results indicated that HMIPv6 suffers considerably less handover signaling overhead than FMIPv6. FMIPv6 achieves the best handover performance exhibiting the lowest latency and data loss. FHMIPv6 achieves similar handover performance to that of FMIPv6 but with improved handover signaling overhead. FHMIPv6 is also more robust to AR and HA failures.

Table 1: *Handover latency presented by Gwon et al.[10]*.

Protocols	Handover latency in ms
MIPv6	1300
HMIPv6	300 - 500
FMIPv6	200
FHMIPv6	200 - 400

Hsieh and Seneviratne [13] also compared MIPv6 and its extensions (see Table 2). The authors use the topology and link delays shown in Figure 1.The results show that S-MIP performs best under both ping-pong and linear movement during handover. All other protocols suffer from packet loss and performance degradation. Optimization of S-MIP is proposed to improve performance. Chow *et al*. [9] proposed a protocol for both macro and micro mobility management in mobile broadband wireless access networks. The mobile-initiated handovers are based on Signal-to-Noise-and-Interference-Ratio (SNIR). The proposed protocol is similar to FHMIPv6, although the terminology used is different, for example, the MAP is replaced by a domain AR. The experiments are conducted in the OPNET simulator. The topology used is similar to Figure 1 but uses the 802.16e standard. In the results, the handover latency is defined as the delay incurred for obtaining a new CoA. It is not the communication between the MN and the CN. The proposed scheme experiences 128 milliseconds (ms) delay while obtaining a new CoA.

Table 2: *Handover latency presented by Hsieh and Seneviratne [13]*.

Protocol	Handover latency in ms
MIPv6	814
HMIPv6	326
FMIPv6	358
FHMIPv6	270
S-MIP	100

Figure 1 shows the topology used in both [9] and [13]. Both CN and HA are connected to an intermediate node (N1) with 2ms link delay and 100 Mbps links. The link between N1 and the MAP is a 100 Mbps link with 50 ms link delay. The MAP is further connected to the intermediate nodes N2 and N3 with 2 ms link delay over 10 Mbps links. N1 and N2 are connected to PAR and NAR with 2 ms link delay over 1 Mbps links.

III. EXPERIMENTAL DESIGN

Our task is to examine handover latency when incorporating WMNs. We constructed a simulated environment in which MIPv6 and FHMIPv6 are applied within a WMN. MIPv6 is used as a baseline to study the performance of FHMIPv6 in WMNs. The simulation experiment for this prototype is carried out in network simulator 2 (ns2) version 2.32.

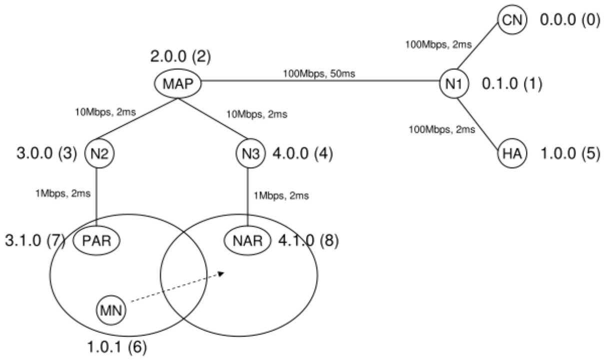

Figure 1: *Topology used in [9] and [13]*.

We used an extension developed by Hsieh and Seneviratne that supports MIPv6, HMIPv6, FMIPv6 and FHMIPv6. S-MIP is not supported although it was proposed by the same people who developed this extension. The FHMIPv6 extension was developed by extending a special MAP Agent and fast handover functionality to the standard mobile IP and NOAH (no ad hoc routing agent) extensions. The MAP Agent is attached to a wired node to make a MAP, which behaves as a hop between the HA and the pAR. The packets destined for the MN are encapsulated by the HA and tunneled to the MAP. The MAP decapsulates packets and encapsulates them again, by using the address of the FA. Finally, the FA decapsulates the packets and delivers them to the MN.

Originally, the FHMIPv6 patch did not support ad hoc routing. To handle this problem, a new routing agent called Ad Hoc Routing Agent (AHRA) is introduced to the patch. AHRA enables the FHMIPv6 patch in ns2 to support ad hoc multi-hop routing and this is made possible by making modifications to the NOAH routing agent. FHMIPv6 with AHRA (FHAMIPv6) was proposed by Ortiz *et al.* [14]. AHRA involves two operational stages. The first, *routing discovery,* takes place during the registration process where the modified NOAH learns about the available routes by taking each mesh node's registered message's address. MIP agents exchange registration messages and the NOAH agent takes the information. The second stage is *sending of data through defined routes*, which happens after establishing the TCP connection. The modified NOAH uses the captured information and forwards the TCP packets until they arrive at their destination.

This experiment was planned to produce realistic results and at the same time make sure ns2 is able to handle the simulation resourcefully. The simulation setup consists of nodes in a wireless mesh network. The mesh nodes include the MN, within the vicinity of the HA in the home network. It also includes the CN, intermediate routers (N1, N2 and N3), the pAR, the nAR and the MAP. All mesh nodes possess a hierarchical address and the nodes are distributed in 5 domains.

In the simulations, the performance metrics are studied as observed by the MN, which is communicating with the CN. The MN follows a pre-determined path from position t1 to position t2, then to position t3 (see Figure 2). The simulation duration is 30 seconds. This setup permits full control of the MN and the handover while the interruption from the other mesh nodes is still realistic as a result of the mesh nodes fighting for resources. When the MN moves towards the vicinity of the nAR (see Figure 2), different handover scenarios behave in different ways:

MIPv6 scenario: The MN does not respond to advertisements from the nAR when it is receiving advertisements from the pAR. As soon as the MN loses its connection to the pAR, it sends a registration request to the nAR and changes its CoA. In the scenario of MIPv6 with priority handover, priorities are allocated to the base stations (pAR and nAR). If the nAR possess a higher priority than the pAR, then the handover is triggered right away.

FHMIPv6 scenario: combines FMIPv6 functionality of the extension and the FHMIPv6 draft. The MN sends RtSolPr message to the pAR once receiving an advertisement from the nAR. Instead of sending the message to the MAP (to imitate FHMIPv6), pAR and nAR construct a HI-HACK conversation like in FMIPv6. The MN receives the PrRtAdv message from the pAR and sends a request to register with the nAR. The MAP receives a request from the nAR and the MAP begins sending packets to nAR. This does not really create a bi-directional tunnel that minimizes packet loss since packets are sent after the registration is completed. FHMIPv6 was chosen to compare with MIPv6 because it is a combination of HMIPv6 and FMIPv6, which adds up the advantages of the two protocols and provides additional improvements.

When the simulation starts, the MN is positioned at t1 in the home network and begins to communicate with the CN right away. At 3 seconds into the simulation, the MN starts moving towards the pAR passing nodes N1, the MAP and N2 on its way, until it reaches position t2 in the network of the pAR. 15 seconds into the simulation the MN starts to move towards the nAR. At this point in time the registration process is complete and the MN has already registered its CoA with the HA.

The main objective of this simulation experiment is to observe and compare the effects of FHMIPv6 in the WMN on the QoS parameters described in the previous section. There are two different scenarios simulated using the same simulation setup. The first scenario uses MIPv6, as a baseline for this experiment, and the second scenario uses FHMIPv6. For this experiment, the independent variables are the protocols (MIPv6 and FHMIPv6), while the dependent variables are throughput, delay and packet loss.

IV. RESULTS

The results of the horizontal handover simulations are presented in this section and focus on delay, throughput, and packet loss. The studied MN performs horizontal handovers within the WMN roaming from the home network moving towards the pAR and then to the nAR during the 30 sec of the simulation (see Figure 2). The MN starts moving towards the pAR 3 sec into the simulation, then at 20 sec, it moves towards the nAR. The MN communicates with the CN using UDP-CBR throughout the simulation. The CN is connected to the UDP-CBR agent and the MN acts as a sink of the UDP-CBR agent. After the simulation, a trace file (*.tr file) and an animation file (*.nam file) are produced. The trace file is used to trace the performance metrics being studied. AWK is used to filter the trace file to construct a graph in Microsoft Excel.

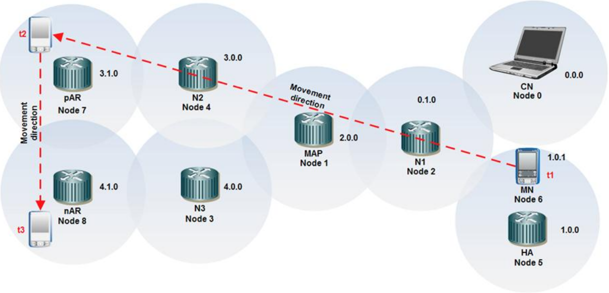

Figure 2: *Horizontal handover topology consists of nodes in a WMN. The MN follows a pre-determined path from position t1 to position t2, then to position t3.*

A. Delay

Figure 3 shows the delay for MIPv6 and FHMIPv6 scenarios incurred during the experiment. The blue line in the graph indicates delay for MIPv6 and the red line indicates delay produced with FHMIPv6. 3 seconds into the simulation, when the MN starts moving, MIPv6's delay begins to increase peaking at 8 seconds with 1000 ms. The delay remains at 1000 ms up to the end of the simulation except at 21 sec when delay decreases to 790 ms. In contrast, FHMIPv6's delay is at its peak (460 ms) at 5 sec into the simulation. Throughout the simulation, its delay stays at around 200 ms. The only time delay is at 350 ms is when horizontal handover occurs.

Figure 3 illustrates that FHMIPv6 experiences less latency than MIPv6. Less latency shows that communication between the MN and the CN will have a better quality than communication with higher latency.

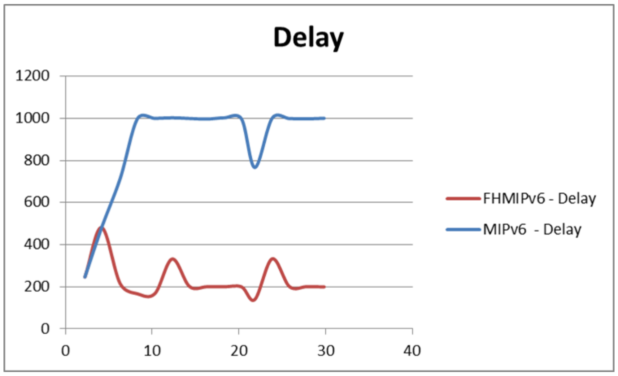

Figure 3: *Delay (Latency) is the time period that passes between the last data packet received by the MN through the previous point of attachment and the first data packet received by the MN through the new point of attachment during handover.*

B. Throughput

Figure 4 shows throughput incurred during this experiment. MIPv6's throughput is indicated in blue and FHMIPv6's throughput is shown in red in the graph. MIPv6's throughput shows that as soon as the MN starts moving, throughput begins to go down until 5 sec into the simulation and it stabilizes at 0.5 kbps. The throughput goes up briefly when the MN starts moving from the pAR to the nAR and goes down back to 0.5 kbps up to the end of the simulation. In contrast, FHMIPv6's throughput begins to rise up to 3.1 kbps when the MN starts moving towards the pAR. As soon as the MN reaches the pAR and begins to associate with it, the throughput drops to 0.5 kbps. After finalizing pAR association, the throughput goes up again to 2.4 kbps. The MN starts moving from the pAR to the nAR at 20 sec into the simulation, which causes throughput to shoot up to 4.5 kbps then begins to drop to 0.5 kbps. After association with the nAR completes, the throughput goes back to 2.4 kbps.

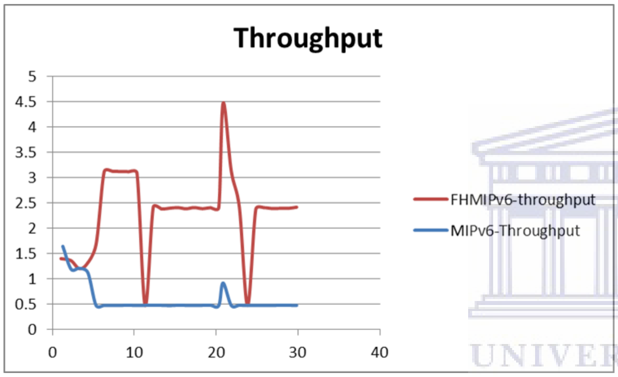

Figure 4: *The throughput is measured in kilobit per second (kbps) and corresponds to the amount of data that is transmitted between the MN and the CN per period of time. CBR packets are the only data considered; the rest are filtered out, including the overhead in the network.*

C. Packet loss

We can represent packet loss as a ratio of the number of packets lost to the total number of packets transmitted between the MN and the CN. Packet loss is a consequence of packets that are sent by the nodes but not received by the final destination. 712 UDP data packets are sent by the CN during the simulations, but in the MIPv6 scenario, only 638 packets are received by the MN and in FHMIPv6, the MN receives 686 packets. MIPv6 incurs 10.3933 percent packet loss while FHMIPv6 experiences 3.6517 percent packet loss (see Figure 3).

Table 3: *Packet loss statistics of horizontal handover.*

Protocol	Sent data	Received data	% loss
MIPv6	712	638	10.3933
FHMIPv6	712	686	3.6517

D. Discussion

Comparing throughput of MIPv6 with throughput of FHMIPv6, it can be seen that FHMIPv6 scenario has higher throughput than MIPv6 scenario. Even though FHMIPv6's throughput drops twice during the simulation, its throughput is still better than MIPv6's throughput, which remains mostly at 0.5 bits/sec. FHMIPv6's throughput also illustrates the drop of throughput when the MN is on the move and associates with a new mesh router. For example, when the MN is associating with the pAR, throughput drops. Another drop occurs when the MN moves from the pAR to the nAR at 20 sec into the simulation. Figure 4 clearly shows that FHMIPv6 is better than MIPv6 at handling throughput in a WMN.

Table 4 shows that FHMIPv6 has higher average rate of successful message delivery than MIPv6 during simulation. FHMIPv6 produces 2.300405 average throughput, compared to MIPv6 with 0.613884. This is so because FHMIPv6 experiences lower latency than MIPv6. FHMIPv6's latency outperforms MIPv6's latency since the distance in order to update the node that is forwarding packets to the MN is always shorter. A MAP is used to send updates locally, which reduces latency. FHMIPv6 also uses the FMIPv6 mechanisms by preparing the handover in advance. After handover, there is no wait for the old AR to be updated to start receiving packets again. When the MN receives the Fast Binding Acknowledgement (FBAck) from the MAP indicating that the handover should be performed, the re-directed packets are already waiting in the nAR.

Table 4: *Average statistics of the handover simulation.*

Protocol	**Average delay**	**Average throughput**	**Average packet loss**
MIPv6	0.613884	880.26	10.3933
FHMIPv6	2.300405	231.92	3.6517

When packets are experiencing delay during handover, the FBAck acts as a synchronization packet informing the mechanism that new packets are already waiting or about to arrive to the nAR. This way handover latency is reduced or removed. FHMIPv6 waits as long as possible for the FBAck at the old point of attachment to start handover. If the MN performs the handover right after sending the FBU, it will not immediately receive any redirected packets, which increases the handover latency and packet loss. FHMIPv6 assures that when FBAck is received, no packets lost sent to the old CoA and the packets redirected to the new CoA are buffered. This result in reduced or no packet loss at all. Table 4 summarizes the performance of the two protocols. FHMIPv6 achieves better results than MIPv6 in all three performance metrics that are studied.

Table 5: *Handover latency - mesh vs non-mesh.*

Protocol	Non-mesh related work		Mesh
	Gwon *et. al*	Hsieh and Seneviratne	Our experiment
MIPv6	1300	814	880.26
FHMIPv6	200 - 400	270	231.92

Mobility management studies are based on different assumptions about the experiment environment, the topology, the network links, as well as the definition of QoS metrics being involved. Although the numerical results might be available, it is not possible to compare the results with related work directly. Latency is the main factor that affects how much throughput is delivered and how much packet loss is experienced. Low latency means better performance. Table 5 illustrates handover latency comparison of mesh and non-mesh experiments. Gwon *et al*. [10] and Hsieh and Seneviratne [13] experiments involved non-mesh network infrastructure. This research is mesh-based experiment. The mesh handover delay results show a better performance against Gwon *et al*.'s results, in both MIPv6 and FHMIPv6. It also achieves better against Hsieh and Seneviratne's FHMIPv6 handover delay, but their MIPv6 delay is lower.

V. CONCLUSION AND FUTURE WORK

This paper addressed how mobility management protocols such as MIPv6 and FHMIPv6 behave during handover with wireless mesh networks. A wireless network was constructed in ns2 simulator in which MIPv6 and FHMIPv6 were applied within a WMN. As expected, FHMIPv6 performed better than MIPv6 in all three focus areas of throughput, delay and packet loss. FHMIPv6 experienced higher throughput, less delay and less packet loss than MIPv6. FHMIPv6 benefits from the help of HMIPv6 procedures and FMIPv6 processes. HMIPv6 procedures in FHMIPv6 allows the MN to register locally, which reduces network overhead because the MN does not require sending BUs to the CN and the HA as in MIPv6. The FMIPv6 mechanism in FHMIPv6 enables the MN to send or receive packets from the period of time the MN de-associates with one point of attachment in a subnet to the period of time the MN associates with a new CoA from the new point of attachment. These extensions help to reduce handover delay and packet loss while maximizing throughput. Comparing mesh's MIPv6 and FHMIPv6 with non-mesh handover delays, it is clear that MIPv6 and its extensions can behave the same way whether in mesh or non-mesh environment. Considering that these protocols are meant for infrastructure-based networks with wireless nodes at the edge and rely on the good performance of the network infrastructure, our mesh simulation produced results similar to non-mesh related work. MIPv6 and its extensions can be used effectively in mesh networks.

For future work, it will be good to simulate and compare all MIPv6 extensions to see their performance in mesh networks. Even though FHMIPv6 is a hybrid of HMIPv6 and FMIPv6, it will be interesting to see individual performance of the two in mesh networks.

VI. ACKNOWLEDGEMENTS

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Zimani Chitedze received his Honours degree in Computer Science from the University of the Western Cape (UWC) in 2009 and is presently studying towards his MSc degree with the Bridging Applications and Networks Group (BANG) at the same institution. His research interests include wireless mesh and Next Generation Networks.

William D. Tucker is a Senior Lecturer of Computer Science at UWC and leads BANG research there. His research interest includes Internet Protocol (IP) networks and their applications in developing regions.

Appendix B

SATNAC 2011 full paper

Mobile Vertical Handover between Wireless LAN and Wireless Mesh Network

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Abstract-This paper addresses mobility management issues in an environment with both wireless LAN and wireless mesh networks. We first examine wireless mesh network client side transparency within mesh mobility management protocols and then look at standard mobility management protocols. The client side transparency scheme enables mobile nodes to support mobility in heterogeneous and homogeneous networks. However, they are not necessarily compatible with mobile IP protocols. Although a typical mesh topology tends to be an unplanned graph and routes change dynamically, standard mobility management protocols such as MIPv6, HMIPv6, and FMIPv6 may be used for mobility management in wireless mesh networks. To learn how MIPv6 operates, we used the OPNET 16.0 MIPv6 model to simulate a heterogeneous wireless environment comprising both WLAN and WMN. The simulation results show that MIPv6 is able to manage vertical handover between WLAN and WMN. However, in our opinion, its performance with both route optimization and tunneled traffic mechanisms is not effective enough. MIPv6 suffers from handover latency and packet loss which can combine to compromise delay-sensitive applications such as video conferencing.

Index Terms—Fixed/Mobile Handover protocols Mobile/wireless protocols

I. INTRODUCTION

Fourth generation (4G) networks will include all-IP (Internet Protocol) wired and wireless networks interworking together as heterogeneous networks [1]. 4G promises to provide higher data rates up to a hundred times faster than the current networks. Its high capacity will be beneficial as it is projected that by 2015 overall global data traffic will grow up to 6.3 exabytes per month [2]. This is due to the introduction of more and more laptops, tablets and high-end handsets on to mobile networks. These devices generate much higher traffic than a basic feature phone, e.g. a laptop can generate as much traffic as 515 basic-featured phones and a smartphone can generate as much as 24 [2].

It is suggested that operators may be able to offload this traffic onto other IP networks such as Wireless Mesh Networks (WMNs) by offering subscribers dual-mode mobile phones. WMNs are attracting attention because of their characteristics such as ease of installation and scalability, low cost network deployment, ease of network reconfiguration, reduction in wired links, robust communication, spectrum reuse efficiency and network capacity improvement [3].

WMNs can be connected to other wireless communication networks such as generic wireless fidelity (Wi-Fi) networks, worldwide interoperability microwave access (WiMAX), cellular and sensor networks (see Fig. 1). Even though WMNs have turned out to be attractive and hold a great potential for 4G networks due to their capability to integrate with other wireless networks, there are still challenges that need to be addressed.

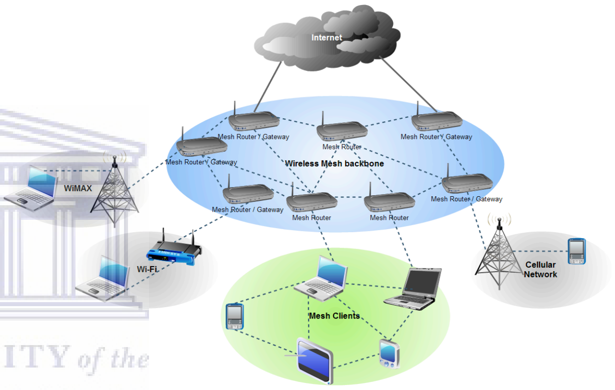

Fig. 1: Hybrid WMN

One well-known challenge is IP-based mobility management in WMN environments. A typical WMN topology tends to be an unplanned graph and routes change dynamically. Mobility management in WMNs has still not been researched thoroughly, although a significant amount of research on Wi-Fi, cellular and mobile ad hoc mobility management has been addressed [4].

As the world progress towards all-IP next generation heterogeneous networks, mobility management becomes an important ingredient in ubiquitous wireless networking. Mobility management provides seamless support of real-time and non-real-time services for mobile subscribers and facilitates the maintenance of connections for subscribers on the move when they change points of attachment. Mobility management involves *location management* and *handover management* [5]. Location management allows the network to keep track of the location of mobile clients and handover management is the procedure by which a mobile node keeps its connection active when it moves from one point of attachment to another.

Several protocols and mechanisms have been developed to support handover for multimedia services. Depending on the movement of the mobile node, the handover can be classified as horizontal or vertical handover. Horizontal handover (see Fig. 2) refers to the ability to handover from one access point to another within the homogeneous technology, for example handover from one 802.11n network to another 802.11n network [5].

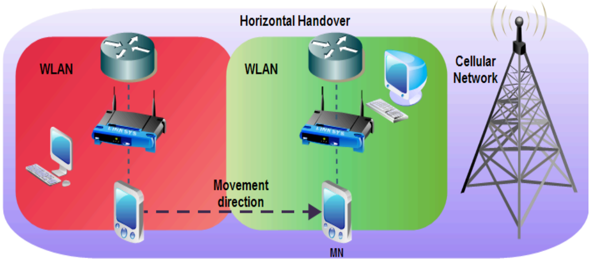

Fig. 2: Horizontal handover from one 802.11n WLAN to another 802.11n WLAN.

On the other hand, vertical handover (see Fig. 3) refers to the ability to handover across heterogeneous wireless technologies, for example, handover from a Wi-Fi wireless local area network (WLAN) technology to GPRS/UMTS. Vertical handover in heterogeneous networks is a much more complex matter. That is why it has been researched on different levels of the OSI reference stack.

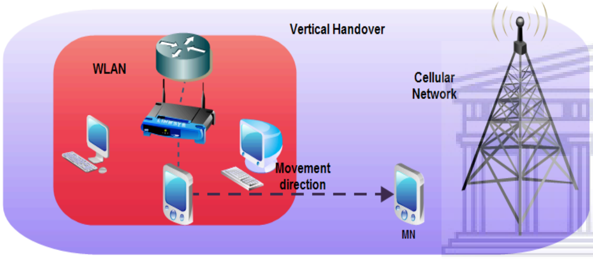

Fig. 3: Vertical handover from WLAN to a cellular network.

Although, there is no specific solution for the mobility management issues in WMN environment, protocols for wired networks such as mobile IP may be used as guidelines to tailor and evaluate strategies for wireless mesh mobility management. The aim of this paper is to examine vertical handover between WMN and WLAN using mobile IP version 6 (MIPv6) and compare the performance of its signaling mechanisms: route optimization and bi-directional tunneling. MIPv6 is studied and evaluated with the OPNET 16.0 simulator. The remainder of this paper is arranged as follows. Related work is presented in Section II. Section III details the experimental design. Results are presented and discussed in Section IV. Section V concludes the paper and also points toward future work.

II. RELATED WORK

One of the objectives of mobility management is seamless support for real-time communication. This seamless support refers to achieving a low latency and packet loss during handover. This section presents related work toward attaining these objectives for WLANs and WMNs. First we examine WMN client side transparency mobility management protocols. Then we look at standard mobility management protocols.

A. WMN Client-side Transparency mobility protocols

SMesh [6] was developed at John Hopkins University by the Distributed System and Networks Lab. SMesh provides seamless mobility and fast handover without a client pre-installing anything. Any 802.11 mobile device which supports DHCP (Dynamic Host Configuration Protocol) will be able to connect to an SMesh network. SMesh is a wireless mesh network that allows unmodified clients to connect and roam freely between access points on a wireless coverage area. The wireless clients perceive the wireless mesh as a single omnipresent AP (access point). All nodes have the same SSID (service set identifier) using IBSS (independent basic service set), or ad hoc, mode. Mesh Internet gateways nodes provide access to the Internet. As a client moves, the mesh nodes continuously monitor the mobile client connectivity to decide the best access point to service the client. SMesh uses a DHCP server to allow mesh routers to rapidly locate and manage a mobile client's connectivity. An SMesh client is associated with a client control group (CCG) and a client data group (CDG) which are multicast groups. CCG consists of a group of access points which communicate among each other to determine the best set of access points to serve a client. CDG consists of a group of access points from CCG which have the best connectivity to the client. Although handover performance is acceptable using this multicast approach, bandwidth usage is heavy.

iMesh [7] is another WMN architecture, used for community networking applications. iMesh uses 802.11b technology for its access mesh routers and aims to provide seamless network services to mobile clients. Like SMesh, *client side transparency* is an essential objective of the design of this architecture. Mesh clients are not aware of the mesh backbone. Hence they view they whole network as a single AP. When a mesh client is on the move and associates with a different AP, a Layer 2 handover mechanism initiates routing updates in the mesh backbone. The handover procedure involves both Layer 2 and Layer 3 mechanisms. When implementing iMesh, [7] used two solutions: *transparent mobile IP*, which is similar to mobile IP and a flat routing scheme, which according to [7] is much better than a traditional Layer 3 handover technique.

Ant [8] is a another WMN mobility management scheme which also employs client side transparency like SMesh and iMesh. It creates bi-directional tunnels between previous mesh nodes and a new mesh node during handover, similar to fast handoff [RFC 4068]. This scheme is used to reduce handover latency and packet loss. A location server on a neighborhood mesh node is used by the new mesh node to determine the previous mesh node's IP address. The previous node decreases packet loss by buffering the packets when the MAC layer de-association event is triggered.

Even though SMesh, iMesh and Ant WMN mobility management protocols are implemented differently, they all use a *client side transparency* scheme. This transparency feature enables mesh nodes to support mobility in any heterogeneous network because the mobility management protocol is not incorporated into a mesh node's (MN) stack. However there will be limitations to a MN trying to roam between a 4G network and these client side transparency networks. This is because these networks will be using different mobility management mechanisms. 4G networks will be a combination of wired and wireless networks interworking together. Therefore, mobility management protocols for wired networks such as MIPv6, HMIPv6 and FMIPv6 will be essential for future seamless mobility in 4G networks. These are discussed in the next section.

B. Standard Mobility Protocols

In the past, several mobility management protocols have been proposed. These protocols can be categorized as *micro-mobility* and *macro-mobility* protocols. In micro-mobility, the MN moves within a given domain between subnets and engages in *intra* domain handovers. Micro-mobility solutions include Cellular IP and Handoff-Aware Wireless Access Internet Infrastructure (HAWAII) [9]. Cellular IP, from Columbia University and Ericsson Research, supports paging and several handover techniques and optimization. Host location information is updated regularly using packets, to minimize signaling. However, Cellular IP relies on MIP to support global mobility. Hence, there is a limitation to support heterogeneous mobility between different domains. HAWAII, from Lucent Technologies, also relies on MIP for inter-domain mobility. HAWAII is not a standalone solution but extends Mobile IP to provide intra-domain mobility with Quality of Service (QoS) support. HAWAII leverages Mobile IP to enable QoS mobility [9].

In macro-mobility, the MN moves from one administrative domain to another, and engages in *inter* domain handovers. Mobile IP is the most widely used protocol for macro-mobility management [10]. MIPv6 is able to support seamless mobility more efficiently than MIPv4 because of its robustness, easiness and reliability. MIPv6 also supports Route Optimization which results in effective route formation between an MN and a corresponding node (CN). Nevertheless, sometimes it takes too long to send binding updates (BUs) after handover in MIPv6 which results in packets destined for the MN being dropped [11].

HMIPv6 and FMIPv6 were proposed by the IETF as extensions to MIPv6 to enhance its benefits. HMIPv6 concentrates on localizing the mobility management by minimizing signaling load within a network. FMIPv6 offers anticipated handovers by using layer 2 triggers to initiate the handover process beforehand.

MIPv6 is intended to deal with MNs in motion between IPv6 networks. When an MN is on the move and connects to a new access router in another subnet, its home address is not valid any longer. Therefore, it requires a new address in the visiting subnet. The MN obtains a new address called the care-of-address (COA) to register with its home address (HA) and the CN whilst the MN is away from the home network. The mapping of the home address and COA of the MN so that the HA can always recognize the communication of the MN is called *binding* [11].

In MIPv6, the handover procedure occurs when a MN examines router advertisements sent by the access router (AR) from time to time or the MN requests the AR to send router advertisements (router solicitation) and realizes that it is no longer in the home network. The COA is created using information in the router advertisements. The MN confirms that the link-local address is unique, and then creates the new COA by auto-configuring a either a stateful or stateless address. The process of verifying the address if it is unique is called *duplication address detection* (DAD) and it involves sending a neighbor solicitation to the new address. DAD takes some time which results in an increase of handover latency. To deal with DAD's additional time during handover, the MN carries out DAD at the same time of its communications. The MN sends *binding updates* to the HA and CN when the assembling of COA is finalized [10].

III. EXPERIMENTAL DESIGN

Now that we understand how MIP operates in general, we want to learn how to apply it in a heterogeneous wireless environment comprising WLAN and WMN. We used an OPNET MIPv6 model to do this. This section describes the MIPv6 OPNET model, and then presents the simulation setup that involves a mobile node moving from one network to the other so we can example vertical handover delays.

A. MIPv6 Model

The MIPv6 model in OPNET has been designed and developed with a lot of standard MIPv6 features. The OPNET MIPv6 model supports features such as router optimization, MN–HA bi-directional tunneling, IP extension headers which include mobility, routing and destination option extension headers. It also supports neighbor discovery, duplicate address destination modeled as a delay and router advertisements for movement detection, address auto-configuration (stateless) and home agent address detection.

In OPNET, a WLAN workstation or server node can be configured as MIPv6 MN or CN with route optimization either enabled or disabled. Yet all regular workstation nodes behave as CNs with no route optimization support. If the MN is initially away from home and more than one AP exist, the HA needs to be specified. Otherwise, this can be learned from the HA's router advertisements when the MN is at home. Furthermore, the global address of the MN should also be specified and use the same network prefix as the HA.

WLAN roaming capability should be enabled on the node to allow the MN to scan and switch to other APs when the signal from the connected AP becomes weak. A router can have many wired or wireless interfaces that act as HAs but each interface needs to be configured individually. HAs and FAs also need to have router advertisements enabled so that MNs can learn of the closest HA.

B. Simulation Setup

The simulation topology was designed to produce realistic results in the OPNET simulator. The topology (see Fig. 4) is composed of WMN (BSS_2) that is connected to the Internet (depicted as a cloud) via a gateway using a point to point (PPP) duplex link. The gateway has two interfaces, one running Router Information Protocol next generation (RIPng) and the other running Ad-hoc On-Demand Distance Vector (AODV) routing protocol. The interface running RIPng is connected to the Internet while the interface running AODV communicates with the rest of the WMN. AODV is the ad-hoc routing protocol in the WMN.

WLAN subnets (BSS_0, BSS_1 and BSS_3) are each connected to the internet via a router in their basic service sets (BSS) running RIPng routing protocol. BSS_0 is the home network of the MN and BSS_3 is the home network of the CN. The nodes in the simulation are positioned in a way to provide a total coverage to an area of approximately 200 square meters after considering a transmission range of the 802.11b standard which is being used by all nodes in the scenario. The nodes' transmission power is set to 0.005 watts and the data rate is set to 11Mbps. This is the data rate that will be used by the MAC for transmission of data frames via the physical layer. The routers also act as APs for the BSSs.

MN, CN and HA are configured as explained in the previous section. We analyze the degradation of the performance metrics from the point of view of a single MN that follows a deterministic path, roaming through two WLAN subnets (BSS_0 and BSS_1) to the WMN (BSS_2). All simulations have a duration of five minutes. During this simulation time, a MN communicates with a CN using a video conferencing application.

There are two simulation scenarios in this setup. The first setup has the route optimization signaling mechanism enabled while the second setup has the route optimization signaling mechanism disabled and uses the tunneling signaling mechanism only. Route optimization allows MN to communicate directly with its CN instead of tunneling the traffic via the HA node. If enabled, an MN tries to establish an optimized route with the CN it is communicating with. On the other side, the CN accepts the request from MN to establish route optimization only if it is also enabled for this attribute. When disabled, the MN will not try to start the route optimization procedure at any time. The alternative mechanism used instead of route optimization will be tunneling traffic via a HA.

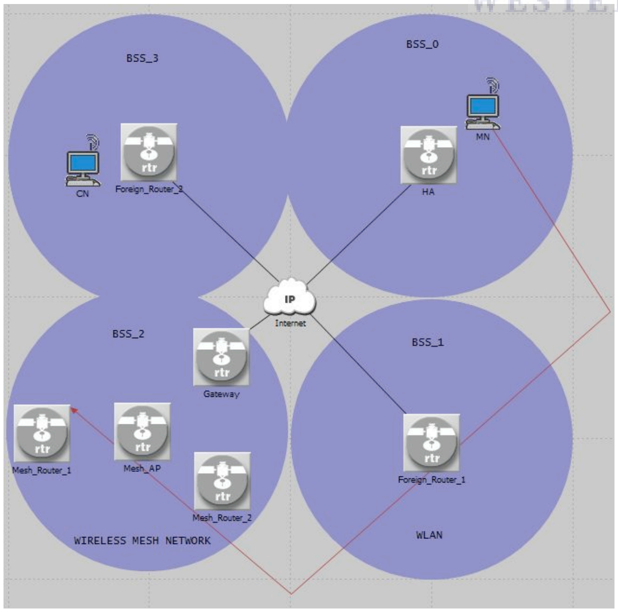

Fig. 4: Simulation Topology

IV. RESULTS AND DISCUSSION

This section discusses the performance of handover in our evaluation. Running the simulation in OPNET, we were able to analyze the following metrics: network load, traffic received by MN, end-to-end packet delay, packet loss, and handover delay are analyzed. These metrics are addressed in turn, below. The impact of MIPv6 signaling mechanisms (route optimization and bi-directional tunneling) are measured and compared with respect to these metrics.

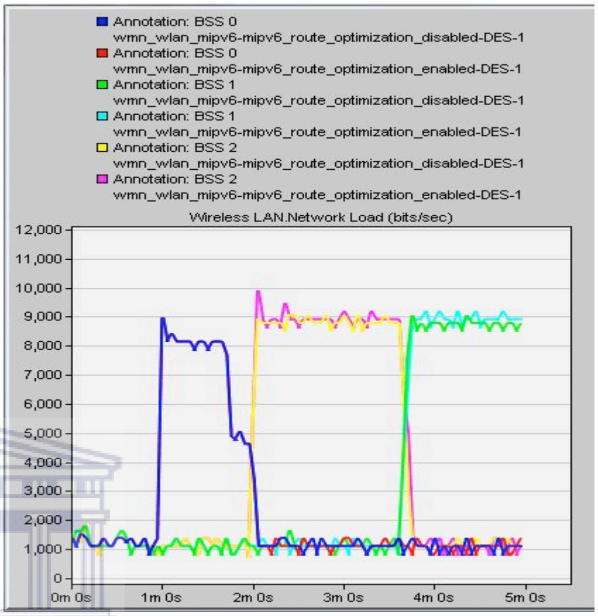

Fig. 5: Network load

Fig. 5 shows network load that represents the total traffic in bits per second received by the entire BSS at Layer 2 that are accepted and queued for transmission. This illustrates that the MN managed to roam from the home network, BSS_0 (1m 0s – 2m 0s), to another WLAN network, BSS_1 (2m 0s – 3m 40s), and finally to the foreign WMN network, BSS_2 (3m 40s – 5m 0s).

Fig. 6 shows traffic received by the MN which represents the average number of packets per second forwarded to all video conferencing applications at the transport layer in the network. Fig. 6 also shows gaps in the communication at 2m 0s and 3m 40s. Each gap is created when the MN changes its current AP. This initiates MIPv6 binding procedures to report to the HA about the MN's new COA. All traffic directed to the MN is lost while the binding procedure updates HA and CN. The video conferencing application response time is directly affected by the MIPv6 mechanism used by the MN in order to communicate with the CN. Fig. 6 also illustrates that the route optimization scenario application delay at 3m 40s is slightly less than the tunneled traffic scenario. This is so because the route taken by the route optimization scenario to communicate with the CN is shorter than tunneling. The MN communicates directly with the CN.

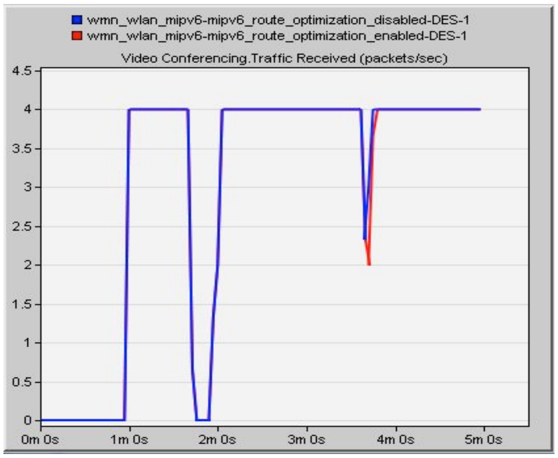

Fig. 6: Traffic Received by MN

Fig. 7 shows the time taken to send a video application packet to a destination node application layer. These statistic record data from all nodes in the network. The statistics in Fig. 7 show that the route optimization scenario is slightly lower than the tunneled traffic scenario. The route optimization mechanism uses routing and destination IPv6 extension headers to directly transport the traffic between the MN and the CN. On the other hand, the tunneled traffic mechanism uses tunnels via the HA, producing two times the data traffic.

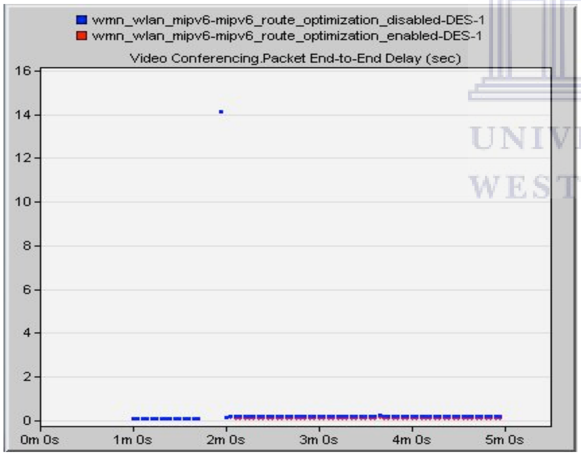

Fig. 7: Video conferencing packet end-to-end delay

Fig. 8 shows total higher layer data traffic in bits per second dropped by wireless nodes in the network as a result of consistently failing retransmissions. This diagram reports the number of higher layer packets that are dropped because the MAC Layer could not receive any acknowledgements (ACKs) for the (re)transmissions of those packets and their fragments. Comparing Fig. 8 with Fig. 9, we can see that data dropped is not directly proportional to delay. In this case, data is dropped in two separate occasions: the time period between 1m 40s and 2m 0s, and between 3m 40s and 3m 50s. Handover is triggered at these times. Delay of 3.55s (see Fig. 9) takes place at 1m 50s which is during handover between BSS_0 and BSS_1. Fig. 9 illustrates no delay during WLAN and WMN handover. Although, the tunneled traffic scenario fairs slightly better than route optimization scenario, the data loss is still high during handover.

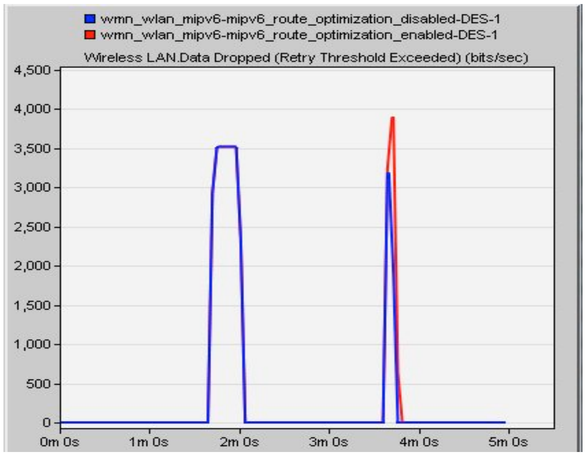

Fig. 8: Data dropped

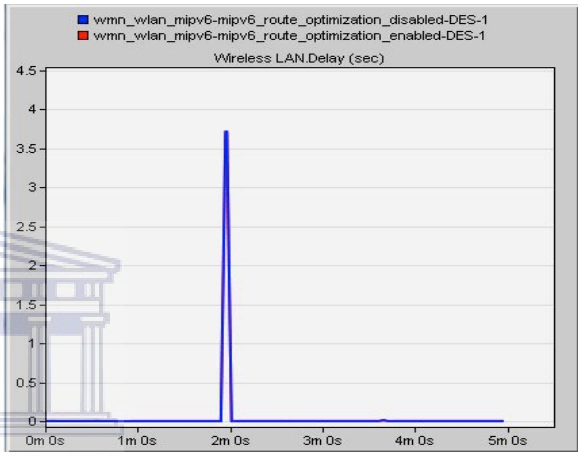

Fig. 9: Delay

V. CONCLUSION AND FUTURE WORK

This paper addressed mobility management issues in an environment with both WLAN and WMN. We examined WMN client side transparency within mesh mobility management protocols and then looked at standard mobility management protocols. The client side transparency scheme enables MNs to support mobility in heterogeneous and homogeneous networks. However, they are not necessarily compatible with mobile IP protocols. Although a typical WMN topology tends to be an unplanned graph and routes change dynamically, standard mobility management protocols such as MIPv6, HMIPv6, and FMIPv6 may be used for WMN mobility management. To learn how MIPv6 operates, we used the OPNET 16.0 MIPv6 model to simulate a heterogeneous wireless environment comprising WLAN and WMN. The simulation results show that MIPv6 is able to manage vertical handover for WLAN and WMN. However, in our opinion, its performance with both route optimization and tunneled traffic mechanisms is not effective enough. MIPv6 suffers from handover latency and packet loss which can combine to compromise delay-sensitive applications such as video conferencing.

For future work, we are considering enhancements to MIPv6 for better performance. According to [5], HMIPv6 has better performance than MIPv6 in the wireless domain. Handover latency and packet loss is minimized when

HMIPv6 is implemented. However, to improve handover performance even more, Fast Handover for Hierarchical Mobile IPv6 (FHMIPv6) could be incorporated to the MIPv6 handover mechanism. FHMIPv6 combines the outstanding features of FMIPv6 and HMIPv6, which could result in even more minimized handover latency and packet loss.

VI. ACKNOWLEDGMENTS

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William D. Tucker is a Senior Lecturer of Computer Science at UWC and leads BANG research there. His research interest includes Internet Protocol (IP) networks and their applications in developing regions.

Appendix C

SATNAC 2010 work-in-progress paper

Wireless Mesh Network and General Packet Radio Service Interworking

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Abstract-This paper reports work in progress on interworking between wireless mesh network and general packet radio service. Since there is no solid mobility management in Wireless Mesh Network environment, mobility protocols for wired networks are used as guidelines. These mobility protocols are studied and compared focusing on mobility latency reduction during handover. This study will provide a deep understanding of the mobility protocols performance which will help recommend one or more of them to tailor and evaluation for wireless mesh and general packet radio service interworking.

Index Terms— Mobile Handover protocols, Mobility, Handover, Wireless mesh networks, General packet radio service

I. INTRODUCTION

Mobility between wireless mesh (WMN) and cellular networks is a problem, despite being researched a lot in recent years. Standards for mobility management such as Hierarchical Mobile Internet Protocol version 6 (HMIPv6) [1], Fast Handover for Mobile Internet Protocol version 6 (FMIPv6) [2], Third Generation Partnership Project (3GPP)'s IP Multimedia Subsystem (IMS) [3] and Institution of Electrical and Electronics Engineers (IEEE) 802.21[4] have been proposed. Nevertheless, these standards are more appropriate for wired communication networks, in contrast, WMN connectivity is wireless. Even though, there is no specific solution for the mobility management issues in WMN environment, standards for wired networks may be used as guidelines to tailor and evaluation for wireless mesh and general packet radio service interworking [5]. This paper reports on work in progress on mobility between WMN and GPRS focusing on handover latency.

The popularity of portable devices that support real-time data services, such as Smart phones, Laptops and PDAs has caused the need for the convergence of the cellular networks and wireless networks. Mobility between cellular networks such as GPRS and wireless networks such as WMN is an important element to providing ubiquitous data services at high data rates (see Figure 1). GPRS cellular network is capable of providing high mobility but at high cost whereas WMN is capable of providing high data rates at low cost. Hence a need for a mobility mechanism so that users of this heterogeneous network can experience ubiquitous high rate data services at lowest possible cost [6].

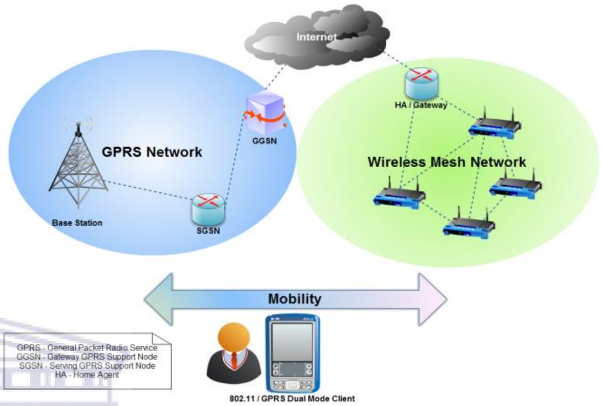

Figure 1: User roaming between GPRS and Wireless mesh networks

This work is motivated by words from Koffi Annan, former United Nations Secretary General, who said; "*Wireless technologies have a key role to play everywhere, but especially in developing countries… With considerable speed and without enormous investments, Wi-Fi can facilitate access to Knowledge and Information… helping countries to leapfrog generations of telecommunications technology and infrastructure and empower their people.*"

The remaining of the paper is arranged as follows; Section II explains the work done by others on this topic. Section III describes the methodology that will be used in this work. Furthermore, Section IV sums up what will be done in the coming year and wraps up the paper.

II. RELATED WORK

One of the objectives of mobility management is seamless support. This seamless support refers to achieving a low latency and packet loss during handover. This work focuses on handover latency.

A. *Handover Latency*

Handover latency is the time that elapses between the last packet received by old point of attachment and the first packet received using the new point of attachment after handover takes place. Real-time applications such as VoIP are susceptible to delay that is why different methods have been developed to reduce latency during handover. Work has included MIPv6, HMIPv6, FMIPv6, IEEE 802.21 and 3GPP's IMS-based solution. HMIPv6 [1] manages mobility locally by using Mobility Anchor Points (MAPs) and uses

MIPv6 to manage mobility between two domains. Mobility between two Access Points (APs) within a domain (horizontal handover) involves only a MAP. This approach is intended to reduce the amount of signaling required and to improve handover rate for mobile connections by managing local mobility in a more resourceful way. FMIPv6 reduces latency by using bi-directional tunnels that are formed between the old node and the new node following the handover [2]. In 3GPP's IMS, a new network entity called Mobility Manager (MM) is introduced to initiate and monitor handovers which reduces latency. IEEE 802.21 is a recent IEEE media independent handover standard to facilitate handover and interoperability between heterogeneous networks. The IEEE 802.21 use the process of network discovery and selection to facilitate vertical handover. The results achieved in [7] after experiments reveal the effectiveness of 802.21 for handover latency reduction.

Other initiatives relating to vertical handovers in WMN environment include S-mesh [8] which claims to be the first work that that has been conducted to offer seamless services in the WMN. S-mesh proposed a fast handover for WMN in which the mobile terminals are transparent to the infrastructure of the mesh nodes. S-mesh uses multicasting to improve the handover performance in regards to handover latency and packet loss but increases bandwidth use. Another work is I-mesh [9] which is similar to S-mesh in terms of client side transparency mobility management. I-mesh reveal that using flat-routing scheme is much better than a layer-3 handover technique for the performance of handover latency. Work proposed in [10] is a network-based mobility management scheme and also offers a client side transparency. It reduces handover latency by a scheme similar to FMIPv6 by using bi-directional tunnels. Experiment results in [10] show that total handover latency realized is good enough for real-time traffic.

III. METHOD

This work is designed to establish how cell phone applications that use packet based data can interwork between WMN and GPRS. And also to determine if handover latency during handover is acceptable for real-time traffic. To answer the research question and sub-question, this work is divided into three parts, literature study, simulation and report.

Literature study will be done to gain insight into interworking in WMN environment. This method is built on already existing research and information. It is made up of web research, journals, conference papers, white papers and books. An in depth literature study of mobility standards, handover latency, WMNs, GPRS and various network simulators will be conducted.

The second part will be work in a network simulator, OPNET. Performance experiments focusing on handover latency will be done with the network simulator. One or more mobility standards studied in literature review will be simulated with the prospect of being recommended to be tailored for WMN environment interworking. The recommended mobility standard will probably be enhanced to suit WMN and GPRS interworking. Finally, all findings of this work will be compiled in a report.

IV. CONCLUSION AND FUTURE WORK

This paper has outlined the mobility management issues in WMN environment. According to related work, mobility standards for wired networks may be used as guidelines for WMN mobility management. Mobility standards have been discussed focusing on handover latency reduction. Performance experiments will be done in a network simulator. This study will provide a deep understanding of mobility standards performance in regards to handover latency during handover. This will help recommend one of them to tailor and evaluation for wireless mesh and general packet radio service interworking.

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