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Link-layer Triggers Assisted Proxy Mobile IPv6 with Enhanced Bicasting and Buffering

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This dissertation is submitted in partial fulfillment of the academic requirements for the degree
of Masters of Science in Electrical Engineering
in the Faculty of Engineering and The Built Environment
University of Cape Town
September 2012

As the candidate's supervisor, I have approved this dissertation for submission.

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Declaration

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Abstract

The next generation wireless networks promise ubiquitous services for mobile users roaming different radio access technologies that make use of an IP-based core network. Therefore, it is paramount for handovers to be seamless in the next generation wireless networks to maintain an acceptable quality of service (QoS) for mobile users. It is due to this that mobility management research groups are continually proposing and implementing extensions to the currently existing mobility management schemes as an endeavour to improve the handover performance. Mobile users should not experience a perceivable disruption in the offered service as the point of attachment changes.

Among the current and well-accepted solutions, Proxy Mobile IPv6 (PMIPv6) is one of the most promising network-layer mobility solutions for the next generation wireless networks. PMIPv6 has been recommended for the Third generation partnership project's (3GPP) Evolved packet core (EPC) and has been adopted by the WiMAX forum. However, PMIPv6 in its current state does not meet the stringent handover delay requirements required to support high QoS for real time services. On this account, many researchers are still proposing, modelling and testing extensions to PMIPv6 to enhance its handover performance. This is due to the high handover latency that in turn results into packet loss as a mobile node performs handovers.

To improve PMIPv6's handover performance, bicasting schemes for PMIPv6 have also been proposed in the literature to minimize packet loss and handover delay during a PMIPv6 handover. However, the problem in the existing bicasting schemes for PMIPv6 is that they require a significant amount of backhaul bandwidth as well as the mobile access gateway (MAG) buffer space to attain a seamless handover. This is due to duplication and routing of packets to both the current and candidate points of attachment during the handover. Therefore, this research studies bicasting schemes for PMIPv6 and consequently proposes an enhanced bicasting for PMIPv6 that not only reduces the handover delay and packet loss but also efficiently utilizes the scarce and shared network resources (backhaul bandwidth and buffer space).

This study proposes a signal-strength based bicasting scheme for PMIPv6 that employs a coordinated service for execution of timely and more accurate bicasting operations. The proposed solution uses the signal strength behaviour to make decisions on when to start and stop

bicasting such that the bicasting operation is executed in a timely and accurate manner to achieve the better network resources utilization efficiency.

A model of the proposed solution is implemented and incorporated into the Network simulator-2 (NS-2) for proof of concept purposes. The results that have been obtained from the evaluation indeed show that the proposed solution surpasses the currently existing bicasting solutions for PMIPv6 by improving the PMIPv6 handovers performance whilst also ensuring efficient network resources utilization, thus making it a much more scalable bicasting solution for PMIPv6. The performance metrics used to analyze the bicasting solutions are packet loss, handover delay, backhaul bandwidth utilization, buffer space utilization, and signaling overhead.

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Table of Contents

Declaration.....	iii
Abstract.....	iv
Acknowledgements	vi
Table of Contents	vii
List of Figures.....	x
List of Tables	xii
Publications	xiii
Peer-Reviewed Conferences	xiii
Work-in Progress	xiii
Glossary	xiv
Chapter 1 Introduction.....	1
1.1 Mobility Management Overview in Wireless Networks.....	1
1.2 Problem Statement.....	5
1.3 Need for this Research.....	5
1.4 Objectives of the Research	6
1.5 Research Scope and Limitations.....	7
1.6 Research Contributions.....	7
1.7 Thesis Outline.....	8
Chapter 2 Background and Literature Review.....	10
2.1 Introduction.....	10
2.2 Overview of IPv6 Mobility Management.....	10
2.3 Network-layer Mobility Management.....	11
2.3.1 Host-based Solutions.....	11
2.3.2 Network-based Solutions.....	17
2.4 Link layer triggers	26
2.5 Media Independent Handovers.....	28
2.6 Summary.....	30
Chapter 3 Enhanced Bicasting for Proxy Mobile IPv6	31
3.1 Introduction.....	31

3.2 Design Goals	31
3.2.1 <i>Seamless handover support.....</i>	31
3.2.2 <i>Network resources utilization efficiency.....</i>	32
3.2.3 <i>Robustness with respect to handover predictions errors.....</i>	32
3.3 Bicastng in PMIPv6	33
3.4 Enhanced Bicastng for PMIPv6 Design.....	37
3.4.1 <i>EB-PMIPv6 – MAG Design</i>	37
3.4.2 <i>EB-PMIPv6 – LMA Design.....</i>	44
3.5 Signaling Flow	45
3.6 Summary.....	47
<u>Chapter 4 Experimental Implementation of EB-PMIPv6.....</u>	<u>48</u>
4.1 Introduction.....	48
4.2 Implementation and Simulation Environment.....	48
4.2.1 <i>Network simulator – 2</i>	48
4.2.2 <i>PMIPv6 model.....</i>	50
4.2.3 <i>Link-layer triggers.....</i>	52
4.3 Implementation on NS-2.....	52
4.3.1 <i>EB-PMIPv6 MAG Implementation.....</i>	52
4.3.2 <i>EB-PMIPv6 LMA Implementation</i>	58
4.4 Simulation setup.....	62
4.4.1 <i>Network Models.....</i>	62
4.4.2 <i>Simulation Parameters.....</i>	64
4.5 Summary.....	66
<u>Chapter 5 Experimental Results.....</u>	<u>67</u>
5.1 Introduction.....	67
5.2 Evaluation Metrics.....	67
5.2.1 <i>Handover performance.....</i>	67
5.2.2 <i>Network resources utilization.....</i>	68
5.3 Handover Performance Results.....	69
5.3.1 <i>Handover delay and packet loss.....</i>	69
5.3.2 <i>Throughput.....</i>	73
5.3.3 <i>Mobile node speed impact on handover performance.....</i>	75
5.3.4 <i>Deductions on Handover Performance</i>	79
5.4 Network Resources Utilization	80
5.4.1 <i>Buffer Utilization.....</i>	80

5.4.2	<i>Backhaul Bandwidth Utilization</i>	82
5.4.3	<i>Packet duplicates</i>	86
5.4.4	<i>Packet loss due to misrouting</i>	87
5.4.5	<i>MN Numbers Impact on Network Resources Utilization</i>	89
5.5	Signaling Overhead	92
5.6	Summary	93
<u>Chapter 6 Conclusions and Recommendations for Future Work</u>		95
6.1	Concluding Remarks	95
6.2	Recommendations for Future Work	97
<u>References</u>		98
<u>Appendix A:</u>		101
Accompanying CD-ROM		101

University of Cape Town

List of Figures

Figure 1.1. Packet reception behaviour at the mobile node during a handover.....	3
Figure 1.2 Duplication of packets and transmission to both MAGs.....	4
Figure 1.3. Bicasting analysis timeline.....	5
Figure 2.1 MIPv6 handover signalling.....	12
Figure 2.2 FMIPv6 handover signalling.....	14
Figure 2.3 HMIPv6 network model.....	16
Figure 2.4 HMIPv6 handover signalling.....	16
Figure 2.5 PMIPv6 network model overview [5].....	18
Figure 2.6 PMIPv6 MN attachment and handover signalling.....	19
Figure 2.7 Predictive FPMIPv6 handover signaling and operations.....	22
Figure 2.8 B-PMIPv6 handover signaling and operations.....	24
Figure 2.9 PB-PMIPv6 handover signaling and operations.....	26
Figure 2.10 Media Independent Handovers Architecture.....	29
Figure 3.1 Bicasting in PMIPv6.....	33
Figure 3.2 Bicasting execution in B-PMIPv6 [20].....	34
Figure 3.3 Bicasting execution in SPMIPv6.....	34
Figure 3.4 Bicasting execution in PB-PMIPv6.....	35
Figure 3.5 Bicasting execution in EB-PMIPv6.....	36
Figure 3.6 Signal strength thresholds/boundaries.....	37
Figure 3.7 EB-PMIPv6 design on the MAG side.....	38
Figure 3.8 Mobile node movement and signal strength.....	40
Figure 3.9 EB-PMIPv6 Design on the LMA side.....	45
Figure 3.10 EB-PMIPv6 handover signalling and operations.....	46

Figure 4.1 NS-2 Overview [33]	49
Figure 4.2 PMIPv6 Implementation Data and Signaling Flow [35].....	51
Figure 4.3 RSS Monitor flow chart.....	53
Figure 4.4 Events scheduler flow chart.....	56
Figure 4.5 Buffering flowchart	57
Figure 4.6 LMA binding cache.....	59
Figure 4.7 PMIPv6 LMA after completion of route-setup [35].....	60
Figure 4.8 Enhanced bicasting PMIPv6 LMA during bicasting.....	61
Figure 4.9 Simulation network model setup	63
Figure 4.10 Simulation setup for multiple MNs	64
Figure 5.1 CBR packets received by the MN	70
Figure 5.2 MN throughput for PMIPv6, B-PMIPv6, PB-PMIPv6 and EB-PMIPv6.....	74
Figure 5.3 Handover delay at different MN speeds	76
Figure 5.4 Packet loss at different MN speeds	78
Figure 5.5 Buffer Utilization at different MN speeds.....	81
Figure 5.6 Backhaul bandwidth utilization.....	83
Figure 5.7 Backhaul bandwidth utilization for different MN speeds	85
Figure 5.8 Packet duplicates received by MN	86
Figure 5.9 Packets dropped on PMAG	88
Figure 5.10 Buffer utilization as number of MNs increase	90
Figure 5.11 Backhaul bandwidth utilization for 2 MNs	91
Figure 5.12 Signaling overhead as MNs increase.....	92

List of Tables

Table 2.1 Link layer triggers and functions	27
Table 4.1 Handover events scheduling	55
Table 4.2 Simulation parameters	65
Table 5.1 Events and time of occurrence at 30 m/s	69
Table 5.2 Handover performance characteristics.....	72
Table 5.3 Events and corresponding times of occurrence at different MN speeds.....	84

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Publications

The following are the technical papers that emanated from this MSc research:

Peer-Reviewed Conferences

1. **Lebajoa A. Mphatsi** and Olabisi E. Falowo, “Achieving Efficient Network Resources Utilization in Bicasting Proxy Mobile IPv6,” To Appear in the Proceedings of 8th *IEEE* International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob 2012), Barcelona, Spain, 8-10 October, 2012
2. **Lebajoa A. Mphatsi** and Olabisi E. Falowo, “A Cross-Layer Approach to Optimize Proxy Mobile IPv6 Handovers Performance,” to appear in the 23rd *IEEE* International Symposium Personal, Indoor, and Mobile Radio Communications (PIMRC 2012), Sydney, Australia, 9-12 September, 2012
3. **Lebajoa A. Mphatsi** and Olabisi E. Falowo, “An Enhanced Bicasting Scheme for Proxy Mobile IPv6 with Buffering,” to appear in Southern Africa Telecommunication Networks and Applications Conference (SATNAC 2012), George, South Africa, 2-5 September, 2012

Work-in Progress

1. **Lebajoa A. Mphatsi** and Olabisi E. Falowo, “An Optimized Bicasting Scheme for Proxy Mobile IPv6,” Southern Africa Telecommunication Networks and Applications Conference (SATNAC 2011), East London, South Africa, 4-7 September, 2011

Glossary

Access Point (AP): A layer-2 device that offers wireless connectivity to a mobile device using a radio access technology such as the IEEE 802.11 (Wi-Fi).

Access Router (AR): Performs standard IP routing and is the default router for the mobile node. It lies at the edge of the network and provides mobility functionality for visiting mobile nodes.

Base Station (BS): A layer-2 device that offers wireless connectivity to the mobile node.

Bicasting: Involves duplication of packets and routing of duplicated packets to more than one point of attachment.

Care of Address (CoA): A temporary IP address that is assigned by a foreign access router to a mobile node as it roams out of its home network.

Correspondent node (CN): A mobile or conventional fixed node that communicates (sends/receives packets to/from) to a mobile node.

Duplicate Address Detection (DAD): is a mechanism to verify the MN's IP address uniqueness to evade IP address conflicts.

Handover: A process whereby an ongoing communication on the MN is transferred to another AR (layer-3) or to another AP/BS (layer-2).

Handover operations: These are the procedures that are carried out to attain an effective transfer of a mobile node's ongoing communication (handover) from one AP/BS/AR to another.

Handover Initiate (HI): is a message sent from the previous mobile access gateway to the next mobile access gateway regarding the mobile node.

Handover Acknowledgement (HACK): is a response message from the next mobile access gateway to the previous mobile access gateway to acknowledge the reception of the HI message.

Local Mobility Anchor (LMA): A data packets anchor in the PMIPv6 architecture.

Mobile Access Gateway (MAG): An AR that tracks the mobile node and performs mobility-related signaling for the mobile node.

Mobile node (MN): is a node that connects to the network wirelessly and has capabilities of engaging in motion.

Next MAG (NMAG): the MN's tentative AR after the handover.

Previous MAG (PMAG): the MN's default AR before the handover.

Received signal strength (RSS): is a measurement of the power present in the radio signal received.

Seamless handover: A process whereby packet flow migrations from an AR or AP or BS to another does not cause a perceivable disruption on the service being consumed by the MN.

Transmission Control Protocol (TCP): is a connection-oriented transport layer protocol that offers a reliable service by employing handshakes and acknowledgements.

User Datagram Protocol (UDP): is a connectionless transport layer protocol and does not guarantee reliable transmission.

WLAN: is an acronym for wireless local area network.

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Chapter 1 Introduction

1.1 Mobility Management Overview in Wireless Networks

Current research trends show that wireless networks are evolving to the next generation networks where several radio access technologies will be used to provide ubiquitous services to users by interworking through a common all Internet Protocol (IP)-based core network [1]. In the next generation wireless networks, handovers should be seamless to ensure high Quality of Service (QoS) for a mobile user consuming high bandwidth services. A mobile user should not perceive a service disruption while changing points of attachment in the wireless network. Therefore, mobility management researchers have put a lot of effort in continuously proposing and implementing protocols and solutions that will offer seamless handovers.

However, many well accepted current solutions (e.g. Mobile IPv6, Proxy Mobile IPv6) are still not able to offer a non-perceivable interruption when a mobile user undergoes a handover. This is primarily caused by the duration when the mobile node is unable to either transmit packets to the network or receive packets from the network which is referred to as the handover delay. Handover delay can cause packet loss, resulting in a disruption on an ongoing communication.

Mobility management provides a mechanism to maintain a mobile node's active sessions regardless of the mobile node changing its point of attachment. Thus it is concerned with handovers, routing/re-routing, location management, address management, session identification, session migration, etc [2].

A mobility management solution may be implemented at different layers of the network protocol stack. It could be at the link layer, where it concerns a change in access points that form overlapping coverage areas. In this case, a handover is triggered by channel conditions, such as the received signal strength (RSS), and the bit error rate. The IEEE standard 802.21-2008 (Media Independent Handovers) provides a framework for handovers between different access networks which could have different implementations from the link layer downwards [2].

A mobility management solution can also be implemented at the network layer. In this case, it is concerned with the change of subnets. Mobility management at the network layer can

further be categorized according to the approach it adopts. In routing-based approaches, the mobile node's address does not change and is used for both locating the mobile and for delivering packets. The routing system keeps track of the current location (up-to-date location) of the mobile node. This approach is however not scalable with the exponential increase of mobile devices. Routing based approaches are used in Cellular IP, Handoff-aware wireless access Internet Infrastructure (HAWAII) and Terminal independent mobility for IP (TIMIP) [2]. On the other hand, there are mapping-based approaches. In this case, two addresses are used; one does not change namely the Home Address (HoA) and is mapped to the other which changes to reflect the location of the mobile node, namely the Care of Address (CoA). Mapping-based approaches are used in Mobile IPv6, Proxy Mobile IPv6 and Hierarchical Mobile IPv6 [2].

Mobility management can alternatively be implemented at the transport layer whereby it plays the role of handling how to migrate Transmission Control Protocol (TCP) connections when a mobile node's IP address changes [2]. Mobility management at the application layer on the other hand, allows applications to manage mobility using end-to-end signaling. In this case, mobility management schemes are either implemented for each application that needs mobility support (e.g. using Session Initiation Protocol (SIP)) or a middleware that handles mobility management is implemented between the communicating applications that need mobility support [2].

Network layer based mobility management solutions are mostly studied because the network layer is present in all Internet nodes and consequently, these solutions can offer mobility support to all applications running on the Internet nodes. Mobile IPv6 (MIPv6) being the most discussed solution has many variants/extensions Hierarchical MIPv6, Fast handovers for MIPv6, Dual Stack MIPv6, Proxy MIPv6, etc [2].

In order to improve the handover performance of MIPv6, the state of the art solution that provides IP mobility, the Internet Engineering Task Force (IETF) through the Network-based and Localized Mobility Management group (NetLMM) standardized the Proxy Mobile IPv6 (PMIPv6) [3]. Handover performance is analyzed in terms of handover delay, packet loss and signaling overhead incurred to offer IP mobility to a mobile node. Fundamentally, PMIPv6 is based on MIPv6 as it extends MIPv6 signaling. It possesses an anchor point namely the Local Mobility Anchor (LMA) which enhances MIPv6's Home Agent (HA) functionalities. In

PMIPv6, the mobile node's protocol stack needs no modification as required by MIPv6. This is because the mobile node is not involved in any mobility related signaling. A network element named the Mobile access gateway (MAG) acts as a proxy for the mobile node and hence performs signaling on behalf of the mobile node. Thus, there is no need to tunnel packets on the air interface; thereby significantly reducing the signaling on the air interface. PMIPv6 incurs lower handover delays and consequently lower packet loss during a handover [4, 5].

It is due to PMIPv6's robustness that it has attracted a considerable amount of attention and gained a lot of popularity. PMIPv6 appears to be a promising mobility management solution for the next generation wireless networks since it has already been adopted by the WiMAX forum [6] and has been recommended for the Third Generation Partnership Project (3GPP) Evolved Packet Core (EPC) [1]. However, PMIPv6 in its current state does not meet the stringent handover delay requirements required to support high QoS for real time services. On this account, many researchers are still proposing, modeling and testing extensions to PMIPv6 to enhance its handover performance. Figure 1.1 below shows how packets are lost during a handover and hence causing a perceivable disruption to an ongoing service.

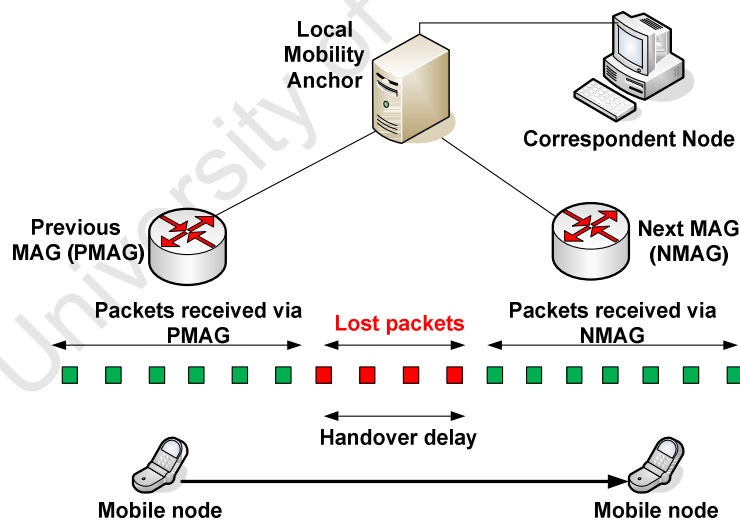


Figure 1.1. Packet reception behaviour at the mobile node during a handover.

When the mobile node cannot receive packets from the PMAG, the Correspondent node (CN) continues to send packets which are ultimately lost. It can be observed from Figure 1.1 that to provide less disruption to an ongoing communication, the handover delay is a parameter of utmost importance to minimize so as to lower the packet loss. The total handover delay includes

the layer-2 handover latency (channel scanning, authentication, association, etc) and the layer-3 handover latency (Prefix advertisement, IP address configuration).

In an endeavor to achieve seamless handovers, bicasting schemes for PMIPv6 have also been proposed in the literature to reduce packet loss and handover delay during a PMIPv6 handover. With these solutions, packets are duplicated and sent to both the current MAG (PMAG) and the candidate MAG (NMAG) during the handover. Thus, packets that were lost on the then previous MAG (PMAG) because the mobile node was then out of coverage can be buffered on the candidate/next MAG (NMAG) and be forwarded as soon as the mobile node successfully attaches to NMAG. Therefore, the packet delivery ratio is increased. Bicasting solutions also employ the technique of proactive handovers, thereby allowing a number of handover procedures to be carried out in advance to lower the handover delay. This is achieved by employing cross-layer techniques whereby the link-layer information is used to predict the handover occurrence. Figure 1.2 below provides a high-level abstraction of how bicasting-based schemes for PMIPv6 operate.

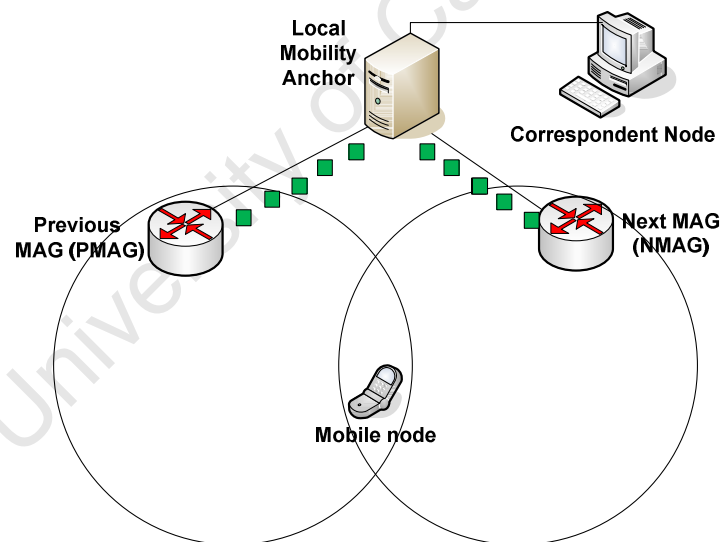


Figure 1.2 Duplication of packets and transmission to both MAGs

It can however be seen that there is room for improvement in the existing bicasting schemes for PMIPv6. This is because during the bicasting duration, packets are then routed to both PMAG and NMAG. This however requires a significant amount of backhaul bandwidth as well as MAG buffer space to achieve a seamless handover.

1.2 Problem Statement

Bicasting-based extensions for PMIPv6 proposed in the literature require a significant amount of backhaul bandwidth and thus use the network resources inefficiently (e.g. buffer). Given that in the near future, more bandwidth hungry applications and higher data rates access technologies (e.g. Long Term Evolution (LTE), LTE-Advanced) are going to prevail, such bicasting solutions may not scale to the increased mobile data traffic volumes.

Therefore, the problem that still remains to be solved is how to optimize the bicasting period. This entails when to start and when to stop bicasting in a timely and accurate manner such that the network resources (buffer space, backhaul bandwidth, etc) will be utilized much more efficiently as they are scarce and shared resources. If bicasting starts too early or stops too late, a significant amount of backhaul bandwidth is required. In addition, if starts too late or stops prematurely, packet loss occurs.

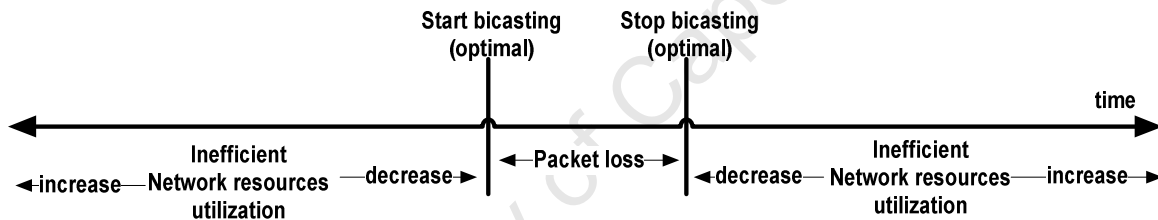


Figure 1.3. Bicasting analysis timeline

1.3 Need for this Research

Current packet-loss minimization techniques and solutions for Proxy Mobile IPv6 that are based on bicasting of IP packets during a handover result into wastage of network resources. This is due to the fact that packets are duplicated and hence the need for utilization of more network resources and an increased network load. This translates to an increased bandwidth requirement. On the other hand, buffering requirements are highly needed for these solutions to work. But, since the buffer space is not infinite, these solutions may not scale to the increase of mobile data traffic that is anticipated in the future.

The above arguments are supported by the Motorola LTE Technical Review White paper [7]. It is argued that a bicasting solution requires significantly higher backhaul bandwidth, and may still not be able to avoid data loss altogether. Moreover, determining when to start bicasting

is an important issue to address in the bicasting solution. If bicasting starts too early, there will be a significant increase in the backhaul bandwidth requirement. If bicasting starts too late, it will result in packet loss. There will also be a high bandwidth requirement if bicasting delays to stop or stops too late. On the other hand, if it stops prematurely/too early, it will result to higher packet losses [7].

In [8], performance analysis of various MIPv6 protocols was carried out with the help of simulations and it was found that simultaneous binding MIPv6 (bicasting-based) achieves the least packet loss but has the highest bandwidth requirements. From the above information, it is clear that there is need for further research in developing a network-resource efficient solution for bicasting PMIPv6.

1.4 Objectives of the Research

The main objectives of this study are to:

- i. Investigate the challenges in IP mobility especially Bicasting schemes for Proxy Mobile IPv6.
- ii. Design an IP mobility solution that does not only improve the PMIPv6 handover performance by lowering the handover delay and packet loss incurred during a handover, but also improves usage efficiency of the network resources.
- iii. Implement and analyse the proposed mobility management solution for proof of concept purposes
- iv. Perform extensive experimentation of the proposed solution and compare it to the current related solutions for validation purposes.

The specific objectives of the proposed solution are to:

- Enhance handover performance by minimizing packet loss and handover delay.
- Improve the backhaul bandwidth and buffer space usage efficiency in bicasting PMIPv6.

1.5 Research Scope and Limitations

As mentioned earlier, mobility management solutions can be implemented at different layers of the TCP/IP protocol stack. This study focuses on network-based mobility management particularly the PMIPv6. The major focus of this research is to improve the efficiency of utilization of network resources (buffer space and backhaul bandwidth) that are required for bicasting PMIPv6 to offer better handover performance.

The proposed solution makes use of the link layer triggers, which are generated based on the signal strength behaviour in order to trigger the execution of handover operations. To model the signal strength behaviour in the wireless environment, a deterministic radio-wave propagation model, two-ray ground, which considers the direct and the ground reflected paths is used. Thus, the solution is limited to usage in rural areas where there are no many tall building or obstacles that would favour other more robust radio-wave propagation models. The proposed solution may be improved by modelling it using other more robust radio-wave propagation models, such as the shadowing model.

The proposed scheme is simulated to evaluate its performance considering handover delay, packet loss, backhaul bandwidth requirements, as well as buffer space requirements. The experimentation carried out in this thesis is in a homogenous environment where the IEEE 802.11 radio access technology is used. It is also assumes that the network coverage areas overlap.

1.6 Research Contributions

The contributions of this study are summarized as follows:

- i. This research contributes to the body of knowledge as it shows how bicasting for PMIPv6 can be enhanced to better utilize the scarce network resources thereby allowing the network operator to service more users and increase the revenues. (Network operator centric benefit)
- ii. The proposed solution has practical applications. It contributes to the reduction of network congestion as the proposed solution improves PMIPv6 handover performance to achieve better Quality of Experience (QoE) for the mobile user

while also paying attention to improving the efficiency of network bandwidth usage (network operator centric and customer centric benefits).

- iii. Furthermore, as PMIPv6 has been identified as a promising network-based mobility solution by the WiMAX forum and 3GPP by recommending it for the System Architecture Evolution EPC, the proposed PMIPv6 extension can be incorporated as it improves network resources utilization efficiency as well as handover performance.

1.7 Thesis Outline

The remainder of the thesis is organized as follows:

Chapter 2 discusses IPv6 mobility solutions at the network layer that have been proposed in the literature to address mobility management challenges. It provides a survey of network-based mobility management protocols at the network layer in terms of their handover approaches to achieve seamless handovers. The chapter also discusses some bicasting schemes proposed in the literature for PMIPv6 to demonstrate the need for further research in bicasting schemes for PMIPv6. Lastly, the chapter discusses link-layer triggers that are utilized in this study to facilitate handover predictions for better handover performance.

Chapter 3 presents an in-depth discussion of the proposed bicasting scheme for PMIPv6 design. Firstly, the chapter highlights the design goals of the proposed solution. Secondly, formulation of the approach employed by the proposed solution to better utilize network resources is discussed. Thirdly, system models/designs for the proposed solution on the MAG and LMA are presented. Lastly, the handover signaling diagram for the proposed solution is presented and analyzed.

Chapter 4 discusses the details of the evaluation framework used for this study. It begins by giving a brief discussion of the objectives of the framework and then proceeds to an overview of software models used. The chapter then proceeds to discuss how the proposed bicasting solution for PMIPv6 was implemented in the Network simulator-2. Lastly, the experimental setups used to test the proposed solution as well as the simulation parameters are discussed.

Chapter 5 presents the evaluation results obtained and their performance analyses. The chapter begins by defining the evaluation performance metrics of interest to the study. Then

after, results obtained for each metric are presented and analyzed. This is where the proposed bicasting solution is compared to other bicasting schemes for PMIPv6 proposed in the literature.

Chapter 6 concludes the study by presenting conclusions on the proposed bicasting solution for PMIPv6 and highlights some recommendations for future improvements and investigations.

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Chapter 2 Background and Literature Review

2.1 Introduction

This chapter provides an overview of some network layer mobility management solutions; particularly Mobile IPv6 based solutions in the literature. It offers a specific focus on network layer mobility management schemes. It further discusses and analyses the currently proposed bicasting solutions for PMIPv6 in the literature. It discusses the merits and de-merits of these solutions to demonstrate the need for this study. Lastly, this chapter gives an overview of link-layer triggers and the IEEE 802.21 (Media Independent Handovers) as they are utilized in the solution proposed in this work.

2.2 Overview of IPv6 Mobility Management

Next generation wireless networks propose an all IP-based network infrastructure that interconnects heterogeneous radio access networks. One of characteristics of the next generation wireless that is expected is that handovers will be fast and seamless as the mobile user roams across multiple radio access technologies performing intra-technology (horizontal) and inter-technology (vertical) handovers. Thus, mobility management for the next generation wireless networks is of utmost importance.

Mobility management is concerned with two main tasks; Location management and Handoff management [9]. Location management is responsible for locating and tracking the mobile node throughout the entire wireless network. This involves registration, location updates and routing updates so as to optimize paths followed by traffic streams destined to the mobile node as it changes its points of attachment in the wireless network. Handoff management provides mechanisms to maintain a mobile node's ongoing sessions as a change in access points occurs. Handoff management also involves handover preparation by allocating resources for services being consumed by the mobile node as well as re-routing of traffic to the subsequent point of attachment.

Mobility management solutions can be implemented on different layers of the TCP/IP protocol stack as discussed in Chapter 1. This study focuses on the prominent solutions that are implemented on the network layer (layer-3). These solutions have attracted a lot of attention and

have been deemed to pave the way towards providing IPv6 mobility in the next generation wireless networks which will be all-IP based. This is because the next generation networks will consist of IPv6 nodes. Moreover, since most Internet nodes possess the network-layer, then network-layer mobility solutions offer mobility support transparently to applications running on these nodes [2].

2.3 Network-layer Mobility Management

This section discusses mobility management solutions at the network layer. It starts with host-based solutions in which the mobile node is involved in layer-3 mobility-related signaling. Then after, network-based solutions at the network-layer are discussed in which the mobile node is relieved of any layer-3 mobility-related signaling.

2.3.1 Host-based Solutions

2.3.1.1 Mobile IPv6

Mobility support in IPv6 known as Mobile IPv6 (MIPv6) is a host-based IPv6 mobility solution that was standardized by IETF. It paves the way towards providing mobility management in all-IP next generation networks. MIPv6 solves many of the MIPv4 demerits such as non-optimal header, longer end-to-end delay caused by triangular routing [10].

MIPv4 is not considered to be a solution that will suffice for the next generation wireless networks mobility management needs because IPv4's address space has run out and will not be able to support the current and future predicted increase in mobile nodes proliferation in the next generation networks. Thus, MIPv6 which extends on IPv6 is a much more favorable solution over MIPv4. This is because among many advantages over MIPv4 it provides neighbor discovery mechanism, enhanced security as well as stateless IP address configuration to lower the handover delay.

MIPv6 is able to achieve persistence in the mobile node's active connections as it roams the wireless networks (Internet domain) and changing subnets which trigger IP address changes on the mobile node. The main objective of MIPv6 is to enable the correspondent nodes to reach the mobile node as it changes IP addresses. MIPv6 attains this by utilizing two IP addresses; namely the Home address (HoA) and the Care of Address (CoA) [11]. The HoA is a permanent/static IP address assigned to the mobile node by the Home Agent which is the data

packets anchor point for the mobile node traffic in the home network. Thus for as long as the mobile node is in the home network, packets destined for the mobile node are routed normally (standard IP routing) without any modification on the packets.

The CoA on the other hand, changes each time the mobile node alters its point of attachment and its subnet-network. It is assigned by the visited network through the Foreign Agent (FA). The mobile node is required to signal an update to the HA of its CoA when it moves to a visited network. But, since the CN is oblivious of the mobile node's movement, it will continue to send packets to the IP destination HoA. The HA is then responsible to intercept any packets destined to HoA and encapsulate them in an IP-in-IP tunnel to the mobile node on the current CoA. The tunnel starts at the HA and ends at the mobile node in the visited network.

The signaling diagram below shows the sequence of steps that occur when the mobile node is in the home network and when it moves to visited network.

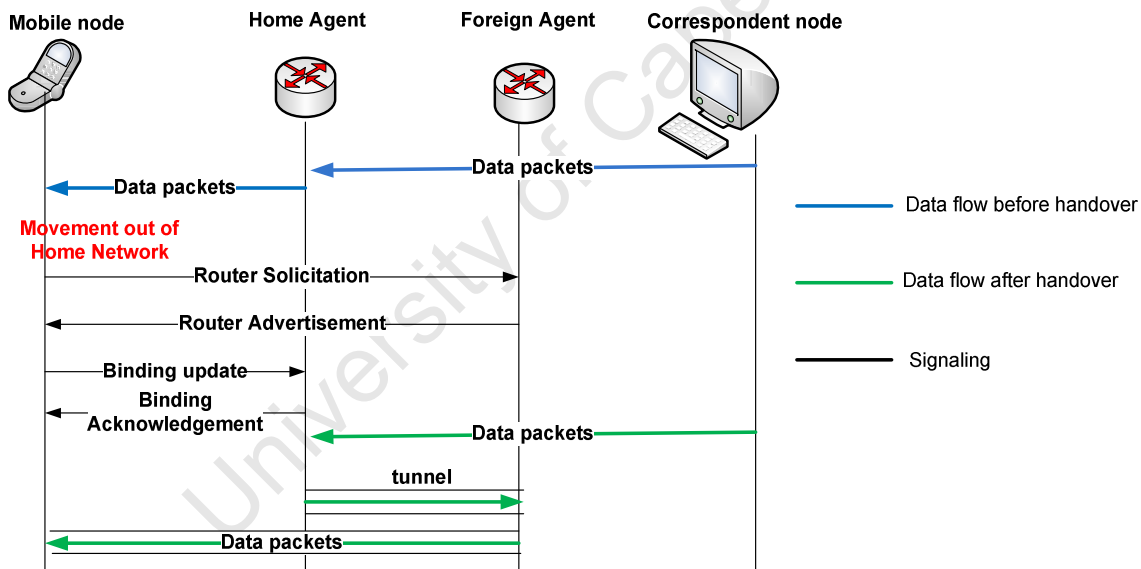


Figure 2.1 MIPv6 handover signalling

The message sequence chart above shows that in MIPv6, for detection of the MN movement, the router solicitation (RS) and router advertisement (RA) messages are used. The RS is sent by the Mobile node (MN) to the network to find an access router whereas the Access Router sends the RA to the MN and carries a prefix that is used by the MN to configure an IP address. Furthermore, to ensure that the HA is aware of the most current CoA of the MN as it roams the wireless networks, the MN is required to send a binding update (BU) so as to update

the binding cache entries (bind HoA to CoA) on the HA for reach-ability purposes. The HA responds with a binding acknowledgement (BA) message to acknowledge the MN's location update. To eliminate triangular routing, MIPv6 can apply route optimization thereby allowing the MN to send a BU to the CN so that the CN can send packets directly to the MN instead of the HA and hence improve the end-to-end packet delay. This is very essential in cases where the CN is closer to the MN and the HA is far from the MN.

Even though MIPv6 enables the MN to maintain ongoing communications as it changes points of attachment in the wireless network, it possesses some demerits that are addressed by proposals of extensions such as the Fast Handovers for MIPv6 [12] and Hierarchical MIPv6 [13]. MIPv6 incurs a high handover delay that in turn causes packet arrival fluctuations at the mobile node consuming services from the network. It also incurs packet loss during a handover, which can result in degradation in Quality of Service on the mobile user end. This is mainly caused by its reactive approach to handovers whereby some handover operations are performed after losing connectivity to the Home network. These are movement detection, duplicate address detection (DAD) which is utilized to ensure the uniqueness of the IP address configured by the MN, and sending of binding updates. In addition, MIPv6 possesses a drawback of for dealing with local mobility in the same way as global mobility thus increasing signaling overhead [5]. Since it is envisaged that in the next generation wireless networks, handovers should be transparent or non-perceivable to mobile users, this led to a need to enhance MIPv6's handover performance.

2.3.1.2 Fast Handovers for Mobile IPv6

An extension to MIPv6; Fast handovers for MIPv6 has been proposed in the literature to enhance MIPv6's handover performance. Fast Handovers for MIPv6's major objective is to improve the handover delay, packet loss and signaling overhead encountered as a mobile node performs a handover. Fast Handovers for MIPv6 (FMIPv6) offers a much more optimized header format and better security compared to MIPv6 [12]. Lowering the handover delay is an important improvement since with longer handover delays; the transport protocol may terminate the ongoing connection with the assumption that the connection is broken [5].

FMIPv6 also utilizes a predictive approach to handovers to anticipate a handover. This is accomplished by employing cross-layer techniques as well as using link-layer triggers to proactively execute some handover operations before the mobile node can actually detach from a

previous point of attachment. These operations include configuring a new CoA on the MN for the subsequent network and packet flow redirection to the subsequent point of attachment subnet [12].

Since, the previous access router (PAR – Access router that the MN moves away from) has to be notified as quickly as possible of the MN's change of CoA to lower packet loss, FMIPv6 tackles this by sending fast binding update (FBU) to the PAR proactively. Hence as the handover progresses, packets are tunnelled from PAR to the next access router (NAR – Access router in the subsequent subnet). This is performed in an effort to avoid misrouting of packets and avoid sending packets to the MN through PAR when the MN is no longer within PAR's subnet.

The sequence chart in Figure 2.2 below depicts the handover operations as well as the signaling performed to achieve fast handovers for MIPv6 when MN moves from PAR subnet to NAR subnet. It should however be noted that FMIPv6 has both a reactive and predictive mode of operation. However, the predictive approach is discussed due to its better handover performance.

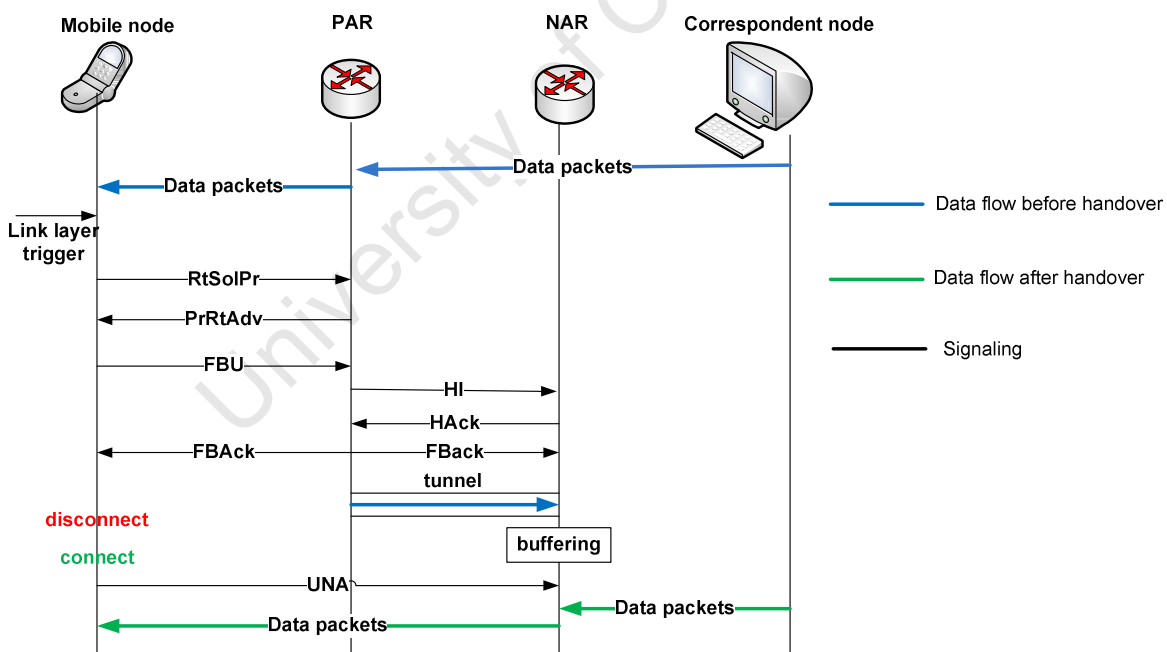


Figure 2.2 FMIPv6 handover signalling

As depicted in Figure 2.2 above, after the MN has performed router discovery or responding to a link-layer event, it sends a router solicitation for proxy (RtSolPr) message to the PAR and the PAR responds with a proxy router advertisement (PrRtAdv) which contains

information about one or more access points that the MN may handover to. The MN configures a prospective new care of address (NCoA) and sends a fast binding update (FBU) to the PAR so that the PAR can associate the previous care of address (PCoA) to the NCoA and start tunnelling packets destined to the MN on PCoA to NCoA. Thereafter, the PAR sends a handover initiate (HI) message to NAR. The HI carries the prospective NCoA proposed by the MN. NAR verifies that there are no IP address collisions through DAD. The NAR responds to PAR with a handover acknowledgement (HACK) message and indicates if the NCoA proposed by MN is approved or the NAR includes and NCoA assigned by it. The PAR then sends a fast binding acknowledgement (FBACK) message to the MN that includes an assigned NCoA from the NAR. The MN is also required to send an unsolicited neighbour advertisement (UNA) message to NAR as soon as it re-attaches to the network so that NAR can forward any buffered packets as soon as possible [12].

As was mentioned earlier, FMIPv6 has a reactive mode as well. This mode applies in the case whereby the MN was unable to send an FBU to the PAR or a case whereby the MN failed to receive an FBACK from PAR before moving out of PAR's subnet. The MN is then required to send the FBU to PAR through NAR immediately after sending UNA to NAR. Therefore, FMIPv6 reactive mode incurs an undesirably longer handover delay, and higher packet loss than the predictive mode.

However, FMIPv6 predictive mode relies on the possibility of successful reception of signalling messages carried out during the preparation for a handover. Therefore, there is a possibility that when the mobile node traverses from PAR subnet to NAR subnet at a high speed, FMIPv6 will have to fall back to reactive mode and hence offer non-optimal handover performance. FMIPv6 has also been criticized for high signaling overhead on the air interface that is aggravated by the need for the MN to anticipate the handover [10]. Furthermore, there is a need for the use of timely and more accurate link-layer triggers since if the trigger to perform a handover is generated too early, the PAR will begin to tunnel packets to NAR too early when MN can still receive packets through PAR. On the other hand, if the trigger is late, the handover performance will not be acceptable for real-time interactive applications [14].

2.3.1.3 Hierarchical Mobile IPv6 Mobility Management

Hierarchical MIPv6 (HMIPv6) is one other MIPv6-based extension that is important in

the evolution of MIPv6 variants. It introduces a regional or local HA namely the mobility anchor point (MAP) to mitigate longer handover delays that the long distance between the MN and the HA could contribute towards. A regional CoA (RCoA) on the MAP link addresses the MAP. A local CoA (LCoA) which changes as the MN changes access gateways (AGs) within a MAP domain addresses the MN [13].

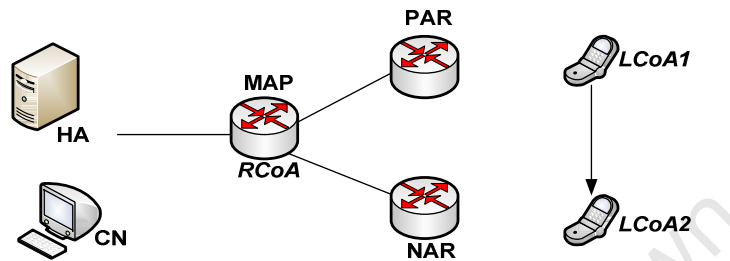


Figure 2.3 HMIPv6 network model

Instead of sending BUs to a HA that could be far away from the MN, the MN sends the BU to the regional MAP. The MN is required to update the HA of its RCoA so that all packets destined to the MN can be encapsulated in an IP-in-IP tunnel to the MAP, and in turn, the MAP tunnels packets destined to the MN to the current LCoA. An important advantage is that local (within a single MAP domain) MN handovers do not have to be signalled to the HA, thus lowering the signaling overhead as well as avoiding longer signal propagation overheads. Figure 2.4 below shows the sequence of steps and signalling messages that occur in a HMIPv6 handover.

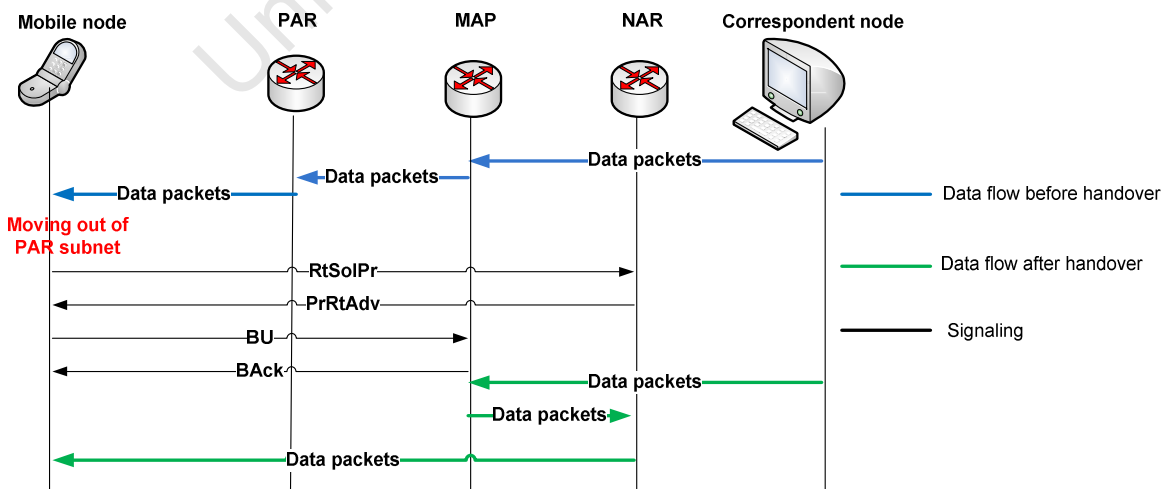


Figure 2.4 HMIPv6 handover signalling

As depicted in Figure 2.4 above, when the MN performs a handover from PAR to NAR subnet, the MN has to send a binding update (BU) to the MAP to update its current LCoA. The MAP then creates a binding between RCoA and LCoA and sends a binding acknowledgement (BAck) to the MN. However, in the case of an inter-MAP domain handover, the MN is required to send the second BU to the home agent (HA) and the corresponding node (CN) since the MN relocates to a new MAP thus changing the RCoA [13]. Therefore, there is a reduction in mobility-related signaling traffic for localized mobility.

The MIPv6-based solutions discussed above are classified as host-based network-layer mobility management solutions. This is mainly due to the principle of operation in these solutions whereby the MN is involved in the mobility-related signaling. Thus these solutions require implementation modifications on the MN's protocol stack to support the generation and sending of signaling messages required by the host-based solutions. Furthermore, in host-based solutions, there is a high signaling overhead on the air-interface that has a scarce bandwidth resource [10]. Lastly, the MN stack modifications increase the MN's complexity and the involvement of the MN in mobility signaling increases the battery consumption. Thus, the requirement for a mobility management solution that addresses the highlighted demerits of host-based becomes apparent. The next section discusses the IETF standardization - the Proxy Mobile IPv6 that aims to solve host-based solutions' drawbacks.

2.3.2 Network-based Solutions

2.3.2.1 Proxy Mobile IPv6

In 2008, Proxy Mobile IPv6 (PMIPv6) was standardized by the IETF through the NetLMM to offer better handover performance. PMIPv6 is fundamentally based on a host-based protocol Mobile IPv6 (MIPv6) and extends the MIPv6 signaling [3]. It inherits and modifies some of the MIPv6 entities such as the Home Agent (HA) which is named the Local mobility anchor (LMA) and offers more functionality [3].

PMIPv6 is network-based network-layer mobility management solution as it employs only the network elements to offer mobility support to a mobile node. In a PMIPv6 domain, the MN is not involved in any mobility-related signaling. In PMIPv6, the MIP implementation modifications required for mobility support are moved to the network. A special access router namely the mobile access gateway (MAG) carries out any mobility-related signaling on behalf of

the MN. Thus, the MAG provides a proxy for the MN.

The LMA is an anchor point that intercepts packets destined to mobile nodes in the PMIPv6 domain. It then forwards the packets to the MAG that provides a proxy CoA (PCoA) for the mobile node through the bi-directional tunnel set up between the respective MAG and the LMA. The mobile node connects to different subnets in the PMIPv6 domain with its HoA whilst the MAG and the LMA manage bindings between the HoA and the PCoA. The MAG is also responsible for emulating a home link for the MN by advertising the MN's home network prefix (HNP). Figure 2.5 below shows a PMIPv6 architecture which consists of the highlighted network components. It also gives an overview of the PMIPv6 terminology in terms of signaling messages (e.g. proxy binding update (PBU)), addressing (e.g. PCoA), and the network elements.

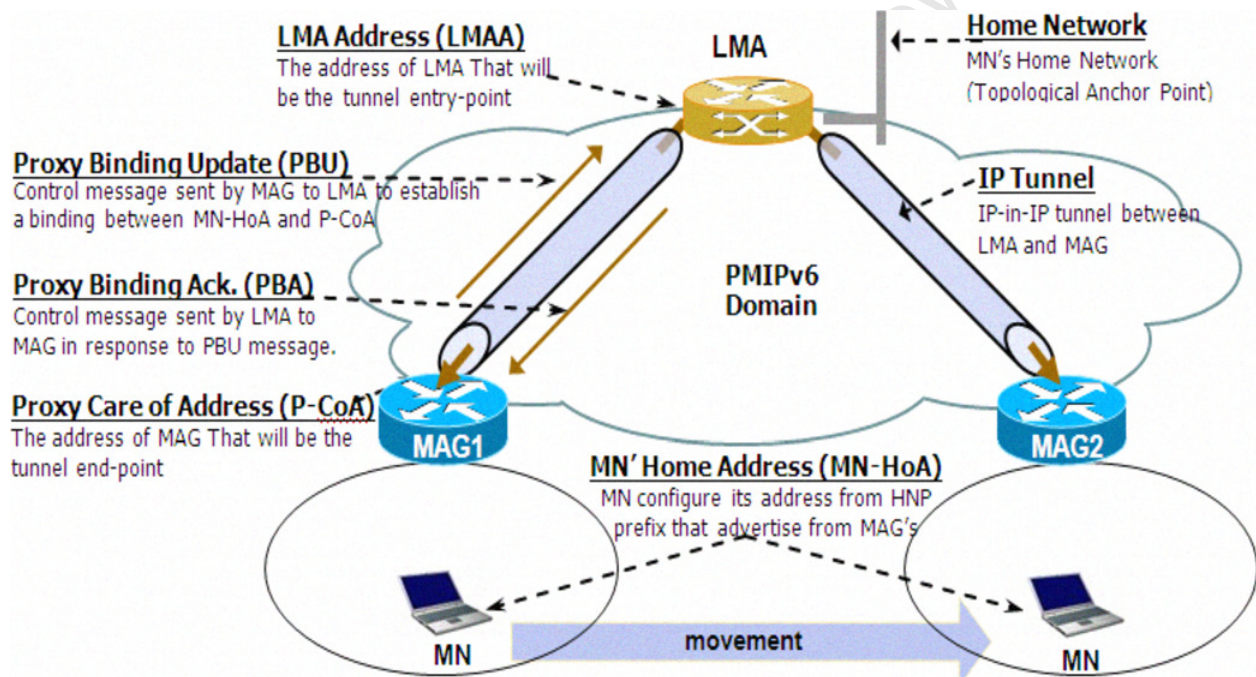


Figure 2.5 PMIPv6 network model overview [5]

PMIPv6 uses per MN prefix model as opposed to other mobility management solutions (e.g. MIPv6) that use a shared prefix model. Upon attachment of the MN to the MAG, the MAG advertises a HNP to the MN. The MN then uses the HNP to configure a HoA, which the MN continually configures as it changes MAGs within the PMIPv6 domain. Thus, to the MN, the entire PMIPv6 domain is perceived as a home network and hence there is no need to configure a CoA at the MN. The overall operations and signalling flow in PMIPv6 is depicted in Figure 2.6.

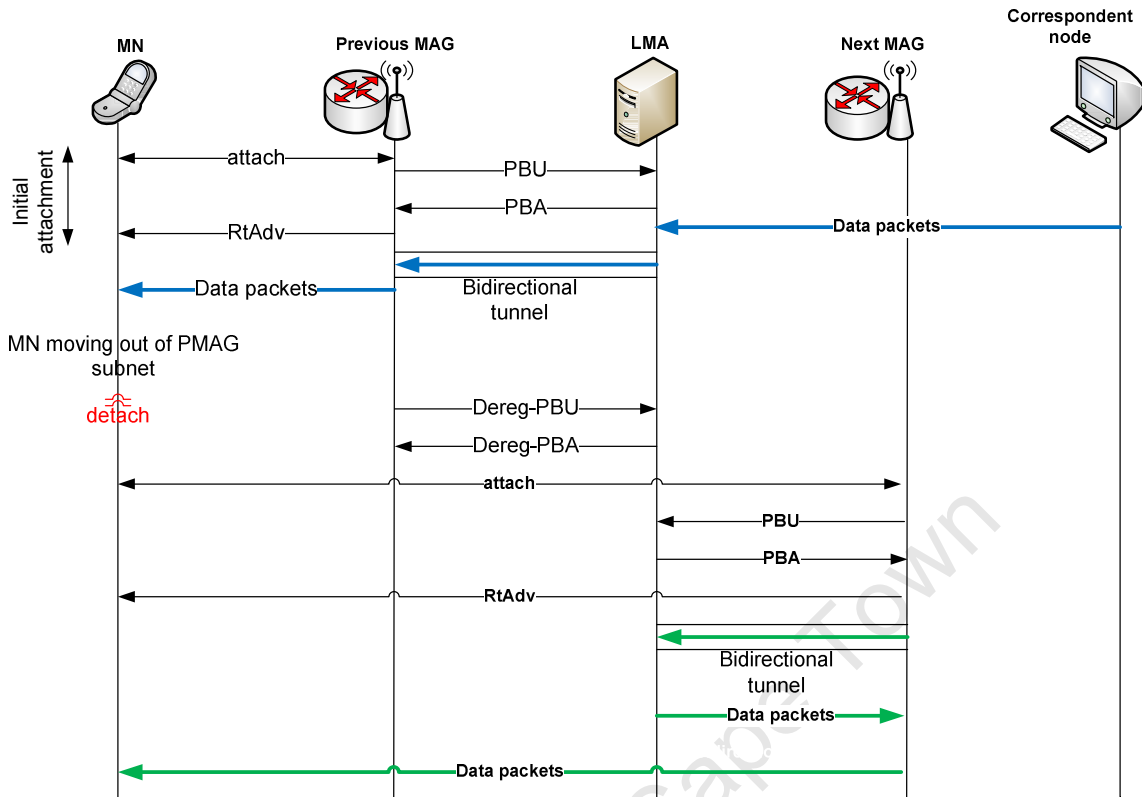


Figure 2.6 PMIPv6 MN attachment and handover signalling

As can be seen in Figure 2.6, firstly, during the initial attachment phase, the MN attaches to the MAG (Previous MAG) after performing layer-2 attachment procedures such as scanning of channels on the point of attachment (e.g. Access Point), authentication and association. As soon as the MAG detects MN's attachment, it sends a PBU to the LMA to establish or register a routing state on the MN's behalf. The LMA responds by sending a PBA to the PMAG and a bidirectional tunnel is created for encapsulating packets to and from the MN. With the binding update process, the LMA and PMAG establish binding cache entries for the MN, and the LMA assigns a MN a unique home-network prefix (HNP) since PMIPv6 uses a per MN Prefix model. The HNP is carried with the PBA message that the LMA sends to the PMAG. The PMAG then advertises the HNP to the MN through the router advertisement (RtAdv) message. When the MN receives the HNP, it configures an IP address that it uses throughout the PMIPv6 domain. With the MN's routing state established, and the MN IP address configured, the MN can send or receive packets.

Uplink packets from the MN are encapsulated in an IP-in-IP header with the PCoA address provided by the MAG as a source IP address and the LMA as the destination IP

address. This hides the inner (original) IP packet header with the MN's IP address as the source IP address and the CN IP address as the destination IP address. The LMA, decapsulates the packets by removing the outer header and exposing original source IP address and the packet is routed normally (standard IP routing) to the destination CN. On the other hand, downlink packets that are intercepted by the LMA, are encapsulated by adding an IP header with the LMA as the source IP address, and the PCoA as the destination IP address. Similarly, the MAG decapsulates the packets and exposes the original header and the data packets are sent to the MN.

In the case of a handover, when an MN moves from PMAG subnet to next MAG (NMAG) subnet, packets intercepted by the LMA have to follow the MN and be redirected to NMAG instead of PMAG. To achieve this, upon PMAG detecting that the MN has moved out of its subnet, it sends a deregistration PBU (Dereg-PBU) to the LMA to remove the MN routing state between LMA and PMAG. LMA then responds with a Dereg-PBA. The standard specifies that during this time, the LMA may buffer packets destined to the MN [3]. Furthermore, the LMA waits for the *MinDelayBeforeBCEDelete* to completely erase the MN's reach-ability state [3].

As soon as MN's attachment is detected on NMAG, NMAG carries out the binding update process to update MN's routing state and the current PCoA of the MN. The LMA responds with a PBA that carries the same HNP that was advertised to the MN when it initially attached to PMAG. The MN receives the same HNP through the RtAdv from NMAG and configures the same IP address (i.e. the MN retains its IP address). Thus, to the MN, it perceives the entire PMIPv6 domain as a home network since it configures the same IP address regardless of it changing subnets.

It is observable from the above discussion that PMIPv6 eliminates excessive signaling on the air-interface as well as tunnelling that terminates at the MN as in other MIPv6-based solutions. It is also important to note that since PMIPv6 uses a per-MN prefix model as opposed to the shared prefix model employed in other host-based MIPv6 variants. This eliminates the need to perform DAD to verify the uniqueness of the MN IP address thus improving the handover performance in terms of handover latency.

2.3.2.2 Fast Handovers for Proxy Mobile IPv6

Other studies such as [15] have shown through evaluations that PMIPv6 can offer better

handover performance as well as lower signaling overhead compared to other mobility management protocols. However, it has been acknowledged that PMIPv6 still cannot incur acceptable handover delays for real-time interactive multimedia applications [10]. With that notion, many researchers have proposed extensions to PMIPv6 with fast handovers to pave the way towards seamless handovers.

One other approach that has been extensively studied and proposed to address the non-optimal handover performance demerit in PMIPv6 is that of adopting the FMIPv6 approach which utilizes a proactive handover mechanism as opposed to the reactive approach. With this technique an even better handover performance can be achieved through anticipating the handover and allowing some handover operations to be executed before the handover occurs. One of the proposals that employs a proactive handover approach standardized by the IETF is Fast handovers for PMIPv6 (FPMIPv6).

FPMIPv6 [16] utilizes the link layer information such as received signal strength to anticipate the handover. FPMIPv6 also has both a predictive mode as well as a reactive mode. In a predictive mode, when the handover is predicted, the MN notifies the PMAG and includes information about the next point of attachment that it is likely to handover to. The PMAG then sends a handover indication (HI) message to NMAG to notify it of the MN that will be attaching to it in the near future. The NMAG responds with a Handover acknowledgement message (HACK). A bidirectional tunnel is then set up between PMAG and NMAG to deliver the MN's packets. Thus, packets that reach PMAG from the LMA are sent through the bidirectional tunnel between PMAG and NMAG. Therefore, packets that would otherwise be dropped by PMAG when the MN is out of its subnet and establishing a connection to NMAG's subnet are sent to NMAG and are buffered until the MN successfully attaches. Therefore, FPMIPv6 incurs a much lower packet loss than PMIPv6. When the MN attaches the NMAG subnet, NMAG and LMA exchange binding messages to update the MN's routing state and the LMA redirects the packet flow destined to the MN to NMAG. NMAG advertises the HNP for the MN to configure and retain its IP address and hence starts consuming an ongoing packet stream. The overall handover signaling and operations carried out during an FPMIPv6 handover is shown in Figure 2.7.

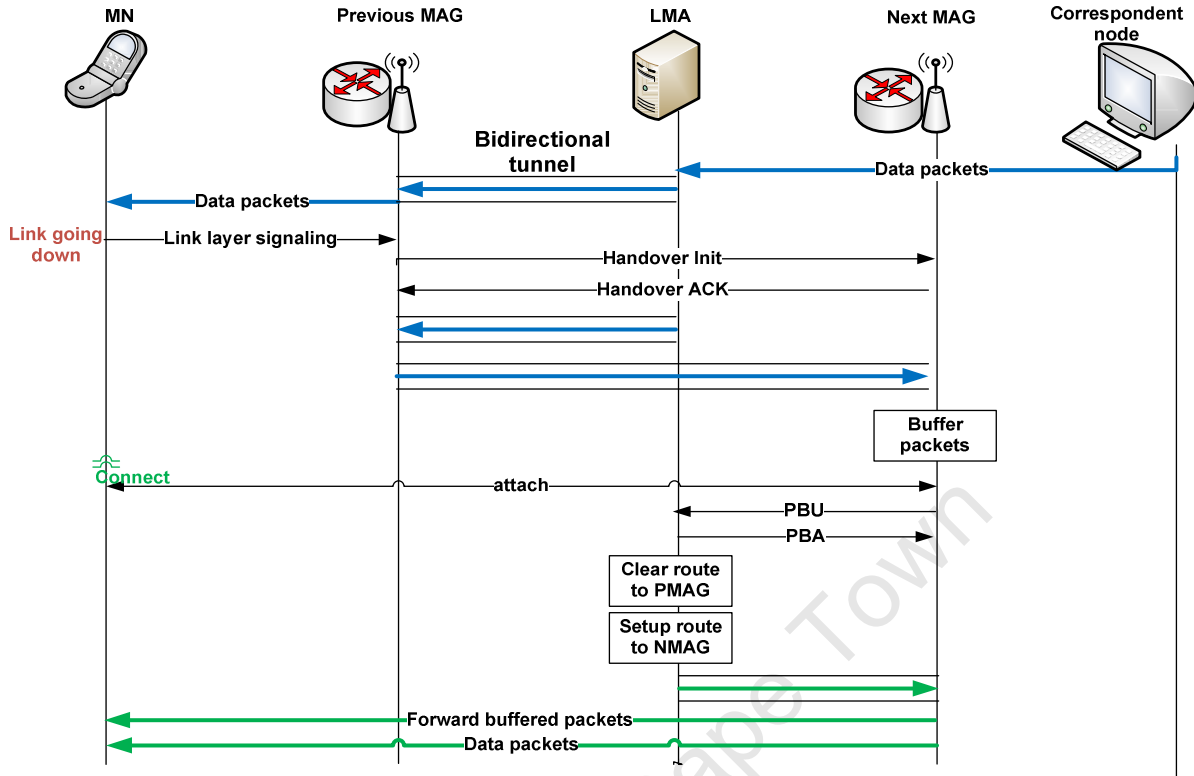


Figure 2.7 Predictive FPMIPv6 handover signaling and operations

In [17] an enhanced fast handovers for PMIPv6 (eFPMIPv6) is proposed and its performance is compared to that of FPMIPv6 using analytical modeling. In eFPMIPv6, link layer information is also used to anticipate a handover. The main difference between FPMIPv6 and eFPMIPv6 is that in eFPMIPv6, when the handover is imminent, after the PMAG has sent a HI message to NMAG, NMAG and LMA exchange binding update messages so as to set-up a bidirectional tunnel between the LMA and NMAG. Thus, in this solution, the MN is pre-registered in the binding cache entry, and the routing state of the MN is pre-set-up while the MN is performing the handover. Therefore, eFPMIPv6 eliminates the latency incurred in updating the MN routing state between the LMA and NMAG and binding cache entries from the total handover delay incurred. Thus, in eFPMIPv6, the handover latency is constituted by the layer-2 attachment latency, the latency to advertise the HNP, and the IP address configuration.

2.3.2.3 Bicasting Extensions for Proxy Mobile IPv6

Amongst the efforts of enhancing PMIPv6 handover performance to suffice for real-time applications such as Voice over IP (VoIP), bicasting-based solutions have been proposed. With bicasting incorporated into a mobility management protocol, packets destined to the mobile node

are duplicated and sent to the current point of attachment as well as the point(s) of attachment that the MN is likely to attach/handover to. With this technique, the probability that packets that may not be received by the MN since it had recently lost connectivity with the current (then previous) point of attachment and be received when attaching to the next point of attachment is increased. Thus, with a lower amount of packets lost due to a transient loss in connectivity, the mobile user may not experience a perceivable degradation in the QoS.

A number of studies in the literature have explored bicasting to enhance handover performance for the next generation wireless networks. In [18], Kim, D. *et al* propose a velocity-based bicasting solution that schedules the bicasting operation based on the speed of the mobile node. It uses a concept of a bicasting threshold determined on the basis of specific mobile speed groups to ensure that the solution is robust in terms of utilization of network resources efficiency. However, the solution provides a layer-2 bicasting solution. This study focuses on layer-3 bicasting solutions for PMIPv6 which are discussed below.

Ji-In *et al* in [19][20] proposed a bicasting based PMIPv6 (B-PMIPv6) scheme to lower handover delay and packets loss so as to evade packet arrival fluctuations caused by a handover. Firstly, B-PMIPv6 employs the use of predictive handovers so as to lower the handover delay whereby the route to the next point of attachment is set up in advance when a handover is imminent. Secondly, B-PMIPv6 increases the possibility of receiving all packets send by the corresponding node by duplicating packets to the current and candidate (subsequent) points of attachment (MAGs) when the signal strength degrades to a certain set threshold namely the LINK_GOING_DOWN (LGD) power level/threshold. Figure 2.8 below shows the flow of signaling messages during a B-PMIPv6 handover.

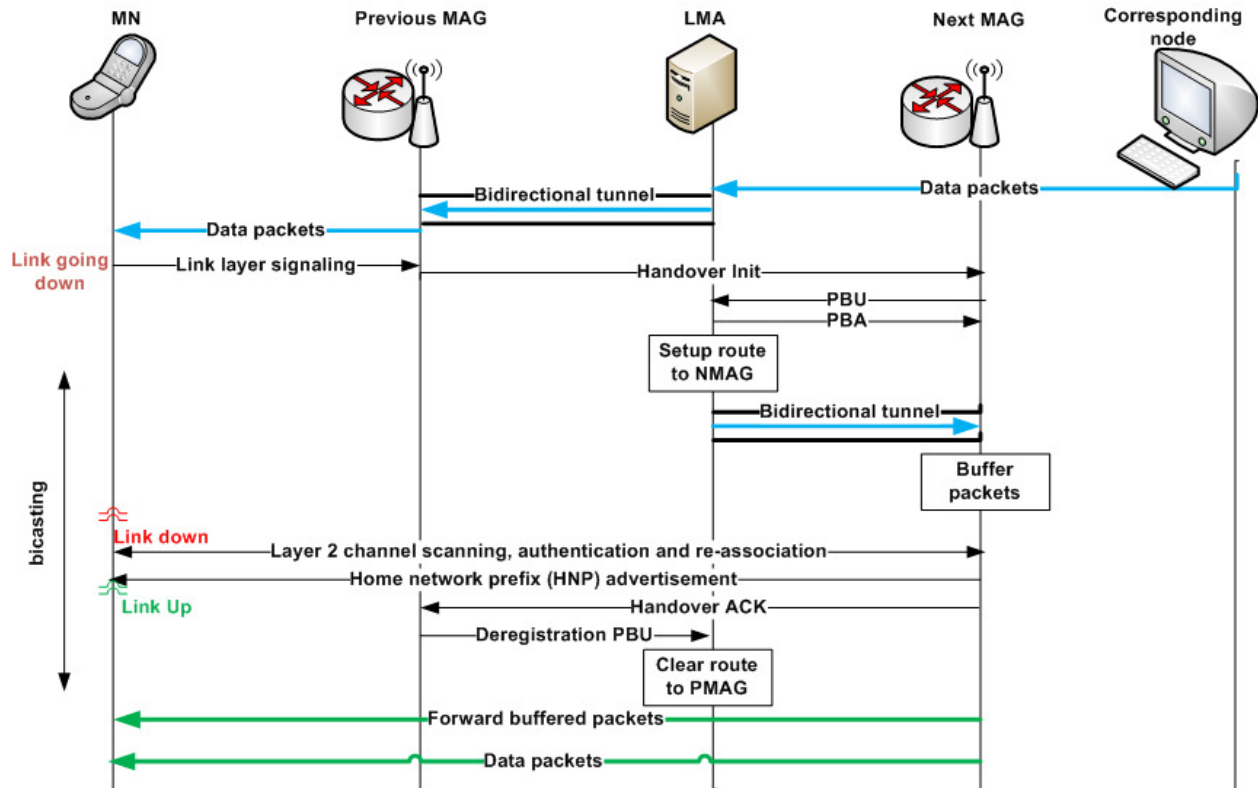


Figure 2.8 B-PMIPv6 handover signaling and operations

Even though this solution also proves to minimize handover delay and packet losses, it utilizes a significant amount of network resources (backhaul bandwidth and buffer space) since it delays to stop bicasting. It is observable that the LMA continues to route packets to PMAG even when the signal strength is below the receive threshold (i.e. Link is down on PMAG). Therefore, the backhaul bandwidth and the PMAG's resources are utilized unnecessarily.

Furthermore, if the mobile node is moving from PMAG to NMAG at a low speed (e.g. pedestrian speed), the B-PMIPv6 solution will require a large buffer space on NMAG which may not be available as it is a scarce resource. This is because bicasting starts too early for a mobile node moving at a low speed. Lastly, there is a high possibility of reception of duplicate packets at the mobile node. This could be undesirable if the User Datagram Protocol (UDP) is the transport protocol used since the higher layers will have to provide a mechanism to detect and discard duplicate packets, otherwise there will be hiccups in the service being consumed on the mobile device.

Bargh S.M. *et al* also proposed PMIPv6 with simultaneous bindings (SPMIPv6) [21] to

reduce the handover latency for the next generation wireless networks. The solution uses multiple triggers as proposed by Guan W. *et al* in [22] to facilitate anticipation of a handover. Through the adoption of a proactive handover, the solution is able to perform other handover operations before the handover occurs and hence lower the handover delay. Packet bicasting occurs during the handover and is controlled by PMAG (Handover coordinator). Two triggers $t1$ and $t2$ are used to achieve coordination of the handover operations. The first trigger $t1$ is triggered when a handover is imminent. In this solution, when a handover is imminent, PMAG instructs NMAG to send a PBU with a bicasting option set. Thus, similar to B-PMIPv6, SPMIPv6 starts bicasting when a handover is imminent.

In addition to starting bicasting, the MN is instructed to carry out the layer-2 attachment to the next point of attachment to eliminate the layer-2 latency from the total handover delay. The second trigger $t2$ is triggered when the MN's connection to PMAG breaks. When $t2$ is triggered, PMAG sends a de-registration PBU to LMA for the bicasting to stop. It can be observed that in this solution, packets are not continuously sent to PMAG when the link is down; hence, the backhaul link bandwidth is not as inefficiently used as in B-PMIPv6.

Ji-In *et al* in [23] further improved B-PMIPv6 and proposed a partially bicasting PMIPv6 (PB-PMIPv6) whose aim was to solve the problem of inefficient backhaul bandwidth utilization by bicasting packets to PMAG and NMAG for a very short time. Similar to B-PMIPv6, PB-PMIPv6 also employs the use of predictive handovers to lower the handover delay incurred when a mobile node changes points of attachment within a PMIPv6 domain.

Figure 2.9 below depicts the signaling messages flow and operations during a PB-PMIPv6 handover. It can be noticed that as opposed to B-PMIPv6, bicasting is stopped in advance by releasing the tunnel to PMAG before the link is up on NMAG.

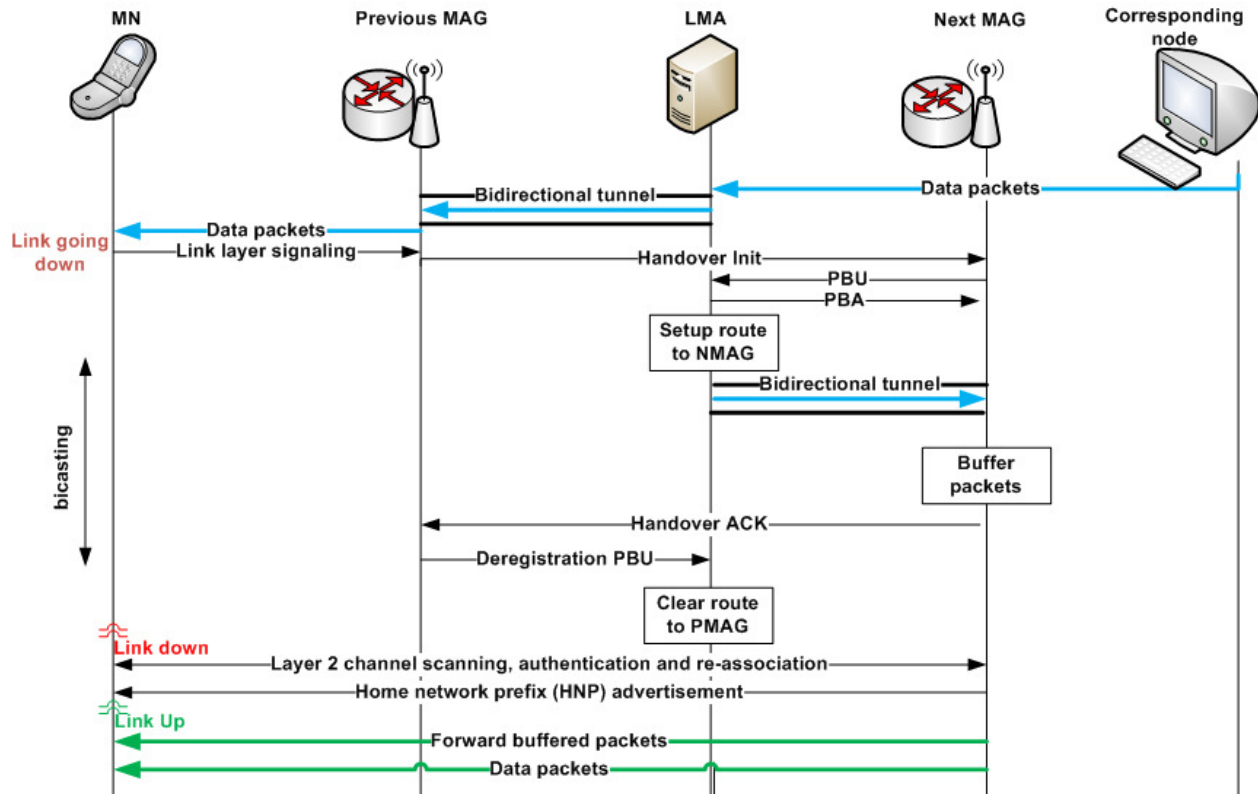


Figure 2.9 PB-PMIPv6 handover signaling and operations

The PB-PMIPv6 signaling diagram (Figure 2.9) shows that there is a possibility of stopping bicasting prematurely as the route to PMAG is cleared even though the signal strength may still be strong enough for the mobile node to receive packets without errors. Moreover, this would negatively affect the reception of packets by the mobile node especially when the mobile node is moving at a low speed. Lastly, this solution may also require a large buffer space on NMAG to alleviate packet losses since bicasting may start too early for a mobile node performing a handover at a low speed. Thus, there is a possibility of buffer overflows since the buffer is a scarce resource.

2.4 Link layer triggers

Link layer (layer-2) triggers provide a means of notifying the network layer or any upper layers (e.g. application layer) of the conditions and/or events in the lower layers such as the physical layer and/or link layer. These triggers provide important information that can be utilized by higher layers to better streamline their operations appropriately to offer better quality of service for the mobile user. Network layer mobility solutions heavily rely on link layer triggers

for anticipation of handovers and hence schedule some handover operations proactively so as to prepare for the handover. The usage of these link-layer trigger models forms a cross-layer communication mechanism which is widely adopted for solutions that require anticipation and prediction of future events.

Link layer triggers are classified into two categories depending on the information they report to the upper layers. These are predictive link layer triggers and event link layer triggers [24]. Predictive triggers are used to notify upper layers of the likelihood of certain events that may occur in the future; such as the LINK_GOING_DOWN trigger. The LINK_GOING_DOWN can be used to notify the higher layers that the current link's signal strength for example is decreasing. This provides awareness that the link-layer connection that the upper layers depend on for the services being consumed, may soon break, thus allowing the upper layers to prepare for the link failure or disruption. On the other hand, event triggers are used to communicate definite events or conditions that have occurred of the link layer, such as the LINK_DOWN or LINK_UP trigger.

But, since predictive triggers could raise false alarm predictions, predictive link-layer triggers are required to carry some information such as the confidence level of the predicted event that will supposedly occur in the future. Table 2.1 below shows link-layer triggers as well as their categories that are used in this study for handover performance enhancement.

Table 2.1 Link layer triggers and functions

Link-layer trigger	Function	Category
LINK_UP	Indicates that layer-2 setup has been completed and layer-3 can commence sending packets.	Event trigger
LINK_DOWN	Indicates that layer-2 connection has been broken hence the network layer cannot send packets successfully.	Event trigger
LINK_GOING_DOWN	Indicates that the LINK_DOWN event is	Predictive trigger

	imminent and hence the link-layer connection will break in the near future.	
TRIGGER_ROLLBACK	This trigger is fired if the opposite of what was predicted occurs so as to recover from a false alarm. (e.g. A false LINK_GOING-DOWN prediction)	Event trigger

Link-layer triggers have been used in many studies of handover performance enhancement for anticipation of the handover as well as employing predictive handover approaches. The works of FMIPv6 and FPMIPv6 for example utilize movement anticipation mechanisms that heavily rely on predictive link-layer triggers. Other studies that seek to achieve seamless handovers by optimizing the handover performance using standardized link-layer triggers are in [25] where MIH is used to assist the smart-triggers proposed to perform cross-layer communication with the application layer protocol; Session Initiation Protocol (SIP). This is done to provide better Quality of service for on-going communications by attempting to make handovers transparent to the mobile user. The scheme proposed in the research also employs these predictive link-layer triggers to better streamline handover operations proactively as well as execute the bicasting operations such that efficient utilization of network resources is enforced while also attempting to enhance the handover performance.

2.5 Media Independent Handovers

The IEEE 802.21 Media Independent Handovers provides a de-facto standard and uniform link-layer triggers solution for handover enhancement for heterogeneous wireless networks whereby handovers occur between radio accesses of different link layers (media access control (MAC) layers and physical (PHY) layers). These include 3GPP wireless accesses, 3GPP2 wireless accesses, as well standardized radio access technologies from the IEEE 802 family (e.g. IEEE 802.11 (Wi-Fi), IEEE 802.16 (WiMAX)) [26].

The MIH solution introduces a Media Independent Handovers Function (MIHF) which is commonly referred to as layer-2.5 of the protocol stack as it introduces a shim layer in between

the traditional layers 2 and 3. Thus, MIH provides a generic link layer intelligence as well as network information to the upper layers of the protocol stack [14]. A pictorial illustration of the MIHF integration into the protocol stack is depicted in Figure 2.10 below.

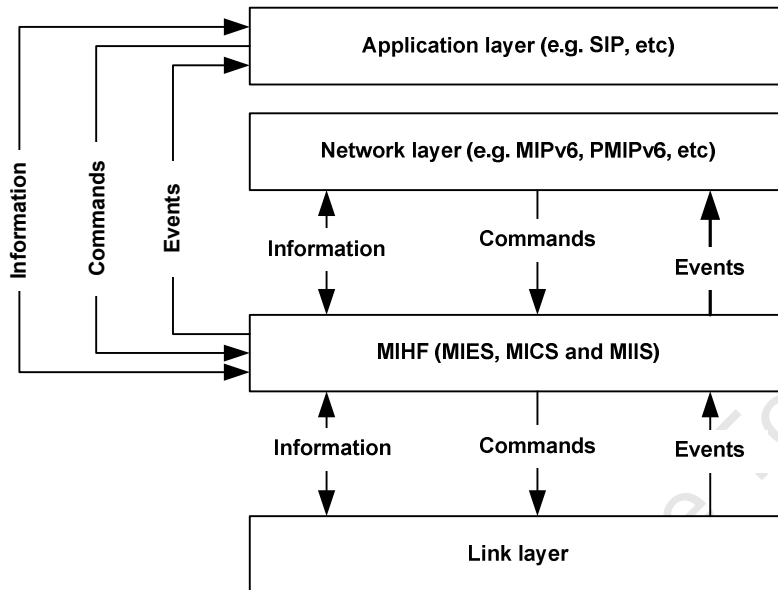


Figure 2.10 Media Independent Handovers Architecture

The MIHF communicates to upper layers as well as lower layers through well-defined service access points (SAP) to offer the MIH three major services. All these services are housed in a MIHF. These are the Media Independent Events Service (MIES), the Media Independent Command Service (MICS) and the Media Independent Information Service (MIIS).

The MIES provides event reporting to upper layers referred to as the respective MIH users. The MIH users could be any upper layer protocols (e.g. SIP, PMIPv6, etc) or entities that need services offered by the MIHF. The MIH users are required to subscribe for events they need to be notified of. The motive is that applications, layers (MIH users) may require different events notifications. These events include link quality, link status, etc which are communicated through well-known link layer events such as LINK_UP, LINK_DOWN, LINK_GOING_DOWN, etc. MIES can report both local and remote events that MIH users subscribe for.

The MICS enables higher layers (e.g. Applications, Mobility management protocols, etc) to issue commands to lower layers. This functionality is essential in cases whereby for example, a mobility protocol needs to instruct the link-layer to switch from one network interface to

another. This also allows the upper layers to inquire for link-layer information for intelligent and proactive decision-making.

Lastly, the MIIS offers an information base for available neighboring networks information within a certain area to aid the facilitation of the handover process. This is particularly essential for network discovery in mobility management. The information also entails services provided by serving and neighboring networks and is made available through both the upper and lower layers [27].

2.6 Summary

This chapter has provided an overview of network-layer mobility management solutions in the literature. It further discusses the evolution path as well the driving forces behind network-layer mobility protocols from being host-based to being network-based. It also provides illustrations of handover approaches employed in each of the mobility protocols discussed to provide soft handovers as a mobile user roams the wireless network. As this study proposes an enhanced bicasting scheme for PMIPv6, a review on the range of bicasting PMIPv6 solutions proposed in the literature was carried out. Moreover, this chapter provides a background of link-layer triggers that have proved to be essential in handover predictions for optimizations of handover performance. The generalized model for link-layer triggers that provides a robust feature of link-layer independence, IEEE 802.21 (MIH) is also discussed.

In the review that has been carried out on bicasting schemes for PMIPv6 in this chapter, it has been identified that the challenge that still remains to be addressed is that of the substantial amount of network resources required by bicasting solutions to provide a soft handover. Therefore, the next chapter discusses the design of proposed enhanced bicasting scheme that seeks to achieve seamless handovers whilst also efficiently utilizing the scarce and limited network resources.

Chapter 3 Enhanced Bicasting for Proxy Mobile IPv6

3.1 Introduction

This chapter discusses the proposed enhanced bicasting scheme for PMIPv6 (EB-PMIPv6) whose sole purpose is to address the drawbacks identified in bicasting schemes for PMIPv6 in the literature. The motive behind bicasting schemes for PMIPv6 is to achieve seamless handovers by minimizing packet loss and handover delay incurred during a handover in a PMIPv6 domain. Bicasting schemes are able to alleviate packet loss during a handover at the expense of utilization of a significant amount of backhaul bandwidth since packets are duplicated to the current and candidate point of attachment during the bicasting period.

This work therefore proposes an enhanced bicasting scheme for PMIPv6 that will not only lower handover delay and packet loss but also promote efficient use of the backhaul bandwidth and network elements' buffer space required as a mobile node changes points of attachment. The proposed solution uses link-layer triggers for timely execution of handover operations such as routing updates and bicasting. The proposed solution entails modifications on the MAG side of the PMIPv6 architecture as well as on the LMA side which are discussed in detail in this chapter.

The chapter begins by highlighting the design requirements of the proposed solution in order to achieve the mentioned objectives. Then, it discusses the designs and integration of the proposed solution's architecture on both the MAG as well as the LMA. Lastly, it presents the overall handover signaling and operations in a message sequence diagram to provide the holistic view of the proposed solution.

3.2 Design Goals

3.2.1 Seamless handover support

It is paramount for EB-PMIPv6 to improve the handover performance of PMIPv6. Therefore, EB-PMIPv6 seeks to lower packets loss, and the handover delay that causes packet arrival fluctuations at the MN. The mobile user consuming real-time delay sensitive multimedia services should not perceive degradation in the QoS as handovers are performed. EB-PMIPv6

attains this by anticipating the handover and thus performs some handover operations ahead of time so as to eliminate their latencies from the total delay incurred for the mobile node to continue its communication after the transient disruption caused by a handover.

3.2.2 Network resources utilization efficiency

Since bicasting solutions are criticized for their significant requirement of network resources to provide soft handovers, EB-PMIPv6 seeks to address this demerit. The proposed EB-PMIPv6 routes (bicasts) packets to the current and subsequent points of attachments for a short duration. This is performed to minimize the time taken utilizing double the amount of backhaul bandwidth that is utilized under normal circumstances (when there is no handover). Secondly, EB-PMIPv6 attempts to timely and accurately execute bicasting such that:

- Packets will not be misrouted to PMAG when the signal strength is below the receive threshold since packets will ultimately not reach MN through the PMAG.
- The number of packet duplicates that reach the MN which results from bicasting that starts too early, is minimal. This is particularly essential as it can cause hiccups in the service that is being consumed on the mobile device if the User datagram protocol is the means of transport protocol being used; otherwise, upper layers would have to provide a way of detecting and getting rid of duplicate packets.
- The buffer space required on the next point of attachment should be lower to avoid potential buffer overflows especially when a significant number of mobile nodes simultaneously perform a handover. This also results from starting bicasting packets too early.

3.2.3 Robustness with respect to handover predictions errors

The proposed solution heavily relies on predictive link-layer triggers to prepare for execution of handover operations as well as bicasting. Since predictions could raise false alarms, EB-PMIPv6 should be able to recover from the errors (e.g. false alarms) with (1) no effect on the QoS experienced by the mobile user and (2) no substantial waste of network resources. The

scheme employs a received signal strength monitor component that continuously monitors the signal strength and is expected to detect if the opposite of a prediction occurs. However, in the case of false negatives, in which case an imminent handover is not detected the solution falls back to the PMIPv6 handover.

3.3 Bicasting in PMIPv6

The technique of bicasting was conceived as a means to alleviate packet loss incurred during a handover. It enables the MN to receive packets that would have otherwise not been received by the MN since they were sent (misrouted) to the previous point of attachment when the handover was about to occur (i.e. Increase the packet delivery ratio). Thus from the perspective of the customer (mobile user), the quality of service is maintained as the customer enjoys uninterrupted services. However, from the network service provider's side, an increase in the network resources becomes apparent. The illustration in Figure 3.1 below depicts a high level model of bicasting as employed in PMIPv6 to avoid packet loss.

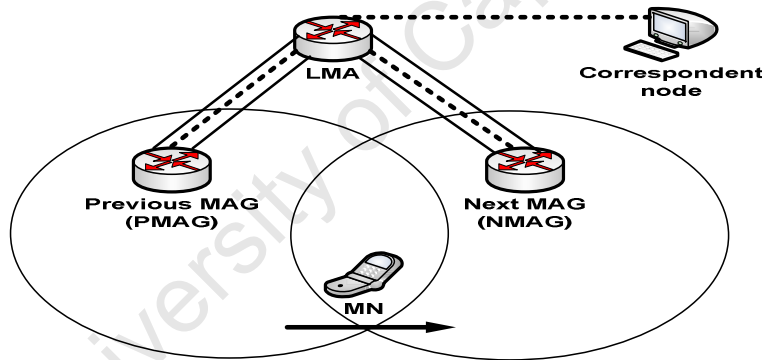


Figure 3.1 Bicasting in PMIPv6

In the design requirements of the EB-PMIPv6, it has been mentioned that one of the main objectives of this study is to determine/find the most suitable time to execute the bicasting operation such that the handover performance is enhanced while the efficiency in network resources utilization is improved. To solve the problem, the research looks at the underlying factors/causes of the significant use of network resources during bicasting. Firstly, the time-span of the bicasting (time taken during bicasting) operation is a major contributor towards the amount of network resources utilized. This is because during bicasting, twice the amount of backhaul bandwidth is utilized. Thus, EB-PMIPv6 should lower the time spent bicasting packets to both PMAG and NMAG. Secondly, there is a need to determine the optimal time to execute

bicasting. This is deduced by making demonstrations of the bicasting schemes for PMIPv6 in the literature, being; Bicasting for PMIPv6 [20], Simultaneous bindings for PMIPv6 [21] and Partial bicasting for PMIPv6 [23]. These solutions execute bicasting at different times and hence the amount of network resources required in each case is observed and analyzed.

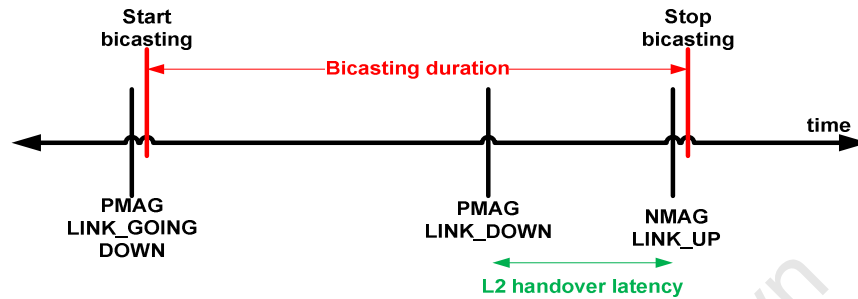


Figure 3.2 Bicasting execution in B-PMIPv6 [20]

In this illustration (Figure 3.2), bicasting starts when the handover is imminent (LINK_GOING_DOWN trigger) and stops after the MN has successfully re-attached to the next point of attachment. In this case, it can be observed that the amount of time during which double bandwidth is required by the bicasting solution is long and can be even longer at lower mobile node speeds (e.g. pedestrian speed). This results from bicasting that starts too early and delays to stop. Moreover, it can be observed that because bicasting delays to stop, packets are routed to PMAG even when the MN is no longer in the range of coverage of PMAG. Thus, packets are sent unnecessarily to PMAG as they will not reach MN through the PMAG. This leads to inefficient use of the backhaul bandwidth as well as the network elements (LMA and PMAG) resources. The number of duplicate packets that reach the MN can also be high in this solution which is unfavorable. Lastly, the bicasting duration length depends on the MN speed, which could result in even higher usage of network resources for an elongated time at low MN speeds.

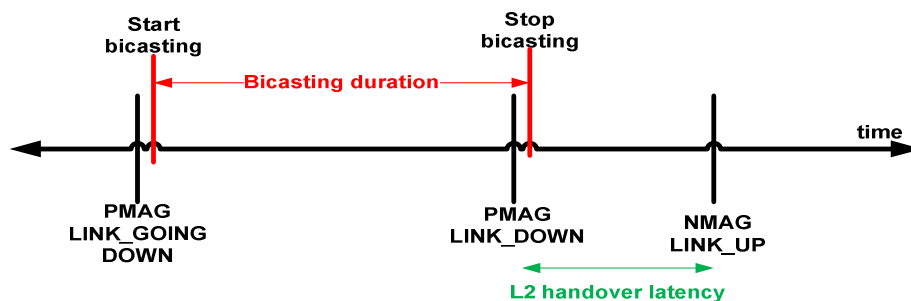


Figure 3.3 Bicasting execution in SPMIPv6

In the above illustration (Figure 3.3), bicasting starts when a handover is imminent and stops when the MN's link to PMAG breaks (LINK_DOWN trigger). In this solution, the bicasting duration is shorter than that of the B-PMIPv6 solution and hence better in terms of backhaul link bandwidth usage. However, the bicasting period in this solution still depends on the MN speed and could be longer at low MN speeds thus using twice the amount of backhaul bandwidth for an elongated time. Consequently, (buffering also depends on bicasting duration) there can also be a high number of packet duplicates that reach the MN. This is because all packets that are routed to NMAG during the bicasting interval shown above are buffered and sent to the MN as soon as it attaches to NMAG. This number of packet duplicates could also be higher at low MN speeds. An advantage that can be noted in this solution is that bicasting stops when the link down event is triggered as there is no need to continue sending packets to PMAG when the signal strength is below the receive threshold. Therefore, resource utilization for SPMIPv6 is better than that of B-PMIPv6.

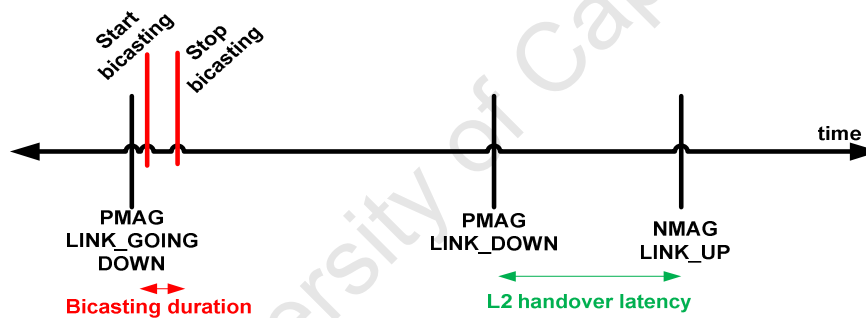


Figure 3.4 Bicasting execution in PB-PMIPv6

In the above illustration (Figure 3.4), bicasting starts when a handover is imminent and stops after a bidirectional tunnel has been established between the LMA and NMAG. An essential observation to make is that the bicasting duration is very short hence double the amount of backhaul bandwidth usage is much lower than in B-PMIPv6 and S-PMIPv6. The duration of bicasting also does not depend on the mobile node speed which is an advantage because the backhaul bandwidth utilization remains constant regardless of the MN speed.

However, the time at which the bicasting operation itself occurs varies with the speed of the MN. At low MN speeds, the bicasting operation will be executed close to the LGD event on PMAG, and will be executed closer to the LD on PMAG as the MN speed increases. Therefore,

there is no proper control as to when the bicasting operation occurs which leads to varying buffer requirements as the MN speed changes. For example, at a lower MN speed, the bicasting operation is close to the LGD event, hence packets start being buffered at NMAG and ends when the MN attaches to NMAG. This leads to a higher buffer space requirement on NMAG at lower MN speeds. Secondly, in this case bicasting stops too early, hence packets are not sent to PMAG even though the signal strength is still strong enough to deliver packets and hence the mobile terminal may take a longer time without receiving packets. However, at higher MN speeds, the bicasting operation occurs close to the LD event and hence the time taken sending packets to NMAG for buffering before MN attaches becomes shorter and hence lower buffer space is required. Lastly, the number of packet duplicates is much lower due to the very short bicasting operation.

From the above illustrations it is observed that to accomplish the design goals,

- 1) Bicasting should stop when the LD event is triggered on PMAG.
- 2) The bicasting duration has to be very short (transient bicasting).

Therefore, to satisfy 1) and 2), EB-PMIPv6 requires to ensure that a short bicasting operation is timely and accurately executed as close as possible to the LD event regardless of the MN speed. Figure 3.5 below shows the positioning of the bicasting operation as desired in EB-PMIPv6.

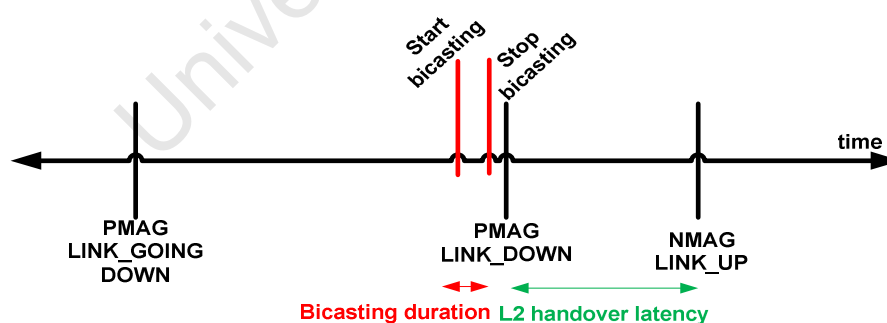


Figure 3.5 Bicasting execution in EB-PMIPv6

In this case, the number of packet duplicates will be low as the bicasting duration is very short (transient bicasting). Consequently, twice the amount of backhaul link bandwidth will be required only for a short duration. Secondly, since the bicasting operation is always scheduled to

be as close as possible to the LD event, the amount of time taken sending packets to NMAG for buffering before MN attaches to consume them is constant. This is the time incurred for the layer-2 handover latency. Therefore, the amount of buffer space required on NMAG is bounded by the layer-2 latency and can be improved through the use of more optimized layer-2 handover techniques. All in all, the optimal time for executing the bicasting operations such that the efficiency in network resources utilization is enhanced is determined to be as close as possible to the LD event on the PMAG. The next section discusses the design of the proposed EB-PMIPv6 that seeks to prove the hypothesis.

3.4 Enhanced Bicasting for PMIPv6 Design

3.4.1 EB-PMIPv6 – MAG Design

This sub-section discusses the design of the EB-PMIPv6 model on the MAG side. EB-PMIPv6 on the MAG side provides a coordinated service for link-layer trigger generation to assist in handover preparation (for proactive handovers) as well as timely and accurate execution of bicasting operations. Link-layer triggers can be generated based on a range of link layer quality factors such as the received signal strength, data rate, packet errors, etc. In this proposed solution, the received signal strength (RSS) is used to reflect the link-layer quality because the signal strength is one of the main determining factors for successful reception of packets at the mobile node (MN). The link-layer triggers employed in the proposed solution are triggered at the signal strength (power) boundaries/thresholds identified in the document by the National Institute of Standards and Technology (NIST) Seamless and Secure [28]. The link-layer triggers that are applicable in wireless networks as shown in Figure 3.6 below.

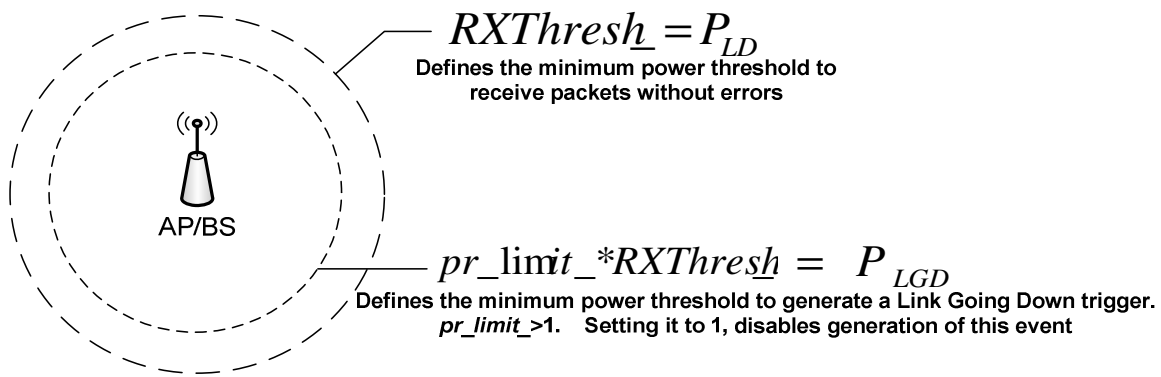


Figure 3.6 Signal strength thresholds/boundaries

The received signal strength at the MN is a function of distance of the MN from the access point/base station (AP/BS). However, the signal strength can be affected by the environment, interference, noise, channel propagation properties and antenna design. The schematic in Figure 3.6 above shows that as the MN moves away from the AP/BS, the LINK_GOING_DOWN (LGD) trigger is generated when the MN is moving closer to being out of the AP/BS's area of coverage. Whereas at the distance beyond the edge, the MN can no longer receive packets successfully at which the signal strength is below the receive threshold ($RXThresh_{_}$).

The EB-PMIPv6 model on the MAG side is composed of four modules namely Received signal strength monitor (RSS monitor), Prediction module, Event Scheduler, and Rollback Facilitator. The EB-PMIPv6 design is shown in Figure 3.7.

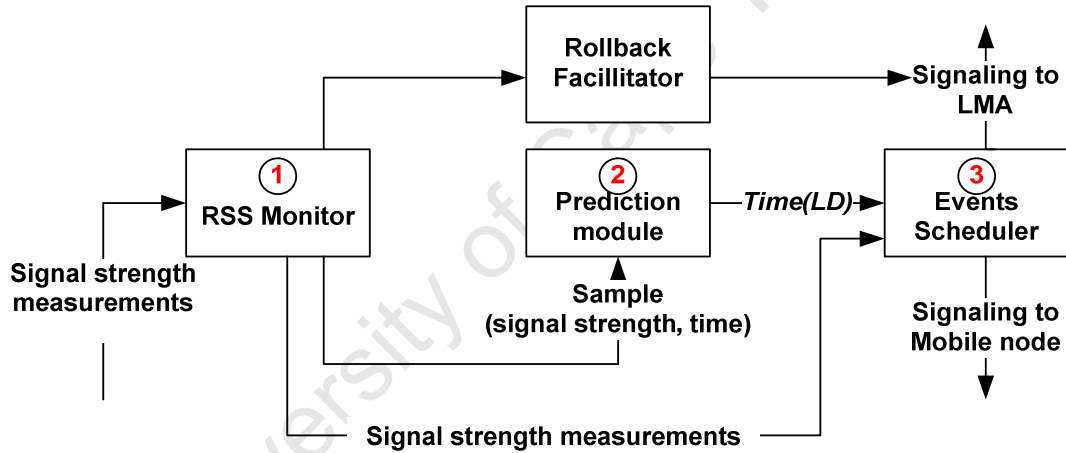


Figure 3.7 EB-PMIPv6 design on the MAG side.

3.4.1.1 Received signal strength monitor (RSS monitor)

The primary function of the RSS Monitor is to monitor the MN's signal strength as the mobile node roams the wireless networks. Besides the thresholds adopted from Figure 3.6, EB-PMIPv6 defines two other triggers $T1$ and $T2$ at two signal strength (power) levels P_{T1} and P_{T2} respectively that are equally spaced from P_{LGD} by a small offset Δ_p as stated in equations (1) and (2).

$$P_{T1} = P_{LGD} + \Delta_p \quad (1)$$

$$P_{T2} = P_{LGD} - \Delta_p \quad (2)$$

The RSS monitor starts monitoring the signal strength once it decays to threshold P_{T1} . During RSS monitoring, the RSS Monitor, records the power level of the packet received and the corresponding time as the signal decays to P_{T1} , P_{LGD} and P_{T2} . The RSS Monitor is also responsible for alerting the Rollback facilitator module if the signal strength then increases instead of decreasing as previously predicted. Once the signal strength deteriorates to P_{T2} , the recorded tuples (*power level, time*) collected are passed to the prediction module.

3.4.1.2 Prediction module

The Prediction module uses the samples passed by the RSS Monitor to predict the viability of the decaying link through the pattern shown by the samples from the monitor. The prediction module estimates the amount of time left before the link actually breaks which is called link viability in the report. Knowing the link viability, the proposed scheme can then timely and accurately execute the *start bicasting* and *stop bicasting* events as close as possible to the LINK_DOWN event. The viability is also used to determine when to trigger a redirection of the flow of packets at the LMA from PMAG to NMAG. The output of the prediction module is the time at which the Link down (LD) event is estimated to be, which is when the mobile node will no longer successfully receive packets from the PMAG (below signal strength $RXThresh_{(P_{LD})}$).

As mentioned, the prediction module facilitates the timely scheduling of the bicasting operations which is the main objective of this study. Thus, for proof of concept purposes, the proposed EB-PMIPv6 solution adopts a link breakage prediction algorithm used for a dynamic source routing (DSR) protocol in [29] to increase packet delivery ratio. In this prediction algorithm, the Two-ray ground radio wave propagation model is utilized in modeling the signal strength decay behavior in the wireless network. In the literature, there is a wide range of prediction algorithms and tools that have been used in signal strength predictions. Some of them are the least mean square adaptive filters and Fast Fourier Transform-based signal analysis algorithms. However, to focus on the timely execution of bicasting operations problem mentioned earlier, this work utilizes a simpler prediction algorithm used in [29] that employs the two ray ground propagation model.

The two-ray ground propagation model considers both the direct path and a ground reflected path, and is more accurate than the Free Space propagation model for longer distances

whereby direct line of sight is not the only means of propagation employed. The power received by a mobile node at a distance d away from a base station or access point as per the model is shown in (3) below.

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \quad (3)$$

Where: P_t , G_t and h_t are the power transmitted by the AP/BS, gain and height of the AP/BS transmitter antenna, respectively. G_r and h_r are the gain and the height of the mobile node's receiver antenna. L is the system loss.

In order to discuss the prediction algorithm, this research considers a scenario whereby a mobile node moves away from an access point (AP) or base station (BS) which is collocated with the MAG as shown in Figure 3.8 in a uniform linear motion.

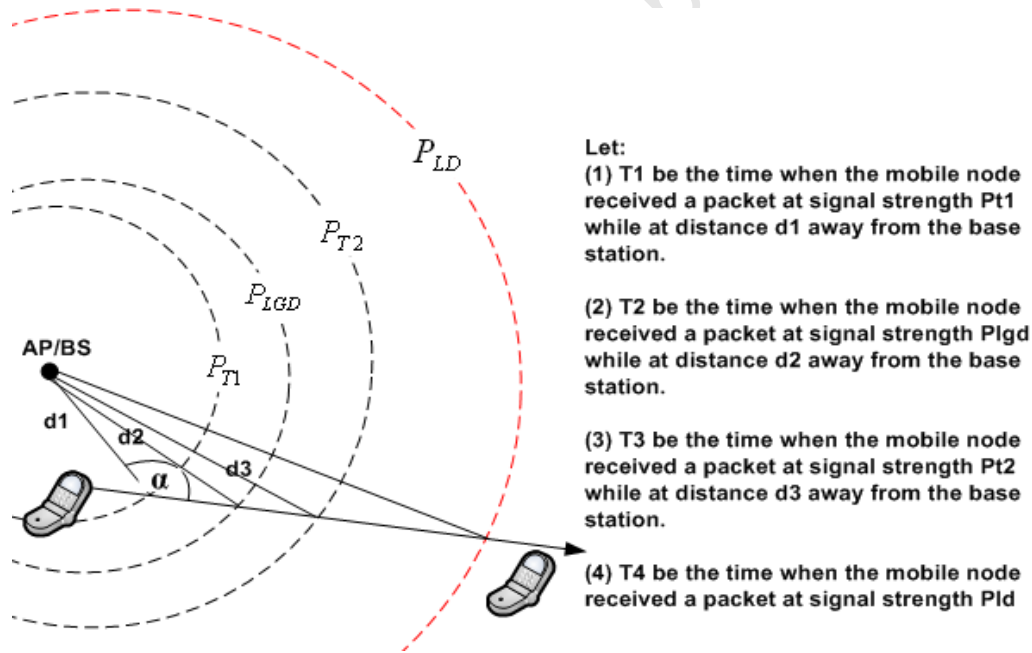


Figure 3.8 Mobile node movement and signal strength

The prediction algorithm uses the tuples passed by the RSS Monitor. These are $(P_{T1}, T1)$, $(P_{LGD}, T2)$ and $(P_{T2}, T3)$ (As depicted on Figure 3.8). From Figure 3.8 above, equations that lead to the estimation of the time when the signal strength will be at P_{LD} beyond which the mobile node will no longer be able to receive packets successfully can be deduced. For

simplification of the equations, let $t_2 = T2 - T1$, $t_3 = T3 - T1$ and $t = T4 - T1$.

$$\text{At time } T1, P_r(d_1) = P_{T1} = \frac{kP_t}{d_1^4} \quad (4)$$

$$\text{At } T2, P_r(d_2) = P_{LGD} = \frac{kP_t}{(d_1^2 + (vt_2)^2 - 2d_1vt_2 \cos \alpha)^2} \quad (5)$$

$$\text{At } T3, P_r(d_3) = P_{T2} = \frac{kP_t}{(d_1^2 + (vt_3)^2 - 2d_1vt_3 \cos \alpha)^2} \quad (6)$$

$$\text{And, at } T4 \text{ (when link is down), } P_r(d_3) = P_{T2} = \frac{kP_t}{(d_1^2 + (vt)^2 - 2d_1vt \cos \alpha)^2} \quad (7)$$

$$\text{Where, } k = \frac{G_t G_r h_t^2 h_r^2}{L}$$

In solving the above equations for t , mathematical substitutions, eliminations of variables such as the velocity v of the mobile node and the angle α , are performed. The solution obtained is of the form $at^2 + bt + c = 0$ which is a quadratic equation. The constants a , b and c are as shown in (8), (9) and (10).

$$a = t_2 \beta \sqrt{P_{LD} P_{LGD}} \quad (8)$$

$$b = \sqrt{P_{LD}} \left(\sqrt{P_{T1}} - \sqrt{P_{LGD}} - t_2^2 \beta \sqrt{P_{LGD}} \right) \quad (9)$$

$$c = t_2 \left(\sqrt{P_{LGD} P_{LD}} - \sqrt{P_{T1} P_{LGD}} \right) \quad (10)$$

$$\text{Where, } \beta = \frac{t_2 \left(\sqrt{P_{T1} P_{LGD}} - \sqrt{P_{LGD} P_{T2}} \right) + t_3 \left(\sqrt{P_{LGD} P_{T2}} - \sqrt{P_{T1} P_{T2}} \right)}{(t_2 t_3^2 - t_2^2 t_3) \sqrt{P_{LGD} P_{T2}}}$$

From the solutions of the quadratic equation, the positive one is considered since it is of interest in a future prediction. Thus, an approximate amount of time left before the link actually goes down (breaks) is given by $t = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$. Therefore, the time estimate as to when the link will be down (LD on PMAG) is as given by (11).

$$\text{Time(LD)} = T4 = T1 + t \quad (11)$$

3.4.1.3 Events scheduler

The events scheduler generates event trigger signaling messages and sends them to the LMA and the mobile node. These signaling messages instruct the LMA and mobile node to carry out certain commands (execute certain functionality). The signaling message sent to the mobile node instructs the mobile node to disconnect from the point of attachment with degrading signal strength. This aids the mobile node to start the layer-2 handover (scanning new channels, authentication, and re-association) to the new point of attachment at the earliest possible time. Thus, the mobile node is forced to disconnect at $Time(LD)$ since there is no need for the mobile node to continue to remain attached to PMAG when the signal strength is below the receive threshold ($RXThresh$) or P_{LD} .

Moreover, the events scheduler sends a signaling message to facilitate a proactive layer-3 handover approach. When the LMA receives this signaling message from the events scheduler, it performs pre-registration for the mobile node and sets up a route to the candidate point of attachment (between LMA and NMAG) when a handover is imminent. The expressions below show how performing a proactive handover lowers the handover delay in PMIPv6 whereby other handover operations are performed in advance. Therefore the proposed EB-PMIPv6 also performs predictive handovers thus lowering the handover delay.

$$t_{PMIPv6} = t_{L2-L3} + t_{PBU} + t_{PBA} + t_{MN_HNP_Adv}$$

$$t_{Predictive_PMIPv6} \approx t_{MN_HNP_Adv}$$

t_{L2-L3} is the latency for layer-2 to notify layer-3 of the mobile node's attachment. t_{PBU} and t_{PBA} accounts for the delay of the proxy binding update from the MAG and the proxy binding acknowledgement from the LMA. And, $t_{MN_HNP_Adv}$ is the delay incurred for the router advertisement that contains the home network prefix for the mobile node to configure the same home address throughout the PMIPv6 domain. In the case of a predictive PMIPv6 handover, the binding update process and pre-registration for the mobile node between the NMAG and the LMA is done in advance and hence technically the mobile node is in advance attached to the next MAG. It should however be noted that the total handover delay during which the mobile node is unable to receive any packets includes the layer-2 handover latency.

Finally, the events scheduler sends the LMA signaling messages that instruct the LMA to start bicasting, and stop bicasting such that bicasting is executed in a timely and accurate manner. Unlike in the previously proposed bicasting PMIPv6 solutions, the times to start and stop bicasting are correlated to the behavior of signal strength decay. To minimize the loss of in-flight packets, the proposed EB-PMIPv6 solution the LMA stops sending (routing) packets destined to the mobile node to PMAG slightly ahead of the time when the link will be down as shown by (12). This is done to minimize the loss of in-flight packets. This hence increases the probability that the last packet sent to PMAG by the LMA is received by the mobile node just before signal strength decays beyond $RXThresh_$. Thus, at this time, a route from LMA to PMAG is cleared. Equation 12 is also considered to be a stop bicasting time.

$$t_{stop_bicasting} = Time(LD) - \{t_{LMA-PMAG} + t_{PMAG-MN}\} \quad (12)$$

Where $t_{LMA-PMAG}$ is constituted by the transmission delay on LMA and the propagation delay from the LMA to PMAG; $t_{PMAG-MN}$ is constituted by the transmission delay on PMAG as well as the propagation delay from the PMAG to the mobile node (MN). And, since the propagation delay from PMAG to MN is a function of distance from the Access point or Base station (collocated with the MAG), to increase the probability mentioned above, the propagation delay is given by (13) where d_{max} is the distance from the base station at the edge of the coverage area.

$$t_{propagation_delay(PMAG-MN)} \approx \frac{speed_of_light}{d_{max}} \quad (13)$$

On the other hand, bicasting starts marginally before stopping bicasting by a short time margin Δ_t ($\Delta_t \geq 0$) such that bicasting which results into an increased utilization of backhaul bandwidth occurs for a short period of time as was discussed earlier.

$$t_{start_bicasting} = Time(LD) - \{t_{LMA-PMAG} + t_{PMAG-MN} + \Delta_t\} \quad (14)$$

The proposed EB-PMIPv6 also adds an extra layer of extra accuracy on the timely generation of event triggers that facilitate the accurate execution of the handover operations discussed above by incorporating the use of confidence level indication. The events scheduler computes the confidence level using the signal strength measurements from the RSS monitor to

assess the probability or likelihood that the link is actually going to break in the near future. Equation 15 below shows how the confidence level C is computed. The confidence level gives an approximate indication of how close is the signal strength to the $RXThresh_$ signal strength beyond which the MN will no longer receive packets successfully.

$$C = \left(\frac{P_{LGD} - P_r}{P_{LGD} - P_{LD}} \right) * 100 \quad (15)$$

Where P_r , is the instantaneous power or signal strength received at the mobile node. From (15), when $P_r \rightarrow P_{LGD}$, then $C \rightarrow 0$; and as $P_r \rightarrow P_{LD}$, then $C \rightarrow 100$. Thus with the use of the confidence level, the proposed solution can ensure that the bicasting operation is executed very close to when the mobile node's link to PMAG will break.

3.4.1.4 Rollback facilitator

The rollback facilitator's main function is to signal to the LMA when the opposite of the prediction in the signal strength occurs so that the LMA can release the resources that were setup in preparation for the mobile node's handover. The route to the next anticipated point of attachment is cleared. The encapsulator as well as the binding cache entry for the mobile node is removed so as to conserve the network elements resources such as memory.

3.4.2 EB-PMIPv6 – LMA Design

In this subsection, the design of the EB-PMIPv6 on the LMA side is discussed. The EB-PMIPv6 design components on the LMA assist in performing operations that are coordinated by the EB-PMIPv6 components on the MAG side. These are operations such as the bicasting and the layer-3 handover operations that are coordinated through the use of link-layer triggers. The main functionalities that reside on the LMA side are:

- Facilitation of simultaneous bindings at the LMA to enable bicasting, as well as the encapsulation of packets to more than one point of attachment.
- Facilitation of proactive layer-3 handovers by supporting the in-advance binding update process as well as the mobile node's routing state update.

The proposed EB-PMIPv6 on the LMA side design is depicted in Figure 3.9 below.

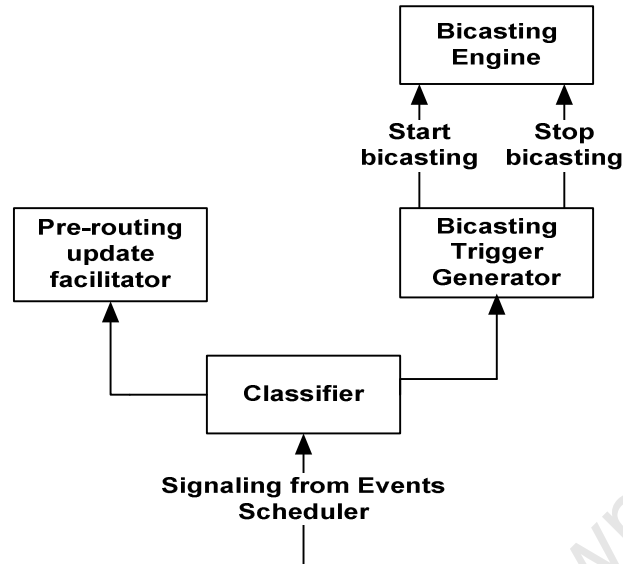


Figure 3.9 EB-PMIPv6 Design on the LMA side

The classifier classifies and routes the signaling messages appropriately to either the Bicasting Trigger Generator or the Pre-routing update facilitator. The Pre-routing update facilitator ensures that the mobile node is pre-registered and sets up a route between LMA and NMAG in advance and ensures that the mobile node is pre-inserted into the binding cache list. Lastly, the Bicasting Trigger generator generates triggers to start and stop bicasting. The Bicasting engine is responsible for performing the actual packets duplication and then encapsulates them in an IP-in-IP tunnel to both the PMAG and NMAG during the bicasting period. Thus during bicasting, a mobile node has two simultaneous bindings in the LMA binding cache entry list associating it to PMAG and NMAG. Packets destined for the mobile node that arrive at NMAG (Next (Candidate) MAG) during the layer-2 handover are buffered at NMAG and sent to the mobile node as soon as it attaches.

3.5 Signaling Flow

The overall flow of signaling messages and operations that have been discussed in detail in the preceding sections and subsections are collectively shown in the message sequence chart in Figure 3.10 below.

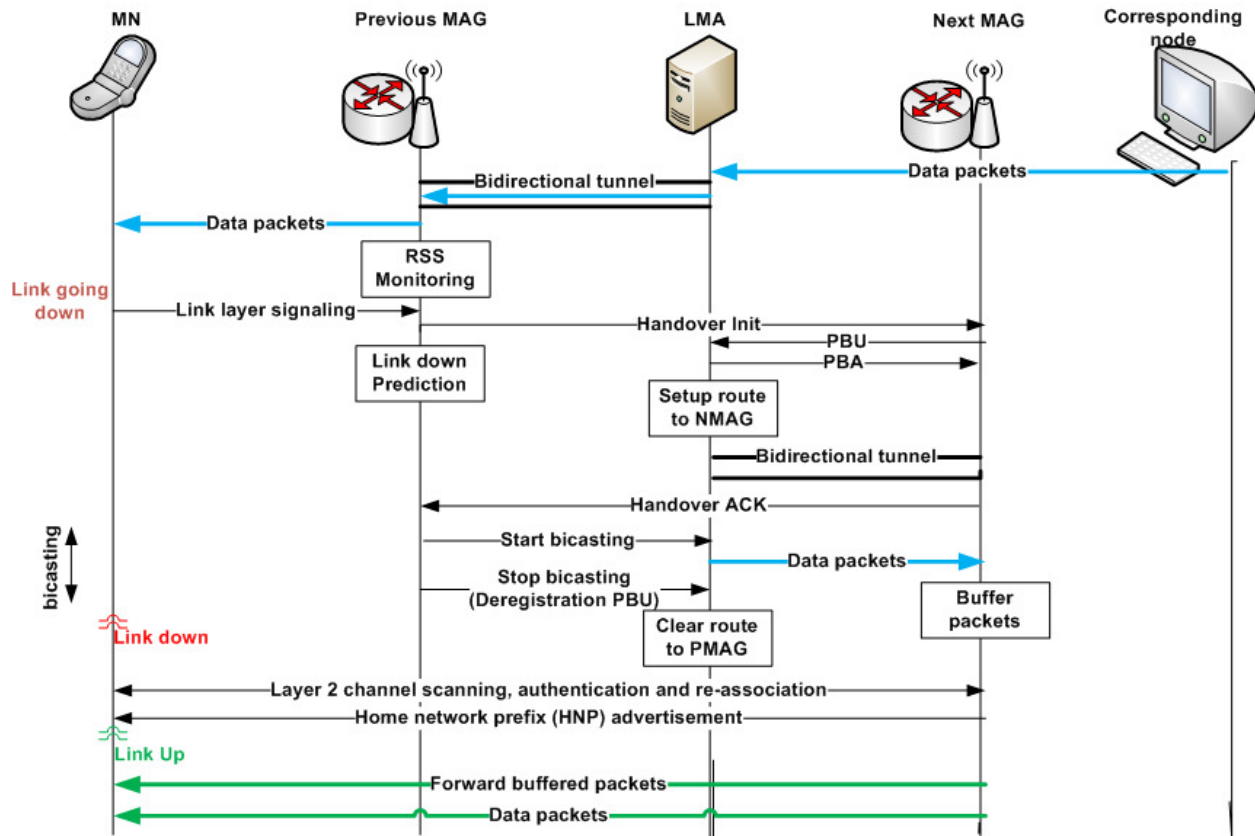


Figure 3.10 EB-PMIPv6 handover signalling and operations

In this solution, the received signal strength (RSS) is monitored and its decaying pattern is used to predict an estimate of the time at which the link down event on PMAG will be. The link down time estimate is then used to schedule and execute the bicasting operation very close to the link down event such that bicasting stops just before the signal strength goes below the receive threshold. It can be observed from Figure 3.10 that, when a handover is imminent (when signal strength is at the LINK_GOING-DOWN threshold), after the binding update process a route to NMAG is setup but packets are not immediately sent. Packets routed to NMAG are only sent after the bicasting start trigger.

Since the bicasting operation is scheduled very close to the link down event, the amount of buffer space required on NMAG to buffer packets while the mobile node is performing a handover is lower than in the previously proposed bicasting schemes for PMIPv6. Lastly, since EB-PMIPv6 uses the signal strength behavior to schedule the bicasting process, bicasting will be executed close to the link-down event regardless of the speed of the mobile node. Packets destined to the mobile node that reach NMAG during the time when the mobile node is

performing a layer-2 handover as shown are buffered on NMAG. As soon as the mobile node attaches to NMAG, NMAG sends a router advertisement that includes the mobile node's home network prefix for the mobile node to configure an IP address. Packets that were being buffered on NMAG are then sent to the mobile node to continue with its ongoing communications.

3.6 Summary

In this chapter, the design of the proposed EB-PMIPv6 solution design has been discussed. The discussion details the components required on the MAG side as well as on the LMA side of the PMIPv6 infrastructure. The MAG houses the coordination functions of the EB-PMIPv6 solution and thus provides a controlled service of coordinated bicasting and proactive layer-3 handover execution. The proposed EB-PMIPv6 applies a signal-strength based approach to better streamline handover operations as well as bicasting operations to offer enhanced handover performance while efficiently utilizing the scarce and shared network resources.

The main advantages of the proposal as discussed are two-fold as it provides both customer-centric advantages as well as network-service provider centric advantages. On the customer's side, EB-PMIPv6 provides better handover performance by lowering the handover delay and packet loss. This hence aids in maintaining good QoS for the mobile customer as handovers are performed. On the other hand, EB-PMIPv6 requires lower buffer space on the NMAG to evade packet loss which is an advantage on the network-service provider's side as buffer overflows can be minimized thus allowing the service provider to provide better QoS for the mobile user. Secondly, the proposed solution utilizes the backhaul bandwidth much more efficiently. Lastly, since EB-PMIPv6 bicasting does not start too early, a rollback with low or without network resources can be attained.

The next chapter presents the implementation of the proposed EB-PMIPv6 designs using the network simulator (NS-2) as discussed in the schematics presented in this chapter.

Chapter 4 Experimental Implementation of EB-PMIPv6

4.1 Introduction

The previous chapter presented the design of the proposed enhanced multicasting scheme for PMIPv6 (EB-PMIPv6). This chapter then discusses the implementation of the EB-PMIPv6 solution for proof of concept purposes. The chapter begins by giving a brief background on the framework used in the implementation and simulation of the proposed solution. Thereafter, the implementation of the EB-PMIPv6 components as well as the algorithms employed on the mobile access gateway and the local mobility anchor respectively are discussed. Lastly the simulation setups, network topology and settings are discussed.

4.2 Implementation and Simulation Environment

There are options on selecting the evaluation framework to be utilized for implementing a proposal. Among these, there are simulation frameworks, and hardware test-bed frameworks. Test-bed implementations provide a more realistic approach for implementation and modeling real systems. However, simulations provide an inexpensive way of testing various complex scenarios as it takes a short time to modify the models as well as obtain results as modifications are done. Therefore, a simulator-based approach is preferred in this study.

There exists a range of simulation tools that are used in research studies. Among these, the Network Simulator - 2 (NS-2) [30] is selected for this study. Firstly, NS-2 is selected because of the availability of the PMIPv6 model implementation that has been extensively used by the mobility management research communities. Secondly and most importantly, NS-2 is an open source based evaluation environment which is suitable for the proposed study as the protocols can be modified with ease for this study's purposes. Therefore, since NS-2 is extensible, the proposed solution design can be incorporated into the NS-2 framework as it allows creation of new protocols and/or altering existing ones. Furthermore, online support is provided for NS-2 and is extensively documented.

4.2.1 Network simulator – 2

NS-2 is an object-oriented, discrete event driven network simulator written in two

programming languages; C++ and Otcl (Object-oriented tcl) [31][32]. NS-2 implements a variety of network protocols such as TCP, UDP, etc. Since NS-2 was specifically designed and implemented as a research tool, new protocols, mobility models, amendments to existing protocols, etc are regularly contributed by various research communities. It is due to its modularity and extensibility that it has gained a lot of popularity in communication networks research studies. As mentioned earlier, an interpreted (Otcl) language and a compiled (C++) language are used to build NS-2. C++ is used for the backend that runs the actual simulation whereas the Otcl is used as a front-end (user interface) [31].

Since Otcl is an interpreted language, changes to its code do not require compilation. On the other hand, C++ needs compilation after changes to the source code for linking and producing an executable file. Therefore, Otcl is much quicker to change but takes longer to run as interpretations have to be performed during run time. However, C++ runs very quickly during runtime but takes longer to change since compilation is required. Thus, with advantages of both languages, NS-2 reaps the benefits offered by C++ and Otcl. C++ is therefore used to program the actual specifications of network protocols, routing algorithms, etc, whilst Otcl is used to setup and configure the network topology. Figure 4.1 below shows a high level schematic of NS-2.

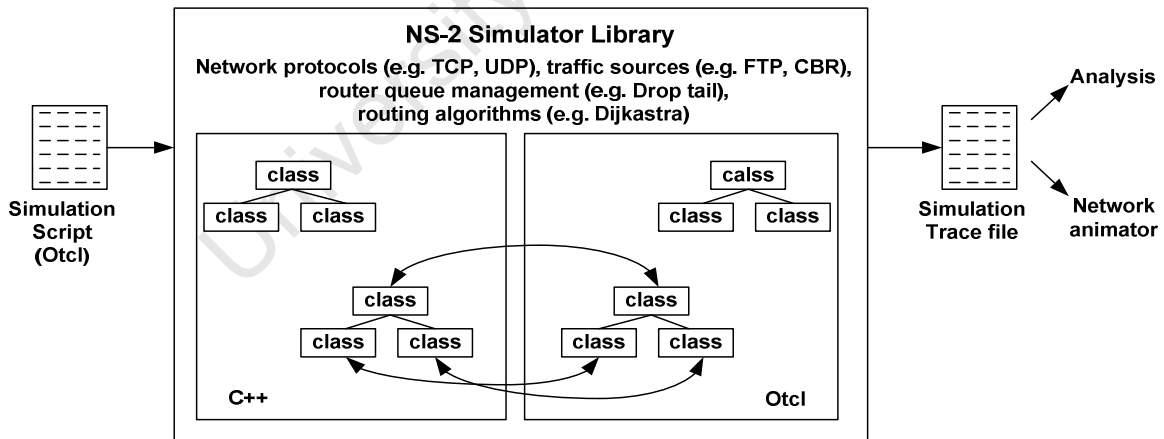


Figure 4.1 NS-2 Overview [33]

As in can be seen in Figure 4.1, Otcl is used to implement the simulation program which entails the network topology setup and node interconnections. It is also used to set the simulation parameters such as when the simulation and/or certain traffic (e.g. CBR (constant bit rate), VBR (variable bit rate)) should start and stop. The NS-2 also provides a library of implementations of

protocols in C++ and Otcl. In some cases, there is a one-to-one correspondence between the C++ and Otcl classes; i.e., for every C++ class, there is a mirror class in Otcl [31].

When the simulation is run, the scheduler is used to schedule the discrete events that are used to simulate and mimic the actual behavior of the simulated protocol(s) in real systems. This behavior is placed into a simulation trace file which presents the times at which different events occurred. In fact, the trace file is a log file of all the events that occur during a simulation. From the trace file further analysis can be performed with the help of tools such as AWK and PERL to extract events that are relevant to the result being investigated. (e.g. packets dropped, end to end delay, etc)

A network animator (NAM) tool is also essential as it provides a graphical representation of the events in the trace file to better conceptualize the series of events and interactions that occur during the simulation. However, NAM does not support graphical representations for wireless simulations. Thus AWK is used for analyses of simulation trace files in this study.

NS-2 also supports wireless networks and offers implementations of MAC protocols such as for IEEE 802.11 (Wi-Fi) and IEEE 802.16 (WiMAX). Implementation of the mobile node is composed of the protocol stack that emulates that of a real mobile node. From the top down, the mobile node's stack has a source/sink which represents the application layer process that generates/consumes traffic (data segments), a link-layer, an interface queue, a MAC layer as well as a network interface that can be configured to use a radio propagation model of choice.

For this study, the NIST mobility package for upgrades on mobility has been installed. The NIST mobility package includes the implementation of neighbor discovery, the generalized model for link-layer triggers namely the IEEE 802.21 (MIH) as well as modifications on MAC protocols (e.g. IEEE 802.11 and IEEE 802.16) for link layer trigger generation and ease of integration with MIH for better modeling of predictive handovers. Lastly, a PMIPv6 model implemented both in C++ and Otcl for NS-2 was installed as a patch for modifications proposed in EB-PMIPv6.

4.2.2 PMIPv6 model

In this study, the NS-2 PMIPv6 implementation [34] developed by Choi H. is modified to

incorporate the modifications required in the proposed EB-PMIPv6. This PMIPv6 model implements the PMIPv6 architecture components as the specification requires. The mobile access gateway (MAG) tracks the MN and offers a way for the MAC protocols to notify it when an MN attaches. This is achieved through the use of a layer-2 trigger that indicates that a new MN has attached. The MAG and local mobility anchor (LMA) exchange binding update messages (proxy binding update (PBU) and proxy binding acknowledgement (PBA)) and consequently install decapsulators and encapsulators for uplink and downlink traffic from and to the MN. This is done to create or update the MN's routing state. Maintenance of the binding cache entries and the home network prefix list are maintained by the LMA. All in all, the PMIPv6 model supports most features that the PMIPv6 specification [3] requires. The data and signaling flow between the objects in the PMIPv6 model implementation is depicted below.

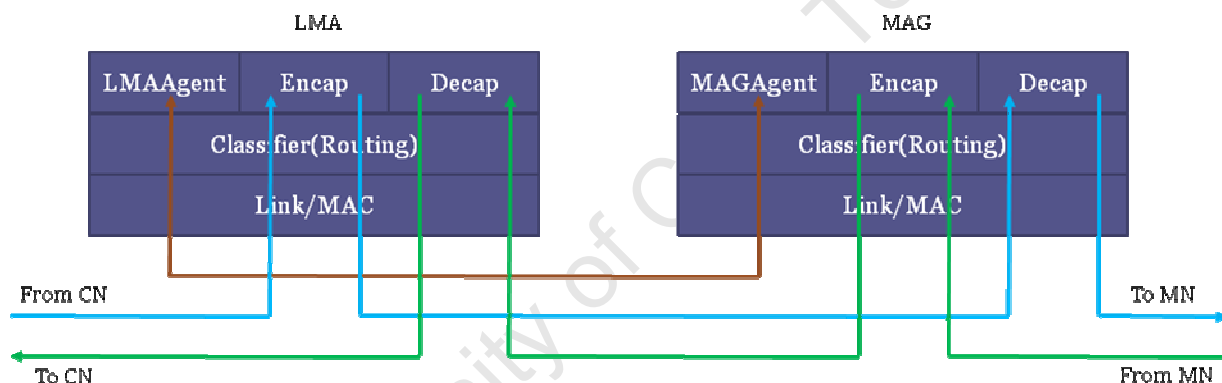


Figure 4.2 PMIPv6 Implementation Data and Signaling Flow [35]

The schematic in Figure 4.2 shows the high-level overview of the implementation of the PMIPv6 model. It shows the separation of the signaling plane and the data plane. The signaling (e.g. binding updates) is handled by the LMAgent and the MAGAgent objects. On the other hand, the data plane involves the encapsulation and decapsulation processes. For the downlink traffic (from the corresponding node (CN)), packets destined to the mobile node (MN), are encapsulated by the LMA *Encap* object through the assistance of the destination classifier to the MAG that provides a proxy for the MN. The MAG then decapsulates the packets using the *Decap* object and sends them towards the MN. The reverse is carried out for uplink traffic whereby the MAG *Encap* object encapsulates from the MN with the assistance of a source classifier to the LMA. The LMA *Decap* object decapsulates the packets and routed them towards the destination CN.

4.2.3 Link-layer triggers

In this study, the IEEE 802.11 is used as the radio access technology to provide wireless connectivity to the mobile node. However the proposed EB-PMIPv6 is not restricted to the IEEE 802.11 as the EB-PMIPv6 does not require specific functionalities from the IEEE 802.11 MAC protocol itself; hence the proposed EB-PMIPv6 can achieve its objectives in other radio access technology networks. The generation of link layer events using MIH has been integrated into the IEEE 802.11 MAC protocol with the help of the NIST mobility package. Therefore, the MAC protocol can generate link layer event and predictive triggers that are required by the proposed EB-PMIPv6. These are the LINK_DOWN, LINK_GOING_DOWN and LINK_UP triggers. These triggers can be generated based on different factors such as the data rate, signal strength, number of re-transmissions, etc. However in this study, the generation of link layer triggers is based on the signal strength as was discussed in the Chapter 3.

4.3 Implementation on NS-2

4.3.1 EB-PMIPv6 MAG Implementation

4.3.1.1 RSS monitor

The functionality that is required on the MAG to achieve the objectives of EB-PMIPv6 is implemented in C++ within the NS-2 library. The RSS Monitor is implemented on the physical layer as its major objective is to monitor a physical layer property; the signal strength. Therefore, the RSS monitor makes modifications on the *wireless-phy.{cc,h}* files. The overall operation of the RSS monitor is depicted in a flow chart in Figure 4.3. It has been discussed in design chapter (chapter 3) that EB-PMIPv6 predefines signal strength thresholds P_{T1} , and P_{T2} that are equally offset from the already proposed and well-known signal strength thresholds P_{LGD} at which the LINK_GOING_DOWN trigger is generated.

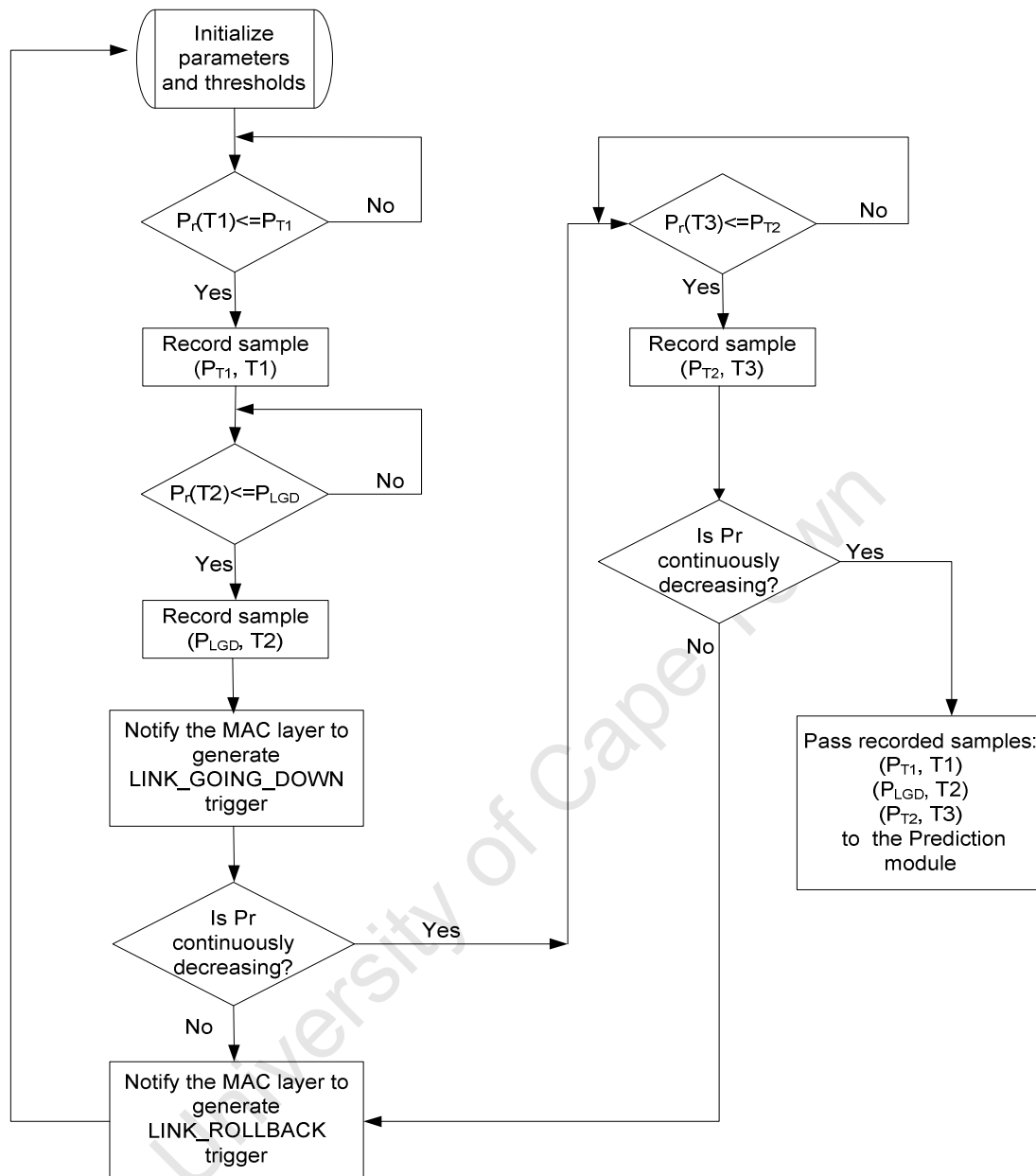


Figure 4.3 RSS Monitor flow chart

The RSS monitor first initializes the parameters utilized as well as the signal strength thresholds. If at time $T1$ the power received/signal strength (P_r) is less or equal to P_{T1} , then the value of the signal strength $P_{T1} \approx P_r(T1)$ is recorded and the corresponding time $T1$. $P_r(t)$ denotes the signal strength received at time t . The same is performed as the signal strength deteriorates to threshold P_{LGD} and P_{T2} . However, when the received power reaches the threshold P_{LGD} , the MAC layer is informed to generate a link-layer predictive trigger to the upper layers;

in this case PMIPv6 so as to carry out other handover operations in advance.

Furthermore, the algorithm keeps verifying that the signal strength is continuously decreasing to ensure that the LINK_GOING_DOWN prediction is correct. However if the signal strength increases; contrary to the prediction, then the MAC is notified to generate a LINK_ROLLBACK event trigger so that the upper layer can tear down the resources that may have been allocated in preparation for the mobile node's handover. If the signal strength continues to decrease, the recorded samples of received power (P_{T1} , P_{LGD} and P_{T2}) and the corresponding times ($T1$, $T2$ and $T3$) respectively are sent to the prediction module.

4.3.1.2 Prediction module

The prediction module's task is to estimate the time at which the signal strength is anticipated to be at $RXThresh_-(P_{LD})$ i.e. time at which the mobile node (MN) will be at the edge of the area of coverage. The prediction module is also implemented in C++ as a function that takes the samples passed by the RSS monitor and applies the operations formulated in chapter 3. The output of the function is the time when the signal strength will be at P_{LD} , based on the signal strength decay pattern from P_{T1} to P_{LGD} which occurs in $T2-T1$ time units and from P_{LGD} to P_{T2} which occurs in $T3-T2$ time units. As discussed in the design chapter, $Time(LD)$ returned by the Prediction module function is passed to the Events scheduler for generation of accurate and timely link-layer trigger.

4.3.1.3 Events scheduler

The proposed EB-PMIPv6 implements the events scheduler in C++ as well. The Events scheduler uses the simulator clock for timely link-layer trigger generation. The events scheduler sends signaling messages to the LMA for proactive handover operations, and bicasting operations scheduling whilst it sends signaling to the MN for the MN to disconnect from a point of attachment. The events are scheduled as discussed in the design chapter and are shown in Table 4.1.

Table 4.1 Handover events scheduling

Event	Scheduling time
Bicasting_Start	$t_{start_bicasting} = Time(LD) - \{t_{LMA-PMAG} + t_{PMAG-MN} + \Delta_t\}$
Bicasting_Stop	$t_{stop_bicasting} = Time(LD) - \{t_{LMA-PMAG} + t_{PMAG-MN}\}$
Disconnect_MN	$t_{disconnect_MN} = Time(LD)$

The overall operation of the events scheduler function is as depicted in the flowchart in Figure 4.4. The algorithm uses the simulator clock which is accessible through *Scheduler::clock* or *Simulator::now* to ensure that the signaling messages are sent as shown in Table 4.1. The LMA is instructed to bicast at the time instances shown in Table 4.1 such that bicasting is transient and occurs very close to LINK_DOWN event. The MN is instructed to detach from the current point of attachment at $t_{disconnect_MN}$ so as to quicken the layer-2 handover execution since there is no need for the MN to remain attached to PMAG. When the MN is instructed to detach, it invokes a *disconnect* function which in turn invokes an *auto-scan* function. The *auto-scan* function enables the MN to scan channels on the subsequent point of attachment and then associate with the point of attachment by exchanging association request and association response messages.

The MN employs a proactive approach to lower the layer-2 handover as opposed to utilizing a reactive approach whereby it would have to wait to receive a beacon (BCN) signal from the Access point (AP). The MN therefore sends a probe request, and the next neighboring AP within range responds with a probe response. However the AP periodically sends BCN signals every 0.1 seconds. This aids the MN to obtain the available AP's information without or before sending a probe request.

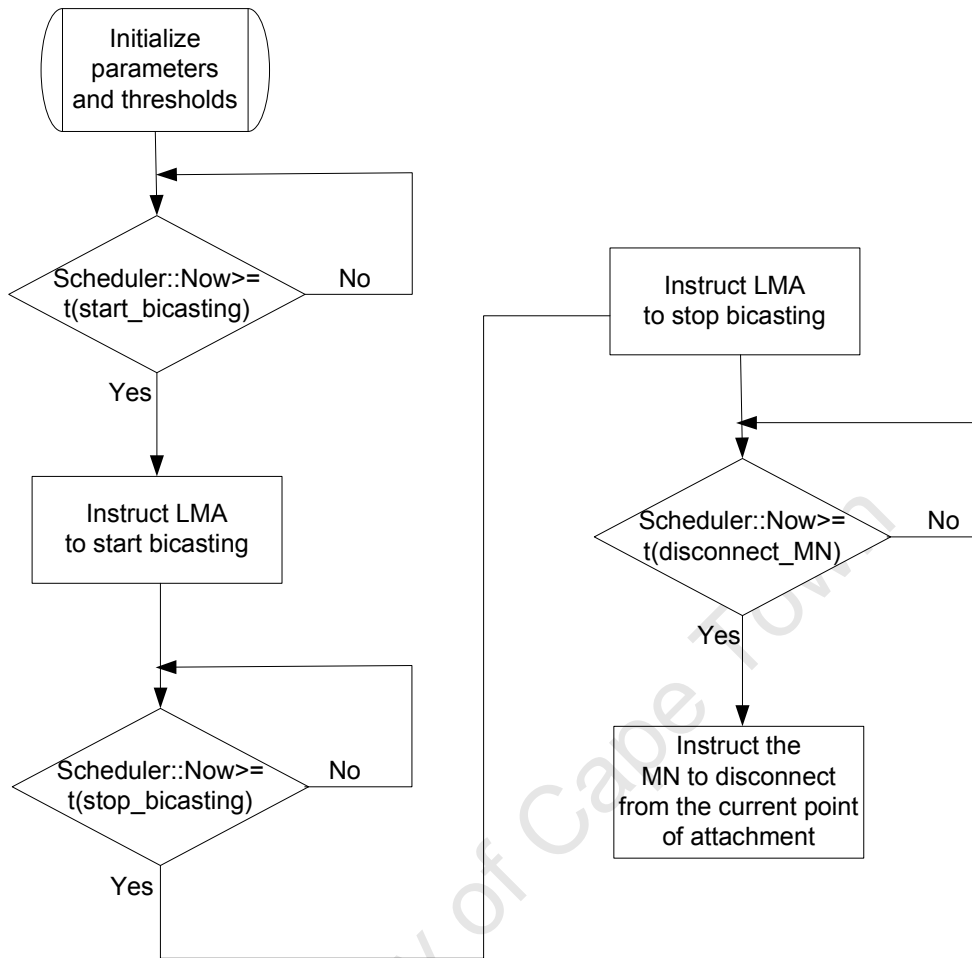


Figure 4.4 Events scheduler flow chart

4.3.1.4 Packet buffering at NMAG

The proposed solution evades packet loss in the packet stream that is routed at the LMA to next mobile access gateway (NMAG) before the MN successfully attaches to NMAG during the layer-2 handover execution. The implementation of buffering extends on the first in first out (FIFO) drop tail packet queue provided by the Queue library in NS-2. The buffering function is implemented following the flow chart shown in Figure 4.5. When packets reach the NMAG while the MN is not yet attached, NMAG buffers the packets destined to the MN and sends them to the MN as soon as it attaches. The algorithm maintains two packet queues q and q_{pmip} for data packets and signaling packets respectively. The separation of data packets and signaling messages enables EB-PMIPv6 to allow the layer-3 handover operations continue whilst buffering the incoming data packets destined to the MN.

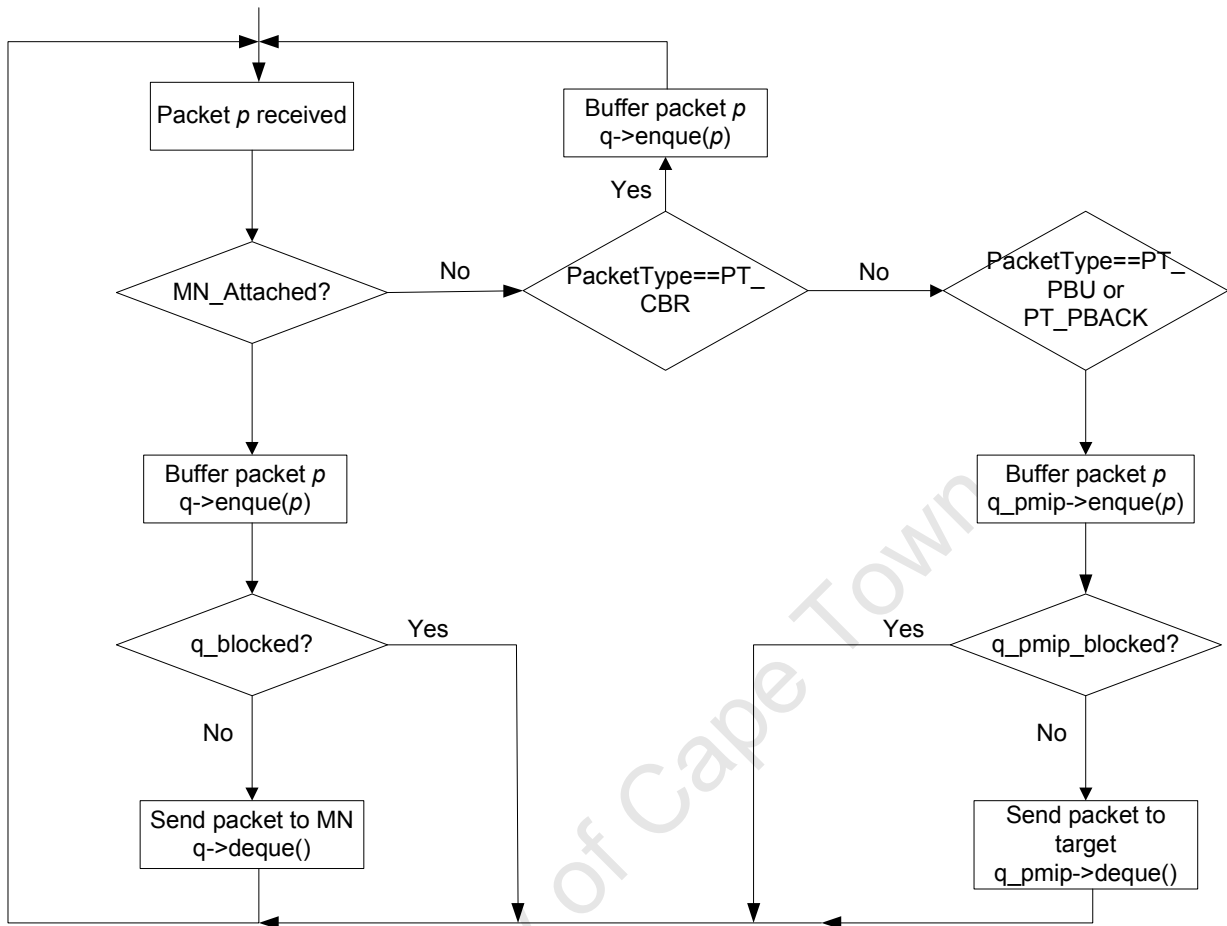


Figure 4.5 Buffering flowchart

As depicted in the flowchart, when the MN is not attached (controlled using a Boolean variable *MN_attached*), all constant bit rate (CBR) packets (*PT_CBR*) that reach the NMAG are enqueued onto the packet queue *q*. The condition can be altered to accommodate all data packets destined to the MN. The CBR packet type is used for testing purposes. However when a PMIPv6 binding messages (*PT_PBU* or *PT_PBA*) are received, they are enqueued on a separate queue *q_pmip* so that the predictive layer-3 handover operations may continue being carried out even though the MN has not yet attached. The PMIPv6 binding messages are then dequeued and passed on to the modules that use the binding messages when the packet queue is unblocked. Both packet queues ensure that before sending a packet to the MN in the case of queue *q* and to the target in the case of *q_pmip*, the recipient of the packet is ready to receive the next packet. This is done to avoid overwhelming the recipient with packets much quicker than the service rate at the recipient. Therefore, when the recipient is ready the Boolean variable *blocked* is set to false

and set to true otherwise.

When a LINK_UP trigger is received from the lower layers (MAC layer) indicating that the MN has attached, the Boolean variable *MNAttached* is set to true. This enables the program flow to follow the path of releasing packets in the buffer to the MN. Since EB-PMIPv6 maintains a single buffer (packet queue) for the MN's downlink traffic, the possibility of packet re-ordering is eliminated because the proposed scheme uses a FIFO packet queue.

4.3.2 EB-PMIPv6 LMA Implementation

This subsection discusses how the implementation of the proposed EB-PMIPv6 on the LMA side has been implemented and incorporated into the PMIPv6 model on NS-2. It also discusses how the classifier routes the signaling messages to the intended recipient class objects to harmonize the communication between the EB-PMIPv6 MAG and LMA modules. It further discusses how the PMIPv6 LMA is modified to support multiple bindings as well as how the multicasting functionality was implemented.

4.3.2.1 Classifier

Classification of signaling messages and data packets that reach the LMA are routed appropriately to the destination module. As depicted in the PMIPv6 model in Figure 4.2, the LMA is modularized. The LMAAgent and the MAGAgent objects receive and send signaling messages, whereas the Encapsulator (*Encap*) and Decapsulator (*Decap*) objects handle the data packets. Thus, there is a separation of the signaling plane and the data plane. Each of the objects uses a receive function *recv(packet *p)* in its class to receive messages from other objects. On the other hand, sending of data packets is achieved by invoking the target object's receive function (*target->recv(packet *p)*, where *target* is the intended recipient object).

Moreover, sending signaling messages is achieved by using a command function. The command function acts as a gateway for signaling messages to each class object. Thus, in the implementation of EB-PMIPv6, to send signaling messages such as "*start multicasting*" the command function is invoked which in turn invokes other functions to duplicate and encapsulate packets to current and candidate point of attachments. The normal routing procedures are not altered hence routing is still carried out by using a destination classifier to locate the message destination.

4.3.2.2 Simultaneous bindings support

The signaling messages from the MAG to the LMA are received through a *recv(packet *p)* function of the LMAAgent. To facilitate a proactive layer-3 handover, the NMAG sends a PBU message to LMA in advance. Upon reception of the PBU on the LMA, the LMA sets up a route to NMAG by invoking the *setup-route* function without clearing the route to the PMAG. However, in the original implementation, when a PBU is received from NMAG, the MN's routing state is updated by clearing a route to PMAG and setting up a route to NMAG. This is due to the lack of simultaneous bindings support.

In EB-PMIPv6, to support multiple bindings which is required to enable bicasting, a new function is implemented that uses the two fields; the mobile node identifier (MN-ID) and the PCoA (address of the MAG acting as a proxy for the MN) in the binding cache list to be a primary key. In the original implementation, the MN-ID only is used as the primary key. And, with the MN-ID only as the primary key, two entries in the binding cache list with the same MN-ID cannot exist. Whereas, in the case of an implemented function used in this research, there can exist more than one binding cache entries (BCEs) of the same MN-ID as long as the PCoAs differ. The figure below shows an overview representation of the binding cache list on the LMA in the case of PMIPv6 as it is and in PMIPv6 that supports simultaneous bindings. The fields of a binding cache include the MN-HNP and the lifetime even though they are not shown below.

PMIPv6 – LMA binding cache		PMIPv6 with simultaneous bindings support – LMA binding cache	
MN-ID	PCoA	MN-ID	PCoA
MN-ID1	PCoA1	MN-ID1	PCoA1
		MN-ID1	PCoA2

Figure 4.6 LMA binding cache

4.3.2.3 Bicasting support

In EB-PMIPv6, during the bicasting period, packets are duplicated and routed to the PCoAs that are associated with the MN in the LMA binding cache. During the route setup phase, a second binding cache entry is inserted in the LMA binding cache list as shown in Figure 4.6 above (simultaneous bindings). Thereafter, over and above the encapsulator object for IP in IP tunnel to PCoA1 that is setup prior to bicasting, another encapsulator object to tunnel traffic to PCoA2 is created. However, in the original PMIPv6 implementation, only one encapsulator

object can be set-up for a single MN to point to one PCoA. This then calls for a way for EB-PMIPv6 to enable the creation of two encapsulators. The schematic in Figure 4.7 below shows the PMIPv6 LMA after setting up a route (tunnel) to a MAG that provides a proxy for an MN.

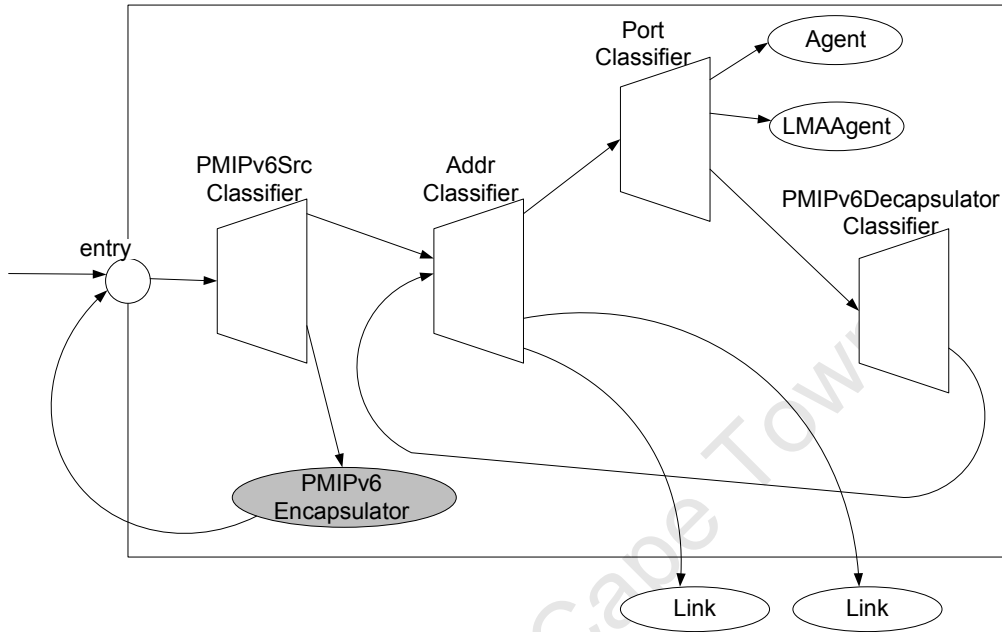


Figure 4.7 PMIPv6 LMA after completion of route-setup [35]

Packets that reach the LMA enter the LMA through the entry point (*entry*), are forwarded to the destination classifier (*PMIPv6DestClassifier*). The destination classifier checks the destination address of the received packet on the packet header. If the packet is destined to the MN whose binding cache entry (BCE) is in the LMA's binding cache, the packet is forwarded to the encapsulator (*PMIPv6Encapsulator*) to encapsulate the packet and tunnel it to the PCoA associated with the MN in the binding cache; otherwise the packet is routed normally. The encapsulator encapsulates the packet by adding another packet header whose destination address is PCoA1, then after normal routing occurs. The schematic in Figure 4.8 shows how the LMA is modified in EB-PMIPv6 to attain tunnelling of packets to both PMAG and NMAG on addresses PCoA1 and PCoA2 respectively for example in IP in IP tunnels.

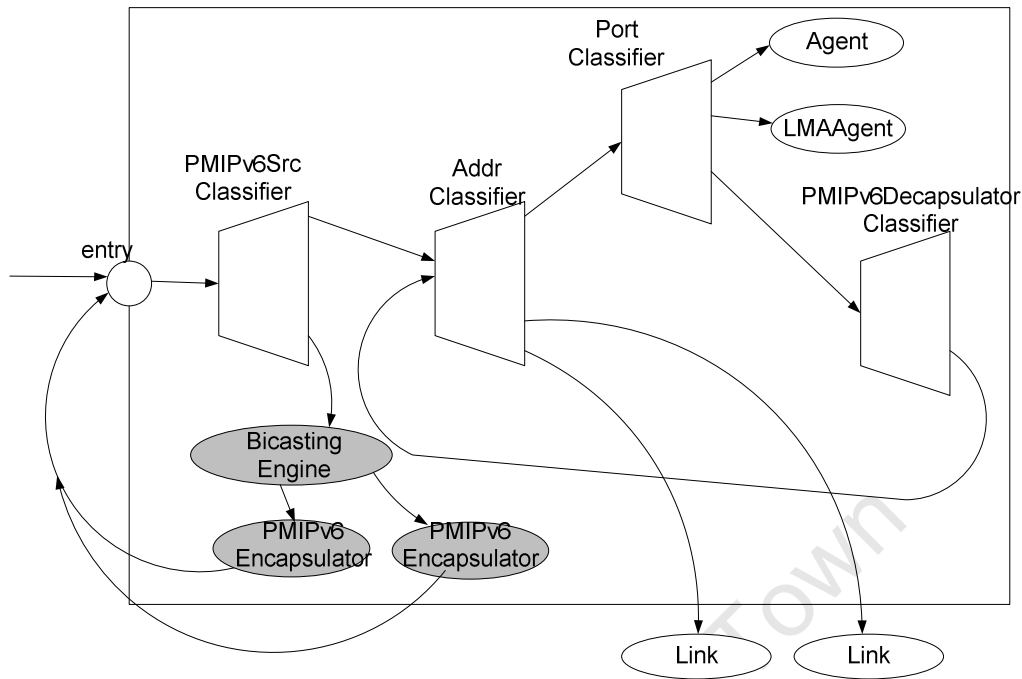


Figure 4.8 Enhanced bicasting PMIPv6 LMA during bicasting

In EB-PMIPv6, after destination classification, the bicasting engine creates a copy of the received packet. The bicasting engine then forwards the original packet to one encapsulator that encapsulated packets to PMAG on PCoA1, whilst the copy is forwarded to another encapsulator for NMAG on PCoA2. The IP addresses of the MAG's (PCoA1 and PCOA2) are obtained in the LMA binding cache list that supports simultaneous bindings for a single MN. However before bicasting starts, the bicasting engine; with aid of the trigger notifications from the bicasting trigger generator, sends packets for encapsulation to PCoA1 alone, and for encapsulation to PCoA2 alone when bicasting stops.

On the other hand, when the MAG sends the MN's uplink packets to the LMA, it encapsulates them by adding a header whose destination address is the LMA Address (LMAA). When the packets reach the LMA, destination classification is also performed and the packets are forwarded to the Port classifier because they will appear to have been addressed to the LMA. The port classifier then forwards the packets to the decapsulator (*PMIPv6DecapsulatorClassifier*). The decapsulator removes the header added by the MAG to reveal the original destination IP address of the corresponding node (CN) and standards IP routing is carried out.

4.4 Simulation setup

This subsection discusses how the proposed EB-PMIPv6 model is simulated and tested for proof of concept purposes. NS-2 is used in carrying out the simulations for comparing the proposed EB-PMIPv6 to the original PMIPv6, B-PMIPv6 [19, 20], and PB-PMIPv6 [23, 36] in terms of handover performance as well as the network resources utilization. The network models used and the simulation parameters are presented in this subsection as follows:

4.4.1 Network Models

The simulation network is set up on a 670 meters by 670 meters topography and is shown in Figure 4.9. It is composed of six NS nodes. The PMIPv6 nodes are constructed by adding functionality on the NS nodes. The LMA is achieved by invoking an *install-lma* function that adds LMA functionality on the node. In a similar way, the MAG is attained by invoking an *install-mag* function that adds MAG functionality to the node. Each MAG is collocated with an IEEE 802.11 (WLAN) access point (AP). The WLAN access points AP1 and AP2 provide the MN with wireless connectivity in the PMIPv6 domain with partially overlapping areas of coverage.

The router RT is not modified and performs standard IP routing. The traffic stream originates from the correspondent node (CN) and is destined to the mobile node (MN). The MN moves within the PMIPv6 domain and performs a handover from one MAG to another. The MAG that the MN moves away from is referred to as the previous MAG (PMAG) whilst the one which the MN moves towards is the next MAG (NMAG). Lastly, the duplex links bandwidth and delays on the wired network are as depicted in the network model in Figure 4.9

670x670
Topography

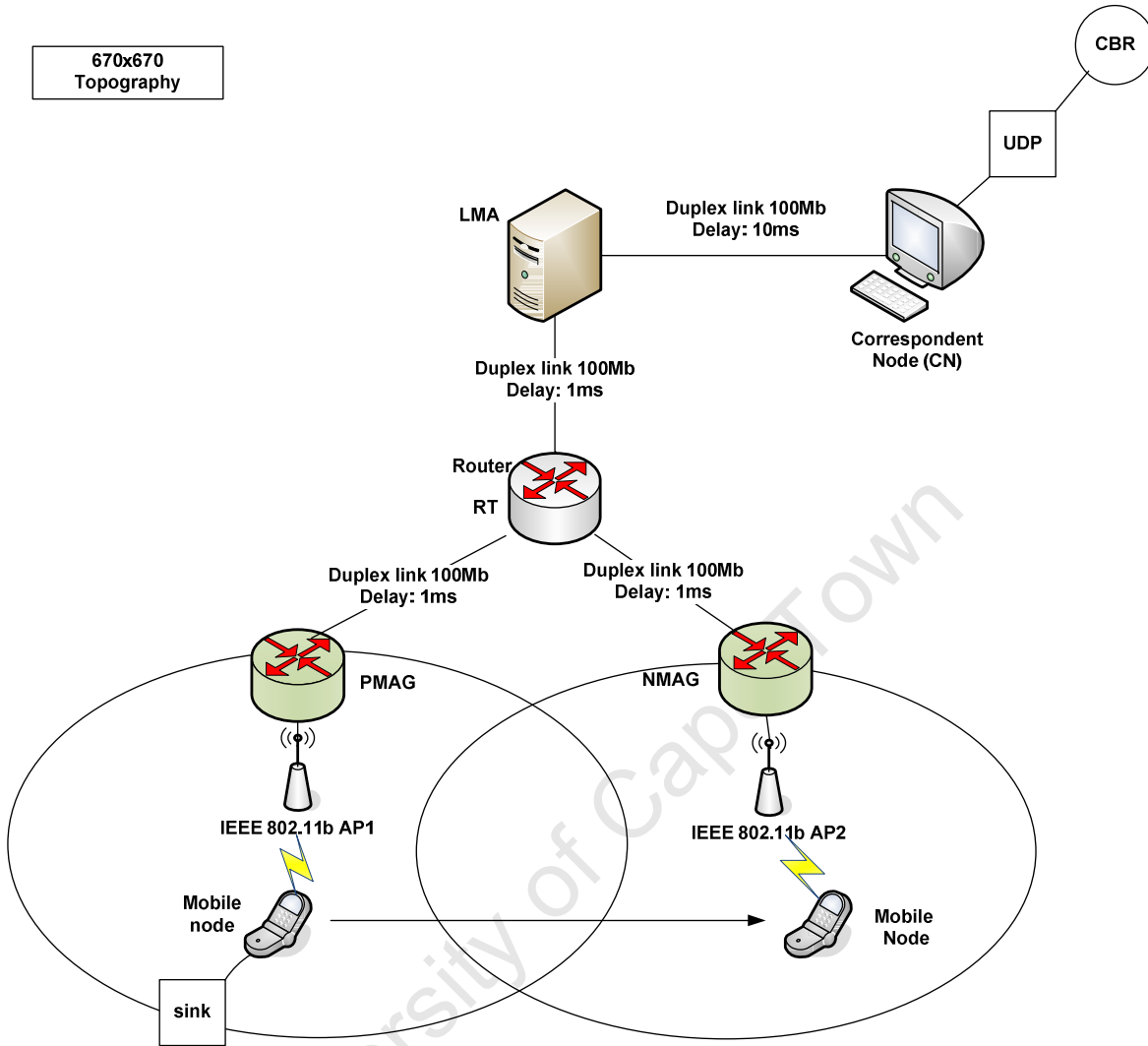


Figure 4.9 Simulation network model setup

The correspondent node (CN) sends constant bit-rate (CBR) packets of size 1000 bytes every 0.001s (CBR packet interval) over User Datagram Protocol (UDP) to the mobile node (MN) to emulate a real-time traffic stream. Thus the CN is the traffic source whereas the MN is the traffic sink. A very short CBR packet interval of 0.001s was used in the simulations so as to approximate the handover delay accurately as packets are received by the mobile node just before the link goes down on PMAG and as soon as the link is up on NMAG

In order to assess the impact that the number of MNs performing handovers simultaneously have on the performance metrics used in this study, the simulation setup shown in Figure 4. 10 is used. More CBR agents (CBR_1, CBR_2, ..., CBR_n) are attached to the CN that generate CBR packets addressed to the MNs (MN_1, MN_2, ..., MN_n) in the wireless

network respectively.

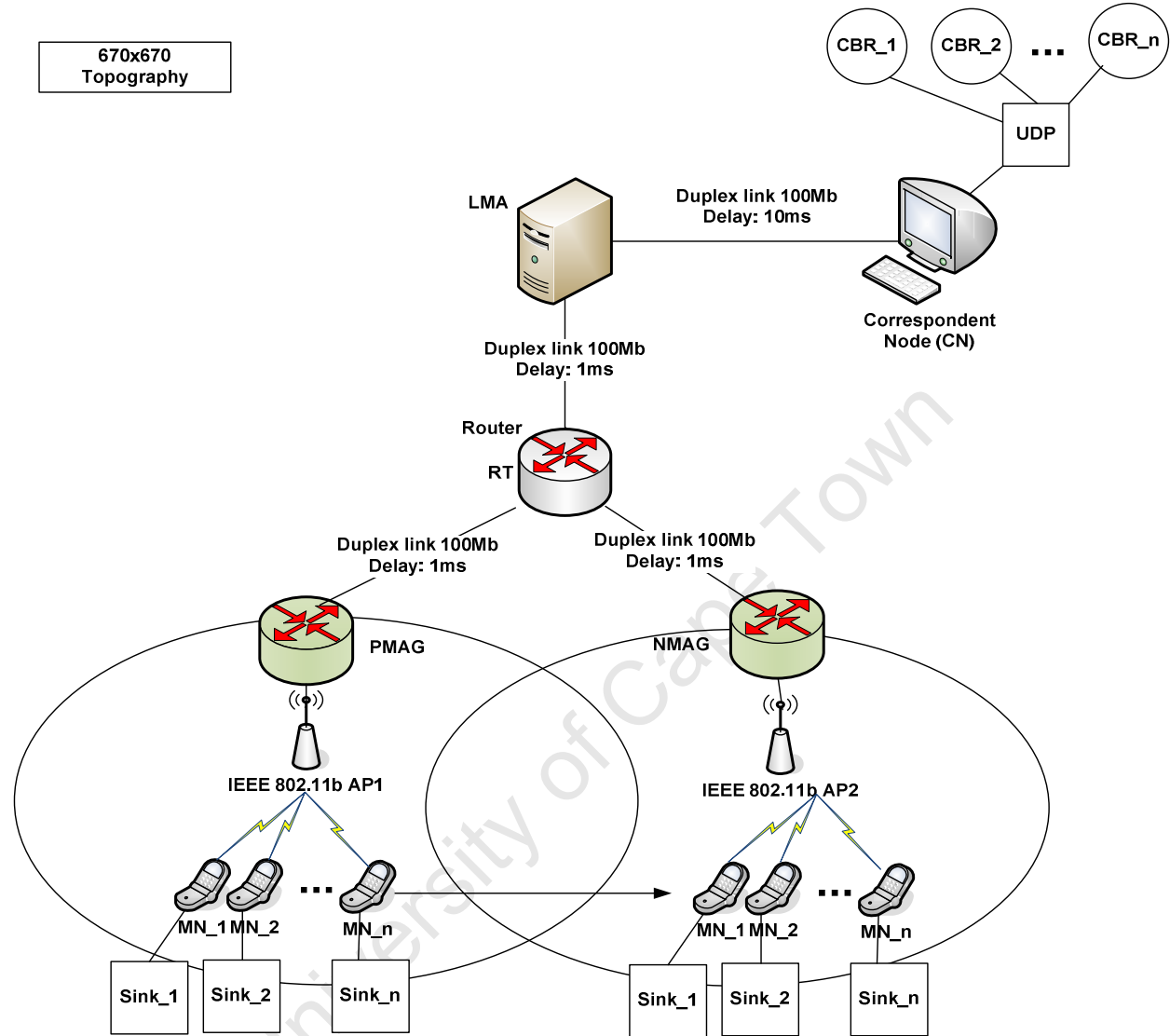


Figure 4.10 Simulation setup for multiple MNs

4.4.2 Simulation Parameters

Table 4.2 below shows the essential simulation parameters. It includes some physical layer parameters such as the AP transmitter power as well as the signal strength at the edge of the coverage area ($RXThresh_{}$). Other parameters of the simulation such as the MN speed are varied to test and evaluate different performance metrics.

Table 4.2 Simulation parameters

General		
Simulation time	60 Seconds	
Number of runs per scenario	10	
Topography	X(m)	Y(m)
	670	670
Traffic considerations		
Transport protocol	User Datagram Protocol (UDP)	
Application	Constant bit rate (CBR)	
	Packet size	Interval
	1000 bytes	0.001 Seconds
Mobile movement		
Linear motion	10m/s, 20m/s, 30m/s, ..., 90m/s	
IEEE 802.11		
Basic rate	1Mbps	
Data rate	11Mbps	
Power transmitted by AP (Pt)	0.025 Watts	
Receive threshold (<i>RXThresh</i> _l)	$2.025 * 10^{-12}$ Watts	
pr_limit (for LINK_GOING_DOWN triggering)	1.2	

4.5 Summary

This chapter has discussed the implementation of the proposed solution in the NS-2 simulation environment as well as how its performance will be evaluated. It first explains the NS-2 simulation framework and highlights its capabilities and why it is a well accepted tool for research. It further discusses the tools within the NS-2 library that the proposed solution reuses. These are the PMIPv6 model developed for NS-2 by *Choi. H*, and the NIST mobility package that incorporates link-layer trigger generation functionality.

Moreover, this chapter discusses how the proposed solution is implemented to attain the objectives mentioned earlier. This has been performed by encapsulating the principle of operation of the EB-PMIPv6 modules through flow-charts. Lastly, it discusses how the simulations for the proposed EB-PMIPv6, PMIPv6, B-PMIPv6 and PB-PMIPv6 are going to be performed for evaluation purposes. This has been done by presenting the simulation network models and the simulation parameters.

The next chapter presents the performance results and analysis on the evaluations carried out to compare the proposed solution against bicasting solutions for PMIPv6 in the literature with regards to handover delay, packet loss, buffer utilization, backhaul bandwidth utilization, and signaling overhead.

Chapter 5 Experimental Results

5.1 Introduction

The previous chapter has covered the implementation of the proposed bicasting solution for PMIPv6 on the NS-2, which addresses the problem of inefficient utilization of network resources. This chapter presents the performance evaluation of the proposed solution obtained by carrying out simulations on NS-2. As mentioned earlier, the proposed solution's performance is compared to that of other bicasting solutions for PMIPv6 (B-PMIPv6 and PB-PMIPv6).

This chapter begins by describing the performance metrics used to evaluate the proposed solution and their relevance to the study. Then, the performance results and their analyses are discussed with respect to each of the performance metrics. Horizontal handovers are performed whereby the MN changes subnets from one MAG to another. The evaluations and analyses are based on downlink traffic (i.e. from CN to MN).

5.2 Evaluation Metrics

5.2.1 Handover performance

The handover performance is characterized by the handover delay and packet loss that are incurred when an MN changes a point of attachment. This study focuses on lowering the layer-3 handover delay. However, for a layer-3 handover to occur, a layer-2 handover must also occur. A layer-2 handover involves scanning, authentication and association which are carried out when a MN changes an AP/BS. On the other hand, the layer-3 handover occurs when a MN changes a subnet. During the time when the layer-2 and layer-3 handovers are performed, the MN is not able to receive packets from either point of attachment.

This study refers to the handover delay as the time when the MN is not able to receive packets from either the previous MAG (PMAG) or the next (candidate) MAG (NMAG). On the other hand, packet loss is measured from the view of the MN. That is, the packet loss is computed by counting the number of packets that were sent by the CN but were however not received by the MN due to the handover. The handover delay and packet loss affect the throughput at the MN. Therefore evaluation results presented in this chapter also present the

effects the handover has on the throughput on the MN.

Overall, the handover performance evaluation metrics used in this study are:

- Handover delay
- Packet loss
- Throughput

5.2.2 Network resources utilization

The proposed solution employs a bicasting technique for packet loss alleviation. As was explained in the previous chapters, bicasting based solutions for PMIPv6 lower packet loss during a handover at the cost of increased network resources utilization. During the time when bicasting occurs, the backhaul bandwidth utilization doubles since packets are duplicated and sent to both PMAG and NMAG. As it has been discussed in chapter 3, scheduling of the bicasting operations determines the duration of time during which twice the amount of bandwidth will be required on the backhaul link. Moreover, bicasting solutions employ the usage of buffer space on the NMAG to hold packets while the MN performs the handover and releases them to the MN when the handover is complete.

In addition, this chapter presents evaluation results concerning the amount of packets dropped on PMAG which results from misrouting packets to PMAG when the MN is no longer within the transmission range of PMAG (i.e. when the signal strength at the MN is below the $RXThresh_{_}$). This is also referred to in-flight packet loss. The amount of packet duplicates that reach the MN is also evaluated as the high number of duplicates signifies an inefficient usage of the network infrastructure. Secondly, if UDP is the transport protocol used, upper layers have to provide a way of eliminating packet duplicates otherwise there will be hiccups in the service being consumed.

Overall, the evaluation metrics used to assess the network resources utilization are:

- Backhaul link bandwidth utilization
- Buffer space requirement
- Number of packets dropped on PMAG (in-flight packet loss)

- Number of packet duplicates

5.3 Handover Performance Results

5.3.1 Handover delay and packet loss

This section discusses and analyzes the handover delay and packet loss performance results obtained from simulating a handover in each of the mobility management schemes. For the result presented in Figure 5.1, in addition to the simulation parameters outlined in Chapter 4, to simulate a handover from PMAG to NMAG, at 1 sec, the MN began to move from PMAG to NMAG at a uniform velocity of 30m/s. Data used to plot the graph in Figure 5.1 has been extracted from the simulation trace output file from the interval 13 seconds to 15.5 seconds within which the handover occurs. In fact, Table 5.1 shows the events and corresponding time of occurrence that take place when the MN traverses from PMAG's subnet to NMAG's subnet at 30 m/s.

Table 5.1 Events and time of occurrence at 30 m/s

Mobility scheme	Event	Time of occurrence
PMIPv6	LINK_DOWN on PMAG	14.334 seconds
	LINK_UP on NMAG	14.762 seconds
B-PMIPv6,	LINK_GOING_DOWN on PMAG	13.394 seconds
PB-PMIPv6 and	LINK_DOWN on PMAG	14.334 seconds
EB-PMIPv6	LINK_UP on NMAG	14.496 seconds

The LINK_GOING_DOWN event is not applicable (N/A) in PMIPv6 as it does not make use of handover anticipation mechanisms. The signal threshold for generating a LINK_DOWN event is reached at a common time for all schemes which is 14.334 seconds. However, the handover completion time differs for PMIPv6 compared to the bicasting schemes under evaluation (B-PMIPv6, PB-PMIPv6 and the proposed EB-PMIPv6). This is attributed to the fact that these bicasting schemes make use of a proactive handover approach thereby allowing some

handover operations latencies to be eliminated from the total handover delay hence the handover is completed earlier than in PMIPv6.

The graph plots the simulation time in seconds against the packets received by the MN. The packets in the simulation are identified using an identification number (ID). Thus, the simulation time is plotted against the packet ID. The break in reception of packets indicates the duration whereby the MN was not able to receive packets from PMAG and handing over to NMAG, and it is referred to as the handover delay.

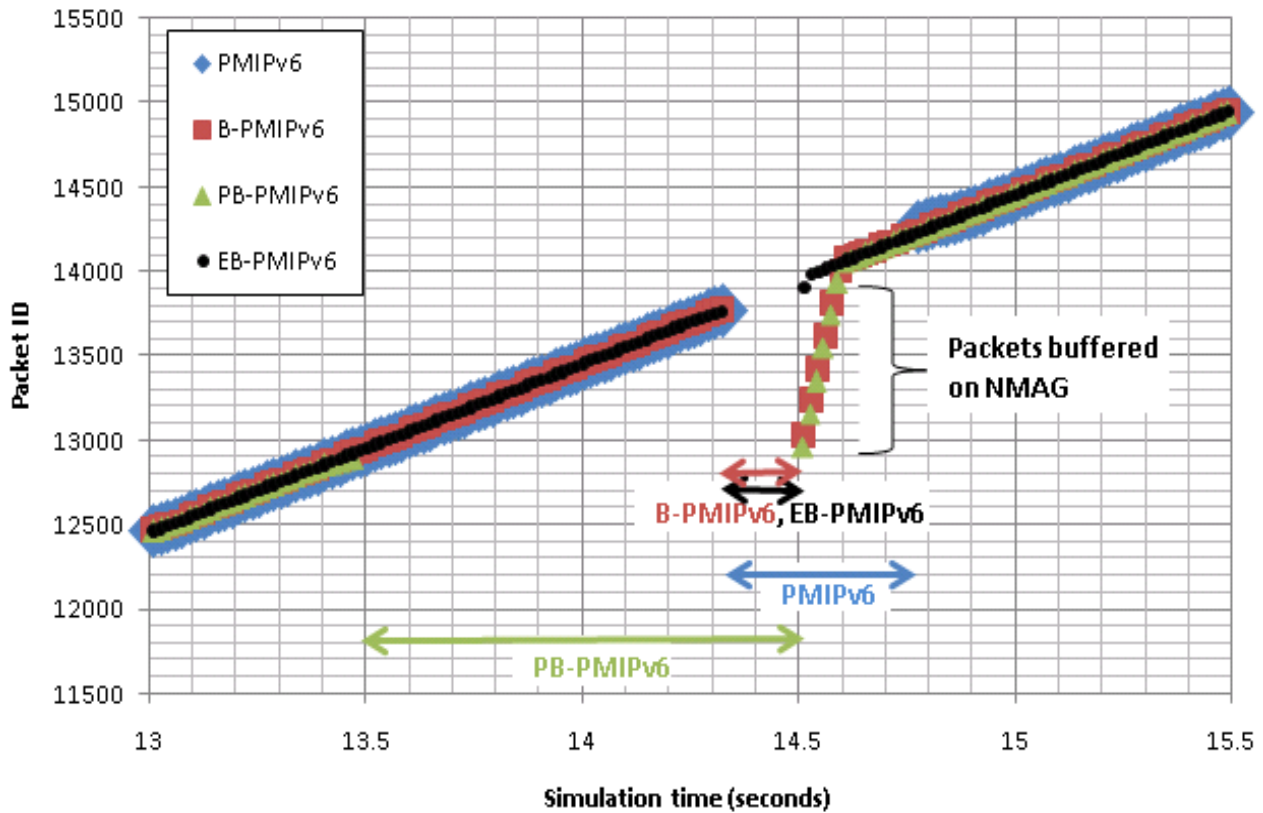


Figure 5.1 CBR packets received by the MN

From Figure 5.1, it can be observed that B-PMIPv6, and the proposed EB-PMIPv6 attain a much shorter handover delay than PMIPv6. This is because B-PMIPv6 and EB-PMIPv6 employ a predictive handover mechanism as opposed to the reactive mechanism used by PMIPv6. The predictive handover approach allows in-advance scheduling of other handover operations such as the PMIPv6 binding updates as well as the MN routing update. Furthermore, it can be observed that for B-PMIPv6 and EB-PMIPv6 the MN is able to receive packets through PMAG till the signal strength reaches the receive threshold and immediately after attaching to

NMAG.

On the other hand, even though PB-PMIPv6 also uses a predictive handover mechanism, the MN takes a much longer time without receiving packets. This is primarily due to the operation of PB-PMIPv6; whereby the scheme stops routing packets to PMAG as soon as a bidirectional tunnel is established between the LMA and the NMAG. This is done regardless of whether the signal strength is still strong enough to deliver packets from PMAG to MN without errors. Thus, it is observable that PB-PMIPv6 can incur even longer handover delays at lower MN speeds (e.g. pedestrian speeds). However, it can perform better at higher MN speeds since the time from when PB-PMIPv6 stops bicasting (stops routing packets to PMAG) to when the MN attaches to NMAG shortens as the speed at which the MN moves when performing a handover increases. Thus, from the perception of the MN, the packet arrival fluctuation in the packet flow destined to the MN that is caused by the handover delay is better for B-PMIPv6 and EB-PMIPv6.

It can further be observed that the utilization of the buffer on NMAG aids B-PMIPv6, PB-PMIPv6 and EB-PMIPv6 to incur lower packet loss after redirecting packets at the anchor point (LMA) to NMAG during the handover before the mobile node re-attaches to the network. As shown in the graph plot, packets that are buffered on NMAG while the MN performs layer-2 handover operations (scanning of channels, authentication and re-association) are sent to the MN once the handover is completed.

Moreover, since PMIPv6 redirects packets to NMAG after MN attaches to NMAG a significant amount of packets are dropped on PMAG. It should however be observed that for B-PMIPv6, the MN receives duplicate packets which depicts an inefficient backhaul link usage, and networking infrastructure.

Table 5.1 shows a summary of the handover performance for each of the simulated mobility schemes when an MN performs a handover from PMAG to NMAG. As it has been mentioned earlier, the handover delay is computed as the latency within which the MN does not receive packets from either PMAG or NMAG. For PMIPv6, at 14.3338 seconds during the simulation, the last packet with ID 13779 from PMAG was received by the MN, whereas the first packet received from NMAG with ID 14264 was received at 14.7718 seconds. Therefore from the MN's perspective packets that were not received (considered to be lost) are 485 in number.

The 485 packets that do not reach the MN are packets that are misrouted to PMAG when the MN is no longer attached till when the MN's routing is updated when it attaches to NMAG. This is during the layer-2 and layer-3 handovers.

On the other hand, with B-PMIPv6 and EB-PMIPv6 the MN takes a much shorter time (0.1763 seconds) without receiving packets which is the latency incurred in performing the layer-2 handover. Furthermore, for B-PMIPv6, the MN receives the last packet of ID 13779 from PMAG at 14.3338 seconds and receives the first packet of ID 12938 from NMAG. This however depicts a significant amount of packet duplicates received by the MN which is undesirable as explained earlier. This is caused by a too early start in bicasting, thus packets are routed to NMAG way in advance.

Table 5.2 Handover performance characteristics

Scheme	Handover delay	Packet loss
<i>PMIPv6</i>	0.4387 seconds	485 packets
<i>B-PMIPv6</i>	0.17632 seconds	0 packets
<i>PB-PMIPv6</i>	1.02291 seconds	43 packets
<i>EB-PMIPv6</i>	0.17632 seconds	52 packets

With PB-PMIPv6, the MN incurs a longer time without receiving packets from either PMAG or NMAG due to the scheme stopping to route packets to PMAG as soon as the completion of layer-3 handover (PMIPv6 binding updates, bidirectional tunnel setup). However, the MN receives the last packet of ID 12900 at 13.4861 seconds whilst the first packet of ID 12943 is received from NMAG at 14.5090 seconds. Therefore, the MN does not receive 43 packets due the handover.

Lastly, with the proposed EB-PMIPv6, the MN receives the last packet from PMAG with ID 13762 at 14.3339 seconds whilst at 14.5102 seconds the first packet with ID 13814 from NMAG. The number of packets lost due to the handover from PMAG to NMAG is 52. The

packets are lost due to two reasons. Firstly, packets are lost at the link-layer of the NMAG while the address resolution protocol (ARP) is still waiting to resolve the MN's MAC address. In the NS-2 implementation, packets are forwarded to the interface queue (IFq) that puts the packets to the MAC layer of the MAG as soon as the MAC address is resolved from the destination IP address. However, while waiting for an ARP response, if multiple packets destined to the same MN arrive, the packet that was buffered earlier is dropped. Thus, only one packet can be buffered while waiting to resolve the MN's MAC address. It should be noted that the increase in packet drops at the link layer for the mentioned reason also results from the short CBR interval (0.001seconds) used in the simulations. Secondly, some packets are dropped by PMAG just after the MN moves out of PMAG's area of coverage.

Therefore, it can be observed that in an EB-PMIPv6 handover, the MN incurs a lower handover delay and packet loss thus improving the handover performance of a PMIPv6 handover.

5.3.2 Throughput

As it has been mentioned earlier, the CN sends 1000 bytes CBR packets every 0.001 seconds. The MN is the traffic flow sink. This study considers throughput as the number of bits that the MN receives per second. The throughput at the MN is the computed in Mbps using the equation below.

$$Throughput = \frac{(bytes_recieved * 8)}{(trace_time * 1,000,000)} \quad (16)$$

Where: *bytes_recieved* are the number of bytes received by the MN.

trace_time defines the *Throughput* calculation period. Set to 0.01 seconds

That is, every *trace_time* seconds, the number of bytes received (*bytes_recieved*) by the traffic flow sink (MN) is used to compute the *Throughput* in Mbps.

The plots presented in Figure 5.2 show the throughput performance for each of the mobility schemes under evaluation as a handover occurs. The plots were separated for clarity purposes. In the same way, the throughput results in Figure 5.2 depict the MN throughput when performing a handover from PMAG to NMAG at a constant speed of 30 m/s.

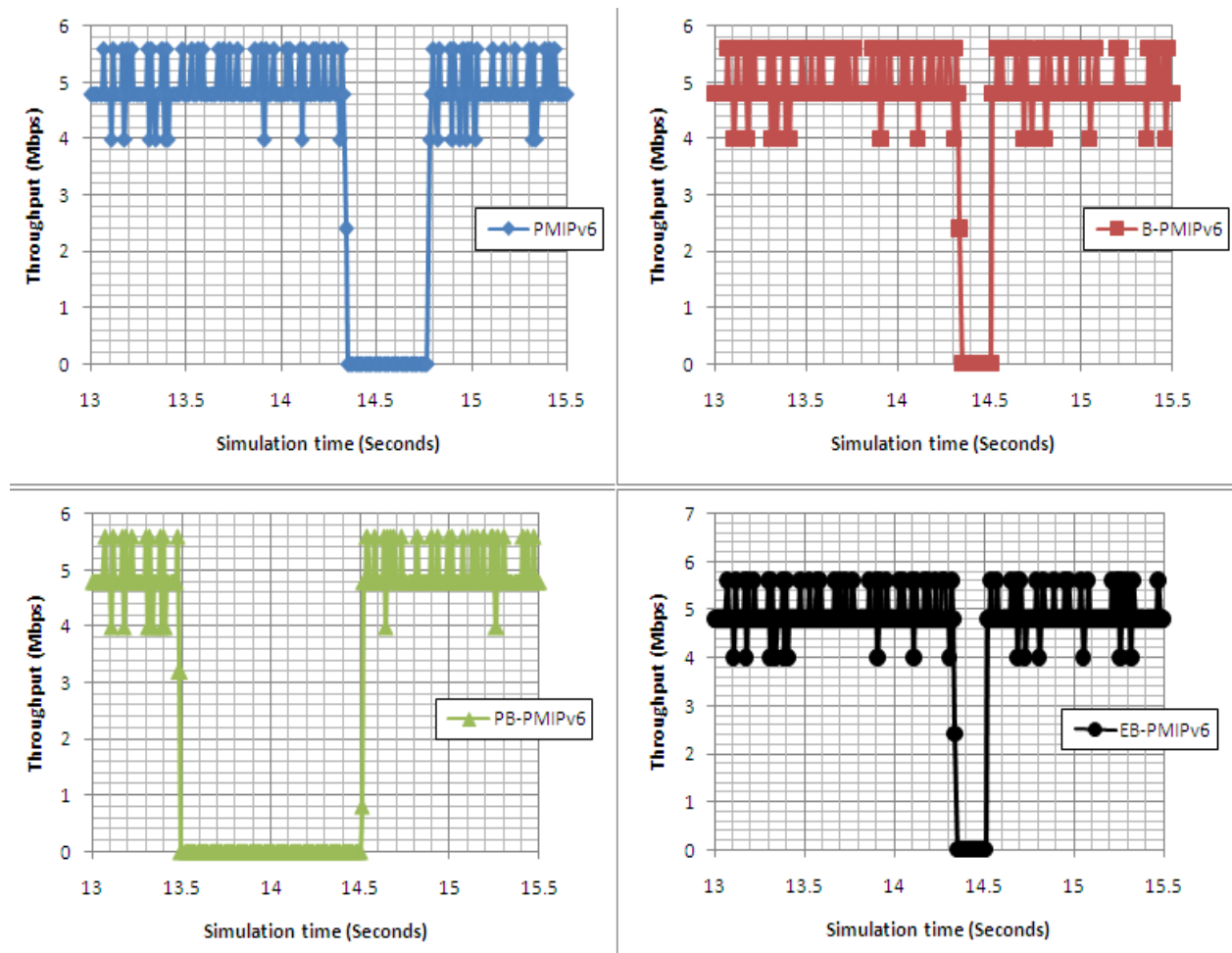


Figure 5.2 MN throughput for PMIPv6, B-PMIPv6, PB-PMIPv6 and EB-PMIPv6

The CN transmits an 8Mbps stream (1000 bytes CBR packet every 0.001 seconds). However, some packets are dropped by the MAG's wireless interface queue (IFq) which is by default set to 50. Thus, the reason that the throughput of the traffic stream received by the MN is on average 5Mbps instead of the transmitted 8Mbps is due to the packet overflow on the IFq which has been ignored. This study considers the packet loss that is caused by handover.

In all of the plots, when the MN is able to receive packets from PMAG, (before the handover) or from NMAG, (after the handover) the throughput is non-zero. However, the throughput drops to zero Mbps when no packets are received by the MN. The above plots give a clear depiction of the length of the handover delay incurred in each of the mobility schemes under evaluation.

It is observable from the above plots that for the PMIPv6 handover, the throughput stays

on zero for a longer duration than B-PMIPv6 and the proposed EB-PMIPv6. This is caused by the reactive handover approach in PMIPv6 whereby layer-2 and layer-3 handover operations are carried out after losing connectivity from PMAG. Whereas for B-PMIPv6, PB-PMIPv6 and EB-PMIPv6, the layer-3 handover operations are performed in advance, thus eliminating their latencies from the total handover delay incurred. This is why the MN starts receiving packets earlier than in the case of PMIPv6. It should however be noted that, even though PB-PMIPv6 employs the proactive handover approach to lower handover delays, PB-PMIPv6 stops sending packets to MN through PMAG much earlier when the MN would still be able to receive packets without errors.

5.3.3 Mobile node speed impact on handover performance

This subsection assesses the handover performance of the mobility schemes under evaluation when the MN performs a handover at different MN speeds. In the graphs presented in this subsection, the CN still transmits 1000 bytes CBR packets every 0.001 seconds to the MN. The graphical plot in Figure 5.3 depicts the handover delay incurred when an MN performs a handover at different MN speeds ranging from 10m/s to 90m/s. As mentioned in the previous sections, in this study, the handover delay is the time incurred by the MN without receiving CBR packets from either PMAG or NMAG.

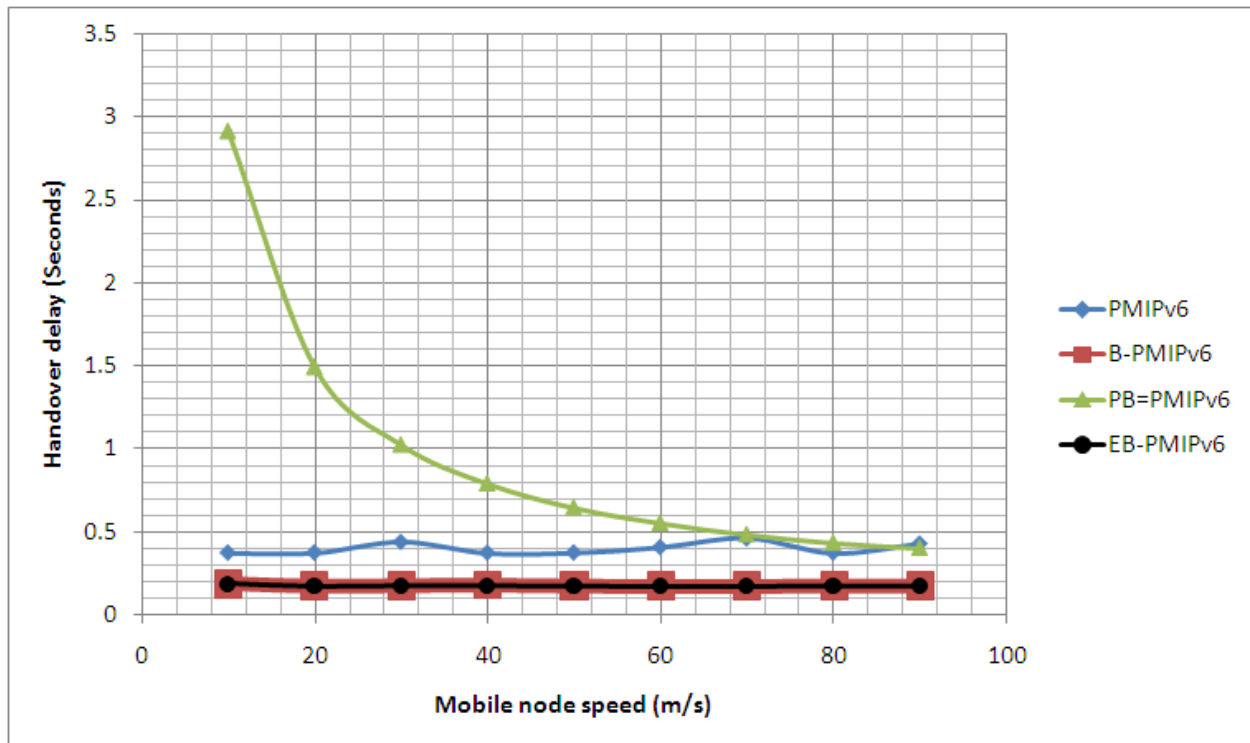


Figure 5.3 Handover delay at different MN speeds

It can be observed that PB-PMIPv6 incurs much higher handover latency at low MN speeds. This is because PB-PMIPv6 stops routing packets to PMAG as soon as the layer-3 handover has been completed after the LINK_GOING_DOWN trigger has been generated. The time duration from when the LINK_GOING_DOWN trigger is generated on PMAG to the time when the MN successfully attaches to NMAG is longer when the MN is traversing from PMAG to NMAG at a low speed. This time duration shortens as the MN's speed increases when traversing from PMAG to NMAG. Therefore, for PB-PMIPv6 the time the MN takes without receiving CBR packets from either PMAG or NMAG decreases as the MN speed increases as shown by the plot in Figure 5.3.

It can further be observed that PMIPv6 incurs much higher handover latency than B-PMIPv6 and the proposed EB-PMIPv6. This is mainly attributed to the fact that PMIPv6 uses a reactive approach to handovers. Thus, during the handover, more time is required to carry out the layer-2 handover operations (scanning, authentication and re-association) as well as to carry the layer-3 handover operations (binding updates, tunnel setup, and home network prefix advertisement). On the other hand, B-PMIPv6 and the proposed EB-PMIPv6 attain much lower

and comparable handover delays since some layer-3 handover operations are performed in advance and hence eliminating their latencies from the total handover latency.

It can also be observed that for PMIPv6, B-PMIPv6 and EB-PMIPv6, the handover delay is not significantly affected by the mobile node speed. This is mainly attributed to the fact that, for these mobility schemes, packets are sent to the MN through PMAG till the signal strength decays to the receive threshold ($RXThresh_{_}$) as well as through NMAG as soon as both the layer-2 and layer-3 operations are completed. Therefore, the time incurred without receiving packets at the MN is determined by the length of the handover delay. Now, the handover delay is dependent on the signaling carried out to perform the handover operations. And, PMIPv6 being a network-based mobility management solution, all mobility-related signaling is handled by the network elements (MAGs and LMA). Thus, the signaling is not dependent on the MN speed. This is why the handover latency does not show a direct relationship with the speed of the MN when traversing from PMAG to NMAG.

The packet loss that is incurred when a handover occurs when performing a handover at mobile node speeds ranging from 10m/s to 90m/s is depicted in Figure 5.4. In this study, packets that are sent by the CN to the MN during the handover but are not received by the MN either through PMAG or NMAG are considered to be lost. Therefore, the number of packets lost (on the vertical axis) indicates the CBR packets that did not reach the MN during the handover period.

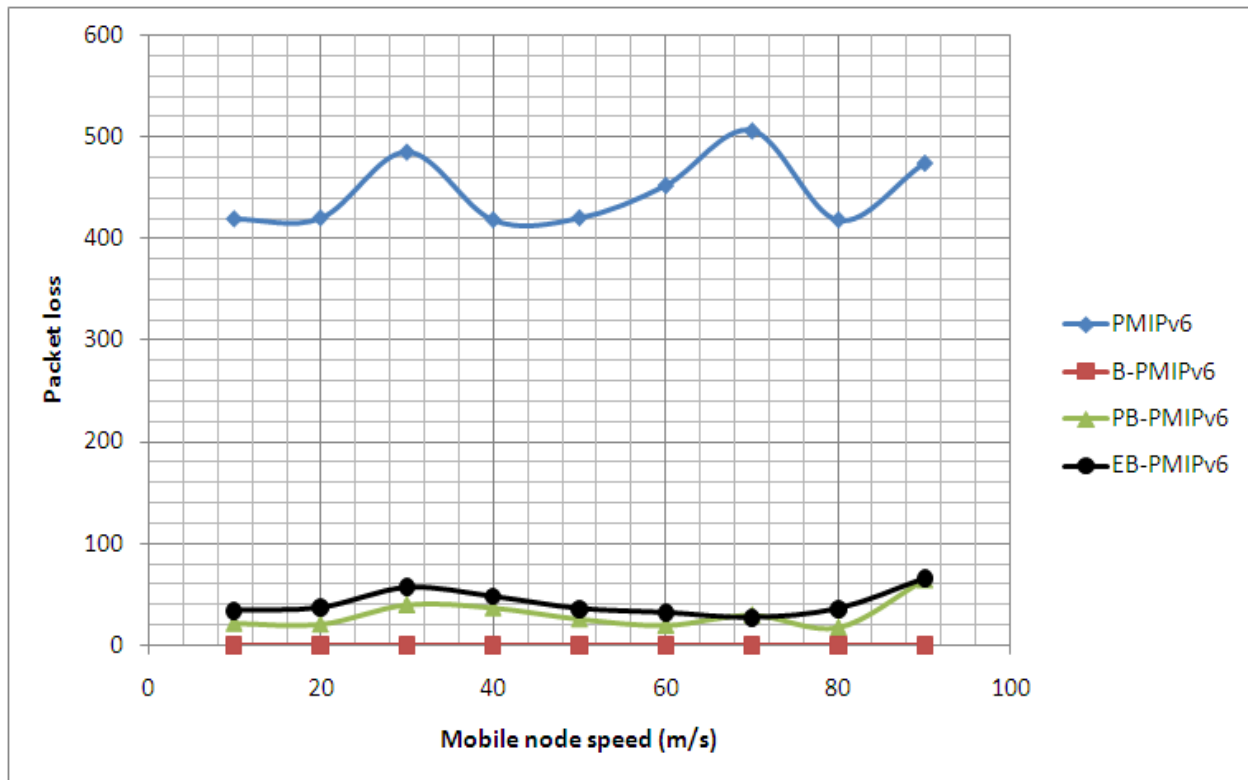


Figure 5.4 Packet loss at different MN speeds

A significant amount of CBR packets do not reach the MN during a PMIPv6 handover compared to B-PMIPv6, PB-PMIPv6 and EB-PMIPv6. This is due to the reactive handover approach used by PMIPv6. Packet redirection to the next point of attachment (NMAG) is only effected when the MN successfully attaches to NMAG. That is after both the layer-2 and layer-3 handover operations have been carried out. Therefore, before the packet flow destined to the MN is redirected to NMAG (during the handover operations execution), packets are misrouted to PMAG and ultimately do not reach the MN. Lastly, in PMIPv6, the LMA is not notified when a handover is imminent therefore in-flight packet losses occur and consequently increase the total number of packets that do not reach the MN.

On the other hand, the bicasting schemes attain much lower packet loss during the handover. The buffer plays an important role of buffering packets that would have otherwise been lost as they are continuously sent by the CN during the handover. With B-PMIPv6, packets sent by the CN during the handover period reach the MN. Packets that the MN received through PMAG from when the handover was imminent are also received through NMAG. This is because, bicasting starts too early and delays to stop, and hence the MN receives packet

duplicates. Therefore, from the MN's view, no packets are lost as a result of the handover. However, this is done at an expense of a significant utilization of the network resources as will be shown in the forthcoming results.

PB-PMIPv6 which was proposed to solve the drawback of inefficient utilization of the network resources imposed by B-PMIPv6 attains a low packet loss with the proposed EB-PMIPv6 incurring slightly higher packet loss as shown in Figure 5.4. Unlike in the case of PMIPv6 whereby the amount of packets lost is only dependent on the length of the handover delay, the packet loss during a handover for PB-PMIPv6 and EB-PMIPv6 is attributed to a number of reasons. Firstly, packets are dropped by NMAG while waiting for the ARP response detailing the resolution of the MN's MAC address. As mentioned earlier, in the NS-2 implementation, only one packet is buffered at the link layer while waiting for the ARP response. An earlier buffered packet is dropped when another packet destined to the MN is received. Secondly, some packets are dropped on the NMAG's interface queue (IFq) whose default size is 50 in the NS-2 framework. Hence, with the high arrival rate of CBR packets from the CN, the IFq overflows and hence packets are dropped from time to time; even when there is no handover occurring.

It can however be observed that the packet loss for EB-PMIPv6 is slightly higher than that of PB-PMIPv6. Over and above the two reasons (ARP and IFq) a slight increase in the number of packets that do not reach the MN is attributed to the in-flight packet loss on MN. That is, there are packets that are sent to the MN and reach the MN when it is no longer within the acceptable signal strength boundary of PMAG to successfully receive the packet. However, this can be corrected by employing a packet error correction mechanism since the packets are not decode-able by the MN and are hence dropped.

5.3.4 Deductions on Handover Performance

The experimental results obtained in evaluating PMIPv6, B-PMIPv6, PB-PMIPv6 and the proposed EB-PMIPv6 show that the proposed EB-PMIPv6 improves the handover performance of PMIPv6 by attaining lower packet losses as well as lower handover delays incurred during a handover. With regards to handover delay, PB-PMIPv6 incurs longer handover delays than B-PMIPv6 and the proposed EB-PMIPv6 whilst B-PMIPv6 and EB-PMIPv6 are on par. On the

other hand, packet loss results depict that B-PMIPv6 attains zero packet loss at an expense of inefficient utilization of network resources whilst the proposed EB-PMIPv6 incurs a slightly higher packet loss than PB-PMIPv6. Therefore, the proposed EB-PMIPv6 solution achieves the objective of improving the handover performance of PMIPv6.

5.4 Network Resources Utilization

Bicasting solutions for PMIPv6 have been criticized on their inefficiency in utilizing the network's shared and scarce resources. Therefore, one of the main objectives that is essential to address is that of efficient utilization of network resources. It is on that account that this section presents the evaluation results of PMIPv6, B-PMIPv6, PB-PMIPv6 and the proposed EB-PMIPv6 with regards to network resources utilization. In this study, the network resources assessed are the backhaul bandwidth as well as the buffer space that are required to support a seamless handover.

5.4.1 Buffer Utilization

Bicasting schemes presented in this thesis make use of the proactive handover approach whereby during the handover period, the LMA redirects the packet flow destined to the MN to the candidate/next MAG (NMAG). To lower the packet loss that occurs during the handover, packets are buffered upon arrival on NMAG if the MN handover operations are still pending completion.

Figure 5.5 indicates the NMAG buffer space required by the schemes under evaluation to alleviate packet loss when the MN cannot receive packets from neither PMAG nor NMAG during the handover. In the experiments for buffer space utilization, an infinite buffer length has been assumed since the aim of the experiment is to assess or quantify the amount of buffer space required in each of the mobility schemes to provide a seamless handover. However in a real network, buffer space is limited and hence buffer overflows would occur and hence lead to packets being dropped for mobility schemes that require a substantial amount of buffer space. The plot in Figure 5.5 shows the variation in buffer space requirement when the MN transits from PMAG's subnet to NMAG's subnet at different MN speeds as a handover is performed for PMIPv6, B-PMIPv6, PB-PMIPv6 and the proposed EB-PMIPv6.

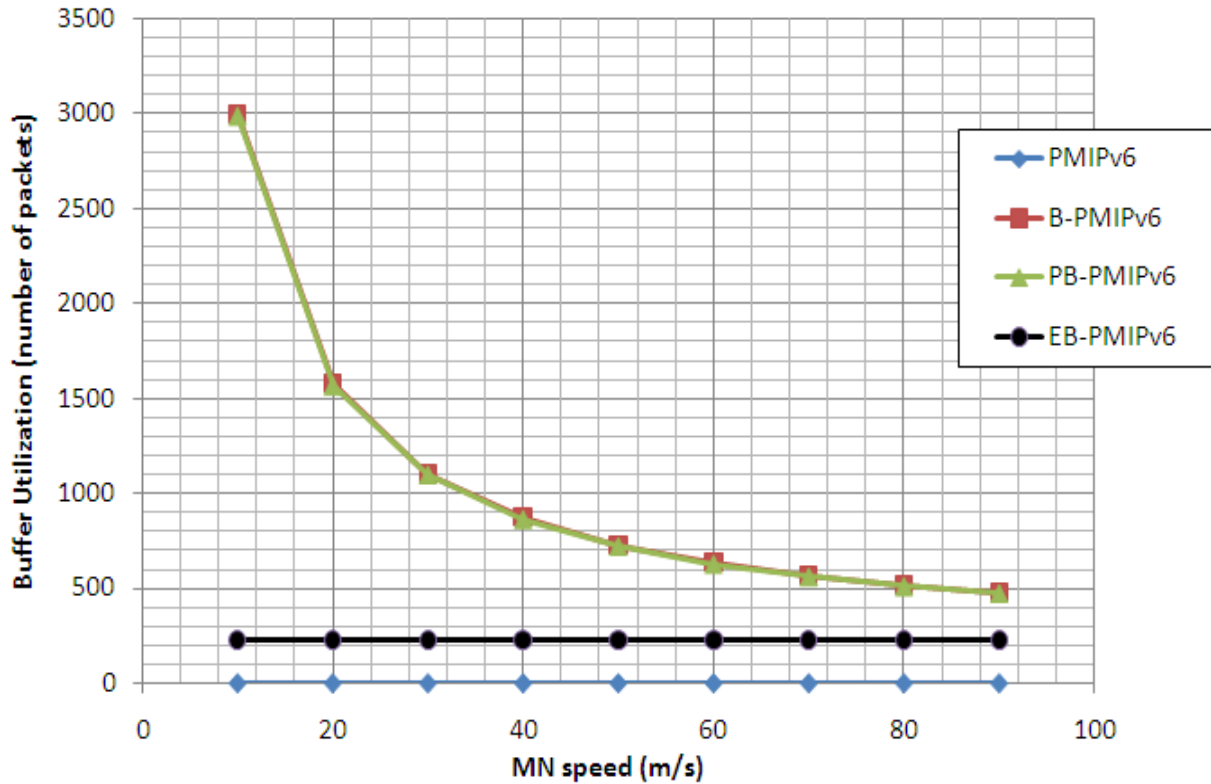


Figure 5.5 Buffer Utilization at different MN speeds

Starting with PMIPv6; this mobility management scheme does not utilize the buffer on NMAG since packets are only redirected to NMAG after a successful handover as a reactive approach is used. The proposed solution; EB-PMIPv6 utilizes much less buffer space than B-PMIPv6 and PB-PMIPv6. This is because for EB-PMIPv6, the bicasting process is always timed to be close to the link down event on PMAG which consequently shortens the time taken buffering packets on NMAG. And, this lowers the chances of buffer overflows if a large number of mobile nodes simultaneously perform a handover requiring packet buffering to lower packet loss when the MN cannot receive packets from PMAG or NMAG.

On the other hand B-PMIPv6 and PB-PMIPv6 route packets to NMAG when the handover is imminent. This implies that if the MN is traversing from PMAG's area of coverage to NMAG's area of coverage at a low speed, the MN will take a longer time from the time buffering started (when the handover is imminent on PMAG) till the time the MN attaches to NMAG for buffered packets to be released. Hence why the amount of buffer space required increases as the speed of the mobile node when traversing from PMAG's subnet to NMAG's

subnet decreases. Moreover, NMAG's buffer space requirement decreases as the MN speed increases for B-PMIPv6 and PB-PMIPv6. Therefore, the lower the mobile node speed, the longer the time it will take the MN to attach to NMAG; which is the element that buffers the packets and hence the more the buffer space is required to alleviate packet loss.

The high buffer utilization required by B-PMIPv6 and PB-PMIPv6 can also lead to an increase to end to end delay of packets as the queuing delay increases as the buffer length increases. This could be undesirable for many real-time applications whereby playback deadlines for packets could end up being missed thereby leading to packets being dropped.

It can also be observed from Figure 5.5 that for EB-PMIPv6 the number of packets buffered is almost constant regardless of the speed of the mobile node. This is because the duration in which packets need to be buffered is constant. This is the time in which the MN performs the layer-2 handover (channel scanning, re-association and authentication). This also shows that through using optimized layer-2 handover mechanisms, the buffer utilization can further be reduced thereby conserving the buffer space which is a limited resource. On the other hand, B-PMIPv6 and PB-PMIPv6 utilize more buffer space, whereas PB-PMIPv6 utilizes slightly less buffer space.

5.4.2 Backhaul Bandwidth Utilization

Bicasting solutions for PMIPv6 employ a technique of duplicating packets of the packet flow destined to the MN at the LMA and the packets are routed to both PMAG and NMAG. Hence the utilization of the backhaul bandwidth resource is elevated during the bicasting period. Therefore, this study finds it essential to assess the backhaul bandwidth utilization in the mobility schemes under evaluation.

Figure 5.6 shows the backhaul bandwidth utilization in each of the mobility management solutions when an MN traverses from PMAG's subnet to NMAG's subnet at a velocity of 30m/s. The backhaul link usage statistics have been collected from the full-duplex link between the LMA and the Router (RT) on Figure 4.9 (Simulation network model setup) which is the path that the duplicated packets traverse from the LMA to the MAGs (NMAG and PMAG). The traffic source which is the corresponding node (CN) sends a 1000 bytes CBR packet every 0.001 seconds to the MN which is an 8Mbps traffic stream. It should however be noted that since all

the schemes evaluated are based on PMIPv6 and that packets are encapsulated in an IP in IP tunnel from the LMA to the MAGs. Due to the packet encapsulation, the CBR packet size increases to 1040 bytes to accommodate the encapsulation header. Therefore, without bicasting the LMA sends an 8.32Mbps stream onto the backhaul link.

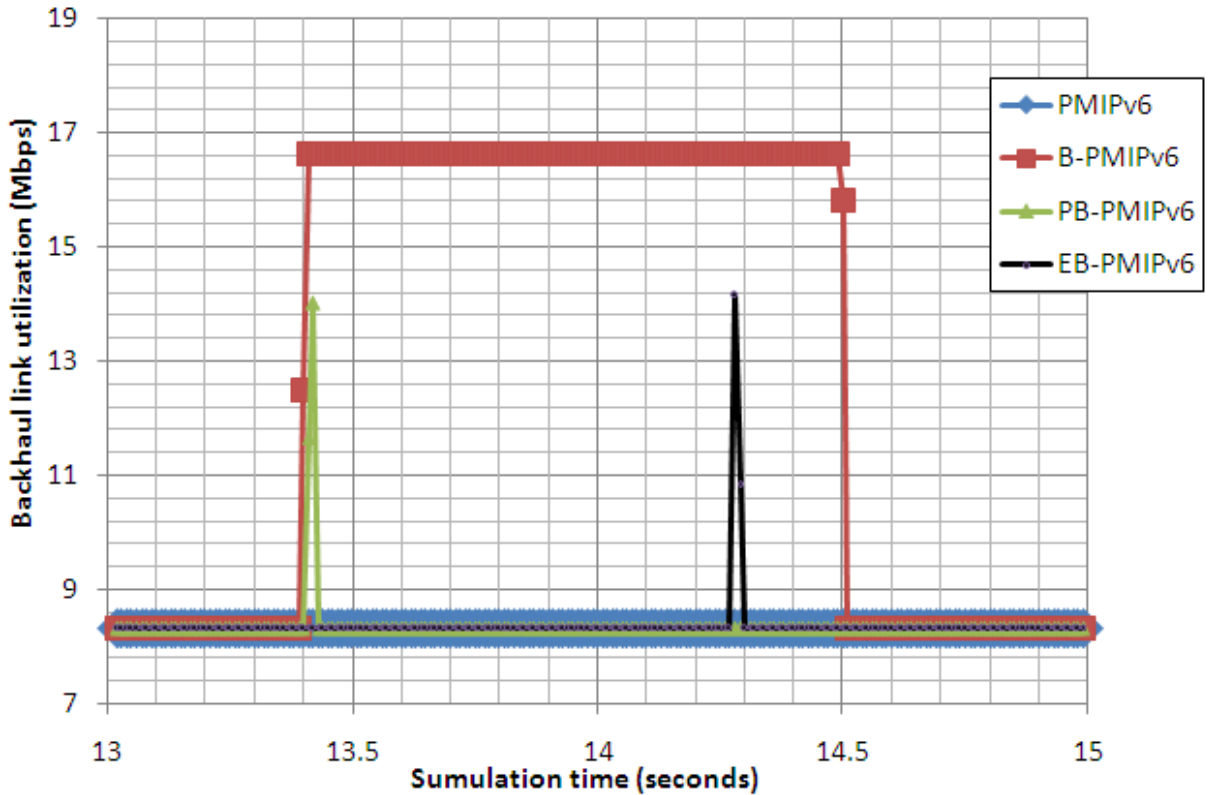


Figure 5.6 Backhaul bandwidth utilization

It can be observed that for PMIPv6, the utilization of backhaul link remains flat during the handover since there is no alteration of the packets in terms of size or duplication by the LMA. On the other hand, for B-PMIPv6, as soon as bicasting starts, the utilization increases to 16.64Mbps because twice the amount of bandwidth is used as packets are sent to both PMAG and NMAG. It is also observable that bicasting starts when a handover is imminent on PMAG and stops after the link is up on NMAG. It can be seen that if a significant number of MN simultaneously perform a handover while consuming high-bandwidth services, there may be congestion or the backhaul link may not be able to offer the required bandwidth.

Figure 5.6 also shows that since PB-PMIPv6 and EB-PMIPv6 bicast/route packets to PMAG and NMAG for a short duration; then the bandwidth increase required from the backhaul

link to support a MN handing over occurs for a much shorter duration. It can further be realized that EB-PMIPv6 not only bicasts for a short time but also schedules the bicasting process very close to the PMAG’s link down event, whereas PB-PMIPv6 bicasts for a short time when the handover is imminent and then stops routing packets to PMAG.

For the sake of completeness, the backhaul link bandwidth utilization pattern for different MN speeds when moving from PMAG to NMAG is also presented. In order to clarify the bandwidth utilization plots, Table 5.3 shows the events and their corresponding times of occurrence at different MN speeds for B-PMIPv6, PB-PMIPv6 and EB-PMIPv6. This table also proves to show that as was mentioned before, that at low MN speeds when traversing from PMAG to NMAG, the time period between the LINK_GOING_DOWN on PMAG to the LINK_UP on NMAG is longer whilst it is shortens as the MN speed increases.

Table 5.3 Events and corresponding times of occurrence at different MN speeds

MN speed / Event	LINK_GOING_DOWN on PMAG	LINK-DOWN on PMAG	LINK_UP on NMAG
10 m/s	38.178 seconds	41.007 seconds	41.168 seconds
30 m/s	13.394 seconds	14.334 seconds	14.496 seconds
50 m/s	8.437 seconds	9.001 seconds	9.162 seconds
70 m/s	6.312 seconds	6.714 seconds	6.876 seconds

The plots presented in Figure 5.7 show the backhaul link bandwidth usage requirements imposed by each of the mobility schemes under evaluation when an MN moves from PMAG’s subnet to NMAG’s subnet at MN speeds 10 m/s, 30 m/s, 50 m/s and 70 m/s. The plots are presented as a single figure to avoid the exhaustion of the limited space.

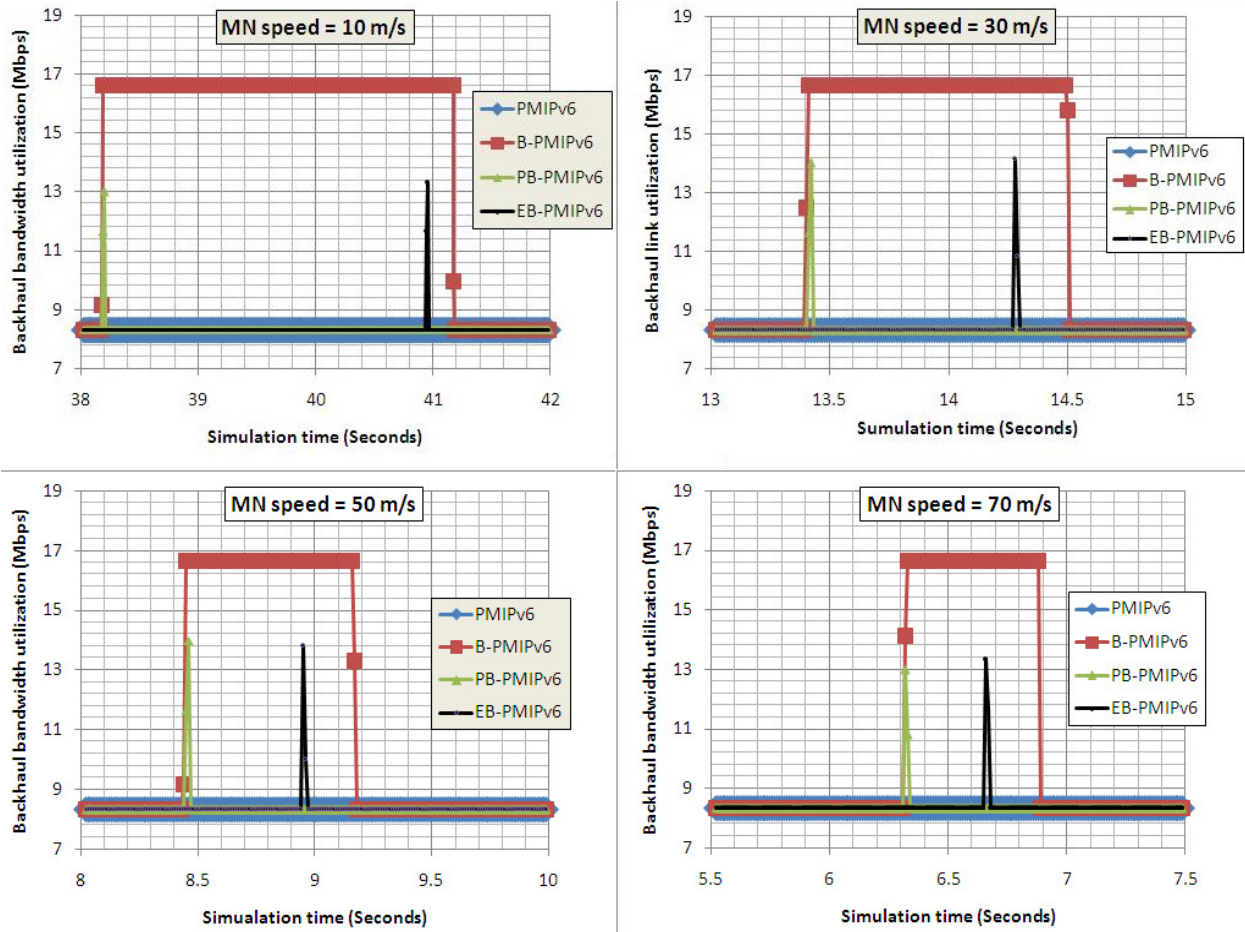


Figure 5.7 Backhaul bandwidth utilization for different MN speeds

From Figure 5.7 above it can be deduced that as the MN speed increases, B-PMIPv6's utilization of the backhaul bandwidth decreases. This is because the bicasting period shortens as a result of the time period between starting bicasting (when LINK_GOING_DOWN is triggered) and the stop bicasting (when the LINK_UP is triggered) lowering. However, for PB-PMIPv6 and the proposed EB-PMIPv6 the length of the bicasting duration (which results into an increase in backhaul bandwidth usage) is shorter than in B-PMIPv6 and is independent of the MN speed.

It can further be seen that for the proposed EB-PMIPv6, the bicasting operations are executed as close as possible to the LINK_DOWN event on PMAG regardless of the MN speed since the signal strength is used to determine the scheduling instances for the bicasting operations. This gives the proposed solution an advantage over B-PMIPv6 and PB-PMIPv6 because the amount of buffer space on NMAG is kept minimal regardless of the MN speed.

5.4.3 Packet duplicates

In this subsection, an assessment on the number of duplicate packets received by the MN is performed. As was mentioned earlier, reception of duplicate packets is undesirable. If UDP is the transport protocol used, then it is required that the upper layers of the MN protocol stack provide a mechanism to eliminate duplicate packets to avoid hiccups in the application being consumed. However if TCP is used, it will discard the duplicate packets with the aid of sequence numbers. Nonetheless, higher numbers of packet duplicates at the MN indicate an inefficient usage of the network infrastructure since the packet duplicates at the MN need to be discarded.

Figure 5.8 below shows the number of packets that are received twice (duplicate) by the MN when an MN performs a handover from PMAG to NMAG at velocities ranging from 10 m/s to 90 m/s. However, it should be noted that some of the packet duplicates destined to the MN that are routed to both the PMAG and NMAG are dropped by PMAG as will be discussed in the next section of dropped on NMAG. Some of the duplicated packets that are dropped on NMAG due to an overflow on the wireless interface queue (IFq) which is set to 50 by default.

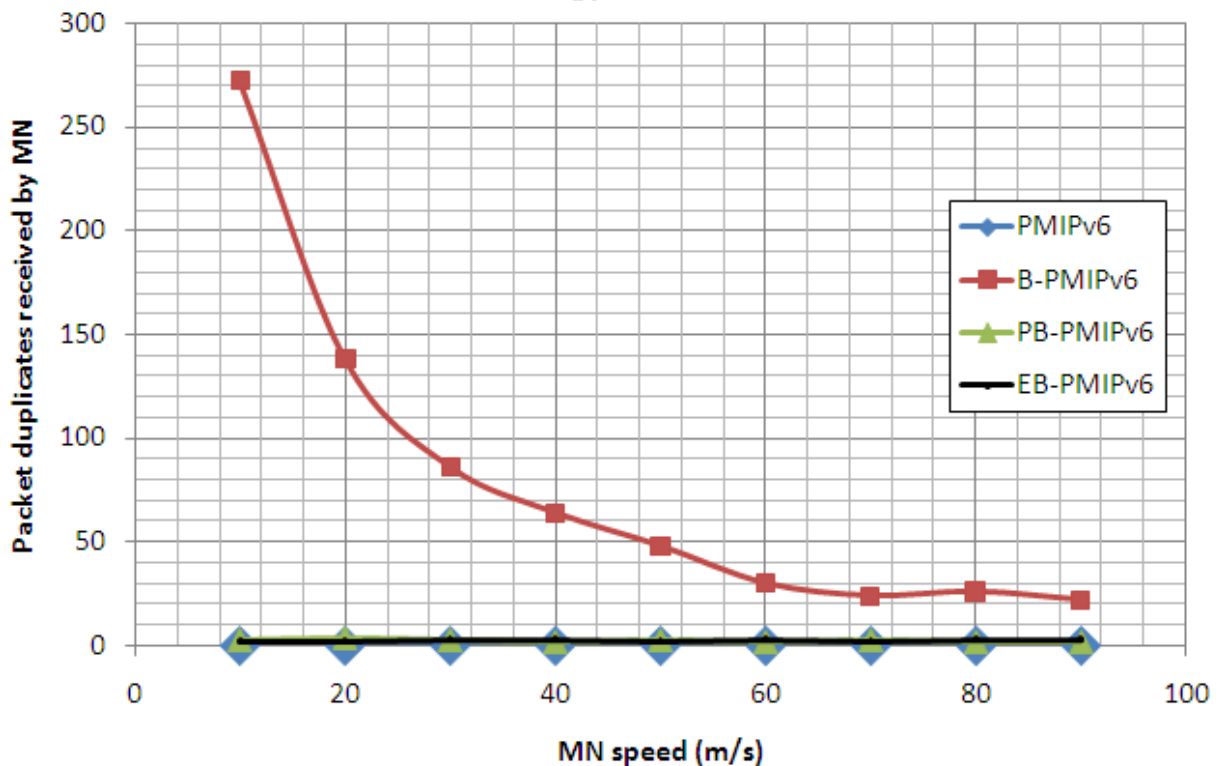


Figure 5.8 Packet duplicates received by MN

As depicted in Figure 5.8, with B-PMIPv6, the MN receives a substantial amount of packet duplicates. The packet duplicates received by the MN decrease as the speed on the MN when performing a handover from PMAG to NMAG increases. This is attributed to the fact that, as the MN speed increases, the bicasting period shortens thereby duplicates that are routed by the LMA to PMAG and NMAG decrease.

On the other hand, with PB-PMIPv6 and the proposed EB-PMIPv6 packet duplicates that reach the MN are very low (on average 3 packets). This is because the bicasting period for EB-PMIPv6 and PB-PMIPv6 is transient and hence the duplication of packets occurs for a very short period of time. Furthermore, it is observable that the number of packet duplicates that reach the MN are almost constant regardless of the MN speed. This is because as shown in Figure 5.7, the bicasting duration for PB-PMIPv6 and EB-PMIPv6 is not influenced by the MN's speed.

Lastly, for PMIPv6, the MN receives no packet duplicates since packets are not duplicated before, during or after the handover.

5.4.4 Packet loss due to misrouting

This subsection presents the results obtained in evaluating the mobility schemes for packets dropped on PMAG which results from routing packets to PMAG (misrouting) when the MN is no longer attached to PMAG or just before the MN moves out of PMAG's coverage area (loss of in-flight packets). Figure 5.9 shows the inefficient utilization of the network infrastructure since packets dropped by PMAG due to the above mentioned reason ultimately do not reach the MN and hence utilize the backhaul bandwidth as well as the network elements (PMAG, AP) unnecessarily.

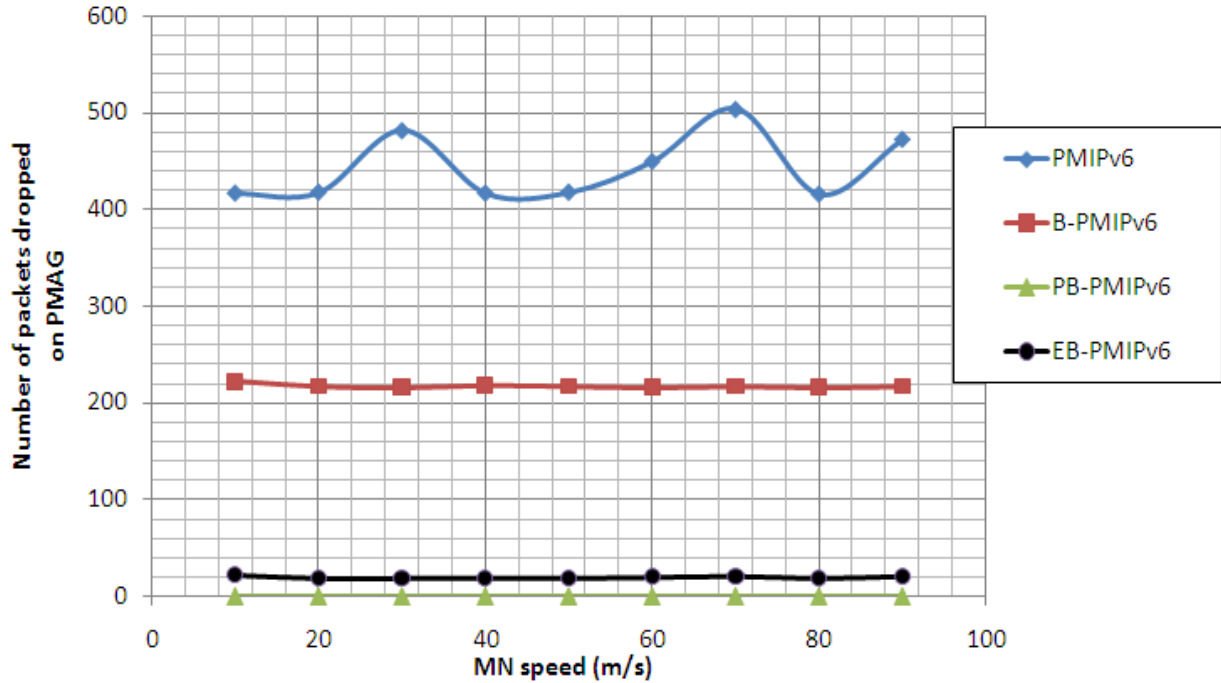


Figure 5.9 Packets dropped on PMAG

From Figure 5.9, it is observable that PMIPv6 incurs the highest packet drops on PMAG. This is primarily because PMIPv6 employs a reactive handover approach whereby the packet flow destined to the MN is still redirected to PMAG. In PMIPv6, during the handover, the LMA is not aware that the MN is no longer attached to PMAG and hence continues to redirect the packet flow destined to the MN to PMAG. Thus, during the handover, packets are continuously routed to PMAG even though they will not reach MN through PMAG. The routing update at the LMA that enables packet flow redirection to the new MAG (NMAG) is effected after the MN successfully attaches to NMAG.

B-PMIPv6 also incurs high packet drops on PMAG because bicasting, which sends packets to both PMAG and NMAG, only stops after the MN has attached to NMAG. Thus, packets are routed to PMAG unnecessarily and hence utilize the backhaul bandwidth and the network elements unnecessarily, which is inefficient. However, B-PMIPv6 incurs a lower packet drops compared to PMIPv6 because B-PMIPv6 handover delay is much shorter than that of PMIPv6.

The proposed solution, EB-PMIPv6, incurs a low packet loss on PMAG because the LMA attempts stop routing packets (stop bicasting) destined to the MN to PMAG as soon as the

signal strength drops below the receive threshold ($RXThresh_{-}$) since the packets will ultimately not reach the MN through PMAG. Thus, EB-PMIPv6 utilizes the backhaul bandwidth much more efficiently. PB-PMIPv6 attains no packet drops on PMAG since the scheme stops routing packets destined to the MN to PMAG way in advance, which aids PB-PMIPv6 to utilize the backhaul bandwidth efficiently. Nevertheless, this in turn affects the MN negatively since the MN stops receiving packets though PMAG even though the signal strength is still strong enough to deliver packets, thus creating a realizable glitch in the service being consumed by the MN.

It should however be noted that, for PMIPv6, the number of packets that do not reach the MN referred to as packet loss in Figure 5.4 is the same as the number of packets dropped on PMAG (depicted in Figure 5.9). This is because, PMIPv6 as-is does not employ bicasting and/or buffering at NMAG. Thus, packets that are routed to PMAG just after the MN disconnects from PMAG to attach to NMAG, are dropped and ultimately do not reach the MN.

However, for the bicasting schemes (B-PMIPv6, PB-PMIPv6 and EB-PMIPv6) some/all packets that are dropped on PMAG because the MN has just disconnected from PMAG are received through NMAG after handover completion. This is because during the handover period, packets are duplicated and routed to both PMAG and NMAG. This is a perfect demonstration of why bicasting increases the packet delivery ratio when viewed from the MN's perspective. Packets that would have otherwise not reached the MN because of in-flight packet loss on PMAG are routed to NMAG as well and are received by the MN as soon as the handover is complete.

5.4.5 MN Numbers Impact on Network Resources Utilization

This subsection evaluates the impact that the number of MNs performing a handover simultaneously imposes on the amount of network resources required to support seamless handovers. The simulation setup used for evaluation of the mobility schemes under evaluation is as depicted in a schematic in Figure 4.10 in Chapter 4.

Figure 5.10 below presents the amount of buffers space required on the NMAG buffer to hold the packets that are redirected to it in-advance by the LMA before the MNs can attach. The MNs move in a linear motion at the velocity of 30 m/s from PMAG's subnet to NMAG's subnet. The CN sends 1000 bytes CBR packets every 0.001 Seconds to each of the MNs.

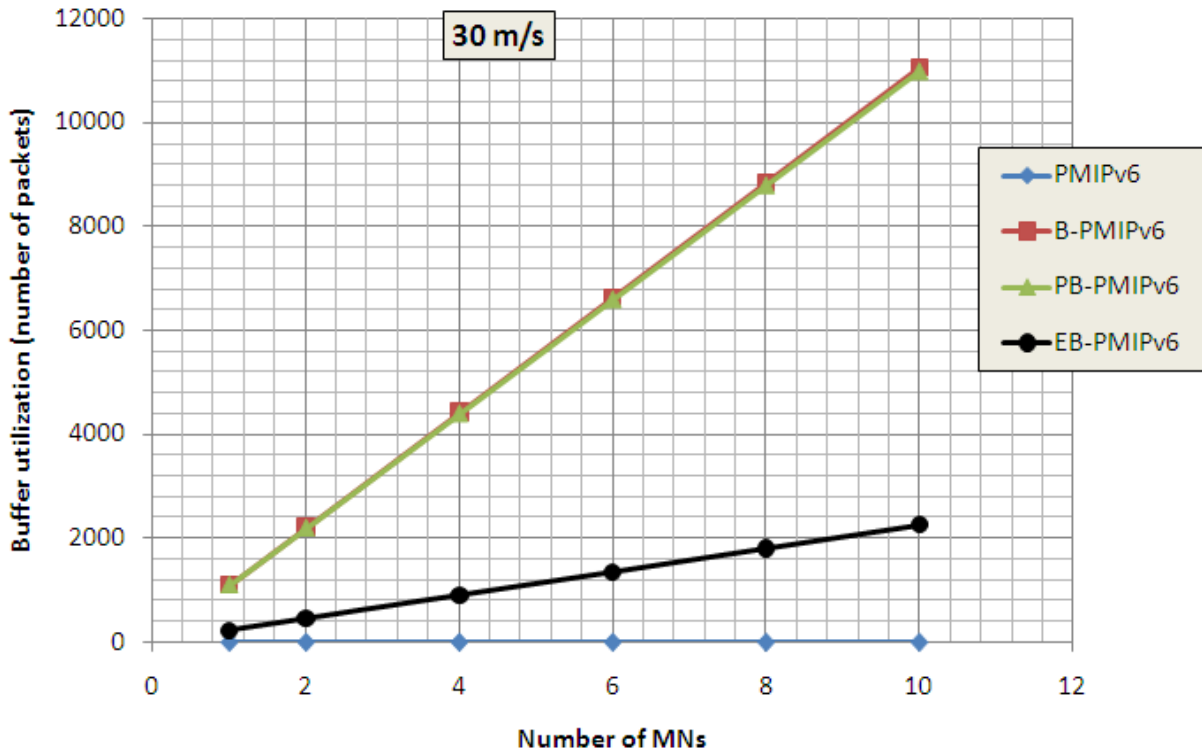


Figure 5.10 Buffer utilization as number of MNs increase

It is observable that the amount of buffer space that is required to alleviate packet loss when mobile nodes perform handover from PMAG's subnet to NMAG's subnet for B-PMIPv6 and PB-PMIPv6 is substantial. As a result, it would be challenging for B-PMIPv6 and PB-PMIPv6 to be scalable with the increase in the number of MNs as a significant amount of buffer space is required to offer MNs a soft handover. PB-PMIPv6 requires slightly less buffer space than B-PMIPv6 which becomes more apparent as the number of MNs increases.

On the other hand, the proposed EB-PMIPv6 solution requires buffer space that is less than the buffer space required by B-PMIPv6 and PB-PMIPv6. This is because of the reasons explained earlier that EB-PMIPv6 starts sending packets to NMAG for buffering as close as possible to the LINK_DOWN event on PMAG. The aim is to shorten the time spent buffering packets and thereby requiring less buffer space. Lastly, as was mentioned before, PMIPv6 does not employ a buffer to hold packets destined to the MNs during the handover. Thus, the buffer utilization remains at zero.

This subsection further assesses the impact that increases in the number of MNs that perform a handover simultaneously have on the backhaul link bandwidth utilization using the

simulation setup depicted in Figure 4.10.

Figure 5.11 shows the backhaul link utilization when 2 MNs traverse from PMAG's subnet to NMAG's subnet at a velocity of 30 m/s while receiving a CBR packet stream from the CN. In the same way, the CN sends 1000 bytes packets to each MN every 0.001 Seconds. Thus, the aggregate traffic stream sent to the MNs is 16Mbps. However, after IP in IP encapsulation at the LMA which increases the packet size to 1040 bytes, the aggregate packet flow consumes 16.64 Mbps of bandwidth. In B-PMIPv6, during the bicasting period, the bandwidth utilization increases to 33.28 Mbps until the MN attaches to NMAG. On the other hand, PB-PMIPv6 and EB-PMIPv6 increase to 33.28 Mbps during the bicasting period even though it is not apparent in Figure 5.11. The bandwidth measurement frequency is performed every 0.01 seconds to lower the number of points to be plotted on the graph. Hence, the indication that the bandwidth utilization increases to 33.28 Mbps for PB-PMIPv6 and EB-PMIPv6 is not reflected on the plot.

Therefore, it can be observed that the backhaul bandwidth utilization increases as the number of MN's increase. However, PB-PMIPv6 and the proposed EB-PMIPv6 offer much better efficiency in utilization of the backhaul bandwidth compared to B-PMIPv6. PB-PMIPv6 and EB-PMIPv6 schemes duplicate and bicast packets to PMAG and NMAG for a short period hence requiring an increased amount of bandwidth for a short duration.

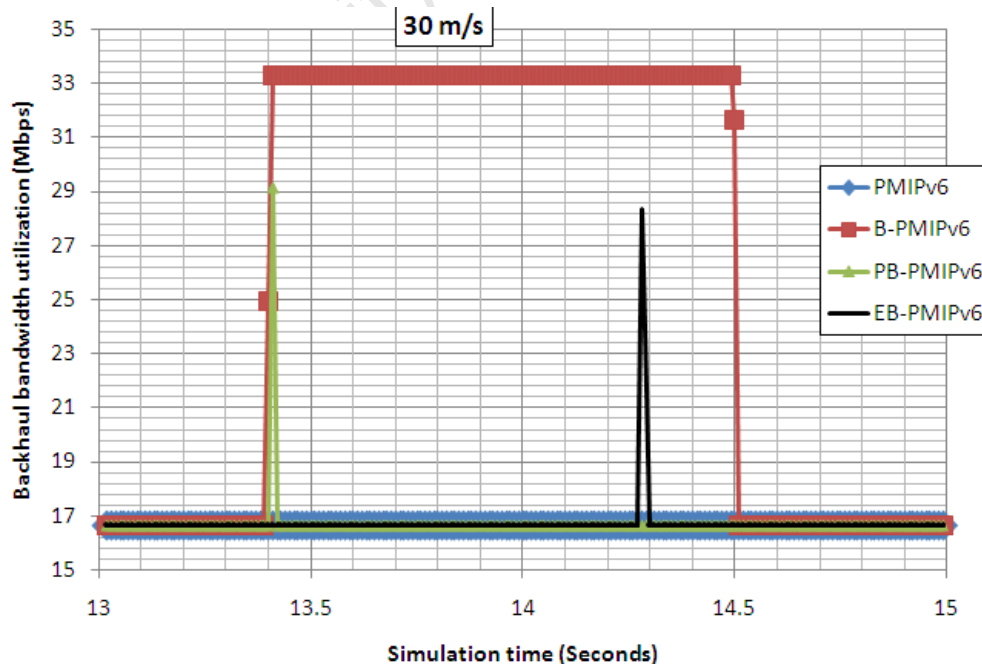


Figure 5.11 Backhaul bandwidth utilization for 2 MNs

5.5 Signaling Overhead

Lastly, this subsection presents an evaluation of the signaling overhead incurred in the mobility management schemes under evaluation. The number of MNs is varied from 1 to 10 to identify the trend in which the handover signaling overhead behaves as MNs simultaneously performing a handover increases. Signaling overhead is an important performance metric to evaluate since signaling messages consume the scarce bandwidth in wireless networks. Secondly, an increased signaling overhead impacts the handover performance (handover delay and packet loss). This is because as the signaling messages that reach the MAG and LMA increase significantly, the PMIPv6 network elements may be saturated and overwhelmed by a high number of signaling messages that need to be served simultaneously. Therefore, an increase in processing delay may be apparent. Figure 5.12 below shows the signaling overhead in bytes that occurs as MNs simultaneously perform handovers moving from PMAG to NMAG.

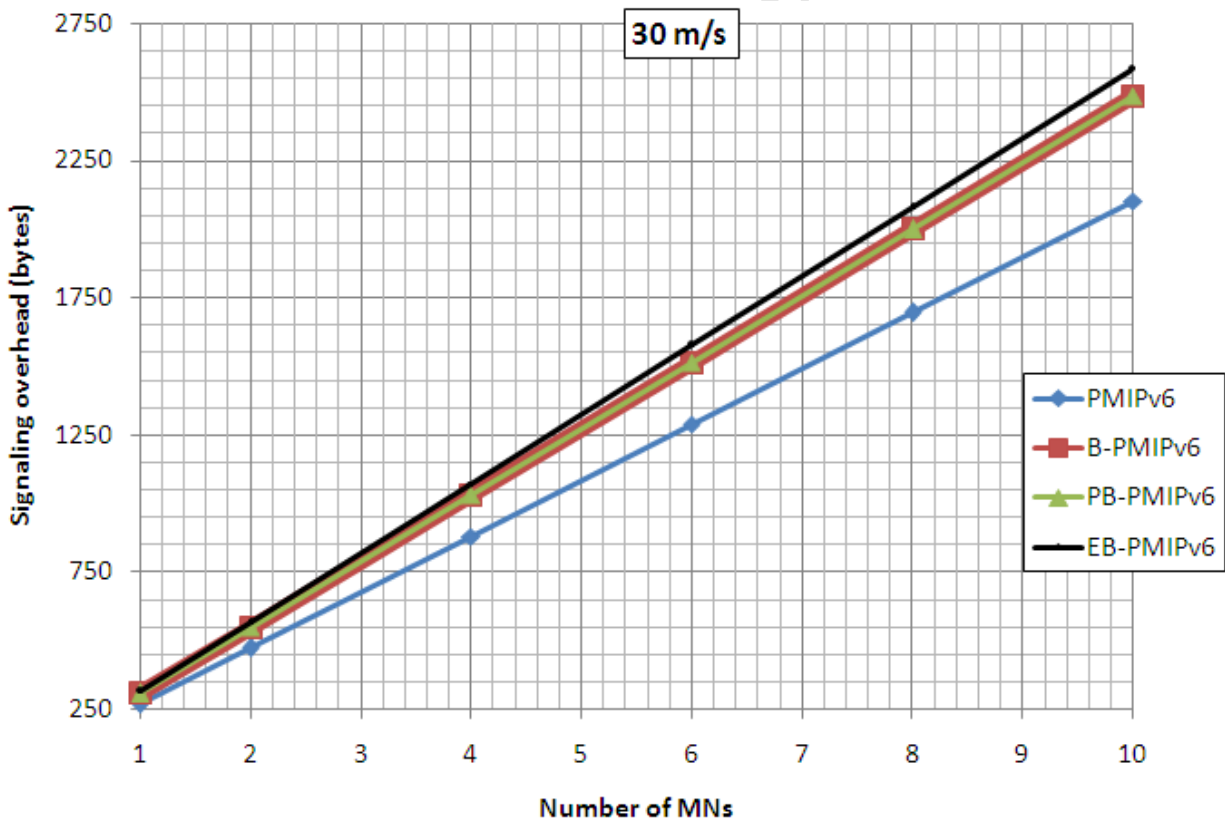


Figure 5.12 Signaling overhead as MNs increase

Firstly, it can be seen that for all mobility schemes under evaluation, the signaling

overhead increase as the MNs increase. It can be observed in the above figure that, PMIPv6 incurs the least signaling overhead among the schemes under evaluation.

On the other hand, B-PMIPv6 and PB-PMIPv6 incur higher signaling overhead than that of PMIPv6. This is attributed to the increase in signaling messages that are required for anticipation of the handover in order to perform proactive handovers. These are the handover initiate and acknowledgement (HI, HAck)) messages. As for the bicasting, the PMIPv6 signaling messages (Proxy binding update (PBU) and Deregistration PBU (Dereg-PBU) are piggybacked to achieve the indication to the LMA to start and stop bicasting. It should however be noted that the signaling overhead incurred by B-PMIPv6 is similar to that of PB-PMIPv6. This is because; the only difference in the handover signaling is the order in which the signaling messages are sent.

Lastly, it can be observed that the proposed EB-PMIPv6 incurs slightly more signaling overhead than B-PMIPv6 and PB-PMIPv6. One of the essential EB-PMIPv6 objectives is to have control and coordination on the bicasting operations to achieve timely and accurate execution. In a similar way to B-PMIPv6 and PB-PMIPv6, to stop bicasting the PMIPv6 signaling Dereg-PBU is piggybacked to signal to the LMA to stop bicasting packets destined to MN. However, additional signaling overhead is incurred to accommodate the start bicasting message sent to the LMA to begin duplication and bicasting of packets destined to MN. Hence, the signaling overhead is slightly increased compared to that of B-PMIPv6 and PB-PMIPv6 as shown in Figure 5.12.

5.6 Summary

This chapter has provided discussion and analyses of the results obtained in evaluating the mobility schemes (PMIPv6, B-PMIPv6, PB-PMIPv6 and EB-PMIPv6). This has been performed through the use of the implementation and simulation setups on the NS-2 evaluation framework as discussed in Chapter 4. Firstly, the mobility management schemes are evaluated with regards to handover performance which is constituted by the handover delay and packet loss. Secondly, the mobility schemes are evaluated in terms of network resources utilization required during the handover to provide seamless handovers in order to maintain an acceptable QoS for the mobile user.

Firstly, the handover performance results show that indeed the proposed EB-PMIPv6 improves the handover performance of a PMIPv6 handover by lowering the packet loss as well as handover delay. The proposed solution surpasses the PB-PMIPv6 in terms of handover delay whilst it is on par with B-PMIPv6. B-PMIPv6 performs better than PB-PMIPv6 and the proposed EB-PMIPv6 in terms of packet loss as viewed by the MN. However, B-PMIPv6 utilizes a substantial amount of the scarce and shared network resources (buffer space and backhaul bandwidth) which consequently makes it more challenging to scale with the mobile node proliferation in the wireless networks.

Secondly, results presented in this chapter concerning the network resources utilization show that indeed the proposed solution surpasses the B-PMIPv6 and PB-PMIPv6 bicasting solution in terms of efficiency on network resources utilization. The proposed EB-PMIPv6 scheme requires a low amount of buffer space as well as backhaul bandwidth to offer a mobile user a seamless handover. On the other hand, PB-PMIPv6 and B-PMIPv6 require a much higher amount of buffer space during a handover to alleviate packet losses. B-PMIPv6 also requires a significant amount of backhaul bandwidth during a handover, whilst PB-PMIPv6 requires a similar and comparable amount of backhaul bandwidth to that of the proposed EB-PMIPv6.

Lastly, the signaling overhead results obtained indicate that the proposed EB-PMIPv6 incurs a slightly higher signaling overhead to accommodate the bicasting coordination signaling mechanism incorporated into EB-PMIPv6. On the other hand, B-PMIPv6 and PB-PMIPv6 incur comparable signaling overhead that is however higher than that of the PMIPv6. This is because the bicasting schemes incorporate extra signaling to facilitate the anticipation of handover events.

Chapter 6 Conclusions and Recommendations for Future Work

6.1 Concluding Remarks

This thesis has investigated issues in the bicasting solutions for PMIPv6. The major challenge that bicasting solutions for PMIPv6 have been criticized for is that of utilizing a significant amount of network resources to support a seamless handover. This therefore puts a strain on the already scarce and shared network resources. Consequently, the issue of scalability becomes apparent since the number of mobile data traffic as well as mobile nodes keeps increasing; hence it becomes difficult for schemes that require a substantial amount of network resources to support a large number of MNs to attain seamless handovers.

With the challenges identified, this study has led to the development of an enhanced bicasting scheme for PMIPv6 (EB-PMIPv6). The main objective of the EB-PMIPv6 is to improve the handover performance of PMIPv6 whilst also paying attention to the efficiency in utilization of the scarce and shared network resources (backhaul bandwidth and network elements buffer space). To attain the objectives, the proposed solution employs timely and accurate link-layer triggers that are generated based on the received signal strength (RSS). The link layer triggers provide a coordinated functionality to facilitate timely execution of handover operations such that the objectives are attained.

Firstly, the link-layer triggers are utilized for handover anticipation in order to facilitate a proactive handover. In this approach, some handover operations are performed in advance and thereby their latencies are eliminated from the total handover delay, thus lowering the handover delay. The proposed solution uses a technique of packet buffering at the next point of attachment for the in-advance packet flow that is redirected to the next MAG such that when the MN attaches, the packets are readily available. Secondly, the link-layer triggers are used to provide a coordinated service for timely and accurate bicasting operations execution. In the proposed solution, the bicasting operation is scheduled very close to the LINK_DOWN event on PMAG regardless of the MN speed so that the amount of buffer space required on the NMAG is kept minimal. Furthermore, the bicasting period is transient to ensure that the amount of backhaul bandwidth required is kept minimal.

The proposed EB-PMIPv6 is evaluated against the PMIPv6, B-PMIPv6 and PB-PMIPv6 with regards to some of the relevant mobility management performance metrics. These are (1) packet loss, (2) handover delay, (3) throughput and (4) signaling overhead. However, since this study has been undertaken to address the network resources utilization imposed by bicasting schemes, evaluation of the proposed scheme has also been performed with regards to buffer utilization, and backhaul link bandwidth utilization.

Apart from the advantages inherited from the PMIPv6, the results obtained show that the proposed EB-PMIPv6 has the following advantages:

- EB-PMIPv6 improves handover performance by lowering the handover delay and packet loss incurred during a handover. With a lower packet loss and handover delay, the packets throughput as well as the packet delivery ration at the MN is enhanced thus improving the QoS for the mobile user. (Customer-centric advantage)
- The proposed solution utilizes resources much more efficiently than the bicasting schemes for PMIPv6 that have been studied in this research. The solution requires a low amount of buffer space and backhaul bandwidth to improve the handover performance. EB-PMIPv6 also ensures that the network resources are used efficiently by ensuring that a low number of packet duplicates is received by the MN. Secondly, packet misrouting is kept minimal by ensuring that packets are not sent to a point of attachment that the MN is no longer associated with. (Network-operator centric advantages)
- The proposed EB-PMIPv6 can be able to scale with the ongoing and future mobile nodes proliferation in the wireless networks. This is because the results depict that a lower amount of network resources required to support MNs performing handovers simultaneously is lower than required by the bicasting schemes (B-PMIPv6 and PB-PMIPv6) evaluated in this study. (Network-provider centric advantage)

All in all, the findings of this research show that the proposed EB-PMIPv6 scheme indeed improves the PMIPv6 handover performance whilst also efficiently utilizing the scarce and limited network resources. Therefore, the solution possesses customer-oriented as well as

network-operator based advantages. This however comes at a cost of a slightly increased signaling overhead.

6.2 Recommendations for Future Work

During the course of this research, a number of interesting ideas came up but could not be included in this research due to time limitation and the scope of this research. The issues listed below can then be considered for further work on this study:

- The first recommendation concerns the improvement of the robustness of the prediction algorithm employed to model the behavior of the future received signal strength (RSS) in order to accurately execute handover operations. This could be performed by employing techniques such as FFT-based and adaptive filters. With this, the non-deterministic behavior of the RSS would be more accurately predicted, thus enhancing the practicality of the proposed solution in the real world.
- In addition, the proposed solution may be implemented on a test-bed. Simulations offer a cost-effective and quick way for verification of system models. However, they are limited in encapsulating the entire exact behavior that would manifest in a real, physical network. Therefore, issues such as the processing delay on a physical network element may differ from the ones depicted in the simulation environment.
- Furthermore, future studies can consider incorporating other factors that impact the QoS in the trigger generation decision making to improve the effectiveness of the proposed scheme. These factors include, the data rate, packet error threshold, number of retransmissions, number of duplicate frames, etc.

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Appendix A:

Accompanying CD-ROM

- **Thesis soft copy**
 - An electronic copy of the thesis can be obtained in the Thesis directory
- **Publications**
 - Papers written while performing this study are placed in the Publications directory
- **Software**
 - All software (source code and binaries) used for the implementation of the evaluation framework is located in the Software directory. The files used are listed below:
 - **For PMIPv6 modifications (e.g. Bicasting support)**
 - ~/Software/ns-allinone-2.29/ns-2.29/pmip6/pmip.{h, cc}
 - **For signal strength monitoring, prediction and triggering implementation:**
 - ~/Software/ns-allinone-2.29/ns-2.29/mac/wireless-phy.{h, cc}
 - **For link-layer triggers, debugging and simulation run-time tracing**
 - ~/Software/ns-allinone-2.29/ns-2.29/mac/mac.{h, cc}
 - ~/Software/ns-allinone-2.29/ns-2.29/mac/mac-802_11.{h, cc}
 - ~/Software/ns-allinone-2.29/ns-2.29/mac/ll.{h, cc}
 - **For packet buffering at next mobile access gateway (NMAG)**
 - ~/Software/ns-allinone-2.29/ns-2.29/queue/mybuffer.{h, cc}
- **Simulation scripts**
 - TCL scripts that are used for simulation setups for different mobility management schemes are located in the Simulation_scripts directory. Under the simulations

directory, scripts are placed into their respective folders as shown below.

- PMIPv6 scripts: ~/Simulation_scripts/pmipv6
- B-PMIPv6 scripts: ~/Simulation_scripts/bpmipv6
- PB-PMIPv6 scripts: ~/Simulation_scripts/pbpmipv6
- EB-PMIPv6 scripts: ~/Simulation_scripts/ebpmipv6

- **Results**

- The results discussed in the thesis are located in the Results folder. The MS Excel files include the Visual Basic for Applications (VBA) scripts used for manipulation of data extracted from the trace files.

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