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A Network-based Coordination Design for Seamless Handover between Heterogeneous Wireless Networks

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This thesis is submitted in partial fulfillment of the academic requirements

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Doctor of Philosophy in Electrical Engineering

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University of Cape Town

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

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Abstract

The rapid growth of mobile and wireless communication over the last few years has spawned many different wireless networks. These heterogeneous wireless networks are envisioned to interwork over an IP-based infrastructure to realize ubiquitous network service provisioning for mobile users. Moreover, the availability of multiple-interface mobile nodes (MNs) will make it possible to communicate through any of these wireless access networks. This wireless network heterogeneity combined with the availability of multiple-interface MNs creates an environment where handovers between the different wireless access technologies become topical during mobility events. Therefore, operators with multiple interworking heterogeneous wireless networks will need to facilitate seamless vertical handovers among their multiple systems. Seamless vertical handovers ensure ubiquitous continuity to active connections hence satisfy the quality of experience of the mobile users.

IP mobility management schemes, particularly Mobile IPv6 (MIPv6) based protocols are the de facto mobility solutions for supporting handovers between the heterogeneous wireless networks, which are envisaged to consist mainly of IPv6 nodes. However, these solutions have unsatisfactory vertical handover performance. They fail to ensure ubiquitous continuity to ongoing real-time communications due to their long handover delay, packet loss, and heavy signaling overhead. Moreover, standard IP mobility management protocols do not provide seamless handovers on their own.

This thesis, therefore, proposes an effective and efficient network-based handover coordination mechanism to support seamless vertical handovers between heterogeneous wireless networks. We analyze the handover performance of the common MIPv6-based IP mobility management extensions in terms of handover delay and signaling overhead. From the analysis, we determine that Proxy Mobile IPv6 (PMIPv6), a network-based MIPv6 extension, generally provides a better handover performance model than the other MIPv6 extensions, i.e., Hierarchical MIPv6 (HMIPv6) and Mobile IPv6 Fast Handovers (FMIPv6). We, therefore, employ PMIPv6 as the basis for seamless handover mechanisms that further improve the handover performance. An example is enhancing the performance of PMIPv6 with IEEE 802.21

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Publications

Peer-Reviewed Journals

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3. Linoh A. Magagula, H. Anthony Chan, and Olabisi E. Falowo, "Achieving Seamless Mobility through Handover Coordination in Network-based Localized Mobility Managed Heterogeneous Environment," to appear in *IEEE Personal, Indoor and Mobile Radio Conference (PIMRC 2010)*, 26-29 September, Istanbul, Turkey, 2010.

4. Linoh A. Magagula, H. Anthony Chan, Olabisi E. Falowo, "Handover Coordinator for Improved Handover Performance in PMIPv6-supported Heterogeneous Wireless Networks," *IEEE Wireless Communications & Networking Conference (WCNC 2010)*, 18-21 April, Sydney, Australia, 2010.
5. Linoh A. Magagula, Olabisi E. Falowo, and H. Anthony Chan, "PMIPv6 and MIH-enhanced PMIPv6 for Mobility Management in Heterogeneous Wireless Networks," *IEEE AFRICON'09*, Nairobi, Kenya, September 2009.
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7. Linoh A. Magagula and H. Anthony Chan, "Early Discovery and Pre-authentication in Proxy MIPv6 for Reducing Handover Delay," *IEEE Broadband Communications, Information Technology and Biomedical Applications (BroadCom'08)*, Pretoria, South Africa, 23-26 November, 2008.
8. Linoh A. Magagula and H. Anthony Chan, "IEEE 802.21-assisted Cross-Layer Design and PMIPv6 Mobility Management Framework for Next Generation Wireless Networks," *IEEE Wireless & Mobile Computing, Network & Communication (WiMob'08)*, Avignon, France, 12-14 October, 2008.

Glossary

AAA: Authentication (verifying an identity claimed by a network entity), Authorization (permission granted to a network entity to access a network resource, and Accounting (billing).

AP: Access point (AP) is a device that offers wireless connectivity to a mobile node and bridges between the wireless medium and the access router and distribution network.

AR: Access router (AR) is the default router for communication for a mobile node

BS: Base station (BS) is a device that offers wireless connectivity to a mobile node and interfaces the wireless medium and the access router and distribution network.

CoA: Care-of-address (CoA) is a temporary IP address allocated to a mobile node while it is attached to a visited network.

CN: Correspondent node (CN) is the communication peer for a mobile node

Handover: The process by which an ongoing communication is transferred from an AR or AP or BS to another when a mobile node engaging in that communication is in motion.

Handover procedures: the processes or procedures that enable a mobile node to successfully handover between points of attachments.

Heterogeneous wireless network environment: an environment or domain that comprises fully or partially overlapping sub-networks, which are based on different wireless technologies.

LMA: acronym for Local Mobility Anchor

MAG: acronym for Mobile Access Gateway

MN: Mobile node (MN) is a network node that is able to communication while moving between different PoAs.

Mobility Management Protocol: A protocol that enables nodes to move around different PoAs

in IP networks while maintaining their ongoing communications.

Multiple-interface MN: A mobile node that has the capability to connect to two or more networks that are based on different radio access technologies.

NGWN: Next generation wireless networks (NGWN) are an integration of heterogeneous wireless networks over a common IP-based infrastructure that enables them to interwork and interoperate.

PoA: Point of Attachment (PoA) is the endpoint of a layer 2 link that includes the MN as the other endpoint. An AP and BS are examples of PoA.

RTT: acronym for round-trip-time

Seamless handover: Handover that ensures non-perceptible disruptions to ongoing real-time communication during mobility.

TCP: acronym for Transmission Control Protocol, which is a transmission model that employs hand-shaking dialogues which ensure reliable and ordered delivery of data streams to the destination.

UDP: acronym for User Datagram Protocol, which is a transmission model without implicit hand-shaking dialogues for guaranteeing reliability.

WLAN: acronym for Wireless Local Area Network

WMAN: acronym for Wireless Metropolitan Area Network

WWAN: acronym for Wireless Wide Area Network

Chapter 1 Introduction

1.1 Overview of Heterogeneous Wireless Networks and Mobility Management

Traditionally, different wireless network systems in the form of wireless local area networks (WLANs), wireless metropolitan area networks (WMANs), and wireless wide area networks (WWANs) are often not compatible with each other. This incompatibility makes it difficult for mobile node (MN) users to experience uninterrupted ubiquitous continuity for ongoing real-time communications as they roam from one network system to another. In fact, the network and application layers of the MN experience severe disconnection when the MN moves between these heterogeneous wireless networks. However, wireless networking technologies have since experienced profound levels of advancement over the last few years, especially with the demand for ubiquitous network access becoming a primary concern in our lives. As these advances in wireless networks continue to increase the possibility of realizing mobile and ubiquitous communication environments, many new challenges are emerging in these heterogeneous wireless networks.

Many real-time multimedia applications, which are sensitive to delay, were originally served via 'fixed Internet Protocol (IP)' communication networks. IP telephony commonly known as Voice over IP (VoIP), video conferencing, real-time audio/video streaming, and high definition television (HD-TV) are few examples of delay-sensitive multimedia applications that are now also served via heterogeneous wireless networks. These wireless networks inherently enforce IP mobility when a MN changes locations which cause IP changes to active connections.

The ITU-T G.114 standard, for example, states that the maximum acceptable one-way delay or latency for good quality VoIP to fulfill real-time requirements is 100-150 milliseconds [1]. Generally, as defined in 3GPP TS22.105 specification, the end-to-end delay for multimedia applications must be less than 400 milliseconds. For purposes of IP mobility management, delays incurred as a result of the type of the audio or video encoding are very small and thus do not influence VoIP performance or any other real-time multimedia performance during handover [2].

Since the volume for User Datagram Protocol (UDP) real-time traffic (e.g. VoIP, video conferencing, etc.) will grow in the next generation wireless networks (NGWN), there is a motivation for enhancing IP mobility management solutions with better handover mechanisms to effectively support the delay-sensitive application services during mobility in these networks. These mechanisms must ensure, for example, that the experienced handover delay does not extensively impact on the end-to-end delay requirements of the real-time traffic hence causing perceptible disruptions to the ongoing communication.

NGWN are envisioned to consist of heterogeneous wireless access networks. These access network heterogeneities will be integrated over an IP-based infrastructure, as shown in the conceptual illustration in Figure 1-1. The integration over a common infrastructure will enable interworking and interoperation.

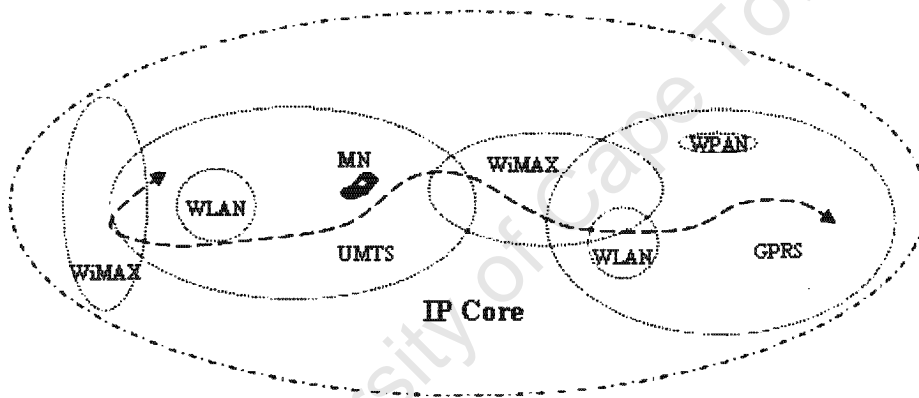


Figure 1-1 Conceptual illustration of NGWN environment.

Therefore, the Internet Protocol (IP) is widely recognized to become the common infrastructure (core) of the NGWN to support ubiquitous communications across the heterogeneous networks [3]. These integrated heterogeneous wireless networks are complementary in terms of their properties hence meet different needs and requirements of the network users. For example, WLANs such as IEEE 802.11b support higher data rates but have smaller coverage with limited mobility, whereas WWANs such as Universal Mobile Telecommunication System (UMTS) support relatively lower data rates but have wider coverage with high-speed mobility capability. The integration of these networks provides ubiquitous

access to network services for capable devices.

Because of the network heterogeneity, NGWN are expected to offer and support a plethora of services, including everything from basic voice telephony to data, video, multimedia applications, and other web-based and innovative mobile data services. These services will be accessible via the IP-core irrespective of the wireless access network a MN is connected to. Furthermore, the MN users will get the information they want, in any media, over any facilities, in any volume, anytime, anywhere, and particularly in consistent connectivity during mobility events.

Traditional individual wireless networks offer basic services related to the network access, transport, routing, switching, resources, session control, or various other value-added services. NGWN on the other hand, will provide a combination of these and other extra services such as content provision services, middleware services, application-specific services, interworking services, unified messaging, and management services among others [4].

However, integration of the different wireless networks generates many research challenges ranging from interworking issues, provisioning of acceptable quality of service (QoS), and mobility management issues between the heterogeneous networks. In particular, the integration of the heterogeneous access networks creates an environment where handovers between the networks become common. Thus, to ensure ubiquitous (“anywhere, anytime”) continuity to active connections, as expected in NGWN, handover facilities between these dissimilar access networks must be in place. These facilities must ensure that the handovers between the heterogeneous networks are seamless and without unpleasant perceptible disruptions to ongoing real-time communications; otherwise, the handovers will adversely affect the quality of the active network service as perceived by the MN users and thus defeat the goal for network access ubiquity in NGWN. Moreover, the main problem with the current IP mobility management protocols is that they do not ensure pleasant quality of communication as the MN traverses the NGWN. That is, they do not support seamless handovers to active connections. These protocols impose long handover delay, high packet loss, and significant signaling overhead during the handover. In fact, the handover delay is the primary cause of packet loss which causes disruption to ongoing communication [5]. Thus, there is a need for mobility management to be

handled in a manner that does not induce long handover delay, high packet loss, and significant signaling overhead. This need calls for the development of effective and efficient handover mechanisms that will enhance the handover performance of the standard IP mobility solutions. We characterize handover performance in terms of handover delay, packet loss, and signaling overhead.

Figure 1-2 below demonstrates a typical ongoing real-time communication disruption due to long handover delay and high packet loss.

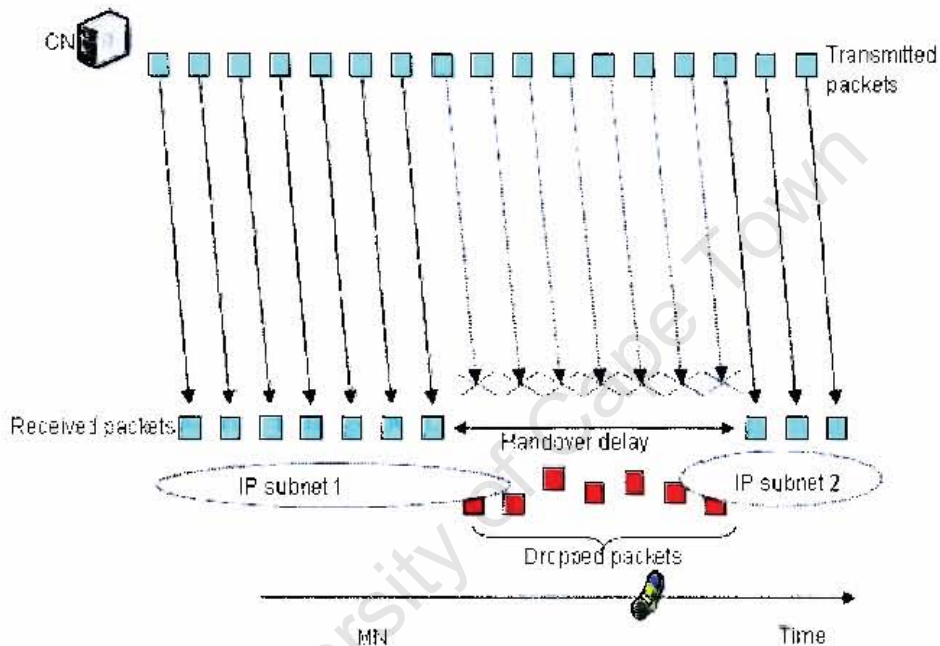


Figure 1-2 Demonstration of ongoing real-time traffic disruption during handover.

We can deduce from Figure 1-2 above that low or negligible handover delay results in fast transition between the subnets. In addition, low or negligible packet loss during the handover results in soft handover between the IP subnets hence non-perceptible disruption to ongoing real-time communication. Thus, it is essential to reduce the handover delay and packet loss due to the handover procedures. This will help in achieving seamless handover.

The objectives of this thesis, therefore, are to reduce handover delay and packet loss while ensuring minimal signaling overhead. This requires an effective and efficient handover

mechanism that will leverage a suitable IP mobility management protocol to enable seamless handovers, which will ensure non-perceptible disruption to ongoing real-time communication during mobility events between heterogeneous wireless networks. However, the notion of Quality of Service (QoS) on the transported real-time traffic in the context of the different characteristics or capacities of the involved heterogeneous wireless networks is generally out of scope of mobility management.

1.2 Mobility Management: Definitions and Taxonomies

The main role of mobility management protocols is to support MNs to remain connected or reachable during roaming within and between networks thus enabling the MNs to maintain ongoing communication with peers. Without mobility management, packets sent to a MN in the home network cannot be received if the MN leaves the home access link. Thus, mobility management is fundamental to supporting IP mobility by ensuring that active connections are maintained as the MN changes network locations. To ensure the connectivity and reachability state, mobility management is facilitated by two complementary operations; location management and handover management. Briefly, location management is concerned with tracking and locating the MN for possible connection by performing operations such as location update, addressing, and location discovery [6]. Handover management, on the other hand, is concerned with maintaining active connections during a MN's change of network points of attachment (PoA), which involves operations such as movement detection, authentication, routing, binding, and connection re-establishment.

Mobility management can be classified according to the mobility context in terms of coverage scale, hence there is global (macro) mobility management and localized (micro) mobility management. Macro-mobility management deals with movements of MNs between broader administrative, geographical, and topological domains while micro-mobility management supports movements within administratively and geographically contiguous set of subnets [7]. User mobility is normally higher in micro-mobility domains hence handovers are much more frequent and bound to cause service interruptions in these environments, especially when the MN user moves to another IP subnet [8]. Figure 1-3 illustrates the localized and global

mobility management scopes.

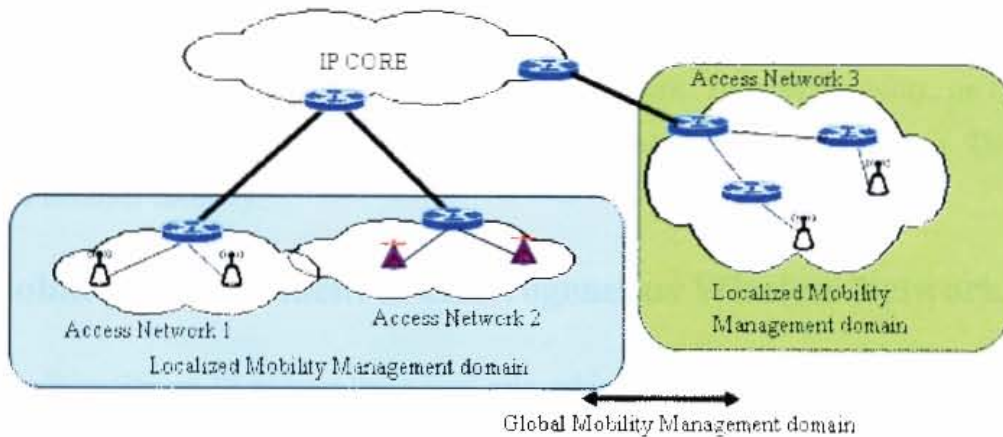


Figure 1-3 Illustration of localized and global mobility management domains.

Furthermore, mobility management can be classified according to the manner in which mobility-related signaling is handled; hence there is host-based and network-based mobility management. In host-based mobility management the MN is fully involved in mobility-related signaling, hence actively exchanges, i.e. initiates and/or terminates, the mobility signaling messages with the network. Yet, in network-based mobility management the MN is not involved. However, even though the MN is not involved in mobility-related signaling in the latter approach, it (MN) is still necessary in terms of assisting with generic mobility functions even though there is no specific MN-to-network protocol required at the MN for the network-based mobility management itself [9]. Generally, network-based mobility management has important advantages over host-based mobility management [9]. For example, the exchange of mobility-related signaling messages in the host-based approach is heavy on the already limited bandwidth in the air interface and adds delays in the signaling process due to long round-trip-time (RTT) of signaling messages. Furthermore, additional mobility management support has to be incorporated in the MN's protocol stack, which increases the MN's complexity, the battery power consumption, and the processing overheads. However, this is avoided in the network-based mobility management approach.

Generally, mobility management supports at least one of different means of mobility;

personal mobility, session mobility, service mobility, and terminal mobility. Personal mobility is when users are able to access network services anywhere by using any device. Session mobility is when users are able to maintain ongoing sessions while changing terminals. In service mobility users are able to obtain subscribed services from any network. Terminal mobility, on the other hand, is the ability to maintain connectivity while changing PoAs in a network(s). This thesis focuses on terminal mobility.

1.3 Mobility Management in Heterogeneous Wireless Networks

Traditionally, an IP address has a dual role, which is to identify a networked device and the location of the device in the network. This IP address dual role is suited for non-mobile devices. More so, these devices are always connected to the same network locations corresponding to their stable IP addresses. As such, higher layer connections such as TCP or UDP connections which are defined with IP addresses of the communicating nodes are not disrupted, e.g., due to packet misrouting. Moreover, the IP addresses always identify the same non-mobile devices and the corresponding network locations.

However, the rapid growth of wireless communications over the past few years has spawned many different wireless networks, e.g., wireless local area networks (WLAN), Worldwide Interoperability for Microwave Access (WiMAX), and Universal Mobile Telecommunications System (UMTS). These heterogeneous wireless networks are envisioned to interwork over an IP- based infrastructure in NGWN. Consequently, wireless IP enabled network access will become heterogeneous in terms of access technologies. This environment creates a scenario where mobility across these access technologies becomes topical. As such, operators with multiple networks will need to facilitate seamless network access across their multiple networks [10]. In such a networking environment, multiple-interface MNs will be able to seamlessly switch between the different networks in order to obtain better performance or to maintain a continuous wireless connection when the previous one becomes suboptimal or unavailable. As a result, the IP information of the MN, which the upper layers use to define their connections with communicating peers, changes each time the MN changes PoAs in the networks. This IP mobility, where MN changes its topological location in the IP-based NGWN,

violates the traditional IP address dual-role definition. Therefore, all connections including the transport and application layers will be disconnected since the IP address of the MN changes every time there is a change in topological location. Moreover, transport protocols in the TCP/IP stack define their connections with the communicating end hosts' IP addresses.

However, the growth of wireless communication and mobile computing has initiated the development of IP mobility solutions that are transparent to upper layer protocols and applications. These solutions alleviate the connection breaks by allowing MNs to roam between networks while maintaining permanent IP addresses. Mobile IP (MIPv4/v6) [11][12], for example, enable topologically incorrect routing of packets by using tunneling techniques and topologically stationary gateways to ensure connectivity and reachability of the MNs. In fact, with the network layer mobility solutions the MN appears stationary to the upper layers since it is always reachable via the same permanent (home) IP address due to the tunneling capability of these solutions.

Besides the network-layer IP mobility management solutions, there are other approaches for supporting mobility that are implemented in the other layers of the TCP/IP protocol stack. These approaches introduce their own criteria of mobility management and hence their own requirements, merits, and trade-offs. For example, Host Identity Protocol (HIP) [13], which is implemented between the network and transport layers, supports mobility through binding upper layers to host identifiers instead of IP addresses, hence effectively separating the dual role of an IP address into two identifiers: a host identifier and a locator. This property allows for IP address changes hence IP mobility support. Moreover, the IP address is used purely for routing (locator) purposes while the unique host identifier takes the role of identifying the host (each host identity uniquely identifies a single host). In fact, with HIP, all network connections remain bound to host identifiers while the underlying bindings to IP care-of-addresses (CoAs) handle the routing of data between the MN and its peers. Thus, with relevant signaling messages an MN is able to inform its peers about other IP addresses under which it can be reached during mobility. Furthermore, HIP transforms the security model of MIP, hence the authentication issues between the MN and peers are eliminated. In fact, HIP promises to simplify host mobility although it requires a complete re-design of the socket implementation, which may pose a major challenge to

its deployment.

Another recent protocol that separates the IP address dual role into two numbering spaces like HIP is the Locator/ID Separation Protocol (LISP) [14]. LISP separates IP addresses into Endpoint Identifiers (EIDs) and Routing Locators (RLOCs) and as such has been proposed to enhance mobility management in other works such as [15] [16]. It does not require protocol stack changes to the host or network core. LISP provides functions to routers to exchange information used to map from non-routable EIDs to RLOCs.

Other alternatives to IP mobility management solutions operate at the transport layer, e.g., the Stream Control Transport Protocol (SCTP) [17], which is a reliable protocol targeting acknowledged transfer of connectionless packet flows. The basic idea of transport layer mobility management is to maintain the end-to-end connection between the MN and its peers at the transport level. Thus, this mobility management approach does not require any support in terms of infrastructure from the underlying network layer. An ongoing Transmission Control Protocol (TCP) connection, for example, is not broken when the MN changes points of attachment (IP addresses). Instead, the corresponding TCP communicating host pause the connection during handover and reactivates (i.e., refreshes the association) from the new point of attachment after handover, without any need for tunneling. As such, an active application uses the same TCP connection before and after handover. Ultimately, transport layer mobility management approaches support mobility among networks without interfering with the natural routing of IP packets. However, in order to support seamless mobility the transport layer solutions require some changes to the transport layer implementation of the TCP/IP protocol stack as well as the applications.

In the application layer there are protocols such as the Session Initiation Protocol (SIP) [18], which provides mobility support for real-time communications through the capability of establishing and tearing down sessions between communicating hosts. This capability enables SIP to inform a correspondent peer about the new IP address at which the MN can be reached after handover. In effect, with SIP the IP layer of the communicating hosts (MN and CN) remain unchanged while SIP messages are exchanged for host location as well as redirection or registration of the MN with the CN. SIP can be used to handle session mobility, user mobility,

and terminal mobility. Furthermore, SIP does not require any changes to the IP stack of the MNs. However, it does require support from the applications, i.e., the applications have to be SIP-aware in order to benefit from SIP-based mobility management. This requirement makes global deployment in NGWN a challenge.

Link layer mobility management solutions support mobility by providing mobility-related features in the underlying access technologies. This approach generally works well for a given link-access technology, hence manages MNs that move within the same type of wireless access network. For example, when the MN moves from one access network to another which supports the same air interface and the same mobile application part, services are provided seamlessly [19]. The current 3G networks like UMTS, for example, provide a mobility solution that is access technology specific whereby the MN gets mobility services within the scope of the UMTS network. Thus when the MN moves out of the scope of the UMTS network, any ongoing communication is interrupted. The IEEE 802.11 family of standards is another common example of a technology that supports link-layer mobility. In fact, with link-layer mobility management, the access technology handles all the mobility and the network layer is unaware of changes in the PoAs when the MN moves between PoAs connected to the same access router's interface. Therefore, link-layer mobility solutions cannot provide seamless mobility across heterogeneous link-access technologies. T. Chiba *et al.* [20] highlight mobility management schemes for supporting roaming between heterogeneous wireless networks. The operational issues associated with roaming and service continuity are addressed. Furthermore, an analysis of various mobility solutions to support the heterogeneity of NGWN is given. It is concluded that only upper layer mobility management solutions can address seamless mobility between heterogeneous networks.

Cross-layer design has recently been employed to improve performance in the context of mobility management in NGWN. For example, cross-layer interactions utilizing the IEEE 802.21 Media Independent Handovers (MIH) services [21] have already been proposed in the literature to efficiently manage mobility between heterogeneous networks. Cross-layer mobility management involves jointly handling mobility-related issues by considering contributions from the different layers of the network TCP/IP protocol stack, hence optimizing handovers.

Z. Zhu *et al.* [22] present a historic survey of mobility support in the Internet. The authors

systematically review previous efforts to understand the solution space of mobility support. Thereafter, they report on their findings and identify remaining issues in providing ubiquitous and efficient global scale mobility support. Their survey covers mobility solutions in all the protocol stack layers.

This thesis, however, focuses on the network-layer solutions (i.e. IP mobility management) since they make support for mobility transparent to upper layer protocols and applications. In addition, they hide the heterogeneity in the link-specific technologies of NGWN. Moreover, the heterogeneous wireless networks will converge at an IP-based infrastructure. Furthermore, the network (IP) layer deals with routing, which is closely related to mobility. Therefore, the IP layer is ideal for handling mobility management.

1.3.1 Mobility and Handovers

Mobility may result in horizontal handovers (i.e., handovers within the same access network technology) and/or vertical handovers (handovers between different types of access technologies). Thus, proper management of handover within similar network technologies and/or between different network technologies is a key aspect to achieving seamless mobility. Figure 1-4 below illustrates horizontal and vertical handovers.

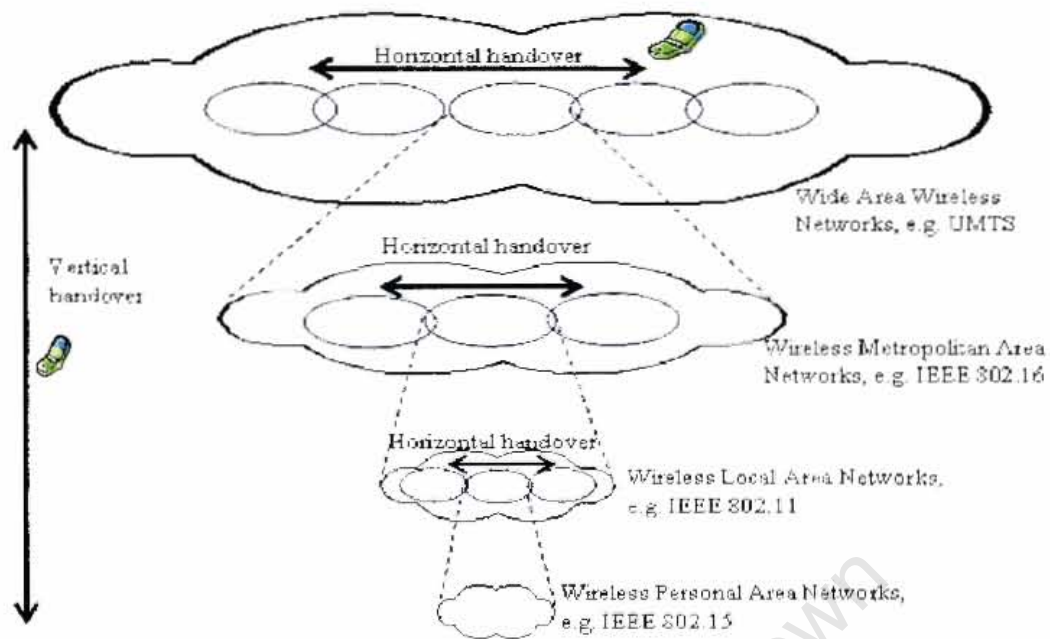


Figure 1-4 Vertical and horizontal handovers between wireless networks.

While horizontal handovers are generally seamless as observed in single homogeneous networks like the 3G cellular network or wireless LAN, vertical handovers are more challenging since they happen between heterogeneous access systems that differ in many aspects such as bandwidth, frequency of operation, coverage, etc. [23]. Vertical handovers will be very common in NGWN hence these need to be properly addressed.

Handovers can also be classified as hard or soft. In hard handovers the MN switches between PoAs in a 'break-before-make' fashion while in soft (or seamless) handovers it switches in a 'make-before-break' fashion. In 'break-before-make' the MN completely disconnects from the previously connected PoA before connecting to a new PoA. Yet, in 'make-before-break' the MN connects to the new PoA while still connected to the current or previous PoA. The 'make-before-break' fashion is the recommended mode since seamless handovers without unpleasant perceptible interruptions to ongoing real-time communication are supported if this mode is properly managed.

The most widely recognized IP mobility solution is the network-level MIP family of mobility management protocols (MIPv4/v6), which are host-based. These MIP protocols have

The MNs are also becoming increasingly multimodal containing multiple communication interfaces such as WLAN, WiMAX and UMTS [32], hence can connect to any of the access networks in the NGWN to obtain improved performance or to maintain a continuous wireless connection during mobility. Although the MNs can connect to multiple heterogeneous wireless networks simultaneously, sometimes known as multi-homing, having multiple interfaces switched on at the same time for a long period results in frequency interference and excessive power consumption. Therefore, efficient handovers among the interfaces and networks are generally necessary.

1.4 The Need for Seamless Handover Mechanisms in IP Mobility Management

The essential challenge for IP mobility management protocols is to ensure non-perceptible disruption or disconnection of ongoing real-time communication for a MN traversing the heterogeneous wireless networks in NGWN. In fact, IP mobility management protocols do not provide seamless handover in their current form [33]. MIPv6, for example, which is regarded as the standard to support mobility management in NGWN suffers from long handover delay, packet loss, and signaling overhead [34] [35]. Similarly, all the MIPv6-based protocol extensions inherit some of these problems. Thus, generally, IP mobility management protocols do not guarantee a ubiquitous network environment where handovers will be seamless, thereby enabling MNs to consistently continue with ongoing communication even as they change access networks. The handover delay is still too large and unacceptable for real-time applications [36], resulting in packet loss that cause unpleasant disruption to these applications during handover. The handover delay at the IP layer level is largely due to movement detection by the MN, router discovery on the new link, binding update and registration in the new network, as well as configuration and validation of the new IP address. Furthermore, delays are also introduced by the authentication procedures at the new network.

However, the requirement by mobile users of the NGWN to have seamless continuity of IP sessions and applications during mobility between the different networks has to be met. Thus, the present IP mobility management protocols need to be enhanced with effective and efficient

seamless handover mechanisms capable of meeting the delay requirements of real-time applications. Most IETF standardized IP mobility protocols are basic mobility solutions that simply ensure MN connectivity and reachability but lack adequate support for seamless vertical handover control. There has been a diverse range of handover mechanisms, e.g. [37] [38] [39] [40], proposed in the literature to address seamless handovers for real-time traffic. However, these mechanisms lack timely coordination of procedures to handover between the involved or affected networks. Timely coordination will ensure seamless vertical handovers between the heterogeneous wireless networks. Thus, there is still a need to further enhance the handover performance of the standard IP mobility protocols by incorporating effective and efficient handover mechanisms.

1.5 Scope of Research

This research focuses on enhancing handover performance in the context of IPv6 mobility management solutions, in particular, network-based mobility management protocol, PMIPv6. The handover performance is evaluated in terms of handover delay, packet loss, and signaling overhead. The research addresses seamless handover across partially overlapping heterogeneous wireless networks in a localized mobility management domain. After all, user mobility is normally higher in localized-mobility domains hence handovers are much more frequent and bound to cause service interruptions, especially when the MN user moves to another IP subnet.

We utilize analytical modeling and simulation to evaluate the handover performance of the common MIPv6-based IP mobility protocols (HMIPv6, FMIPv6, and PMIPv6) during MN's IP handovers. We also demonstrate via analysis and simulation that IEEE 802.21 MIH services enhance handover performance of PMIPv6 in terms of handover delay and packet loss, although at the expense of signaling overhead in the air interface [41] [42]. Furthermore, we analyze and simulate the handover coordinator designs [43] [44], which are proposed to support effective and efficient seamless handovers in the context of further reducing handover delay and packet loss while keeping signaling overhead to a minimal.

Our research is scoped on handovers between interworking WLAN and WiMAX access networks. After all, these network technologies are expected to be very common in NGWN. In

fact, the focus is on partially overlapping heterogeneous wireless networks (WLAN and WiMAX) that are possibly owned by a single operator who might need to facilitate seamless network access across their multiple network systems. However, the heterogeneous wireless networks can also be owned by different cooperating network operators.

The proposed handover coordination mechanism is independent of assumptions about the underlying wireless technologies. In fact, its handover function deals with handover delay due to the network (IP) layer, which can induce perceptible disruptions and packet loss on the transported ongoing communication during MN handovers. This delay usually augments the end-to-end delay of real-time traffic during IP mobility, hence resulting in the ongoing application packets exceeding their end-to-end delay bounds and eventually getting dropped. Thus, the performance evaluation of the proposed handover coordination mechanism remains independent of the underlying technology. After all, the delay factors of the link layer are very difficult to address collectively due to the heterogeneity of the link-layer technologies in NGWN. Link layer handover delay is the period when a MN loses connection from one PoA until it connects to another PoA at layer 2 level. The research focuses only on ensuring seamlessness for the purposes of mobility, and does not consider issues related to resource management in terms of quality of service (QoS) provisioning for the transported ongoing communication during handover between the different network technologies.

In addition, for the purposes of this research, we assume that vertical handover is due to MN movement. However, in NGWN vertical handovers can also happen due to availability of multi-technology networks that are competing in terms of capabilities for satisfying the network users.

Ultimately, we evaluate the proposed handover mechanism by means of discrete event simulations against PMIPv6 and FMIPv6 in terms of handover delay, packet loss and signaling overhead. We further consider the effects of various external parameters on these handover performance metrics.

1.6 Research Contributions to Seamless Vertical Handover

This thesis explores the hypothesis that if interworking heterogeneous wireless networks coordinate the initiation and preparation of handover procedures in a network-based fashion ahead of time, then seamless vertical handovers between these networks can be achieved. Moreover, the handover procedures can be executed in the background while the MN continues with any active communication. Ultimately, the signaling steps during the actual handover can be reduced and the handover performance improved. Thus, a network-based handover coordination design is being proposed to further enhance the handover performance between heterogeneous wireless networks in a typical NGWN.

The main contributions of this thesis are summarized as follows:

- 1) A clear identification of the common approaches that are employed in IP mobility management solutions to achieve seamless handover with shorter delay and reduced packet loss is given. These approaches include address pre-configuration, pre-authentication, hierarchical registration management, bicasting and multicasting, and proxy mobility-related signaling. In addition, a review of handover mechanisms leveraging MIPv6-based mobility management protocols (HMIPv6, FMIPv6, and PMIPv6) to further reduce handover delay, packet loss, and signaling overhead is presented.
- 2) IP handover performance of the common MIPv6-based mobility protocols (HMIPv6, FMIPv6 and PMIPv6) as well as IEEE 802.21-assisted PMIPv6, and later the proposed PMIPv6-HC mechanism, are analyzed in terms of handover delay and signaling overhead. The involved handover-related signaling messages in these mechanisms are investigated and mathematically analyzed to model the handover delay and signaling overhead encountered during the respective handovers.
- 3) A handover mechanism which utilizes the IEEE 802.21 Media Independent Handover (MIH) services and leverages PMIPv6 to further improve handover performance is presented. We verify through simulations that even though the mechanism reduces handover delay and packet loss, the signaling overhead is compromised due to the exchange of MIH messages

between the MN and the relevant network points of attachments during the handover process.

- 4) A network-based handover approach that employs ahead-of-time coordination between the involved heterogeneous wireless networks (i.e., source and target networks) to further enhance the handover performance in terms of ensuring seamless handovers is proposed. The handover coordination mechanism enables the involved wireless networks to coordinate, in an informed manner, the initiation and preparation procedures to handover. Consequently, the handover procedures are executed in the background while the MN continues to communicate as real-time as possible without perceptible interruption before, during, and after the handover. Therefore, the handover coordination approach further reduces handover delay and packet loss while also keeping signaling overhead to a minimal, thus ensuring seamless handover between the heterogeneous wireless networks.
- 5) Two handover coordinator (HC) designs, which address the common handover issues (handover delay, packet loss, signaling overhead) are developed. The designs may be applicable to different network scenarios, e.g., the base-station-level HC design may be more suited for a small-scale localized-mobility scenario while the Local Mobility Anchor (LMA) logical HC design may be suited for large-scale localized-mobility scenarios. The handover performance of these designs is analyzed and evaluated for different external parameters such as MN speed, traffic type, simultaneous MNs handovers, and coverage range of overlapping region. The base-station-level HC design employs 'relaying' to reduce packet loss while the LMA logical HC design utilizes 'bicasting'. The network-based nature of the handover coordinator designs ensures that signaling overhead is kept to a minimal in the air interface while the ahead-of-time coordination of the initiation and preparation of the handover procedures reduces handover delay.

These contributions are contained in the author's publications as listed earlier.

1.7 Thesis outline

The organization of the remainder of this thesis is as follows:

Chapter 2 investigates IPv6 mobility management protocols, their handover procedures as

well as their seamless handover approaches. The background and overview of these IPv6 mobility solutions (MIPv6, HMIPv6, FMIPv6, and PMIPv6) is given. Review of related work in the context of addressing seamless handovers with these MIPv6-based solutions is discussed. The review reveals the benefits of the network-based mobility approach over the host-based approaches in the context of handover performance. Furthermore, the need for further research in the area of seamless mobility management in NGWN, in particular, seamless vertical handover to ensure non-perceptible interruptions to ongoing communications is deduced.

Chapter 3 presents analytical models of handover performance improvement with the MIPv6 extensions (HMIPv6, FMIPv6, and PMIPv6) in terms of handover delay and signaling overhead. The analysis suggests that PMIPv6, a network-based mobility solution, is the most suitable leverage IP mobility protocol for handover mechanisms to further improve the performance during handovers. A handover design that utilizes IEEE 802.21 Media Independent Handover (MIH) services and leverages PMIPv6 mobility management framework is provided and analyzed to show that indeed PMIPv6 is the most suitable leverage protocol for handover mechanisms that further reduce handover delay and packet loss.

Chapter 4 presents the proposed seamless handover coordination design identified as PMIPv6 with handover coordinator (PMIPv6-HC). The design employs ahead-of-time coordination in terms of initiation and preparation of handover procedures between the involved heterogeneous wireless networks to ensure seamless vertical handovers with non-perceptible disruption to a MN's ongoing real-time communication while ensuring that signaling overhead is kept to a minimal. The design goals of the handover coordinator are also highlighted.

Two PMIPv6-HC system models as well as the schematic representations of the respective HC implementations and interactions between the HC's components are presented. The respective PMIPv6-HC principles of operation, signaling flow, and security considerations are also discussed. The PMIPv6-HC handover mechanism is triggered to start the coordination of the initiation and preparation of handovers ahead of time. Thus, the handover procedures are executed in the background while the MN transparently continues with ongoing communication even during the actual handover.

Chapter 5 is dedicated to the implementation and simulation issues of the proposed handover mechanism. It begins by giving a brief overview of the simulation tool, i.e., the NS-2 network simulator, particularly in terms of its wireless and mobility modeling. Furthermore, the limitations related to the simulation of our design and workarounds to mitigate the limitations are discussed. Next, the overview of the evaluation framework in terms of the simulation setup, network topology, and related parameter settings is provided. In fact, all issues related to the implementation and simulations are discussed in this chapter.

Chapter 6 presents and analyzes the handover performance results obtained from our simulation experiments. It provides comparative handover performance analysis between the proposed PMIPv6-HC and PMIPv6 as well as FMIPv6 in terms of handover delay, packet loss, and signaling overhead. The impact of various parameters that influence these handover performance metrics is investigated.

Chapter 7 concludes by summarizing the contributions of this thesis. The chapter further gives some recommendations for future research related to the work discussed in this thesis.

Chapter 2 Review of IPv6 Mobility Management and Seamless Handover Approaches

This chapter introduces IP mobility management and gives an overview of network-layer mobility protocols, in particular, MIPv6-based protocols. Related work on enhancing the handover performance of these mobility solutions is also reviewed. Moreover, the MIPv6-based protocols are the de facto IP mobility solutions for NGWN, which are envisioned to consist of IPv6 nodes. Thus, IP and IPv6 are used interchangeably in this thesis. Understanding the different IP mobility management solutions and the respective handover procedures is important to consider, assess, and evaluate the handover performance. Therefore, this chapter gives a brief overview of MIPv6 and the common MIPv6-based mobility management extensions. Furthermore, the procedures and approaches to support handovers are discussed. We further discuss the strengths and limitations of these approaches, hence revealing the need for further research in the context of enhancing the handover performance.

The related work that has been done in terms of addressing the handover performance limitations of MIPv6 and its host-based extensions is reviewed. In particular, the review focuses on the mechanisms that have been proposed to improve the handover performance in terms of reducing handover delay and/or packet loss and/or signaling overhead of the standard MIPv6 based mobility protocols. The handover performance limitations are identified and the network-based MIPv6 extension (PMIPv6) is deduced to be a viable approach to addressing the limitations effectively and efficiently. Therefore, the related work in the context of addressing the limitations with the network-based mobility management approach is also reviewed. Ultimately, the need for further research in leveraging PMIPv6 to further enhance handover performance is identified.

2.1 IP Mobility Management

Since heterogeneous wireless networks in NGWN are envisioned to be anchored to an IP-based infrastructure, it follows that the IP protocol will play a major role in mobility management

in this environment. In fact, network layer mobility solutions are based on the extension of the fundamental IP protocol. Consequently, solutions that operate at the IP layer are regarded as being more suitable to handle mobility as they do not violate any basic internet design principles [5]. Currently, MIPv6-based protocols are the universal solutions for IP mobility management between heterogeneous wireless networks. These protocols are the most representative solutions in industry and the research community. More so, they hide the heterogeneity in the link-specific technologies used in the different networks in NGWN [45].

This thesis focuses on MIPv6-based mobility management protocols. More so, these protocols are more suited for NGWN as they overcome most of the problems of MIPv4 solutions [46]. Moreover, the IPv6 specification improves many of the weak aspects of IPv4, e.g., provides an optimal header format, neighbor discovery mechanism, improved security and quality of service, reasonable addressing architecture, and stateless auto-configuration. Thus, MIPv6 benefits from these IPv6 improvements.

MIPv4 (and its extensions), on the other hand, is not a sufficient solution for NGWN where users will have high mobility between different wireless networks because it suffers from many weaknesses such as long delays due to triangular routing, ingress filtering issues, tunneling, high signaling overhead, and furthermore, the IPv4 address space is not enough for the many IP nodes that are expected to require ubiquitous wireless internet connectivity in the near future. Thus, MIPv4 (and its extensions) will not be sufficient to provide the functionality and support required by the wireless information services in terms of reliable, effective, and efficient IP mobility management support. Moreover, NGWN are envisaged to mainly consist of IPv6 nodes. Since MIPv6 was designed based on the experiences of MIPv4 it resolves many of the problems identified in MIPv4, e.g., mitigates the delays due to the triangular routing problem by providing route optimization. Detailed information about MIPv4 can be found in [11].

In fact, all MIP-based mobility management protocols deal with mobility at the network layer, thus transport layer connections remain transparent to the user movement. Moreover, network layer mobility management solutions address the routing of IP packets to MNs that change locations and possibly network access types, e.g., due to mobility. Therefore, it is intuitive to manage IP mobility, where an MN changes its topological location in the IP-network,

at the network layer because routing is a network layer function. In fact, mobility features are at the IP (network) layer. Furthermore, IP prevents protocols, services, and upper layer applications from awareness of the interconnecting architecture and possible changes caused [47]. Thus, the IP layer can easily facilitate the handling of seamless mobility across heterogeneous wireless networks without affecting upper layer operations. Various other mobility mechanisms, such as IDMP [48], HAWAII [49], and Cellular IP [50], which have been proposed to overcome the drawbacks of base MIP exist, but are not discussed in this thesis.

The following sections discuss MIPv6 and the most representative MIPv6-based IP mobility management solutions as well as their approaches and limitations to achieving seamless handovers.

2.2 MIPv6 Overview and Related Work on Achieving Seamless Handover

Mobility Support in IPv6 (MIPv6) enables terminal mobility by allowing MNs to remain reachable while moving around in the IPv6 internet or NGWN. MIPv6 achieves this capability by assigning two IP addresses to the MN: a permanent home address (HoA) and a temporary care-of-address (CoA). Thus, an MN is always identified by the HoA regardless of the point of attachment (PoA) in the heterogeneous wireless networks. While away from the home network, the MN is associated with the temporary IP CoA, which provides information about the MN's current location in the network. This IP mobility in the context of the changing CoA is transparent to the transport and higher layers. Moreover, packets addressed to the MN are transparently routed to the CoA.

For detecting the movement of the MN to and from a link of a PoA (i.e., access router), router solicitations (RS) and router advertisements (RA) are exchanged between the MN and the PoA. To ensure that the MN is always reachable wherever it roams in the NGWN, binding update (BU) and binding acknowledgement (BA) messages are exchanged between the MN and the home agent (HA) and/or the correspondent node (CN). The binding update messages facilitate the binding of the HoA with the CoA. Thereafter, the packets destined to the MN can be

sent via the HoA or transparently routed to the CoA as already explained above. The basic components and handover signaling procedure for MIPv6 are shown in Figure 2-1 below.

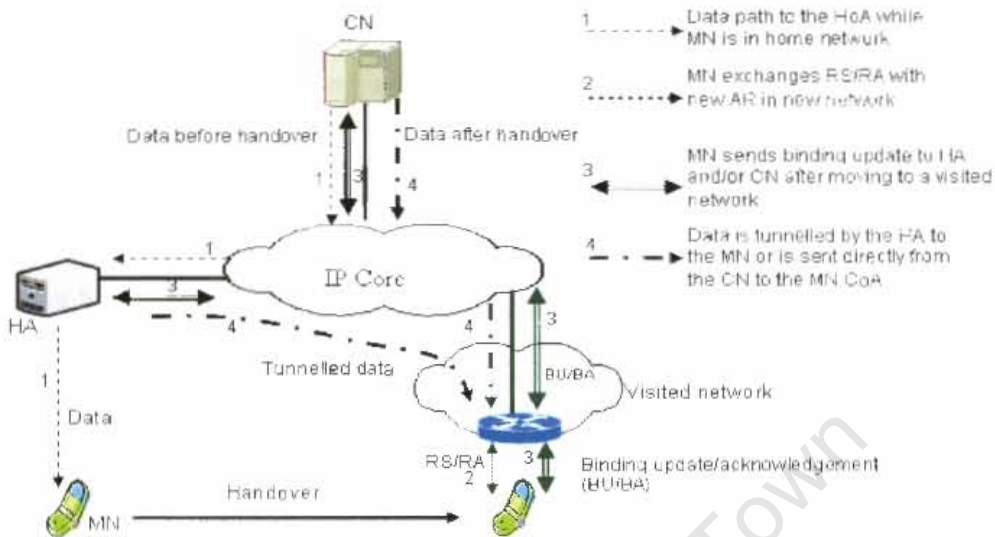


Figure 2-1 MIPv6 handover signaling procedure.

As seen in Figure 2-1 above, a CN can communicate with the MN in one of two ways, 1) indirectly through the HA or 2) directly through normal network routing procedures (also called Route Optimization). When the indirect route is used, the HA intercepts any packets from/to the CN and tunnels them to/from the MN while the MN is roaming in a visited network. Otherwise, the packets are routed with normal IP-routing methods towards the MN using route optimization. Route optimization is a handover technique or approach to reduce packet delays or propagation delays and tunneling overhead due to triangle routing, whereby every packet passes through the HA even when the MN is closer to the CN than the HA.

However, MIPv6 must execute various time-consuming procedures at the IP layer level before the MN is able to continue with ongoing communications in the visited network. In fact, MIPv6 employs a reactive handover approach, whereby handover procedures are only performed after the MN has discovered the new network (new access router or PoA) or discovered that it has left the current access router or PoA. These handover procedures usually include movement detection and router discovery where the MN discovers the new PoA, IP address configuration and duplicate address detection (DAD) where the MN configures a CoA and verifies its

uniqueness with DAD to prevent IP address collision, CoA registration and binding update procedures where the MN notifies the HA and/or CN of its current location, as well as authentication procedures where the MN gets authorization and authentication to use the new network's services and resources. However, these procedures (during the time from movement detection to distribution of binding updates (location information)) induce handover delay, packet loss and signaling overhead, which in turn compromise the MN user experience in terms of perceptible disruption to ongoing communications. In fact, during this period the MN is unable to send or receive data packets, yet the CN continues to send the packets. Thus, for MNs that hand-over between different IP subnets during an ongoing session, MIPv6 is not sufficient in terms of providing seamless handover. Although MIPv6 solves many problems encountered in MIPv4, the handover procedures still take a long time to complete hence cause unpleasant perceptible interruptions to ongoing communications during the handover, especially in micro-mobility domains where handovers are frequent. In fact, the handover delay is the primary cause of packet loss, which in turn causes disruption to ongoing communication during handover [5]. The handover delay, as mentioned earlier, mainly comprise delays due to network discovery, IP address configuration, authentication and binding update procedures associated with a mobility event [51].

Due to the long handover delay, transient packet losses, and signaling overhead, MIPv6 is not suitable for micro-mobility domains where user mobility is high. High user mobility induces frequent handovers, which cause severe service disruptions to ongoing real-time communication if MIPv6 is used. The frequent handovers cause increased signaling overhead between the MN and its peers [52]. To alleviate these MIPv6 limitations, the IETF developed MIPv6 extensions to improve the handover performance. These MIPv6 extensions are FMIPv6 and HMIPv6, and are discussed in the next section. Besides the MIPv6 extensions standardized by IETF, many related works, some of which are discussed below, have been done in the research community in an effort to improve the handover performance of MIPv6. These related works mitigate various aspects of the handover delay with the ultimate goal of reducing the overall handover delay and/or packet loss, hence enabling seamless handovers.

J. Lee *et al.* [53] propose temporary authentication which allows a roaming user to

continue communication activities in a visited network even before the MN is fully authenticated by the Authentication, Authorization, and Accounting (AAA) server in the home network. The proposed authentication procedure, which is temporary, is designed to provide AAA service to expedite fast handover, meaning that it minimizes the time required for AAA service during the actual handover. In effect, the authors show that the handover delay, particularly the delay component due to authentication, is reduced by up to 70%. Moreover, network-access authentication contributes significantly to handover delay in mobility management schemes [54].

A. Dutta *et al.* [10][51] employ IEEE 802.21 MIH services to support seamless handover between heterogeneous wireless networks. A testbed implementation is developed where the MIH services are demonstrated with the media-independent pre-authentication (MPA) client acting as a mobility management entity. MPA facilitates seamless handover by establishing higher layer security associations and configurations, e.g., pre-registration and pre-authentication, with the target network before a link-layer handover is made. Ultimately, the MPA in combination with MIH perform some handover steps before layer 2 switch, hence reducing handover delay and packet loss during the actual handover. In fact, the MPA executes the heterogeneous network handover while the MIH services provide valuable information to assist in handover preparation and initiation.

Yoon-Young An *et al.* [55] propose an enhanced handover mechanism in MIPv6 with new additional primitives and parameters to the MIH services. The mechanism reduces handover latency for MIPv6 by eliminating the router discovery time by utilizing the MIH services to discover the new router ahead of time through the relevant primitives and notifications. The authors further apply the mechanism in FMIPv6 where the delay contribution by the handover initiation time is reduced. Ultimately, high goodput is obtained for UDP and TCP during handover because of the reduced handover delay, which reduces disruption to ongoing communication.

A. Viinikainen *et al.* [56] propose a Flow-based Fast Handover for MIPv6 for fast redirection of the MN's downstream flows during the CoA registration (binding update) process and another method speeding up the upstream handover by using a special Hand-of-Address (HofA) during the registration process. The authors perform theoretical analysis and simulations

of the proposed mechanism, which they verify in a real MIPv6 Linux environment. The mechanism uses the *IPv6 Flow Label* to identify and redirect each traffic flow to the new MN location. In fact, when the MN moves to a new subnet, it receives a new CoA and registers this CoA to the HA. This CoA registration message includes the prior *Flow Label* of the MN connection. Using this *Flow Label* the gateway router redirects the flow to the new location of the MN. The mechanism, which requires some changes to the MIPv6 protocol, enables fast handovers. Therefore, ongoing communication packets are received simultaneously with the binding update registration process. Ultimately, the delay due to the binding registration experienced during handover is minimized. Furthermore, the results show that the handover delay is not dependent on the distance of the CNs the MN is communicating with.

An enhanced handover mechanism for MIPv6 with the support of MIH services and Advanced Duplicate Address Detection (A-DAD) is proposed in [57] [58]. This mechanism utilizes layer 2 triggers, applies advanced DAD (A-DAD), and reduces the number of layer 3 message exchanges during the handover procedure to reduce the overall handover delay in MIPv6 in a heterogeneous wireless environment. An MN with multiple interfaces uses the other interfaces to listen to other access networks. Thus, when the MN moves into another access network the corresponding MN interface generates and reports a Link Detect event to the Media Independent Handover Function (MIHF) and then to MIPv6, which is the MIH User. Thereafter, the MN establishes the layer 2 connection on the new link interface while it is still communicating with CN through the old interface. In effect, the above process prepares for IP handover ahead of time. Furthermore, A-DAD is utilized to reduce the typical DAD latency by keeping a list of duplicate-free addresses at an access router (AR). In A-DAD, each AR randomly generates an address and performs DAD beforehand. Thereafter, the AR acts as a passive proxy for addresses, which silently discards an address if it hears another node performing DAD on an address it already has in its pool. Ultimately, the AR keeps a list of duplicate-free addresses. Therefore, the DAD delay is eliminated from the actual handover phase. The authors analyze the effects of MN speed on the handover delay performance. As expected, the authors conclude that the MN speed affects the handover delay.

G. Wei *et al.* [59] propose the introduction of a new entity, the Extension Handover

Control Function (E-HCF), to improve MIPv6 handover performance over wireless networks. This mechanism involves sending a decisive control message to the MN to accelerate the handover process and reduce the packet loss by managing the traffic belonging to the MN. The functions configured in the E-HCF enable it to provide a list of possible attachment points to the MN beforehand based on its currently attached access point (AP). The E-HCF, therefore, decides which AP the MN should associate with by providing the MN with the relevant access point information. Furthermore, through some defined algorithm and introduction of new messages, the E-HCF is able to configure and distribute a unique IP address to the MN for use in the new subnet. The mechanism achieves packet loss reduction through bi-casting and buffering. This mechanism, therefore, achieves both minimized handover delay and reduced packet.

It is an almost universal recognition that MIPv6 needs to be further enhanced in order to meet the needs of NGWN [60]. In fact, MIPv6 is known to suffer from long handover delay, packet loss, and signaling overhead [35], hence the above-discussed proposals, which endeavor to improve these handover metrics. However, most of the proposed mechanisms in the literature address some aspects of the handover performance at the expense of others, e.g., improve packet loss and handover delay by trading off signaling overhead. More so, these mechanisms do not perform the handover process in a properly coordinated fashion between all the involved networks. Furthermore, mechanisms that leverage MIPv6 are more suited for macro-mobility management environments, whereby user mobility and hence handovers are not very frequent. In micro-mobility domains, these mechanisms incur more delay and high packet loss due to frequent handovers.

Therefore, while the delays of MIPv6 are already well known, an optimized and widely applicable handover approach is yet to be found [61]. The IETF has standardized different MIPv6 extensions such as FMIPv6 and HMIPv6 to alleviate some of the drawbacks of MIPv6.

The next section briefly discusses the MIPv6 extensions, their handover procedures as well as the seamless handover approaches they employ to improve the handover performance. Furthermore, some related work done by other researchers to further improve the handover performance of these extensions are reviewed.

2.3 Mobile IPv6 Extensions and Related Work on Achieving Seamless Handover

MIPv6 extensions are protocols that extend the MIPv6 protocol to mitigate the handover performance limitations. These extensions implement extra functionalities or optimize certain functionalities of MIPv6 to improve specific aspects of the handover performance. In effect, these extensions improve MIPv6's handover performance, especially, in terms of handover delay and/or packet loss and/or signaling overhead. These extensions include FMIPv6, HMIPv6, and recently, PMIPv6.

2.3.1 Mobile IPv6 Fast Handovers

Fast Handovers for Mobile IPv6 (FMIPv6) [62] is the original host-based fast handover extension of MIPv6. However, it has since been upgraded and renamed as Mobile IPv6 Fast Handovers [27], which has improved the security considerations and mobility header format. However, for consistency, the FMIPv6 acronym is still used.

FMIPv6 is designed to reduce packet loss and handover delay experienced in MIPv6 during handovers. The seamless handover approach that FMIPv6 utilizes involves anticipation (i.e., utilizing layer 2 triggers to proactively initiate a handover) and *pre-configuration* of the CoA of the MN in the new network that the MN is likely to move to, before it moves. Thereafter, the protocol pre-establishes a tunnel between the previous access router (PAR) in the old/current network and the new access router (NAR) in the target (new) network. Subsequently, the PAR forwards packets to the NAR when handover takes place. The NAR in the new network buffers the packets and delivers them to the MN when it (MN) finally arrives. FMIPv6 also implements a reactive mode of handover approach, which we do not discuss in this thesis since the predictive mode generally performs better than the reactive mode in terms of improving the handover performance.

Ultimately, FMIPv6 reduces the handover latency by predicting and preparing for the impending handover in advance, i.e., by pre-configuring the CoA ahead of time. This handover approach reduces or eliminates the IP-address configuration delay during the actual handover.

Packet loss, on the other hand, is reduced by forwarding and buffering the packets in the new network during the handover thus avoiding misrouted packets to the PAR when the MN has already moved to the NAR.

Figure 2-2 below shows the signaling flow when a MN moves from the PAR to the NAR in FMIPv6. The exchange of the signaling messages ensures that FMIPv6 is successful in supporting handover as well as effective in improving the handover latency and packet loss experienced in MIPv6. In fact, as mentioned earlier, there are two modes of operation of FMIPv6: predictive and reactive. In the predictive mode, which is the one we just briefly discussed, the MN sends a fast binding update (FBU) message to the PAR while it is still attached to the PAR. In the reactive mode, on the other hand, the MN sends the FBU message only after attaching to the NAR. Thus, the reactive mode has more packet loss and handover delay than the predictive mode.

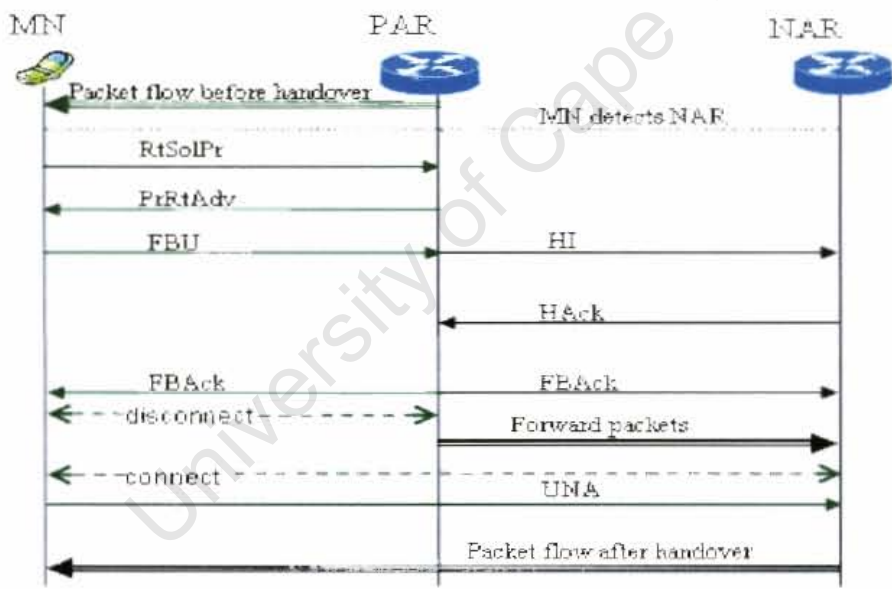


Figure 2-2 Handover procedure signaling flow in predictive FMIPv6.

As can be observed from Figure 2-2 above, as soon as the MN detects and gets some information about the new PoA, i.e., the NAR, through some router advertisements (RAs) or any other router discovery or link layer mechanism, it starts the handover procedures by sending the information about the NAR via a Proxy Router Solicitation (RtSolPr) message to the current

PoA, i.e., the PAR. The PAR resolves the RtSolPr message and helps the MN to configure the new CoA through a Proxy Router Advertisement (PrRtAdv) message. Subsequently, the MN sends an FBU requesting the PAR to facilitate the handover. Thereafter, the PAR sends a message (handover initiate (HI) message) advising the NAR to initiate the handover procedures. The NAR acknowledges (HACK) the message and a tunnel is established between PAR and NAR, and thereafter the PAR sends a fast binding acknowledgment (FBA) message to both the MN and NAR indicating a successful binding. Consequently, packets are forwarded through the established tunnel from the PAR to the NAR where the MN is predicted to attach in the near future. Eventually, the MN sends an unsolicited neighbor advertisement (UNA) message when it attaches to the NAR notifying the NAR to forward the buffered and incoming packets towards it (MN). Authentication activities of the MN may also be required as part of the handover procedures. These activities also influence the handover performance.

However, FMIPv6 is not reliable and has limitations. For example, the IP handover needs to happen at a rate that is suitable for the MN to update the binding of the HA or CNs with which it is having ongoing communication. If the MN moves faster and the signaling are unable to complete, some packets of the ongoing communication may be dropped. Furthermore, FMIPv6 introduces signaling overhead in the air interface with the extra mobility signaling related to the anticipation capability. These signaling may become heavy when there are many MNs simultaneously making handover. In fact, the anticipation mechanism suffers from inconsistent and unpredictable timing of the triggering of the handover signaling messages, hence may cause the handover procedures to start much earlier or much later than the anticipated handover. As a result, the handover delay and packet loss may increase. In fact, even with anticipation the MN cannot use the newly configured CoA until it has been acknowledged by the NAR before or after the IP transition. Therefore, the handover delay, packet loss, and signaling overhead still need more attention, in particular, for ongoing real-time communication, hence the following selected related works.

Y. Kim *et al.* [63] investigate the available timing and accurate criteria of layer 2 triggers in FMIPv6, which are used for facilitating CoA pre-configuration. They deduce that the exact timing and definitive criteria of the layer 2 triggers, which cause a significant effect on the

handover performance of FMIPv6, are not addressed. With accurately timed definitive layer 2 triggers, their paper presents a practical handover scenario that integrates layer 2 and layer 3 for low handover latency and packet loss during handover, and further show that the IP handover operation of FMIPv6 is performed prior to the layer 2 handover thus obtaining a seamless handover. The handover delay and packet loss are reduced for both UDP and TCP traffic.

Q. Mussabir *et al.* [37] also propose to reduce the handover delay experienced in FMIPv6. The proposed mechanism utilizes IEEE 802.21 MIH services with the aid of the information from the lower three layers of the MN and the neighboring access networks to address the radio access discovery and candidate access-router discovery issues of FMIPv6. Moreover, depending on scanning such as in IEEE 802.11 networks, to discover neighboring access networks takes a long time, which has significant contribution to handover delay. Thus, the proposed mechanism introduces an “Information Element Container” to store static and dynamic layers 2 and 3 information of the neighboring access networks, and uses a special cache maintained by the MN to reduce the anticipation time in FMIPv6. Furthermore, the handover decision of FMIPv6 is enhanced by a Policy Engine that makes intelligent decisions about handover. Ultimately, the handover latency contributed by the radio access discovery in FMIPv6 is reduced by using the layer 2 link information retrieved from relevant MIH services. Yet, the handover latency contributed by CoA configuration is reduced by the retrieval of layer 3 information from the “Information Element Container” of the corresponding PoAs, which the MN uses to form the new CoA prior to handover. The authors verify the improvement of their proposed mechanism through analysis and simulations. The results also show that the handover latency increases as the MN speed increases. This behavior is attributed to the host-based nature of FMIPv6, which results in signaling messages getting lost over the deteriorating physical link at MN high speeds.

Y. Song *et al.* [64] reiterate that the handover delay is still too large for ongoing real-time applications during handover in FMIPv6. The paper concludes that the key issues affecting the handover latency of FMIPv6, particularly in IEEE 802.11 networks, are the lack of assistance from the network entities in terms of the link-layer prediction (scanning) phase and the link-layer handover phase. The other issues are the ambiguous link layer triggering times in terms of packet

forwarding and the inefficient interaction between the link layer and the network layer.

2.3.2 Hierarchical Mobile IPv6

Hierarchical Mobile IPv6 (HMIPv6) improves the handover performance of MIPv6 in a micro-mobility domain by reducing the signaling overhead between the MN and its home agent (HA) or peers (CNs), as well as the handover delay during the handover process. Moreover, one of the main contributing factors to handover delay in MIPv6 arises when the MN signals the HA in the home network and/or CN with mobility bindings to help them maintain the reachability state of the MN. This mobility-binding signaling unavoidably injects latency in the delivery of ongoing communications to the MN in the new PoA when the round-trip-time (RTT) exceeds real-time delay bounds of time-sensitive applications [52], especially when the HA and/or CN is farther away from the MN. Consequently, packet loss possibility or loss of active session during handover is high since the binding of the HoA and current CoA takes a long time to complete.

Furthermore, as the handover rate between PoAs in a network domain changes, the handover delay also varies widely because the RTT between the MN and the HA and/or CN changes. As the MN gets farther away from the HA, the RTT gets longer and further transient nesting in tunnels is incurred due to the IP-in-IP encapsulation effected by the forwarding mechanism of the HA on the last visited link [52]. The frequent establishment of tunnels introduces additional delay during handover, hence possible packet loss due to delayed or misrouted packet delivery to real-time applications.

Thus, to alleviate the above mobility issues of MIPv6 in micro-mobility domains, it has been discovered that the mobility management can be efficiently handled if it is broken down into two, macro (global) mobility and micro (local) mobility [7], as seen in Figure 2-3.

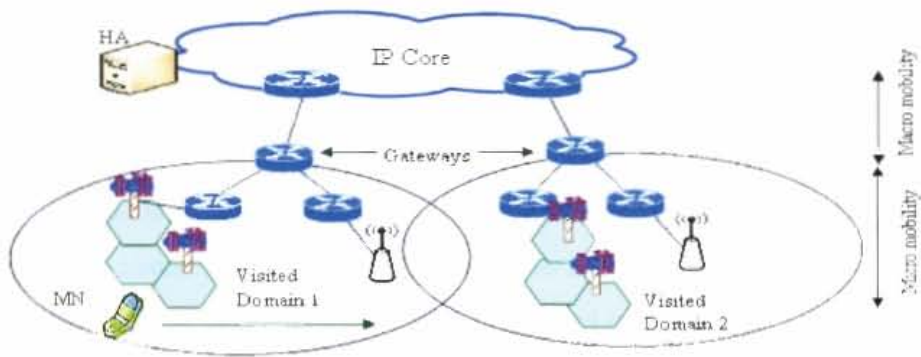


Figure 2-3 Macro and micro mobility domains.

HMIPv6, therefore, improves the MIPv6 handover procedure by utilizing a *hierarchical registration management* seamless handover approach to support localized (micro-) mobility handling. Thus, a Mobility Anchor Point (MAP), typically implemented in a gateway router, is introduced to serve as an HA in the localized domain.

The MAP intercepts all packets destined to an MN under its scope and tunnels them to the MN's on-link CoA (LCoA), which is a CoA local to the micro domain. The address of the MAP is commonly called the regional CoA (RCoA). Thus, as the MN moves between MAP domains in visited networks it configures RCoAs and LCoAs. Consequently, a binding is established between the LCoA and the RCoA while another one is established between the RCoA and the HA to ensure reachability of the MN while roaming in visited networks. When the MN changes access routers (ARs) within the same MAP domain, it simply obtains an LCoA and updates the MAP. Only when it changes to another MAP domain does it update the HA with the RCoA. Effectively, the signaling overhead is reduced in the core network when the MN roams within a localized (MAP) domain. The binding update delay is also reduced due to reduced RTT since the binding messages are exchanged between the MAP and the MN, thereby reducing the overall handover delay.

Generally, as can be deduced from the above discussion of the HMIPv6 operation, micro-mobility management schemes partly address issues related to handover performance, i.e., handover delay, packet loss, and signaling overhead as well as scalability and reliability. These schemes reduce the number of signaling messages to the home network and also reduce the signaling delay by performing registration locally in the micro-mobility domain. Thus, the schemes minimize excessive mobility-related signaling (e.g., binding updates) towards the HA and/or CNs due to frequent changes of CoAs in micro-mobility environments by handling it in the localized domain with the help of the local mobility management routing point, MAP, as long as the MN roams inside the domain. Effectively, the RTT hence the binding update delay is reduced. Furthermore, the signaling overhead is minimized in the core network.

Figure 2-4 below shows a typical handover procedure signalling flow in HMIPv6.

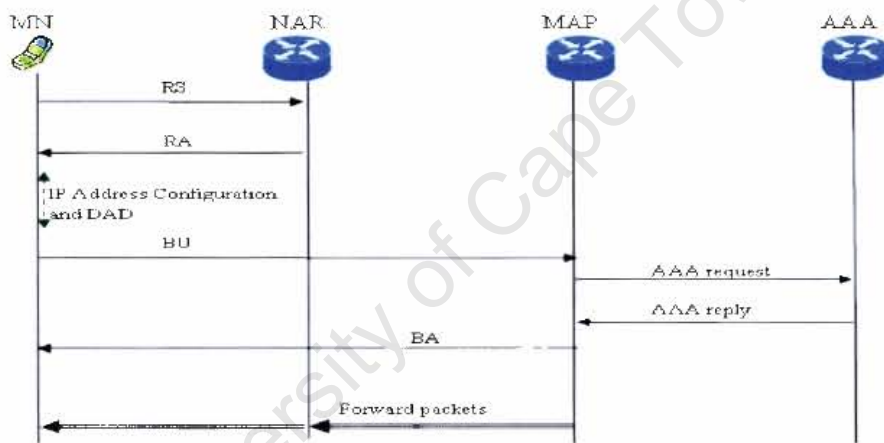


Figure 2-4 Handover procedure signalling flow in HMIPv6.

We can observe from Figure 2-4 that when the MN loses connection to a previous access router, it sends router solicitations (RSs) to discover NAR, which could be under the same MAP domain the MN is currently receiving services from or could be under a new MAP domain. Alternatively, as the MN enters the vicinity of a NAR under the scope of an MAP, it receives router advertisements (RAs). Subsequently, the MN exchanges binding messages with the MAP in the form of a local binding update (BU) and binding acknowledgement (BA), respectively, after which new IP address (LCoA) configuration and DAD procedures are performed. The MN

may have to be authenticated before it gets the network services in the new subnet through an exchange of authentication messages (AAA request/reply) between the MAP and an authentication server (e.g. AAA server) to verify the credentials of the MN. In fact, the admission of an MN at the new PoA or subnet is subject to authorization and authentication. Hence, as observed in Figure 2-4 the binding acknowledgement is sent to the MN after the completion of the authorization and authentication process.

However, as much as HMIPv6 reduces the delay due to binding message exchanges by localizing the handling of these updates, the overall IP address configuration delay is still long because the CoAs have to be configured anew every time the MN changes ARs. Furthermore, there are even more IP address configurations (RCoA and LCoA configurations) required if the MN traverses between different MAP domains. The IP address configurations (RCoA and LCoA) impact on the DAD procedure hence increasing the DAD delay. Thus, the handover delay is still long for ongoing real-time and time-sensitive applications especially because handovers are more frequent in localized domains.

Generally, HMIPv6 employs a reactive handover approach to initiate handovers. However, with reactive signaling deliberations the handover procedures (e.g., IP address configuration, binding updates, authentication, etc.) are initiated only after the MN has detected the new PoA implying that during the actual handover the active connections (ongoing communications) are disrupted.

M. H. Habaebi [65] and Vivaldi *et al.* [66] identify the DAD check and the message exchange transmission time during the process of the registration operation as the cause for handover delay in HMIPv6. The authors, therefore, propose mechanisms that perform fast handover in HMIPv6 by adopting the *multicast* seamless handover technique to the MAP for both macro-mobility and micro-mobility management, hence minimizing the service disruption delay that occurs during the binding registration operation. When the MN reaches the edge of the MAP's coverage area it sends a control message requesting the MAP to build a multicast group, which when built the MAP sends a message to adjacent routers asking them to join the group. Therefore, when there are ongoing packets destined to the MN, the MAP will multicast them to the adjacent routers that have just joined the multicast group. Ultimately, the new access router

will have a copy of the ongoing packets when the MN is still within the old router (for micro-mobility) or MAP (for macro-mobility). When the MN moves to the new router, the router starts forwarding the packets to the MN during the registration operation. The results show an improvement in the handover delay of the proposed mechanism when compared with standard HMIPv6. The handover delay is evaluated with respect to bandwidths and link delays.

The combination of HMIPv6 and FMIPv6 is proposed in Fast Handovers for Hierarchical MIPv6 (FHMIPv6) [67] to further optimize the handover delay. Both CoA configuration and HA registration (binding update) delay are reduced since FHMIPv6 employs *IP address pre-configuration* and *hierarchical registration management* seamless handover approaches. FHMIPv6 does not define new messages but leverages HMIPv6 and FMIPv6 messages. However, it changes the source and/or destination IP addresses of the messages to expedite the handover delay performance.

P. Kim and Y. Kim [68] propose a fast vertical handover scheme for HMIPv6 utilizing MIH services to optimize handover performance. The MIH Information service is extended by including new L3 information to provide domain prefixes of heterogeneous neighboring MAPs. This scheme minimizes the service disruption delay occurring during the registration operation employing the MIH services for network discovery and selection. In particular, the analysis shows that the scheme reduces the handover initiation time, and hence effectively reducing the handover delay.

Based on the above discussion of the MIPv6-based mobility protocols and proposed enhancements, it can be deduced that the seamless handover approaches utilized in these protocols to provide better handover performance include fast network discovery, bicasting or multicasting, hierarchical registration management, pre-authentication, pre-registration, MIH services, and packet forwarding techniques. Furthermore, to reduce packet loss during handover, buffering techniques are employed, which facilitate seamless handover. A. Dutta *et al.* [69] propose buffering packets at an access router near the edge of the current or candidate network. The buffered packets are then forwarded to the MN when handover completes. By dynamically controlling the buffer, a trade-off between handover delay and packet loss is achieved. In other words, buffering reduces packet loss at the expense of end-to-end delay.

Notably, all the above discussed standard mobility protocols and the proposed handover enhancing mechanisms are host-based. Thus, the MN is fully involved in mobility-related signaling. The MN's involvement negatively affects the overall handover delay, especially when too much functionality, as proposed in most handover mechanisms, is added in the MN protocol stack. For example, the periodic exchange of signaling messages between the MN and relevant network node is heavy on the already limited bandwidth in the air interface. In addition, this periodic exchange induces delays in the signaling process due to longer round-trip-time (RTT). Furthermore, the additional handover management support that is incorporated in the MN's protocol stack increases the MN's complexity, the consumption of battery power, as well as adds processing overheads and delays. Most of the proposed mechanisms also require adequate buffering mechanisms to avoid the dropping of packets and packet delays at the candidate network during handover.

Although the host-based IP mobility solutions have been standardized for many years, their deployment has not really taken off. This can be attributed to the fact that these host-based approaches require massive amount of development efforts and expensive MN design investment. It became necessary, therefore, to explore other approaches of efficiently supporting IP mobility, hence the birth of network-based mobility management. In particular, the IETF has recently standardized Proxy Mobile IPv6, which is discussed in the following section.

2.3.3 Proxy Mobile IPv6

Proxy Mobile IPv6 (PMIPv6) is a relatively recent network-based approach to address the IP mobility challenge of unsatisfactory handover performance particularly in terms of signaling overhead, handover delay, and packet loss. This network-based IP mobility approach does not involve the MN in mobility-related signaling, thus, the MN does not actively exchange mobility signaling messages with the HA and/or CN to facilitate handover procedures. A network mobility agent is employed to perform *proxy mobility-related signaling* on behalf of the MN. However, the MN still assists with generic mobility functions yet there is no specific MN-to-network protocol required at the MN for the network-based mobility management itself [9]. Generally, network-based mobility management has important advantages over host-based mobility management [9]. Consequently, recent works propose handover mechanisms that leverage

PMIPv6 to further improve the handover performance.

K. Kong and W. Lee [70] present a qualitative and quantitative analysis of IP mobility protocols in terms of handover latency. The authors highlight the main desirable features and key strengths of PMIPv6, particularly those that optimize handover better than host-based MIPv6 protocols such as HMIPv6 and FMIPv6. It is concluded that PMIPv6 improves handover delay and signaling overhead better than the host-based protocols.

In fact, the 3GPP system architecture evolution has adopted PMIPv6 in the Evolved Packet Core (EPC) specifications to provide seamless mobility at the IP layer as the user moves within and between accesses [71].

J. Guan *et al.* [72] analyze and evaluate the signaling and packet delivery costs of PMIPv6 for UDP and TCP against other most representative mobility management protocols. The authors evaluate the performance in terms of metrics such as throughput, packet loss, handover delay, packet delivery cost, and signaling cost. Their analysis and testbed performance results show that PMIPv6 has lower signaling cost and packet delivery cost than other mobility protocols. And their experimental results show that PMIPv6 can reduce the handover delay and packet loss. It is acknowledged that some fast handover mechanism needs to be introduced to further improve the performance.

Figure 2-5 below illustrates the mobility-related signaling criteria in network-based mobility management and host-based mobility management. It can be observed that the MN is fully involved in mobility signaling in the host-based approach; Figure 2-5(a). The MN initiates and/or terminates the signaling, thus inducing tunneling overhead in the air interface. On the other hand, a proxy mobility agent typically implemented in the access routers, performs the mobility signaling on behalf of the MN in the network-based approach, hence tunneling overhead is minimized in the wireless medium; Figure 2-5(b).

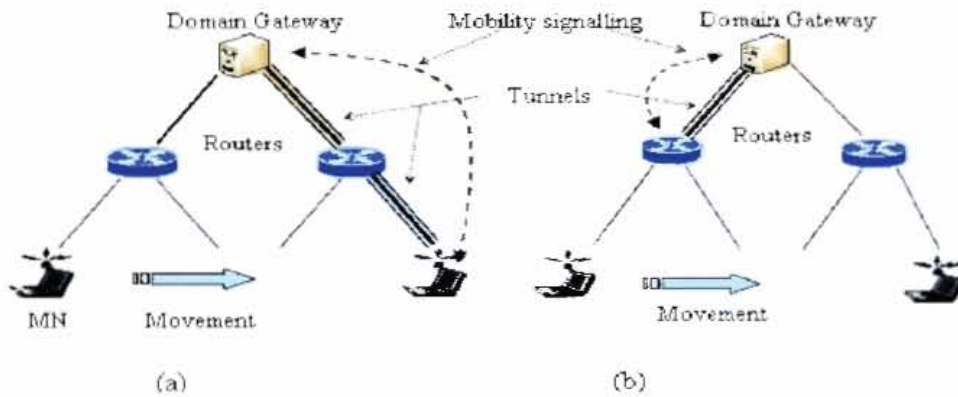


Figure 2-5 (a) Host-based. (b) Network-based.

PMIPv6 extends MIPv6 signaling and reuses many concepts such as the HA functionality. In fact, PMIPv6 leverages all the signaling semantics from MIPv6 yet in a network-based mobility management approach.

PMIPv6 introduces two new network functional entities called Local Mobility Anchor (LMA) and Mobile Access Gateway (MAG), typically implemented in the domain gateway routers and access routers, respectively. The LMA behaves like the HA of the MN in the PMIPv6 domain, thus topologically anchors and maintains the reachability state of the MN.

The MAG is a proxy agent that handles all mobility-related signaling on behalf of the MN. Thus, it tracks the movement of the MN to detect attachment and detachment events to/from the access link. Furthermore, the MAG authenticates and performs binding registration on behalf of the MN. Thereafter, the LMA and MAG establish a tunnel, which enables the MN to use an address from the home network prefix. Finally, the MAG emulates the MN's home network on the access network for each MN on its link.

The PMIPv6 protocol enables the network to assume that the MN obtains the home address on any access network in the domain. Thus, the serving network assigns a unique home network prefix to each MN, i.e., Per-MN-Prefix, and conceptually this prefix follows the MN wherever it roams within the PMIPv6 domain [30]. Consequently, the MN always configures the same address irrespective of its current location within the PMIPv6 domain, hence effectively reducing CoA configuration delay. Furthermore, as observed in Figure 2-5(b), PMIPv6 reduces

the binding update delay by reducing round-trip-time (RTT). In addition, PMIPv6 reduces the delay component introduced by the DAD procedure because of the Per-MN-Prefix property. Ultimately, PMIPv6 reduces the IP handover delay.

Figure 2-6 below shows a typical signaling call flow during handover in PMIPv6.

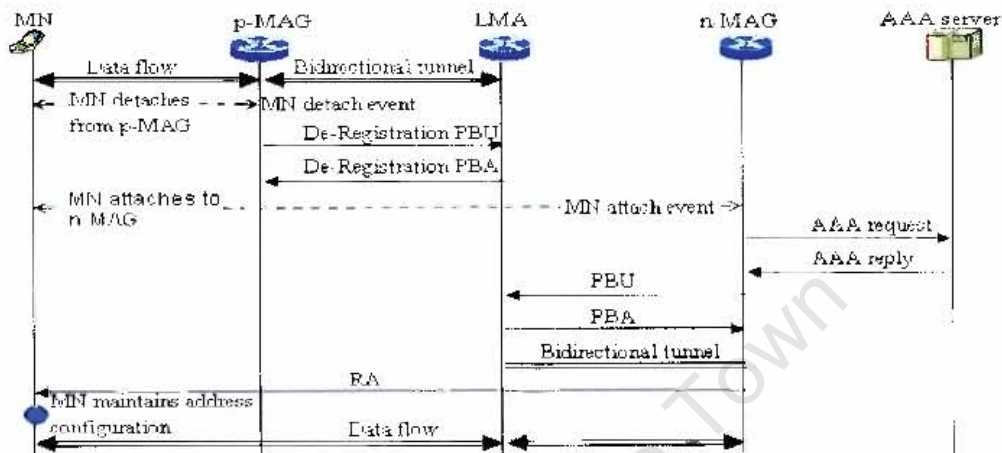


Figure 2-6 Signaling call flow during handover in PMIPv6.

As observed in Figure 2-6 above, the LMA and MAG deregister an MN by exchanging proxy binding update (PBU) and proxy binding acknowledgement (PBA) messages, which facilitate the deletion of the routing state when the MN detaches from the current MAG, p-MAG. However, the LMA maintains the routing/reachability state of the MN for a minimum time period (*MinDelayBeforeBCEDelete*) if it gets a handover hint beforehand. This *MinDelayBeforeBCEDelete* allows the MN time to attach to a new MAG.

When the new MAG, n-MAG, detects the MN on its access link, it sends a registration PBU to the LMA, on behalf of the MN, to update or create the binding and routing states of the MN. The LMA completes the registration by replying with a PBA. However, the n-MAG may have to authenticate the MN with an authentication server (e.g. AAA server). Thereafter, the n-MAG sends a router advertisement (RA) message to the MN that contains the unique home network prefix, which ensures the MN does not detect any change with respect to the Layer 3 attachment of the interface. Therefore, the MN maintains the same IP address configuration as

long as it roams within the same PMIPv6 domain.

However, PMIPv6 also experiences handover delay and packet loss that are not good enough for real-time applications. Moreover, it supports a reactive handover approach similar to MIPv6 and HMIPv6.

Recently, several handover mechanisms have been proposed in the literature to support seamless handover for PMIPv6 by further reducing the handover delay and packet loss. Reduced handover delay and packet loss ensure non-perceptible disruption to ongoing real-time applications during mobility events. Various related works propose mechanisms that reduce different aspects of the handover delay constituents; particularly due to Layer 3 (IP) handover.

P. Kim *et al.* [39] propose a proactive correspondent registration mechanism for PMIPv6 route optimization between a Mobile Access Gateway (MAG) and a correspondent node (CN) in the same domain. The proxy home test and the concurrent CoA are redefined with parameters specified by information on the candidate MAGs. The authors consider scenarios where the CN has MIPv6 functionality and recognize PMIPv6 messages, and where the CN does not have MIPv6 functionality and mobility support is provided by PMIPv6. Ultimately, the correspondent registration through the above messages is performed before the actual handover hence reducing the correspondent registration latency, which also reduces the throughput degradation due to bidirectional tunneling via the Local Mobility Anchor (LMA), and eventually reducing handover delay.

T. Chiba *et al.* [73] also propose route optimization techniques to reduce handover delay between communicating nodes within the same PMIPv6 domain. Indeed, data path reduction between communicating peers reduces one way packet delay when the LMA is further away. Other route Optimization techniques are provided in [74][75], to mention a few. Route optimization also mitigates out-of-sequence packets as presented in the simulation results in [75].

I. Kim *et al.* [76] propose a low latency handover scheme for PMIPv6 using MIH services. The scheme uses the MIH services to minimize the overall scanning delay at layer 2 during network discovery in IEEE 802.11 wireless networks. Thus, the information service provided by MIH is used to provide context transfers and efficient triggering events to speed up

the handover procedures. The proposed scheme further utilizes the proactive handover ideas of FMIPv6 by employing a buffering technique to reduce packet loss during handover. A tunnel is pre-established between the previous and new MAGs, hence packets that could be lost at the previous MAG are delivered to the new MAG. The scheme is evaluated in a homogeneous environment where a VoIP application was simulated for communication between the MN and CN. However, a combination of techniques from different protocols may complicate handover operations and introduce signaling overhead.

A similar approach is proposed in [41] [77]. However, these schemes utilize the MIH services to reduce the delay due to authentication by utilizing the MIH services. With the assistance of MIH, the MN is pre-authenticated beforehand while it is still connected to the old network and not yet attached to the new network. Only quantitative analysis is provided. Many other proposals such as [78] [79] also use the MIH services to reduce different aspects of the handover delay components. The proposals generally involve the activation or initiation of handover-related procedures and/or tunnel pre-establishment to the target networks during the handover preparation phase. Consequently, these procedures are not performed during the actual handover, and hence effectively reduce the handover delay and packet loss. However, by its definition, the MIH services introduce extra signaling messages and add complexity in the MN, which may add some delays.

H. Yokota *et al.* [80] propose the integration of PMIPv6 and FMIPv6 with the aim of improving handover performance of PMIPv6 in terms of handover delay and packet loss. This approach introduces the proactive signaling deliberations with the candidate network while the MN is still in the old network. The mechanism does reduce handover delay and packet loss but requires considerable modifications to FMIPv6 to enable adaptation to network-based mobility management.

J. I. Kim *et al.* [81] utilize multicasting to reduce packet loss hence ensuring soft handover in a PMIPv6 domain. The MIHF services are utilized to provide a link-layer trigger mechanism. The authors investigate handover performance metrics such as handover delay, packet loss, and throughput. Simulation results show that the dropped packets are reduced, and the handover delay is minimized. This mechanism requires proper control to ensure that it is efficient in terms

of network resources. Thus, the multicasting duration must be kept to a minimal.

A seamless handover scheme for PMIPv6 using smart buffering is proposed in [82]. The scheme prevents packet loss by proactively buffering packets that will be lost in a current serving MAG by harnessing network side information. In this scheme the new MAG has to execute a discovery mechanism to discover the previous MAG especially when the previous MAG also has buffered packets which might have to be forwarded to the new MAG where the MN has attached. In addition, the scheme introduces a network-side prediction mechanism to facilitate faster handover. The authors address the usual excessive buffering challenge by limiting the buffering time based on the expected disconnection time during handover. Simulation results show that the proposed smart buffering scheme has a shorter handover time than standard PMIPv6.

P. Taaghoul *et al.* [83] introduce a forward authentication function (FAF) element in PMIPv6 mobility-managed heterogeneous networks to reduce handover delay due to authentication during vertical handover between mobile WiMAX and 3GPP networks. The handover mechanism utilizes single-radio to ensure that the MNs do not need to support simultaneous transmission on both WiMAX and 3GPP accesses, hence mitigates the RF coexistence issues that exists otherwise and improves handover performance. The proposed optimized handover mechanism employs the FAF to authorize the MN access to the new network (3GPP) and prepare the appropriate resources while the MN is still on the old network (WiMAX). Thus, from the 3GPP access network perspective, the FAF emulates a simplified radio network controller or base station, while from the WiMAX access network perspective; it emulates a mobile WiMAX gateway, ASN-GW. Ultimately, the FAF pre-performs authentication-related handover procedures in the candidate on behalf of the MN, thus reducing the signaling steps during the actual handover. If the FAF collocates with the Access Network Discovery and Selection Function (ANDSF), as suggested by the authors, other necessary information for handover (e.g. carrier frequencies of the candidate network) can be received by the MN via a secure connection. Thereafter, pre-registration procedures can be undertaken. Thus, in effect, there is coordination between the MN and FAF/ANDSF, which are located at the source network about the imminent handover and how it should be facilitated or handled.

2.4 Handover Coordination

Handover coordination may be defined as a technique that typically employs a specific entity or entities to handle or communicate handover issues during mobility events among networks. These entity(ies) exchange handover-related signaling messages to ensure that the handover is coordinated between the relevant network elements to facilitate the respective procedures to handover.

2.4.1 Typical Handover Coordination Mechanisms

YS Chen *et al.* [84] propose a handover protocol leveraging PMIPv6 to reduce handover delay and packet loss. The protocol relies on the assistance of relay nodes over LTE networks. For relay node discovery, the proposed protocol extends the access network discovery and selection functionality (ANDSF) in 3GPP specifications to help the MN to obtain the information of the relay nodes. With the assistance of the relay nodes and ANDSF, which facilitate the coordination of the handover, the MN performs the pre-handover procedures including the security operation and the proxy binding update to significantly reduce the overall handover delay and packet loss. Moreover, the relay nodes forward the packets to the new network during the handover period, where the MN receives them after attachment. The simulation results illustrate that the proposed protocol achieves performance improvements in handover delay and packet loss

YS Chen *et al.* in [85] [86] further propose a similar handover approach to [84] where they use a partner node called a partner station (PS) to perform CoA configuration and DAD operations on behalf of the MN in the new network before the MN initializes the handover request. In essence, the PS coordinates the facilitation of handover procedures ahead of time. This mechanism leverages HMIPv6. The PS in this proposed fast handover protocol, called P_HMIPv6, has relay capabilities and is a *static* mobile station, which facilitates CoA configuration and DAD operation only when it (PS) is at the cell edges. The analysis and simulation results show that the mechanism reduces handover delay.

In fact, the general idea behind YS Chen *et al.* [84] has some similarities with our

proposed work as will be discussed in the next chapter. However, in their work, just like in [85] and [86], more functionality needs to be added in all MNs to ensure that they can also perform as PSs. This requirement adds complexity in the MN and induces more signaling overhead in the air interface. More so, before a *static* MN performs as a PS it needs to exchange signaling messages with the relevant base stations as well as the MN that requires the seamless handover assistance. Also, another requirement of a MN to perform as a PS is that it must be located in the boundary of the neighboring base station coverage at the time and must be static. Thus, if at any given time there is no PS located at the boundary of networks, a MN in one network that wants to hand-over to another network will not be afforded any seamless handover support.

The idea of using relay nodes in future generation wireless networks has been discussed in various works such as [87] [88] [89], and has proved to significantly increase the high data rate coverage of base stations. Thus, the concept of using relay nodes was not originally meant for assisting in seamless handover approaches but mainly as solutions for radio range extension in mobile and wireless broadband cellular networks, solutions to combat shadowing at high radio frequencies, and as means to reduce infrastructure deployment costs [88].

S. Cho *et al.* [90] propose a relay-assisted soft handover mechanism, which has some similarities with one of our proposed implementations, in multi-hop cellular networks (IEEE 802.16j). In this mechanism, handover ranging is not required and the association process is significantly simplified because the relay station, which acts as the handover coordinator, is fixed in the overlapping region of the neighboring cells, hence it is not necessary to change a serving node during the handover process. That is, the relay station functions as the serving node for the overlapping cells around the overlapping region. Thus, a MN can make an inter-cell handover across the overlapping region by utilizing the relay station without changing the serving node. The mechanism was developed for horizontal handovers within the same network type, in particular, IEEE 802.16j.

M. S. Bargh *et al.* [91] propose an enhancement of PMIPv6 with simultaneous bindings to reduce handover delay. The work is a proactive network-controlled handover solution that allows some handover processes to be carried proactively while the MN is connected to the serving network. This proposed solution employs the old MAG to act as a handover coordinator

by predicting the handover based on information gathered, yet the real handover might occur later when the MN loses its connectivity. The performance evaluation of the solution shows that the handover delay is reduced while the packet loss due to handover is reduced by appropriately buffering packets at the target access router. However, the authors acknowledge that the earliest packets received at the target router are dropped when the buffer gets full since the size is limited.

Recently, various IETF internet drafts such as [92] [93] [94] [95] exist with proposals to further improve the handover performance of PMIPv6 in terms of handover delay, packet loss, and signaling overhead. These proposals imply or reiterate that the handover delay and packet loss as well as signaling overhead experienced with PMIPv6 approaches are still high for ongoing real-time applications during handovers, and the need for further research in terms of enhancing the handover performance is still strong.

To this end, we propose a network-based handover coordination approach to provide efficient and effective seamless vertical handover that ensures the MN continues to receive near real-time ongoing communications even during the actual handover when the MN is traversing the critical overlapping region of interworking partially-overlapping heterogeneous wireless networks. This is the region where the MN does not receive sufficient signal strength from both the old and new networks, hence does not receive ongoing communications. Instead, the packets are forwarded to the new network, as proposed in most seamless handover solutions, where the MN receives them after handover. Otherwise, the packets are misrouted to the old network where they get dropped.

In fact, most of the previously proposed fast handover mechanisms utilizing the network-based mobility approach, e.g., [83] [96], enhance the mobility management protocols by introducing new functional elements either at the source access or target access, or even both source and target accesses to optimize handover performance in terms of handover delay and packet losses. Thus, the MN stops ongoing communication when it detaches from the old network (i.e., at the cell edges or overlapping region) and only continues with communication when it receives the 'buffered' packets of the ongoing communications when it connects or attaches to the new network after handover.

Therefore, the handover delay and packet loss are still large for ongoing real-time communications. Moreover, the MIPv6-based mobility management protocols generally exploit layer 2 and layer 3 signaling messages sequentially, hence suffer the problems of insufficient handover performance as mentioned above. In fact, it should also be appreciated that mobility protocols do not support seamless handovers, particularly vertical handovers, in their current form. Thus, incorporation of efficient handover mechanisms that effectively coordinate the handover procedures, especially for layer 3, in a non sequential way with respect to those of layer 2 is essential in order to provide seamless vertical handovers across the heterogeneous wireless networks in NGWN. These mechanisms have to further reduce the handover delay and packet loss with minimal signaling overhead in the air interface.

2.5 Summary

This chapter investigated MIPv6 and its extensions, both host-based and network-based, as well as the handover procedures and approaches they employ in handling IP mobility as MNs roam across the wireless networks in NGWN. It was reiterated in this chapter that these mobility solutions, on their own, do not fulfill the requirement of ubiquitous continuity for ongoing communications in terms of ensuring seamless vertical handovers during mobility in NGWN. Thus, different related works that propose to enhance these MIPv6-based mobility solutions to support seamless handovers were reviewed. The reviews basically revealed the need for further research in terms of developing effective and efficient handover mechanisms to further improve the handover performance of these MIPv6-based mobility protocols. Moreover, the performance is still not good enough, especially for ongoing real-time communication. After all, the MIPv6-based mobility protocols are the de facto standards for the envisioned IPv6 NGWN.

Furthermore, this chapter qualitatively discussed the advantages of network-based PMIPv6 over the host-based HMIPv6 and host-based FMIPv6 in terms of handover performance. To support this qualitative discussion, the following chapter verifies, through analytical (quantitative) handover performance models, the benefits of network-based mobility management approach over the host-based approaches, i.e., PMIPv6 over the common MIPv6-based extensions (HMIPv6 and FMIPv6).

The conclusion from the next chapter leads to the formulation of our proposed handover *coordination* mechanism leveraging network-based mobility management to efficiently enhance the handover performance by effectively addressing the above-discussed limitations. Thus, our mechanism proposes to further reduce the handover delay and packet loss while ensuring minimal signaling overhead in heterogeneous wireless networks.

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Chapter 3 Analytical Handover Performance Modeling of MIPv6-based Mobility Management Protocols

This chapter analyzes the handover performance of the MIPv6-based mobility management solutions (HMIPv6, FMIPv6, and PMIPv6) in terms of handover delay and signaling overhead. The analytical handover performance models reiterate that effective and efficient handover mechanisms should leverage network-based mobility management in order to achieve better handover performances. We characterize handover performance in terms of handover delay, packet loss, and signaling overhead.

In other words, this chapter verifies analytically that indeed PMIPv6, a network-based protocol, is a better leverage IP mobility solution in terms of handover performance, i.e., handover delay (hence packet loss) and signaling overhead. This analysis supports and motivates our proposed design of incorporating a handover coordination mechanism in a network-based mobility solution to achieve better handover performance. Therefore, enhancing PMIPv6 with a smartly designed handover mechanism will ensure seamless handover in terms of reduced handover delay, low packet loss, and minimal signaling overhead. Ultimately, transparent handovers to active connections during mobility across heterogeneous wireless networks can be achieved.

3.1 Handover Performance Models

The next subsections mathematically analyze the handover performance of MIPv6, PMIPv6, HMIPv6, and FMIPv6 to model the handover delay and signaling overhead. In addition, we determine the performance model when IEEE 802.21 MIH services are incorporated in the PMIPv6 mobility management framework.

3.1.1 Mobile IPv6

Based on the principle of operation of Mobile IPv6 as discussed in the previous chapter the handover performance model of MIPv6 in terms of handover delay and signaling overhead

can be expressed as the algebraic summation of the involved signaling messages, i.e.,

$$D_{MIPv6} = D_{RS} + D_{RA} + D_{IP_CONFIG} + D_{DAD} + D_{BU} + D_{BA} + D_{AUTH},$$

, where $D_{RS} + D_{RA} = D_{MD(MIPv6)}$ is the movement detection delay, D_{IP_CONFIG} is the IP CoA configuration delay, D_{DAD} is the duplicate address detection delay, $D_{BU} + D_{BA} = D_{BINDING(MIPv6)}$ is the binding update delay, and D_{AUTH} is the authentication delay. Thus, the above equation can also be expressed as

$$D_{MIPv6} = D_{MD(MIPv6)} + D_{BINDING(MIPv6)} + D_{IP_CONFIG} + D_{DAD} + D_{AUTH} \quad (1)$$

It should be emphasized that the binding update messages are always exchanged between the MN and the HA irrespective of how far the MN is from the home network, as well as with the CN if route optimization is employed. Thus, it can be long especially when the MN is in a visited network that is further away from the home network. In the above analytical performance model we have assumed that the MN always sends the RS message when it observes an imminent detachment from the currently attached router in order to facilitate faster handover initiation to expedite handover.

3.1.2 Proxy Mobile IPv6

Figure 3-1 below shows a typical signaling flow during handover to a new MAG or subnet in PMIPv6. We can observe the signaling messages that are involved to ensure successful handovers in the PMIPv6 environment. These messages are exchanged between the relevant network elements (MAG, LMA, and possibly an AAA server) to facilitate the respective procedures for handovers. Notably, in PMIPv6 the binding update messages (PBU and PBA) are initiated and terminated at the MAG, which is in the network infrastructure, as opposed to host-based mobility management schemes such as HMIPv6 (section 3.1.3) where the same signaling is initiated and terminated at the MN, which is usually relatively far from the network infrastructure. Therefore, signaling overhead in the air interface is lower in PMIPv6 than in host-based schemes.

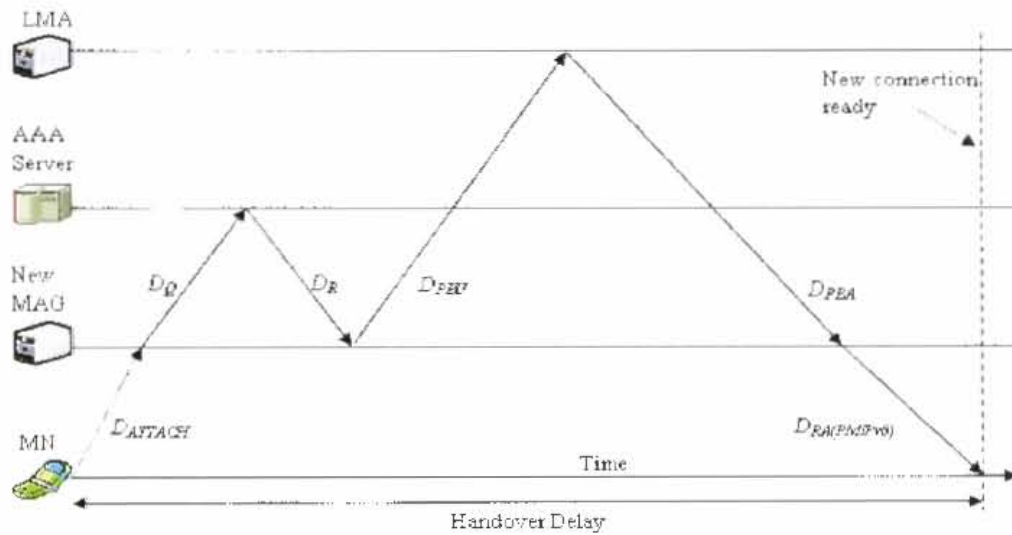


Figure 3-1 Mobility-related signaling flow in PMIPv6.

The handover delay-causing signaling, which facilitates the procedures to handover to the new MAG in PMIPv6 is shown in the above diagram. The round-trip-times (RTT) of these mobility-related signaling messages are easily observed from the above signaling flow. Evidently, the handover delay is due to various essential handover procedures that are facilitated by the above signaling messages. The notation in signaling flow diagram is interpreted as follows: D_X means the delay (D) caused by a signaling message that facilitates procedure X .

D_{ATTACH} : is the attachment notification delay due to the event that informs the new MAG of an MN's attachment. In fact, the MAG tracks the movements of the MN in the access link, e.g. by using a link-layer mechanism, to detect the attachment.

$D_Q + D_R = D_{AUTH}$: the authentication delay (RTT of query(Q) and reply(R) messages) due to the new MAG verifying from an authentication server if the attaching MN is eligible for network-based mobility management service in the subnet,

$D_{PBU} + D_{PBA} = D_{BINDING(PMIPv6)}$: the proxy binding update delay, whereby the new MAG performs binding registration on behalf of the MN (D_{PBU} is the proxy binding update message, D_{PBA} is proxy binding acknowledgement message) to the LMA,

$D_{RA(PMIPv6)}$: the router advertisement (RA) delay, whereby the new MAG advertises the necessary information, some of which is obtained through the PBA from the LMA, for assisting the attaching MN to know its default access router as well as to maintain the same address configuration.

With the PMIPv6 mobility management protocol, IP address configuration and Duplicate Address Detection (DAD) processes are not appreciable especially when the MN is already roaming in the PMIPv6 domain. After all, the Per-MN-Prefix property of PMIPv6, whereby every MN roaming in the domain always gets the same unique network prefix, ensures the same address configuration. Therefore, the Per-MN-Prefix property drastically reduces the probability of ambiguous address configurations. DAD is for checking if another node in the same router access link has not already configured the local address that a newly attaching MN is configuring. Thus, DAD helps to prevent IP address ambiguities. In PMIPv6, these handover procedures (address configuration and DAD) are performed only when the MN first enters the PMIPv6 domain. Thereafter, the obtained network prefix conceptually follows the MN wherever it goes in the domain (Per-MN-Prefix), effectively meaning that the MN maintains the same home IP address configuration.

The handover procedures are inevitable during mobility although optimizing or reducing their impact, i.e., making them transparent to ongoing communication, is necessary to ensure seamless handovers. The various delays experienced due to the exchange of signaling messages that facilitate the handover procedures between MAGs and LMAs in the PMIPv6 domain contribute to the overall handover delay. In fact, the handover delay ultimately augments the end-to-end delay of the ongoing packets hence causing the interruption of active real-time communication that an MN might be having with a CN during the handover period. A long handover delay usually results in high packet loss. This thesis focuses on handover delay due to the IP layer.

Thus, based on the above discussion the overall handover delay in PMIPv6 is the sum of the individual delay components as observed in Figure 3-1:

$$D_{PMIPv6} = D_{ATTACH} + D_{AUTH} + D_{BINDING(PMIPv6)} + D_{RA(PMIPv6)} \quad (2)$$

We assume that $D_{ATTACH} \neq D_{RA(PMIPv6)}$ because the router advertisement (RA) and MN attachment signaling carry different messages hence are bound to encounter different delays. In fact, the RA message is heavier than the MN attachment message since it carries more information, therefore $D_{RA(PMIPv6)} > D_{ATTACH}$.

3.1.3 Hierarchical Mobile IPv6

Figure 3-2 below shows a typical handover signaling flow for host-based HMIPv6 mobility management protocol when an MN moves to a new access router (NAR) or subnet under the same MAP domain.

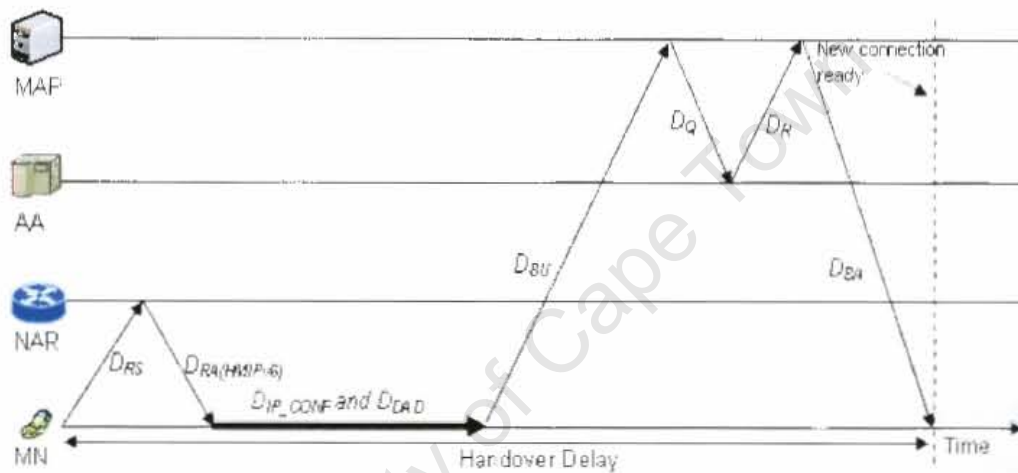


Figure 3-2 Mobility-related signaling in HMIPv6.

Evidently, the MN is directly involved in mobility-related signaling since it initiates and terminates the signaling. Therefore, assuming similar single-level hierarchical network topologies in all the MPv6-based mobility protocols' performance analysis, the binding update time (D_{BU} and D_{BA}) is longer in the host-based mobility management scheme than in the earlier analyzed network-based scheme because of the longer RTT. After all, the MN is normally farther away from its network communicating partner (e.g., MAP) in the context of exchanging binding update signaling, whereas a proxy mobility agent (e.g., MAG) is closer to its network communicating partner (e.g., LMA) than the MN is. Thus, $D_{BINDING(HMIPv6)} > D_{BINDING(PMIPv6)}$, where

$D_{BU} + D_{BA} = D_{BINDING(HMIPv6)}$: the binding update delay, whereby the MN associates its current location with a MAP in the HMIPv6 domain.

$D_{RS} + D_{RA(HMIPv6)} = D_{MD(HMIPv6)}$: the movement detection (or router discovery) delay, whereby the MN realizes that it is leaving the old access router and discovers a new access router (NAR) to attach to. Again, RS and RA do not take the same amount of delay since they carry different messages. In fact, $D_{RA(HMIPv6)} > D_{RS}$.

The movement detection and DAD processes are known to be long and time-consuming operations that can degrade handover performance significantly in host-based mobility management schemes [3]. Thus, unlike in PMIPv6, the HMIPv6 protocol performs IP address configuration anew every time the MN changes IP subnets. Thus, HMIPv6 introduces IP care-of-address configuration delay, D_{IP_CONFIG} , and DAD delay, D_{DAD} .

Furthermore, taking authentication ($D_Q + D_R = D_{AUTH}$) into consideration, the signaling overhead and handover delay experienced in HMIPv6 is,

$$D_{HMIPv6} = D_{MD(HMIPv6)} + D_{BINDING(HMIPv6)} + D_{AUTH} + D_{IP_CONFIG} + D_{DAD}. \quad (3)$$

Notably, from Figure 3-2, the authentication procedure completes before the sending of the binding acknowledgement (BA) to the MN. That is because the admission of the MN at the new point of service (PoS) is subject to authorization and authentication. The authentication is performed with the MN identifier that is contained in the binding update (BU) message.

3.1.4 Mobile IPv6 Fast Handovers

We analyze the handover performance of the predictive mode of FMIPv6. Moreover, predictive FMIPv6 is the most representative mode for fast handovers in mobility management. As observed in the signaling flow diagram in Figure 3-3 below, the handover delay comprises the depicted delay components, which typically includes the authentication delay, $D_{AUTH} = D_Q + D_R$.

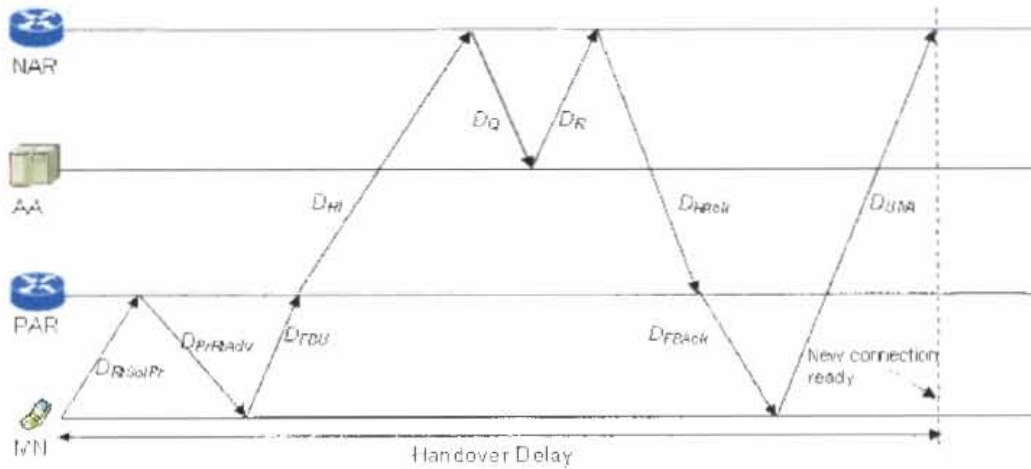


Figure 3-3 Mobility-related signaling in predictive FMIPv6.

Thus, the handover delay in FMIPv6 is given by the algebraic sum of the individual delay components as shown in the following equation. These delay-causing components are as explained in Chapter 2, section 2.3.1

$$D_{FMIPv6} = D_{RtSolPr} + D_{PrRtAdv} + D_{FBU} + D_{HI} + D_{HACK} + D_{FBACk} + D_{AUTH} + D_{UNA} \quad (4)$$

We should highlight that the IP address configuration and DAD delays are avoided in the actual handover in predictive FMIPv6 since they are performed beforehand while the MN is still connected to the PAR.

Again, assuming a single-level hierarchical network topology as in the previous analyses, the binding update delay in the above equation is given by the following expression;

$$D_{BINDING(FMIPv6)} = D_{FBU} + D_{HI} + D_{HACK} + D_{FBACk}$$

, while the movement detection (or router discovery) time is given by

$$D_{MD(FMIPv6)} = D_{RtSolPr} + D_{PrRtAdv}$$

Therefore, substituting into equation (4) we get the following equation to express the handover delay,

$$D_{FMIPv6} = D_{MD(FMIPv6)} + D_{BINDING(FMIPv6)} + D_{AUTH} + D_{UNA} \quad (5)$$

3.1.5 Comparative Analysis of Handover Performance Models for PMIPv6, HMIPv6, and FMIPv6

Assuming that these mobility solutions are applied to similar topologies, i.e., single-level hierarchies, as represented by the signaling flow diagrams in the previous sections, the comparative handover performance analysis is as follows;

We can express the HMIPv6 performance model in terms of PMIPv6 notation as follows,

$$D_{HMIPv6} = 3D_{ATTACH} + D_{RA(PMIPv6)} + D_{BINDING(PMIPv6)} + D_{AUTH} + D_{IP_CONFIG} + D_{DAD} \quad (6)$$

where, based on the principle of operation of the protocols (PMIPv6 and HMIPv6) and the single-level hierarchical network topology we assumed, it follows that,

$$D_{MD(HMIPv6)} > D_{ATTACH}, \text{ and}$$

$$D_{ATTACH} \approx D_{RS} (\neq D_{RA(HMIPv6)} \text{ or } D_{RA(PMIPv6)}),$$

$$D_{BU} \approx D_{ATTACH} + D_{PBU},$$

$$D_{BA} \approx D_{ATTACH} + D_{PBA},$$

$$\text{and } D_{RA(HMIPv6)} \approx D_{RA(PMIPv6)}$$

Therefore,

$$D_{BINDING(HMIPv6)} = D_{ATTACH} + D_{PBU} + D_{ATTACH} + D_{PBA},$$

hence,

$$D_{BINDING(HMIPv6)} \approx 2D_{ATTACH} + D_{BINDING(PMIPv6)}$$

and

$$D_{MD} \approx D_{ATTACH} + D_{RA(PMIPv6)}.$$

Substituting the relevant above expressions into equation (3) in section 3.1.2 and simplifying, we get the above equation (6).

Of note is that the MAG in PMIPv6 only sends the router advertisement (RA) after completing the binding registration with the LMA [30], unlike in HMIPv6 where RA is sent to MN before binding. Furthermore, an HMIPv6 mobility stack has to be added in the MN's protocol stack as opposed to the PMIPv6 scenario where the addition of a mobility stack is not necessary as long as the MN roams within the PMIPv6 domain. The addition of the mobility stack adds complexity and processing delay in the MN while the involvement of the MN in mobility-related signaling adds signaling overhead in the air interface.

Similarly, we can express the FMIPv6 handover performance model in terms of PMIPv6 notation as follows:

$$D_{FMIPv6} = 4D_{ATTACH} + D_{BINDING(PMIPv6)} + D_{RA(PMIPv6)} + D_{AUTH} \quad (7)$$

Note that,

$D_{BINDING(FMIPv6)} = 2D_{ATTACH} + D_{PBU} + D_{PBA} (= 2D_{ATTACH} + D_{BINDING(PMIPv6)})$ if translated into PMIPv6 notation. Again, since we assume similar network topologies (i.e. single-level hierarchies, we can make the following estimations,

$$D_{FBU} \approx D_{RA(PMIPv6)}$$

$$D_{FBACK} \approx D_{ATTACH}$$

$$D_{UNA} \approx D_{ATTACH}$$

$$D_{HI} \approx D_{PBU}$$

$$D_{HACK} \approx D_{PBA}$$

$$D_{RtSolPr} \approx D_{ATTACH}$$

$$, \text{ and } D_{PrRtAdv} = D_{ATTACH}$$

Again, substituting the relevant above expressions into equation (4) in section 3.1.4 gives equation (7) as shown above.

3.1.6 IEEE 802.21-assisted PMIPv6 Handover

However, in predictive FMIPv6, unlike in PMIPv6, some of the handover procedures start while the MN is still connected to the PAR. Thus, the MN gets the CoA in the NAR (subnet) beforehand, hence technically attaching to the NAR. Ultimately, packets are forwarded towards this NAR, where the MN will attach in the near future. Hence, it is safe to assume that $D_{ATTACH} \rightarrow 0$, thus,

$$D_{FMIPv6} = D_{BINDING(PMIPv6)} + D_{RM(PMIPv6)} + D_{AUTH} \quad (8)$$

The above analyses show that indeed PMIPv6 performs better than HMIPv6 in terms of handover delay and signaling overhead, i.e., equation (2) is less than equation (6). However, PMIPv6 performs better than FMIPv6 especially in terms of signaling overhead as can be deduced since equation (4) has more signaling overhead than equation (2), and not necessarily in terms of handover delay since equation (8) is less than equation (2). Thus, FMIPv6 has less handover delay than PMIPv6. Furthermore, FMIPv6 is superior in terms of reducing packet loss because of its forwarding capability through the pre-established tunnel between NAR and PAR. However, the MN complexity increases with FMIPv6 implementation, which effectively induce processing delays and ultimately increasing the handover delay.

Having shown that PMIPv6 generally has better handover performance than its host-based counterparts, handover mechanisms can leverage PMIPv6 to further enhance the handover performance in NGWN in terms of handover delay, packet loss, as well as signaling overhead. After all, PMIPv6's handover delay and packet loss performance is still not good enough for time-sensitive applications [82].

The following subsection demonstrates the above conclusion by utilizing the IEEE 802.21 Media Independent Handover (MIH) services to leverage PMIPv6 to further improve the handover performance, as analyzed in [41]. However, as much as this design reduces handover delay and packet loss, it has a prohibitive trade-off in terms of signaling overhead in the air interface.

3.1.6 IEEE 802.21-assisted PMIPv6 Handover

We briefly discuss the IEEE 802.21 MIH services and then provide a handover design to illustrate the handover performance improvement when the MIH technology leverages PMIPv6. The discussion presents a particular design, which shows that incorporating the MIH services in PMIPv6 mobility management can improve handover performance in terms of reducing some aspects of the handover delay, hence packet loss.

The IEEE 802.21 MIH technology defines information exchanges that provide topological and location related information of service networks, timely communications of wireless environment information to relevant network entities, and commands that can change the state on the wireless link as required. In fact, these services are provided by the Media Independent Handover Function (MIHF), which employs three functional components namely, Media Independent Information Service (MIIS), Media Independent Event Service (MIES), and Media Independent Command Service (MICS).

The MIIS provides static information about characteristics and services of the serving and neighbouring networks. With the necessary information, an MN may discover available neighbouring networks and communicate with elements within these networks beforehand to optimize handovers.

MIES, on the other hand, offers services to upper layers by reporting dynamically changing lower layer events. These services are normally triggered by events which are based on reports on throughput, packet loss, signal strength, etc. of the lower layers.

Finally, MICS is provided to the upper layers to enable them to control and manage the handover-related functions of the lower layers. In fact, the MICS commands are used to execute higher layer mobility and connectivity decisions to the lower layers.

Thus, MIH services provide a report mechanism that conveys useful network status information to entities where a decision is made to cause a command to be executed at some

specific network elements to facilitate seamless handovers. Hence, the handover process is facilitated by the information provided from the network to the MN, in addition to the information that the MN collects from the lower layers. This cooperative information exchange enables handover optimization.

With MIH services, the MN and the PMIPv6 domain network entities, in particular the MAGs in the access routers are informed (via access points or base stations) about the values of the relevant parameters necessary in handover-decision-making prior to the actual handover process. Furthermore, intelligent handover decisions to optimal subnets can be made with collaboration between the MN and the network entities. Thus, the MIH services enhance network discovery, preparation and selection. Therefore, the IEEE 802.21-assisted PMIPv6 scheme [97] exploits the services of the MIHF, in particular MIIS to reduce handover delay, e.g., the access authentication delay-component, which can cause significant delay in network-based mobility management handovers.

Generally, MIH services enable some operations to be performed prior to the handover while the MN is still connected to the old MAG's link. Thus, when the handover is eventually performed, there will be fewer delay-causing procedures executed. For example, the authentication delay is dealt with by enabling the new MAG to pre-authenticate the MN ahead of time.

In the system model shown in Figure 3-4 below, the MN and MAG utilize the MIIS service to know the heterogeneous neighbouring networks' characteristics by requesting from information elements at a centralized information server, which may collocate with a policy store and AAA server. The information (or MIIS) server collocates with the LMA as shown below.

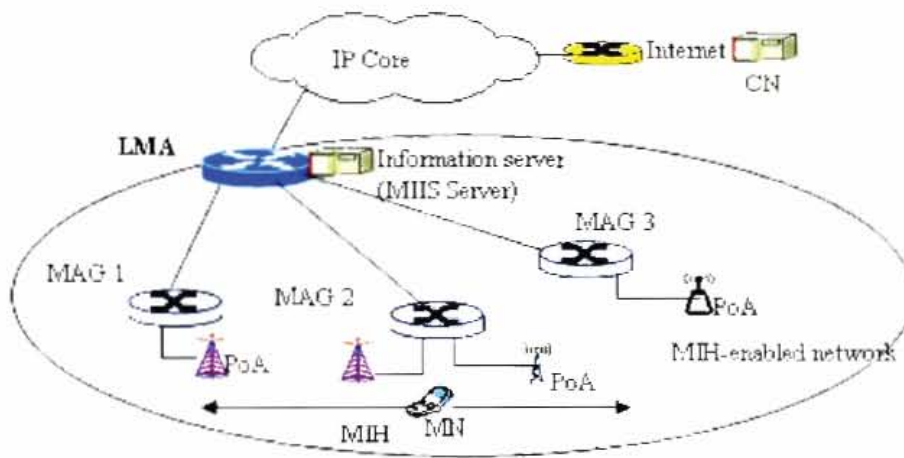


Figure 3-4 IEEE 802.21-enhanced PMIPv6 domain.

The information elements in the server provide information that is essential in making intelligent handover decisions. This information include access network specific information (e.g., network cost, security, QoS capabilities, service level agreements, etc.), point of attachment specific information (e.g., proxy CoA, data rates, MAC addresses, etc.), and other access network specific information.

Dynamic information such as attached MNs' policy profiles together with authentication information and stable identities of the MNs is also included in the information server. Consequently, every MAG in the PMIPv6 domain is always aware of its neighbouring environment by utilizing the MIIS to get information from the common information server.

The MIH services, i.e., MIES and MICS, are triggered by different dynamic events such as the attachment or detachment of an MN in a MAG and varying handover decision-related parameters exceeding predefined thresholds. In particular, the MIES service notifies relevant handover decision engines about imminent handover while also updating the information server. Maintenance of the information server is very feasible since the localized PMIPv6 domain is possibly administered by a single operator or by cooperating service providers.

Assuming a trust relationship between the MAGs in the IEEE 802.21-enhanced PMIPv6 domain, and through the utilization of proactive signaling deliberations via MIH services between the MAGs (on behalf of the attached MNs) and the Information server, a new MAG will

immediately get information, including authentication information, about MNs attaching to neighbouring MAGs. For example, when an MN is handing over from an old MAG (e.g. MAG 1) to a new MAG (e.g. MAG 2), MAG 2 would already be having information about the MN ahead of time through prior deliberations with the MIIS server. On obtaining the information from the server, MAG 2 authenticates the MN ahead of time in anticipation of a handover towards itself (MAG 2) in the near future. Thus, technically the MN is attached (hence, $D_{ATTACH} \rightarrow 0$) to MAG 2 if its service requirements pass some call admission control procedures. However, no resources are reserved until the actual handover happens and the MN has literally attached to MAG 2's link. We assume that MAG 1 has already authenticated the MN and sent the MN's authentication information (with relevant cookies) and policy profile to the information server through MIH services. Moreover, the MN is already in the PMIPv6 domain, where it is receiving as well as sending information to correspondent nodes (CNs) before the handover.

Ultimately, the authentication and attachment notification phases are eliminated from the actual handover process hence reducing handover delay. In fact, the actual handover will not be impeded by authentication and attachment delays. However, the early authentication of the MN may compromise security. Thus, to increase the security provision, the authentication procedure will have to be performed properly once the handover completes and the MN has literally attached to the new MAG. To save resources, once an MN leaves the domain or becomes inactive for a certain predefined period, all its information is deleted from the information server.

Therefore, from the above discussion, we can deduce that the handover delay due to the IEEE 802.21-assisted PMIPv6 scheme significantly enhances the handover performance of PMIPv6,

$$D_{PMIPv6(802.21)} \approx D_{BINDING(PMIPv6)} + D_{RA(PMIPv6)} \quad (9)$$

A typical handover signaling flow for the IEEE 802.21-assisted PMIPv6 is shown in Figure 3-5 below. However, for clarity purposes, the details of the specific involved MIH information and handover message primitives are not shown in the diagram. Instead, they are collectively depicted as 'MIH information updates' and 'MIH handover messages', respectively.

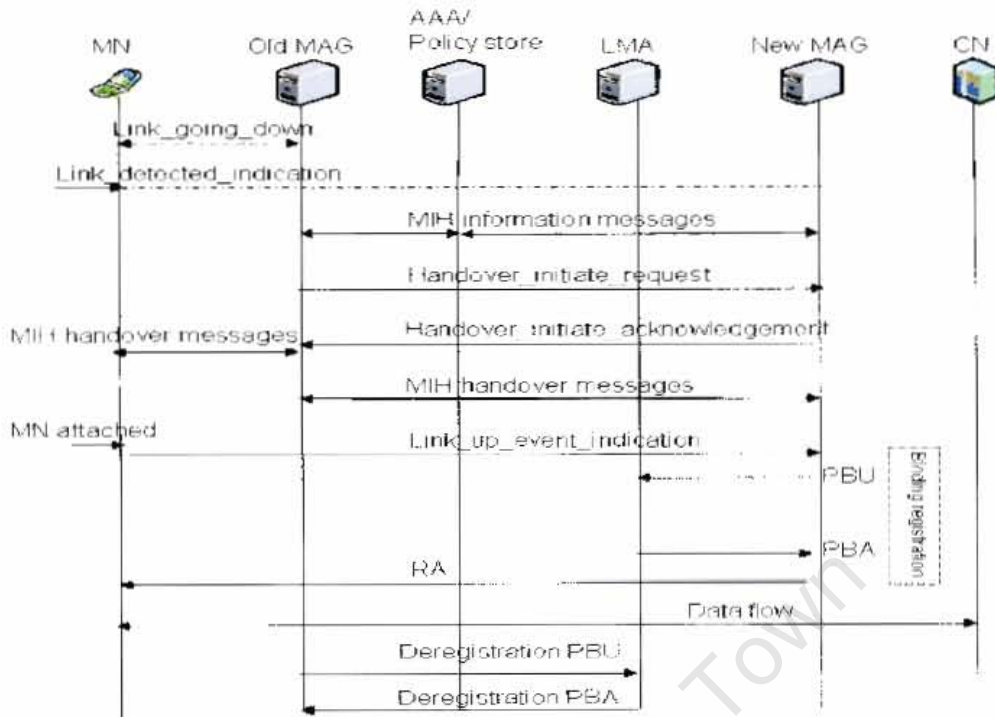


Figure 3-5 Handover procedure signaling flow in IEEE 802.21-assisted PMIPv6.

In utilizing the MIH services, the authentication procedure, for example, is performed in the new PoA while the MN is still attached to its old PoA hence reducing handover delay that normally disrupts real-time service continuity during handover. The PMIPv6 protocol, by definition, reduces the binding update delay. Thus, assisting PMIPv6 with MIH services reduces the handover delay even further. However, as observed in Figure 3-5 above, the signaling overhead in the air interface is sacrificed.

Simulation results that compare the handover performance of IEEE 802.21-assisted PMIPv6 and standard PMIPv6 are shown in Figure 3-6 to Figure 3-8 below.

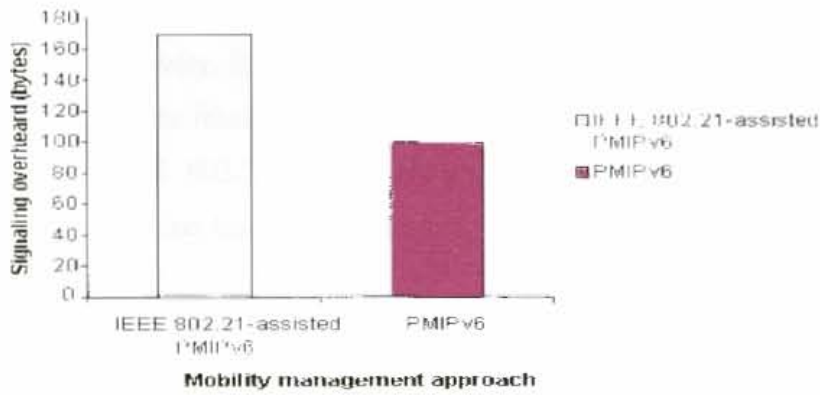


Figure 3-6 Signaling overhead performance of PMIPv6 and IEEE 802.21-assisted PMIPv6.

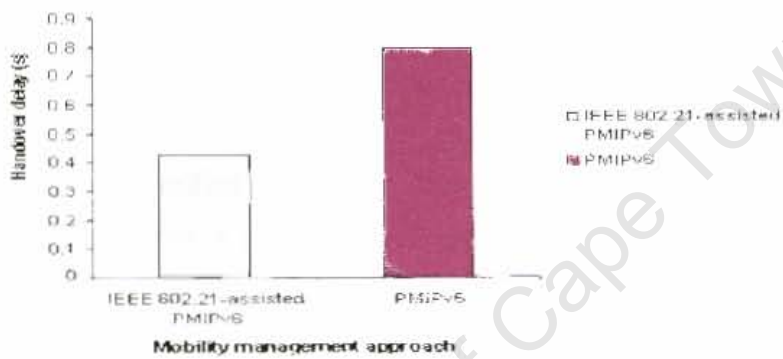


Figure 3-7 Handover delay performance of PMIPv6 and IEEE 802.21-assisted PMIPv6

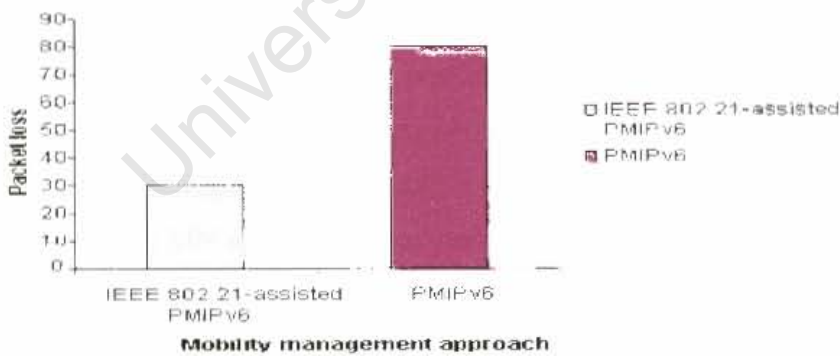


Figure 3-8 Packet loss performance of PMIPv6 and IEEE 802.21-assisted PMIPv6

The above diagrams show the signaling overhead, handover delay, and packet loss performances, respectively, for a MN handover from a WiFi technology network to a WiMAX technology network. The results depict averages of 10 simulations for the respective performance metrics. Indeed, IEEE 802.21-assisted PMIPv6 performs better than PMIPv6 in terms of handover delay and packet loss but compromises signaling overhead.

Having discussed the IEEE 802.21-assisted PMIPv6 scheme, which reduces handover delay and packet loss while trading-off signaling overhead, we introduce a handover coordination mechanism in the following chapter, which leverages PMIPv6 to further enhance the handover performance in terms of further reducing handover delay and packet loss while maintaining minimal signaling overhead.

3.2 Summary

This chapter verified analytically through an algebraic account of individual delay components that PMIPv6, a network-based approach, generally performs better than HMIPv6 and FMIPv6, which are host-based in their mobility management approach, in terms of handover performance. Therefore, PMIPv6 is a suitable leverage IP mobility protocol for better handover performance in terms of further reducing handover delay and packet loss while keeping signaling overhead to a minimal.

The utilization of IEEE 802.21 MIH services to further enhance the performance of PMIPv6 was analyzed and simulated. It was deduced that even though IEEE 802.21-assisted PMIPv6 improves the delay and packet loss performance, the signaling overhead that facilitates the handovers is compromised. The trade-off in signaling overhead is due to the MIIS message exchanges between the MN and the MIIS server or other relevant network entities. Furthermore, the MICS and MIES services add complexity that compromises the processing and battery capacities of the resource-poor MN due to constant local message exchanges, which may introduce some extra delay to the handover latency.

The analyses from this chapter lead to our main proposal, which aims to employ network-based coordination between involved heterogeneous wireless networks to enhance handover

initiation and preparation to reduce the impact of the execution of handover procedures in the context of handover delay, packet loss, as well as signaling overhead.

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Chapter 4 PMIPv6-HC: Base Station Level and Local Mobility Anchor Handover Coordination Designs

This chapter is dedicated to our proposed mechanism, PMIPv6 with Handover Coordinator (PMIPv6-HC), which employs coordination between heterogeneous wireless networks to enhance handover performance of IP mobility management, especially PMIPv6. The chapter starts off by discussing the need for handover coordination. It goes on to highlight the design goals of a handover coordinator (HC), especially in the context of ensuring seamless handovers between heterogeneous wireless networks.

Thereafter, two system designs of the proposed handover coordination mechanism are presented and discussed. These designs are anchored on the PMIPv6 IP mobility management protocol to further enhance the handover performance. Although the system designs differ in terms of architectural implementation, they are both designed to meet essentially the same objectives, i.e., supporting seamless handover between heterogeneous wireless networks in NGWN by further reducing the handover delay and packet loss while keeping minimal signaling overhead. It is worth mentioning that our proposed handover mechanism addresses IP layer handover. Moreover, IP layer handover can be addressed collectively in the context of NGWN since the constituent heterogeneous wireless networks converge at a common IP-based infrastructure. However, link-layer handover is almost impossible to address collectively in the context of the different access technologies in NGWN. More so, link-layer handover is link-technology specific and thus cannot solve the problem of heterogeneity [20]. Lastly, the security considerations as well as limitations of the system models are highlighted.

4.1 Need for Handover Coordination

A challenging problem for coordination within a diverse network environment such as NGWN is vertical handover [98]. IP mobility management protocols enable handovers but do not support *seamless* handovers between heterogeneous wireless access networks in their current form [33]. Yet, vertical handover has to experience negligible delay and negligible packet loss in

order to be seamless. This seamlessness enables ubiquitous continuity to active real-time communication during mobility events.

However, with most of the current IP mobility protocols, the new access router or network to which the MN attaches after handover start the handover procedures (e.g., authentication, binding updates, etc.) only after the detection of the attachment event of the MN. Likewise, the old access router from which the MN is detaching only gets to know about the handover event when the MN is already detaching. Thus, these protocols employ reactive handover approaches, which inherently induce longer handover delay and packet loss. However, this abrupt disconnection from the previous network is not suitable for ongoing real-time or time-sensitive services because it delays the initiation and preparation of the handover procedures. Consequently, the completion of these procedures is delayed and thus resulting in the long handover delay and high packet loss. There is, therefore, lack of timely handover-related coordination between the current network and the candidate network to facilitate seamless handovers.

Coordinating the handover procedures between involved or affected network entities in both the currently attached network and the candidate (new) network, ahead of time, will enhance overall network handover performance in terms of handover delay and packet loss as well as signaling overhead. This coordination enables the respective handover procedures in the networks to be initiated and prepared in accordance with the dynamic conditions of the involved networks, particularly in terms of signal strengths, and hence ensures seamless vertical handovers. More so, the execution of the time-consuming handover procedures ahead of time enables these procedures to run in the background while the MN continues with active connections, which reduces the signaling steps during the actual handover.

FMIPv6 and other proposed protocol enhancements such as [99] and [33] introduce proactive address configuration, adaptation of application sessions, and pre-authentication at the new network to improve handover performance. However, these schemes are host-based hence add excessive signaling overhead in the air interface when facilitating the handover procedures. Furthermore, these host-based protocols and all the other proposed handover mechanisms discussed in related works in the previous chapter do not ensure as real-time as possible

continuity of ongoing communication in the MN during the actual handover when the MN traverses the overlapping region of the interworking heterogeneous wireless networks. In fact, ongoing communication is redirected at the access router of the old network and buffered at the access router in the new network. The communication continues once the MN has fully attached to the new network. The buffering process may result in packet delays as well as packet mis-ordering, which may lead to packet loss.

Thus, handover coordination is needed for several reasons in IP mobility management between heterogeneous wireless networks:

- Vertical handover is demanding and not as straightforward as horizontal handover; therefore the handover procedures have to be performed in a coordinated manner between the affected heterogeneous wireless networks to ensure timely reconfiguration of these networks ahead of the handover.
- To ensure that there are no handover failures by coordinating initiation, preparation, and execution of vertical handovers in all relevant network entities in both the source and candidate networks before the current connection drops.
- To enable sustaining of ongoing communication of the MN during the actual handover as the MN traverses the overlapping region.
- Heterogeneous wireless access networks may require specific handover strategies suited for each access network, thus a common framework is needed to facilitate and coordinate the handover procedures in the diverse network environment in NGWN to ensure seamless vertical migration of active connections.

4.2 Design Goals for the Handover Coordinator

A Handover Coordinator (HC) is the proposed network entity, which interoperates and leverages PMIPv6 mobility management protocol. The HC is responsible for facilitating handover coordination in terms of initiating, preparing, and executing seamless handovers and other relevant signaling between heterogeneous wireless networks in a NGWN domain. Thus, the

design goals of an HC include the following:

- Facilitating the initiation, preparation, and execution of handover-related procedures between the involved networks (current and candidate access networks), ahead of time, to ensure seamless reconfiguration of these networks during mobility.
- Ensuring the reduction of handover delay and packet loss during vertical handovers between heterogeneous wireless networks by effectively and efficiently optimizing the handover procedures of the leverage IP mobility management protocol (PMIPv6).
- Ensuring the MN continues with ongoing communication traffic, as real-time as possible, even during the actual handover when the MN traverses the critical overlapping region of the interworking wireless networks.
- Enhancing transparent terminal mobility between the heterogeneous wireless networks by ensuring that the handover procedures are executed in the background while the MN continues with ongoing communication without realizing the mobility event.
- Ensuring that minimal signaling overhead is maintained in the air interface during the handover procedures.

4.3 Proxy Mobile IPv6 with Handover Coordinator (PMIPv6-HC) System Models

Based on the performance models of the MIPv6-based mobility protocols, our proposed handover coordination mechanism leverages PMIPv6 to further enhance the handover performance. Thus, we develop the handover coordination designs and incorporate them in the PMIPv6 mobility management framework. The main idea behind PMIPv6-HC is to coordinate and facilitate the handover procedures ahead of time between the involved or affected networks to enhance overall handover performance. The proposed mechanism ensures impeccable initiation, preparation, and execution of relevant handover procedures such as the

association/attachment, detachment, binding update registration, authentication, etc. between the source and candidate access networks before the current connection of the MN drops. In effect, handovers are handled in a coordinated fashion and the signaling steps during the actual handover are reduced. Thus, the proposed mechanism eliminates handover delay components such as authentication ($D_{AUTH} \rightarrow 0$), binding registration ($D_{BINDING(PMIPv6)} \rightarrow 0$) as well as the attachment/detachment ($D_{ATTACH} \rightarrow 0$) during the actual handover, while PMIPv6 protocol ensures a stable IP address configuration ($D_{IP_CONF} \rightarrow 0$) for the MN as it roams within the domain. The definition of the delay components is as discussed in Section 3.1.1 in the previous chapter.

Ultimately, abrupt disconnections from the previous network that may cause severe perceptible interruptions to ongoing communication are avoided. Therefore, the analytical handover performance model of our proposed coordination mechanism, PMIPv6-HC, as can be deduced from its *a priori* handling of handover procedures is,

$$D_{PMIPv6-HC} \approx D_{RA(PMIPv6)} \quad (10)$$

The signaling steps during the actual handover are reduced drastically as can be observed in equation (10) above. In fact, the only notable delay and signaling overhead incurred during the actual handover is due to the router advertisement (RA) signaling, whereby the MN is given information by the new MAG. This information helps the MN maintain its address configuration as well as know its default access router as the new MAG in the network. Thus, the network ensures that the MN maintains the same IP address configuration as it roams within the PMIPv6 domain.

The following describes the two system models of the proposed PMIPv6-HC handover coordination mechanism. We discuss these models in terms of their principle of operation, signaling and data paths, as well as limitations and security considerations. These two system models differ in the implementation and location of the HC in the heterogeneous PMIPv6 localized-mobility domain; thus we have **Base Station Level** and **Local Mobility Anchor logical** system models. The Base Station Level HC system model implements the HC as a physical entity with handover-related logical functionalities that is located at the overlapping region of the interworking networks. The Local Mobility Anchor HC system model, on the other

hand, implements the HC as a fully logical entity that is collocated with the Local Mobility Anchor of the interworking networks to facilitate handover-related procedures.

4.3.1 Base Station Level HC Design

Figure 4-1 below illustrates the base-station-level implementation of the handover coordinator (HC) [39].

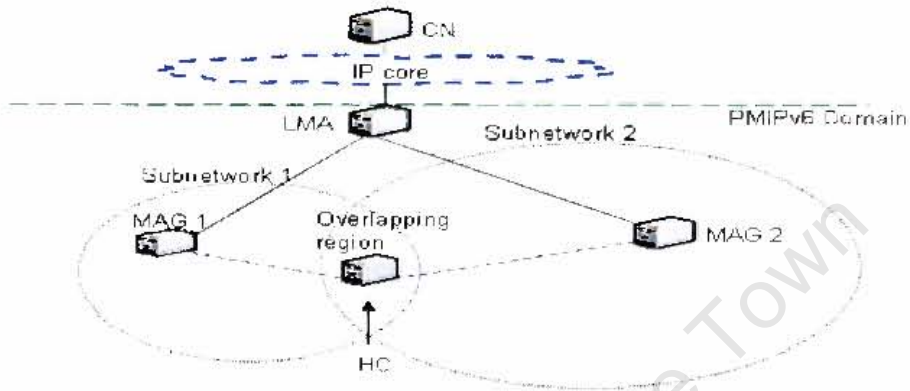


Figure 4-1 Base station level PMIPv6-HC system model.

The HC is an interworking multiple-interface base-station-level entity that has various functions, which help to facilitate the coordination of the seamless vertical handover procedures to ensure negligible handover delay and packet loss for a MN roaming in the heterogeneous wireless environment. The HC's functions include packet relaying, MN tracking in the overlapping region, facilitating MN pre-authentication, as well as timely notification of imminent attachment and detachment events of the MN. The HC executes these functions in coordination with the involved networks beforehand, hence reducing the signaling steps during the actual handover. The reduced signaling steps ensure minimized handover delay and packet loss. The functions of the HC are easily extendable if needed. Figure 4-2 below shows a schematic overview illustrating the interactions of the HC's functional modules.

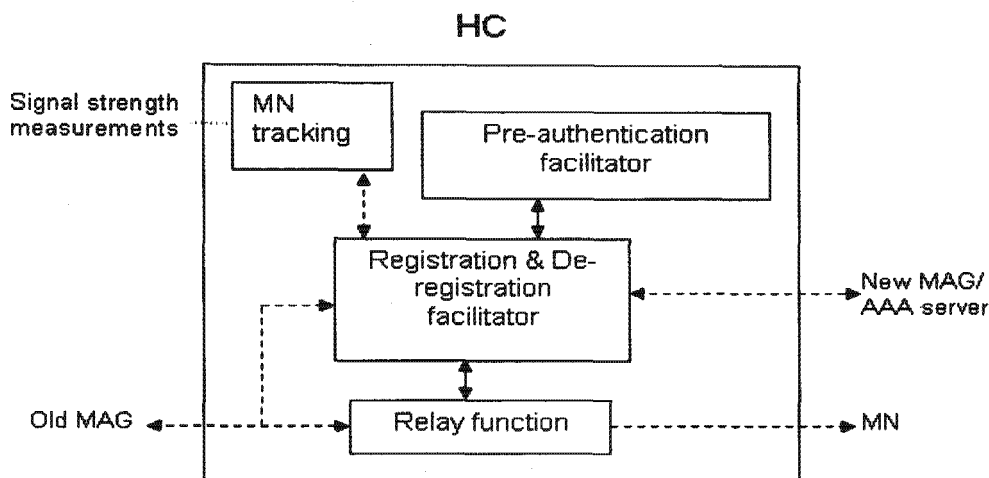


Figure 4-2 Schematic overview of the base-station-level HC.

Generally, heterogeneous wireless networks must overlap, either partially or completely, to enable an MN to maintain ongoing communications, as real-time as possible, as it roams across these networks. Therefore, if the networks have some region of overlap the MN can be reachable through either or both of these networks in the overlapping region. However, the signal strength is normally insufficient for error-free communication in the overlapping region, particularly for partially overlapping networks; more so, this region is at the cell edges where the *free-space path loss* effect is prevalent. Thus, the HC is strategically located in the overlapping region of the interworking wireless networks, acting as some special kind of a relay node with extra functionalities to coordinate handover-related activities between the current and candidate wireless networks. In fact, a relay link is a communication link established between the MN and the HC in the overlapping region, and connection links exist between the MAGs and the HC.

The HC is added to the heterogeneous network environment as a stand-alone entity that provides extra support services related to seamless vertical handover. Therefore, if the HC fails, the networks will still support handovers with the default mobility management protocol albeit with reduced handover performance (we assume that PMIPv6 is already implemented to support mobility between the heterogeneous networks in the domain). The HC essentially facilitates coordination as well as takes part in all handover-related activities within the PMIPv6 domain, and is synchronized with the adjacent MAGs in the heterogeneous wireless networks. The HC is

connected to the MAGs of the overlapping networks through physical connections.

The main objective of this proposed handover design is to reduce handover delay and packet loss while maintaining minimal signaling overhead in the air interface, hence enabling seamless vertical handovers between heterogeneous wireless networks in NGWN.

4.3.1.1 Principle of Operation

With reference to Figure 4-1, we assume that the MN starts from wireless subnetwork 1 and moves linearly through the overlapping region towards wireless subnetwork 2 while having ongoing real-time communication with a fixed CN outside the PMIPv6 domain. Furthermore, the MN connects to the MAGs in the respective subnetworks through Access Points (AP) or Base Stations (BS), but for simplicity, we say the MN connects or communicates with the MAGs, without mentioning AP or BS. We also use network and subnetwork interchangeably.

The following diagram, Figure 4-3, depicts the principle of operation of the base-station-level PMIPv6-HC.

While the MN is within sufficient coverage range of MAG 1 in network 1, packets flow normally from the CN through the LMA to the MN via MAG 1. As the MN enters the overlapping region of the heterogeneous wireless networks, at some point it starts observing a *link_going_down* event with respect to MAG 1. This *link_going_down* event, which is due to deteriorating signal strength, triggers the MN to listen and discover the HC since handover is imminent. Thereafter, the MN sends a handover trigger message through the currently attached network (subnetwork 1) to the recently discovered HC (i.e., Registration & Deregistration facilitator in Figure 4-2), as shown in step 1 in Figure 4-3(a), instructing the HC to coordinate the initiation and preparation of the handover procedures. We call this point *handover trigger 1* (S_{T1}), and is based on a pre-defined signal strength level experienced just when the MN enters the overlapping region of the heterogeneous wireless networks. The overlapping region is the vicinity of operation of the HC. In fact, the HC is carefully configured to sufficiently cover the overlapping region.

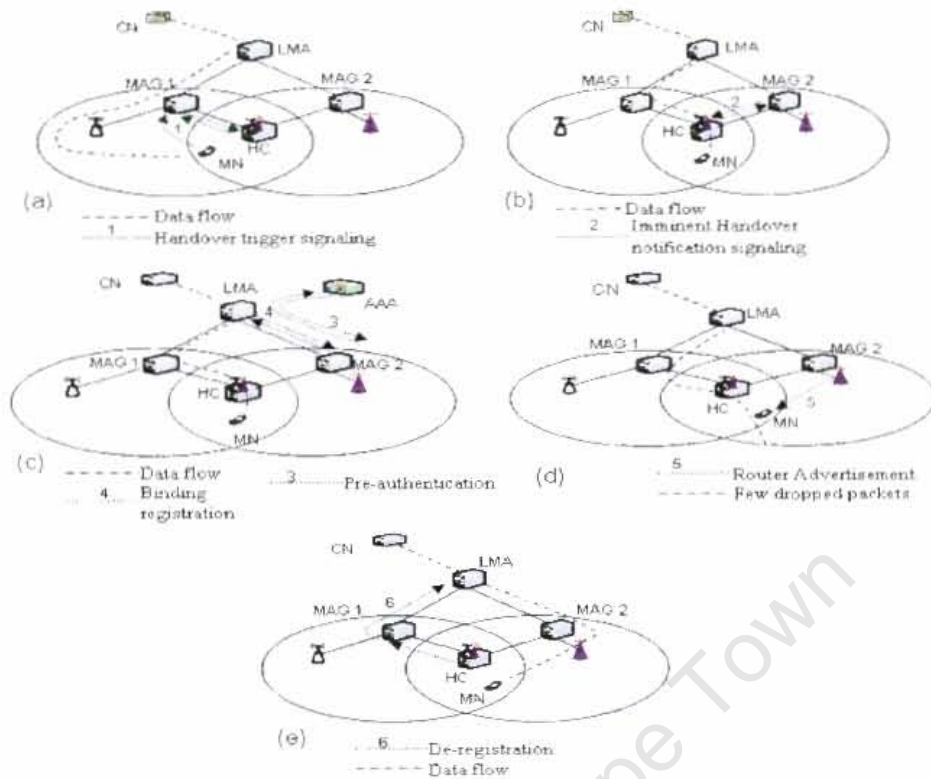


Figure 4-3 Signaling and data paths in base-station-level PMIPv6-HC network.

The MN sends the handover trigger message through the currently attached network (MAG 1) and not directly to the HC to avoid extra signaling overhead and unnecessary delays due to attachment and binding messages that may have to be exchanged with the HC otherwise. In fact, the HC does not actively receive any mobility-related signaling directly from the MN but transmits the usual advertisements as well as relay data packets to the MN. The MN obtains the identity of the HC through the periodic advertisements in the overlapping region. This identity is then included in the handover trigger message sent to MAG 1 by the MN. The identity enables MAG 1 to know which HC to forward the handover trigger message to, in case there is more than one HC. In fact, we can also view the HC (i.e., Relay function in Figure 4-2) as an entity that extends the coverage range of the network to which the MN currently attaches. This coverage range extension enables the MN to continue with ongoing communication in the overlapping region while the handover coordination mechanism facilitates and coordinates seamless vertical handover procedures between the heterogeneous wireless networks in the background.

message. MAG 2 in coordination with the HC (i.e., Pre-authentication facilitator in Figure 4-2) uses the received MN's identity (MN-ID) in the notification message to start pre-authenticating the MN to verify the credentials with respect to using wireless subnetwork 2's resources such as the network-based mobility service: step 3 in Figure 4-3(c). The details of obtaining the MN's profile and performing the AAA services are outside the scope of this thesis.

Subsequently, MAG 2 registers the MN in its binding list entries together with the new proxy-care-of-address (PCoA) to be used by the MN after handover: step 4 in Figure 4-3(c). However, MAG 2 does not immediately update the LMA with the new MN's PCoA. Instead, it updates the LMA after a certain signal strength level has been reached. At this signal strength level, which we call *handover trigger 2* (S_{T2}), MAG 1 is triggered to deregister the MN hence freeing up resources, as shown in step 6 in Figure 4-3(e). This trigger is experienced when the MN is about to get out of the overlapping region and is detecting a *link_up* event with respect to MAG 2. *Handover trigger 2* is similar to *handover trigger 1* except that it is experienced when the MN leaves the overlapping region (i.e., it is with respect to MAG 2) while the latter is experienced when the MN enters the overlapping region (i.e., it is with respect to MAG 1). In fact, *handover trigger 1* timely triggers the initiation of handover coordination in terms of facilitating handover procedures while *handover trigger 2* completes the coordination by, for example, ensuring timely detachment and attachment procedures. These handover triggers are based on predefined signal strength levels and are dynamically coordinated based on the network conditions in the heterogeneous wireless networks at any point in time. The roles of the handover triggers are reversed when the handover is towards the other direction, i.e., wireless subnetwork 2 to wireless subnetwork 1.

Once the MN pre-authentication and binding registrations are complete, MAG 2 acknowledges receipt of the imminent attachment notification message by informing the HC that it is ready for the MN's attachment. The HC receives the acknowledgement and waits until *handover trigger 2* is experienced. Up until this point, the MN is still communicating through its old interface via the HC while the vertical handover procedures happen in the background, as shown in Figure 4-3(c). When *handover trigger 2* is experienced, the HC quickly alerts MAG 1 about the impending detachment of the MN. Thus, MAG 1 fast tracks the deregistration process

of the MN from its binding list entries to avoid abrupt disconnections: step 6 in Figure 4-3(e). Meanwhile, MAG 2 simultaneously updates the LMA with the new PCoA of the MN and subsequently sends the router advertisement to the MN as shown by step 5 in Figure 4-3(d). The LMA completes the tunnel setup to MAG 2. Thereafter, the ongoing communication is redirected smoothly at the LMA towards MAG 2 *en route* to the newly attached MN as seen in Figure 4-3(e). Ultimately, abrupt disconnection that may result in packet loss is mitigated as the MN continues with ongoing communication during the handover period. In fact, the coordination mechanism facilitates the initiation, and preparation of the vertical handover procedures with the respective networks beforehand, ultimately ensuring reduced handover delay and packet loss during the actual handover.

4.3.1.2 Signaling and Data Flow

Figure 4-4 below shows detailed signaling sequence diagram depicting the interactions between the heterogeneous network elements during vertical handover as executed by the PMIPv6-HC base-station-level mechanism. In fact, this diagram is a detailed version of the previous one. The diagram only shows the downstream communication. The exchange of signaling messages before the actual handover facilitates seamless vertical handovers between the networks. S_{T1} and S_{T2} represent *handover trigger 1* and *handover trigger 2*, respectively, while S represents the variable signal strength level.

We can see in Figure 4-4 that even though the MN is not involved in mobility-related signaling, it can still assist in generic mobility functions to facilitate the handover process by providing measurement-related information such as the signal strength levels. Therefore, the MN helps to trigger the HC via MAG 1 to coordinate the handover procedures. It can be clearly observed in the diagram that while the signaling messages are exchanged between the relevant entities, i.e., HC, MAG 2, LMA, and AAA server, the ongoing communication is forwarded and relayed to the old MN interface. In fact, the HC sends pre-authentication and pre-registration trigger messages to MAG 2. MAG 2 and AAA server exchange authentication/authorization messages on behalf of the MN. Furthermore, MAG 2 and LMA exchange the proxy binding messages. All these procedures, as seen in the diagram, are performed in the background.

Thereafter, the communication is swiftly redirected to the new MN interface where the

communication continues after the seamless handover.

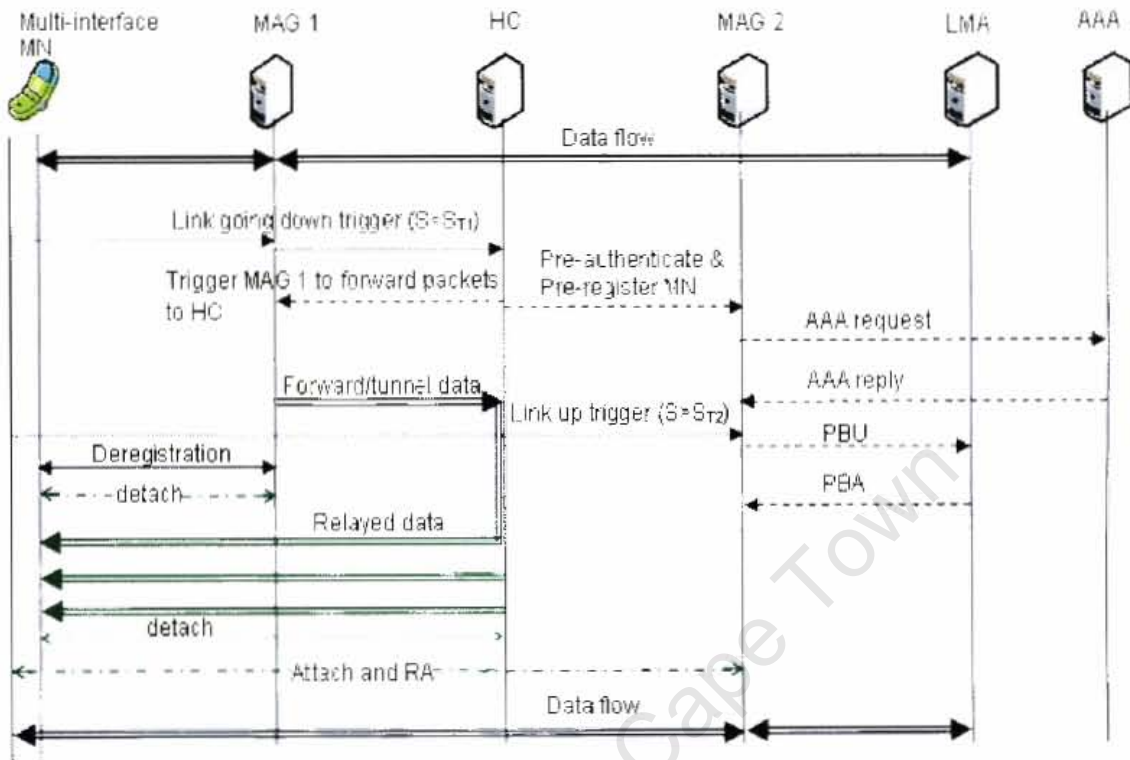


Figure 4-4 Base station level PMIPv6-HC handover signaling flow.

It can be seen from the above diagram that the signaling steps from the actual MN detachment from MAG 1 (or HC) to the attachment to MAG 2 are reduced, hence minimizing the handover delay and packet loss. In fact, only the router advertisement (RA) procedure introduces a meaningful delay during the period of actual detachment and attachment to the respective wireless networks. As mentioned in Section 4.3 above, this RA enables the MN to know its new default access router as well as to maintain its address configuration in wireless network 2. In addition, we observe that the HC does not add signaling overhead in the air interface. More so, it network-based and leverages PMIPv6 functionality.

The relay function of the HC relays ongoing communication between the MAG and the MN minimizing packet loss in the overlapping region of the networks. A typical vertical handover coordination algorithm for PMIPv6-HC base-station-level implementation is provided

in the next chapter.

4.3.1.3 Security Considerations and Limitations

Since PMIPv6-HC is technically an extension of the PMIPv6 mobility management, it leverages PMIPv6 security mechanisms in its operation. PMIPv6-HC is network-based and does not add any security concerns in terms of its coordination of handovers between the heterogeneous wireless networks. In fact, the mechanism does not add entirely new messages but instead piggybacks the extra seamless vertical handover content for facilitating the coordination in the already existing PMIPv6 messages such as the update PBUs.

Mutual authentication between the MN and HC has to be considered since a malevolent HC may compromise the security of the system. Moreover, possible security threats may exist on the interface between the HC and the MN. In addition, mutual authentication between the HC and MAGs is also necessary. A trust relationship between the HC and the MAGs must exist before they exchange messages. However, the HC becomes part of the PMIPv6 domain, hence an authorized entity to send mobility-related messages on behalf of the MN. Thus, an established trust between the MN and the HC must exist. However, we leave the specific details of the actual mechanisms for addressing the security considerations for future work.

In this base-station-level HC implementation, there has to be an HC responsible for ensuring seamless vertical handovers for every partially overlapping region or cell boundaries of heterogeneous wireless networks. This implementation may be more suitable for small-scale interworking heterogeneous wireless networks and appears to have limitation in its use to large-scale network domain. Yet incremental deployment is possible. As the network domain grows, more HC are added to the newly added regions without disturbing the existing network topology.

4.3.2 Local Mobility Anchor (LMA) Logical HC Design

Figure 4-5 below depicts the system model of the logical HC implementation at the LMA in PMIPv6-HC [100].

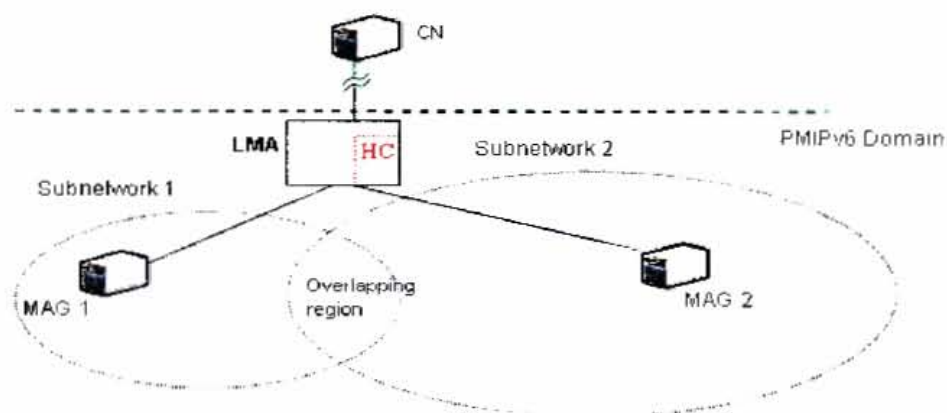


Figure 4-5 LMA logical PMIPv6-HC System model.

The HC is incorporated as a logical entity in the Local Mobility Anchor (LMA) of the PMIPv6 architecture in this handover coordination implementation. The LMA source code is modified to interoperate with the HC entity. Technically, the HC operates in the overlapping region of the interworking heterogeneous wireless networks. Thus, the HC facilitates the handover coordination mechanism when the MN is in the overlapping region.

As mentioned earlier, the PMIPv6 architecture introduces two functional entities in its mobility management criteria: the LMA and the MAG. The LMA operates as a home agent in the PMIPv6 domain while the MAG operates as a proxy mobility agent that performs mobility-related signaling on behalf of the MN. The LMA typically runs in a gateway router while the MAG runs in an access router. The heterogeneous wireless environment in Figure 4-5 above implements PMIPv6 mobility management protocol, which is enhanced with the HC.

A schematic overview illustrating the HC's operational functionality and interactions with the respective network elements in the PMIPv6 domain is shown in Figure 4-6 below.

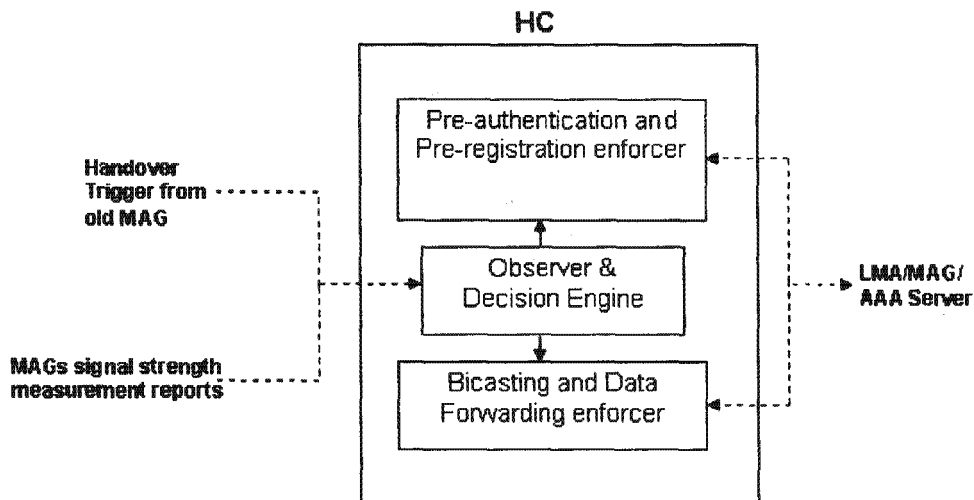


Figure 4-6 A schematic overview of LMA logical HC modules.

The principle of operation of this logical PMIPv6-HC implementation is different from the base-station-level mode discussed earlier. Yet the trigger to initiate the coordination between the relevant elements in the heterogeneous environment is similar. Following is the principle of operation of this implementation mode.

4.3.2.1 Principle of Operation

Figure 4-7 below gives a graphical overview of the principle of operation of logical PMIPv6-HC.

As the MN enters the overlapping region, the currently attached MAG (MAG 1) or the MN experiences a *link_going_down* event when the signal strength falls below a particular signal strength threshold, which implies that a broken link or disconnection is imminent in the near future. At this threshold, the multiple-interface MN momentarily wakes up the other interface(s) to discover or listen for a possible candidate access network to handover to. Subsequently, the MN detects periodic advertisements from MAG 2 that advertise the presence of a new network.

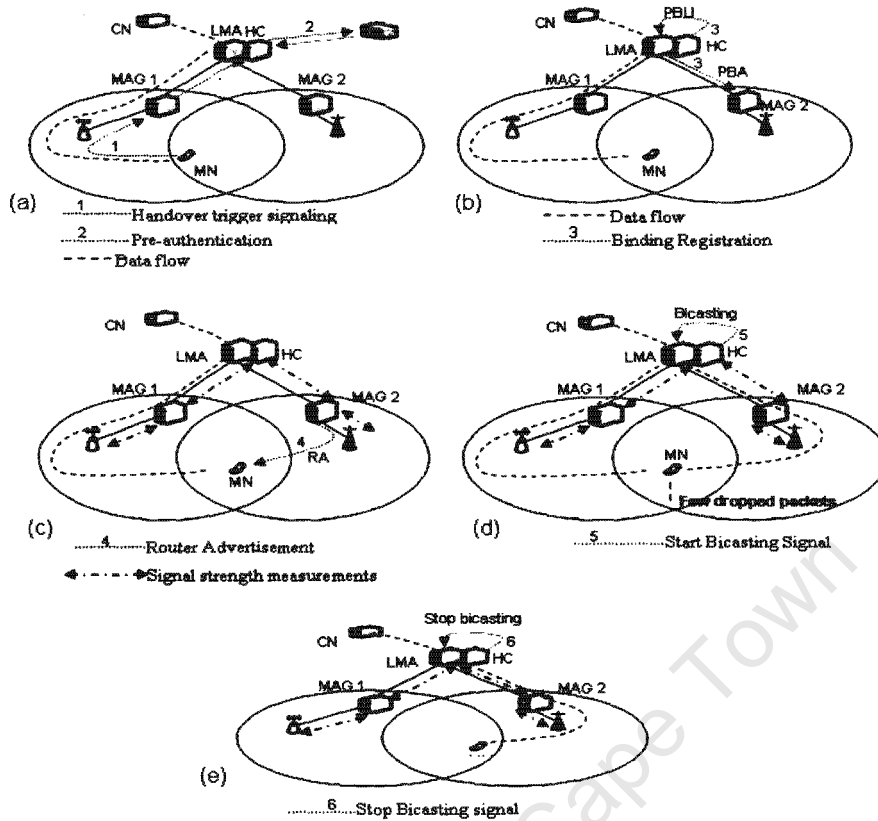


Figure 4-7 Signaling and data path in LMA logical PMIPv6-HC network.

Thereafter, the MN commands MAG 1 to send a handover initiate message to the HC (Observer & Decision Engine (*ODE*) module in Figure 4-6): step 1 in Figure 4-7(a). The handover initiate message alerts the HC about the imminent MN handover. This trigger message contains the identity of the candidate MAG (e.g. MAG 2) that the MN is likely to attach to in the near future. In addition, this trigger serves as a handover hint to the HC. The MN gets MAG 2's ID from the advertisements it receives in the overlapping region. If there is more than one detected MAG, then the ID of the MAG with the strongest received signal strength is sent to MAG 1 as the target MAG. However, any other metric besides the signal strength can be used to select the appropriate MAG to handover to.

The *ODE* module receives the handover trigger message from the MAG 1 and kick-starts the coordination of the relevant HC modules with the respective network elements. Subsequently, the handover procedures are prepared, initiated and executed in the background.

Assuming a trust relationship among all relevant HC modules and the MAGs, on receiving a command from the *ODE* to facilitate handover procedures, the Pre-authentication & Pre-registration Enforcer (*PPE*) creates and sends a proxy binding update (PBU) message to the LMA on behalf of the candidate MAG (i.e., MAG 2): step 3 in Figure 4-7(b). Note that the HC has already received the IDs of the MN and MAG 2 from the current MAG (i.e., MAG 1) through the handover initiate trigger message. Therefore, the *PPE* module is able to create a valid PBU message on behalf of MAG 2. The *PPE* sends the PBU to the LMA in advance while the MN is still attached to MAG 1. However, the *PPE* will coordinate the pre-authentication of the MN between the new network and the home AAA server before the binding pre-registration: step 2 in Figure 4-7(a).

Note that the PMIPv6 domain ensures the MN maintains the same address configuration (Per-MN-Prefix property) as long as it roams in the same domain. However, the proxy care-of-address (PCoA) changes when the MN attaches to a different MAG. The PBU sent to the LMA by the *PPE* module, on behalf of MAG 2, also specifies the interface that the MN will use to attach to the new network. The LMA registers this interface in its binding cache and creates a tunnel towards MAG 2, where the endpoint is the new PCoA of the MN. Some router advertisement information will then be available to MAG 2 to send to the MN accordingly: step 4 in Figure 4-7(c).

The HC (Bicasting and data Forwarding Enforcer (*BFE*)) on command or notification from the *ODE* advises the LMA to bicast subsequent incoming packets to both MAG 1 and MAG 2: step 5 in Figure 4-7(d). This *BFE* receives a command or notification from the *ODE* when imminent loss of signal strength, which can cause perceptible disruption to ongoing communication, is realized due to the *link_going_down* event. Note that the HC has already registered and authenticated the MN in the new access network beforehand, so the MN will be authorized to use the new access network. The reason for bicasting is to ensure that ongoing communication continuity is maintained in the overlapping region. Thus, bicasting mitigates the possible loss of already in-flight packets from MAG 1. Moreover, MAG 1 is losing connection with the MN, and packets are likely to be received in error and hence dropped. Ultimately, because of bicasting, the MN continues with ongoing communication through either MAG 1 or

MAG 2 depending on the stronger signal strength at any point in time in the overlapping region: Figure 4-7(d).

The HC's *ODE* continually monitors the signal strength conditions of the involved networks with the help of the MAGs (BSs/APs) and the heartbeat mechanism for PMIPv6 [101] as long as the MN is in the overlapping region: as seen in Figure 4-7(c). The heartbeat mechanism involves a periodic exchange of messages between MAGs and LMA to check if each party is still in good order. We use these messages to piggyback the network signal-strength information. Thus, when MAG 1 experiences a detachment event (*link_down* event) or MAG 2 experiences an attachment event (*link_up* event) the HC is immediately aware. Thus, the LMA is quickly advised, through setting the relevant flag in the signaling update message, to stop bicasting and use only the newly formed tunnel to forward all the subsequent packets towards MAG 2: step 6 in Figure 4-7(e). We assume that the MN moves linearly from one network to another without any 'ping pong' scenario. The *link_down* and *link_up* events are determined from the signal strength levels with respect to coordinated thresholds between the interworking networks.

Note that the intervention of the HC functionality ensures that the LMA does not wait for the deregistration of the MN from MAG 1 to finish through the usual exchange of 'deregistration' PBU and proxy binding acknowledgement (PBA) messages as is the case in PMIPv6. Instead, the HC initiates the association of the other MN's interface with the new network beforehand, i.e., before the MN's current connection drops. Ultimately, the MN continues to communicate with the CN as it traverses the overlapping region. Therefore, as the MN traverses the overlapping region while still communicating through MAG 1, the handover procedures such as attachment, authentication, and binding registration to the candidate network (MAG 2) begin. These procedures happen without the MN or running services noticing. Thus, the MN transparently continues with ongoing communication. Depending on the relative strengths of the signals from the MAGs with respect to the defined thresholds at the overlapping region, the MN continues to receive error-free packets through either MAG 1 or MAG 2. Ultimately, the MN will always be communicating at any point in time during the handover. Thus, the vertical handover will be transparent to the ongoing communication. More so, the

handover delay-causing procedures happen in the background. Furthermore, the duration for keeping the MN's interfaces simultaneously switched on at the overlapping region is kept to a minimal by the carefully controlled bicasting technique. Ultimately, unnecessary power consumption and possible interference from radio frequency coexistence are avoided.

4.3.2.2 Signaling and Data Flow

Figure 4-8 below shows a different representation of the previous diagram (Figure 4-7) in a signaling sequence form. Thus, the interactions between the different elements in this LMA logical PMIPv6-HC mechanism are clearly depicted.

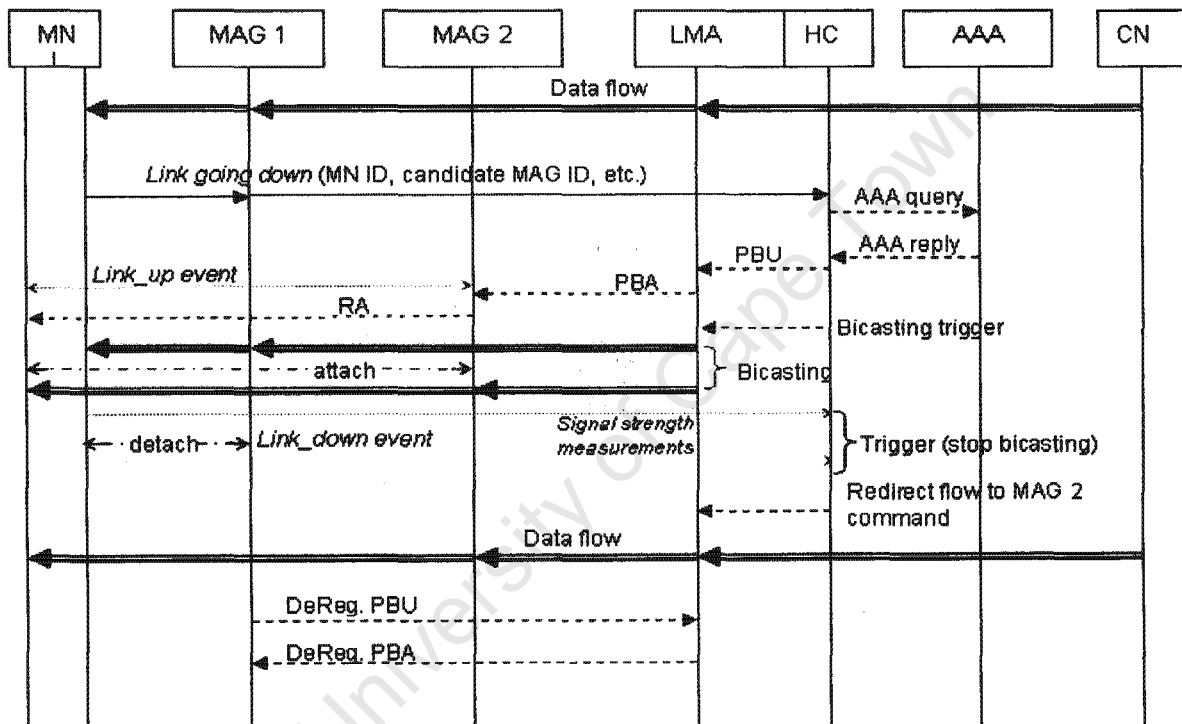


Figure 4-8 LMA logical PMIPv6-HC handover signaling flow.

We can observe that Figure 4-8 shows a sequence diagram depicting the principle of operation of the LMA logical PMIPv6-HC system model. Again, we can deduce from the above diagram that the MN continues to receive ongoing communication while the handover procedures are happening in the background. In fact, as the *link_up* event with respect to MAG 2 is detected in the overlapping region, the bicasting technique in the HC is triggered. Furthermore,

with the relevant signal strength measurements the bicasting duration is controlled, hence ongoing communication redirected only to the newly attached network as shown in the above diagram.

4.3.2.3 Security Considerations and Limitations

LMA logical PMIPv6-HC design implementation leverages PMIPv6 for signaling and communication. We therefore advocate that the same security considerations as in standard PMIPv6 are applicable. Thus, security threats in logical PMIPv6-HC are addressed as suggested for standard PMIPv6. In fact, since the HC is implemented as a logical functional entity extension at the LMA, it inherits the security benefits and flaws of the LMA as defined in PMIPv6.

The security considerations in PMIPv6 include threats to the interface between LMA and MAG, as well as threats to the interface between MAG and MN. These threats involve LMA impersonation, MAG impersonation, MN impersonation, and Men-in-the-middle attack.

However, threats related to impersonation of the HC must be addressed by protecting the signaling messages exchanged between the HC and LMA/MAG by IPsec using the established security association between them. Moreover, the HC also has the privileges of the LMA in terms of having an overall overview of the network topology in the domain. However, the specific details of the actual mechanisms for addressing the security considerations are left for future work.

Generally, bicasting wastes network resources if not properly controlled, particularly if the data packets are sent to networks that the MN is not likely to attach to. However, in our mechanism, bicasting is carefully controlled through the ahead-of-time coordination nature of the mechanism, which ensures that the packets are bicast to the network that the MN is currently connected to, and the target network. Hence the bicasting is employed very briefly especially during the critical range in the overlapping region to ensure negligible packet loss during the handover, which ensures seamless vertical handover.

4.4 Summary

The chapter proposed a seamless handover coordination mechanism, PMIPv6-HC, which leverages PMIPv6 to further enhance the handover performance in the context of reduced handover delay, low packet loss, and minimal signaling overhead during mobility between heterogeneous wireless networks.

This chapter presented and discussed the two system models of the proposed handover coordination mechanism. In addition, the schematic diagrams of the HC implementations as well as the interactions between the functional components were presented. Since the PMIPv6-HC mechanism is network-based and leverages PMIPv6 security mechanisms it does not add any security concerns. Moreover, it does not introduce completely new signaling messages. Instead, this mechanism piggybacks the necessary information for coordination in the already existing PMIPv6 signaling messages.

The next chapter discusses the implementation and simulation issues of our proposed handover mechanism.

Chapter 5 Implementation and Simulation of Handover Coordination Designs

This chapter discusses the implementation and simulation of the proposed handover mechanism. Simulation is used to investigate the proof-of-concept of our mechanism for many reasons; simulation is cheap yet allows for easy testing of complex scenarios, and it allows for testing of many ideas in a short time period while enabling results to be obtained quickly. Furthermore, simulation enables controlled experimental conditions hence repeatability, which helps debugging. However, it does not fully support the actual modeling of real systems.

The chapter starts by briefly introducing the simulation environment, i.e., the network simulator, NS-2 [102], which we use for the implementation and evaluation of our proposed handover mechanism. The focus of the introduction of the network simulator is mainly an overview in the context of the simulator's wireless and mobility modeling capabilities, the limitations related to the implementation of our system models as well as the workarounds to mitigate these limitations.

Thereafter, the chapter gives the overview of the performance evaluation framework in terms of the simulation environment setup, network topologies, scenarios, assumptions, and related parameter settings. In fact, this chapter discusses all implementation and simulation issues.

5.1 Simulation and Implementation Environment

We used the NS-2 discrete-time event simulator as the platform for the implementation of our proposed handover mechanism. More so, NS-2 is a popular network simulator that covers a very large number of applications, protocols, network types, network elements, and traffic models. NS-2 is an open source discrete network simulator that is written in C++ and object-oriented Tcl (OTcl) interpreter. C++ is used for protocol implementation while OTcl (or simply Tcl) is used for simulation configuration and topology definition. NS-2 supports closely related class hierarchies in both C++ and Tcl. Therefore, a class in C++ and a class in Tcl appear as one-

to-one correspondence from the user's perspective. In fact, users create and instantiate new simulator objects, e.g., the network topology, the specific protocols, and applications to simulate, through the interpreter. These objects are then closely mirrored in the C++ compiled hierarchy [103].

Figure 5-1 below depicts the generic model structure of NS-2 as briefly described above, particularly to illustrate the one-to-one correspondence (split objects) of the class hierarchies.

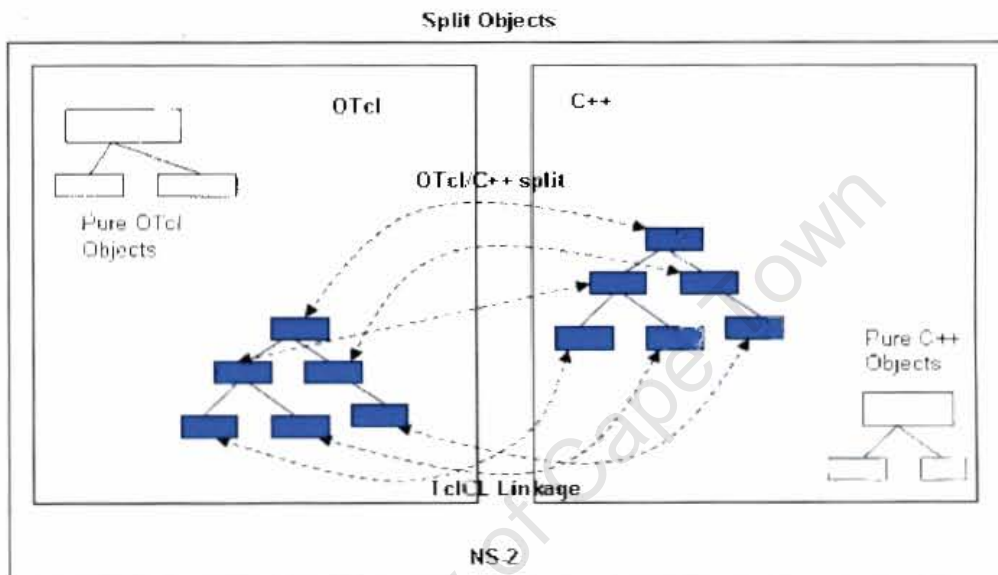


Figure 5-1 Split Language programming illustration in NS-2.

Since NS-2 is open source, the research community constantly improves the scope of the capabilities of this network simulator by contributing different protocols and modules. Thus, NS-2 is easily extendable through modifying the source code and building modules that suit one's needs. It is widely used for networking related research and free support is readily available hence our choice of this network simulator.

5.1.1 Wireless and Mobility Modeling in NS-2

The MobileNode object (which is a split object since it is implemented in both C++ and Tcl) is at the core of the wireless model of NS-2, with additional supporting features that allow simulations of WLANs, WWANs, ad-hoc networks, etc. Therefore, this MobileNode object is

the basic NS-2 Node object with extra functionalities such as the ability to move around a given topology, the ability to transmit and receive signals to and from a wireless channel, etc. [103]. To afford these capabilities, the MobileNode network stack is constructed with components such as the Channel, Network Interface, Radio propagation model, Medium Access Control (MAC) protocol, Interface Queue (IFQ), Link Layer (LL), and Address Resolution Protocol (ARP). Since NS-2 uses two languages, the mobility features of this MobileNode object which include node movement, periodic updates, etc. are implemented in C++ while the network stack plumbing of the components, i.e., the MAC, LL, Channel, etc. is implemented in Tcl. Ultimately, the implementation of the MobileNode object enables support for wireless and mobile communication in NS-2. The MobileNode object does not connect by means of physical links to communicate with other Nodes but instead, it has defined routing mechanisms and protocols over and above its network stack that allow for wireless channel access.

5.1.2 MobileNode Architecture: Design, Limitations and Workarounds

Figure 5-2 below shows the original MobileNode architecture developed as an extension to NS-2 by the CMU Monarch group in the late 1990's. The purpose of this extension was to enable simulation of wireless networks [104]. As explained earlier, the MobileNode architecture has a chain of modules emulating the different protocol stack entities that any real-life network host has; LL, MAC protocol, Routing Agent, ARP, IFQ, and Network Interface. Thus, incoming packets to the MobileNode go up this chain of modules (protocol stack) to the sink agent (i.e., the application destination), while outgoing packets leave the source agent (i.e., the application source) and go through the routing agent and down the protocol stack where they are finally transmitted onto the wireless channel. However, this CMU Monarch MobileNode object implementation does not support multiple wireless interfaces on a single node, and makes it very difficult or even impossible to implement such a feature. Thus, a workaround is required to enable simulation of multiple-interface mobile nodes (MNs) in NS-2.

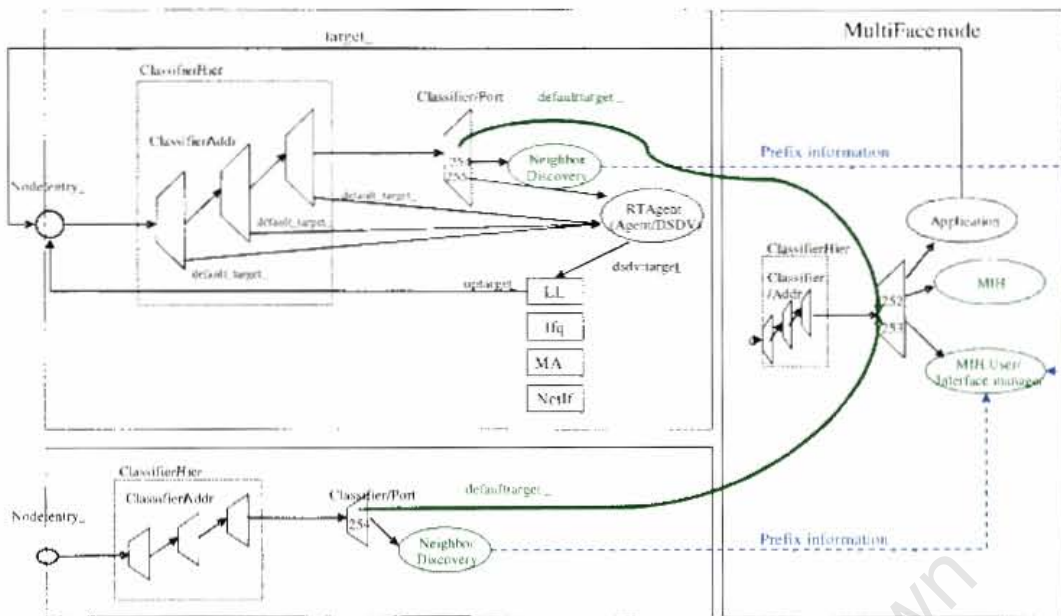


Figure 5-3 NIST Multiple interfaces node design [106].

We can observe in Figure 5-3 that the MultiFace node is a virtual node linking nodes of similar or different technologies, where these linked nodes are considered the interfaces for the MultiFace node. These interface nodes implement neighbour discovery functions (for layer 3 movement detection) that receive router advertisements which, based on the network prefix, determine if layer 3 mobility has occurred or not. The neighbour discovery mechanism then sends notifications to an interface manager, which is implemented in the virtual MultiFace node. The interface manager handles the handovers by redirecting application flows to the relevant interface node during handovers. That is, a mobility management protocol triggers the interface manager to execute the handovers between the heterogeneous wireless network technologies. In particular, the MultiFace node implementation incorporates a generic mobility management protocol, e.g., MIPv6 that is implemented as a Media Independent Handover (MIH) user in the node. Furthermore, a prerequisite to effectively using this NIST MultiFace node implementation in a simulation environment is that the correspondent node (CN) should support flow redirection functions through implementing a default interface manager. The implementation and functioning of the default interface manager requires the CN to receive all relevant signaling messages from MIPv6 or any implemented host-based MIPv6-based protocol in the MultiFace

node.

However, our proposed handover mechanism design is based on PMIPv6, which is a network-based mobility management. We extended the PMIPv6 simulation model developed in [107]. Thus, the NIST implementation of a multiple-interface MN in the form of MultiFace node does not suit our design requirements. For example, in our handover mechanism we require the LMA and/or MAG to perform the packet redirection for handover purposes without the CN being aware of the mobility of the MN. We do not intend to determine what the CN should implement as a prerequisite in order to enable support for MN's seamless mobility. In fact, the CN should be independent and transparent of the mobility of the MN.

To work around the limitation of the NIST MultiFace node design in the context of the requirements of the multiple-interface MN for our model, we superimposed two basic MobileNode objects of different wireless technologies to simulate a single MN (i.e., multiple-interface MN) with two interfaces of different network technologies. We then linked or associated these interfaces with a single stable logical identity that identifies the multiple-interface MN. This identifier is the one that the MAGs acquire during MN attachment for the purposes of facilitating handover activities, e.g., authentication and authorization, binding registration, etc. In fact, the mobility entities in PMIPv6 use this identifier to identify predictably the multiple-interface MN during mobility. Therefore, the network ensures that the multiple-interface MN will be able to obtain the same global address configuration on any connected interface as it traverses the heterogeneous environment. In fact, this global address configuration can be moved from one interface to the other during vertical handover. Link-layer (i.e., interface) identifiers identify the multiple-interface MN's respective interfaces. The address configuration obtained by the multiple-interface MN obviously includes the address from the home network prefix (Per-MN-Prefix property) and the default-router address on the link. In effect, the packets sent by the CN are always delivered to the same multiple-interface MN through any of the two different interfaces depending on which network the multiple-interface MN is currently attaching. That is, if the multiple-interface MN is in a WiFi network then the WiFi interface is the one that receives packets. Yet if it is in the WiMAX network, the WiMAX interface receives the packets. In effect, we were able to simulate seamless vertical handovers of a multiple-

interface MN between heterogeneous wireless networks in the network-based mobility management domain. The registration of the link-layer identifiers of the multiple-interface MN for the respective interfaces to the relevant MAGs (access networks) was triggered based on the attachment event at the respective MAG as well as link-layer information in the overlapping region of the heterogeneous wireless networks.

Furthermore, with the NIST MultiFace node implementation design, the time for packet redirection to a new interface during a handover is defined in the Tcl environment during network topology definition. Yet, we require dynamic handling of packet redirection to the interfaces (or networks) based on certain link-layer events as explained in the principle of operation of our mechanism. Thus, our workaround to multiple-interface MN implementation came in handy in addressing this limitation.

According to the PMIPv6 protocol, the same network prefix (es) can be delivered to different MN interfaces during handover between PoAs (MAGs) as long as it roams within the same PMIPv6 domain and there is a hint to the LMA about the imminent handover. Therefore, the interfaces of the multiple-interface MN maintain the same global address configuration in the PMIPv6 domain. Thus, in our handover mechanism simulation, we prevent the multiple-interface MN from having all the interfaces switched on at the same time as much as possible because it poses requirements on the battery to handle high peak power. In addition, it also poses requirements on the circuitry of one interface to filter off the strong signals from the transmitter of another interface located so close to the first interface. Thus, the need to handle higher peak power and filter off strong signals results in more complicated design and high cost of the MN [108]. We therefore employ single-radio handover where the multiple-interface MN does not have both transmitters of the interfaces switched on at the same time but can have both receivers switched on.

5.2 Simulation environment setup and network topologies

This research is about enhancing seamless vertical handover between heterogeneous wireless networks in NGWN. For proof-of-concept and performance evaluation of our proposed handover mechanism, we simulated terminal mobility hence vertical handovers between WiFi

(IEEE 802.11) and WiMAX (IEEE 802.16) wireless access technologies. We chose these access networks to test our network-based handover mechanism because of their popularity and high possibility of deployment in NGWN. Moreover, their MAC layers in NS-2 are reliably enhanced by the NIST mobility package extension hence they have minimal errors. Our handover mechanism, however, is applicable to any IP-based interworking wireless networks. After all, the handover design leverages network-based mobility management and employs timely facilitated coordination between the interworking networks to manage and handle vertical handovers ahead of time.

In the simulation of the vertical handovers between the interworking WiFi and WiMAX networks, the multiple-interface MN moves linearly across the overlapping region from WiFi to WiMAX and then back to WiFi, thus experiencing vertical handovers in both directions, i.e., WiFi-to-WiMAX and WiMAX-to-WiFi. We carried out many simulation runs with various parameter settings for different MNs' speeds, number of simultaneous MNs' handovers, packet intervals, etc. to observe the effect on important handover performance metrics such as handover delay, signaling overhead, and packet loss on ongoing Constant Bit Rate (CBR) traffic over UDP. However, based on the investigation requirements for the different handover metrics as well as the mobility management criteria, we configured different MN settings and network topology parameters, even though the general network topology remained essentially the same in all the cases for comparison purposes. For example, since we have two system models for our proposed handover mechanism, parameters were set according to the particular system model environment requirements.

The WiFi network was configured for a coverage radius of 50 meters (m) while the WiMAX network was configured for 1000 m coverage radius on a 3000 m by 3000 m area in the NS-2 platform. The overlapping region of these heterogeneous wireless networks was initially 25 m for most of the simulations. However, this overlapping coverage was later varied to observe the effect it has on the handover performance of our proposed handover mechanism in the context of packet loss and handover delay.

Next is the discussion of the network topology, setup, and parameter settings of the proposed base-station-level PMIPv6-HC handover mechanism.

5.2.1 Base-Station-Level HC Implementation

The following diagram in Figure 5-4 depicts the simulated network topology for testing our proposed base-station-level handover coordination mechanism. The topology comprises two interworking and partially overlapping heterogeneous wireless subnetworks, i.e., WiFi (IEEE 802.11b technology) and WiMAX (IEEE 802.16 technology) networks, where the HC is strategically located at the overlapping region with carefully configured settings to ensure that the HC sufficiently covers only the overlapping region.

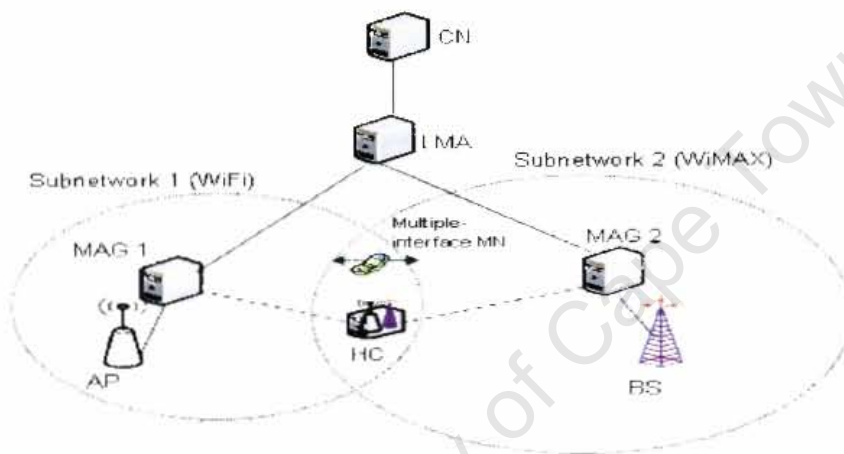


Figure 5-4 Simulation network topology of base-station-level PMIPv6-HC.

For the basic functional operations of the wireless network technologies, we maintained the default simulator parameter settings or configurations as per the respective wireless network technology definition or implementation in NS-2 even though we occasionally adjusted some of these settings to suit our requirements and fulfil our investigations.

The proposed HC entity was strategically located and configured to cover sufficiently only the overlapping region of the interworking heterogeneous wireless networks, and had direct physical connections with MAG 1 and MAG 2. Furthermore, the HC was synchronized with the adjacent MAGs in the WiFi and WiMAX networks. In our implementation of the PMIPv6-HC handover mechanism, we employed a handover anticipation (hint) mechanism based on link-

layer information, i.e., received signal strength, to trigger the operation of the HC. However, any handover prediction algorithm can be employed.

The relay function of the HC, which relays packets to the MN in the overlapping region, ensures minimal packet loss during the vertical handover between the interworking wireless networks. Figure 5-5 below shows the handover coordination algorithm of the base-station-level implementation of PMIPv6-HC. The algorithm is self-explanatory and is according to the description given earlier – Section 4.3.1.1 in the previous chapter. We can observe that the algorithm ensures that ongoing communication between the MN and the CN continues without any perceptible disruptions throughout the handover process.

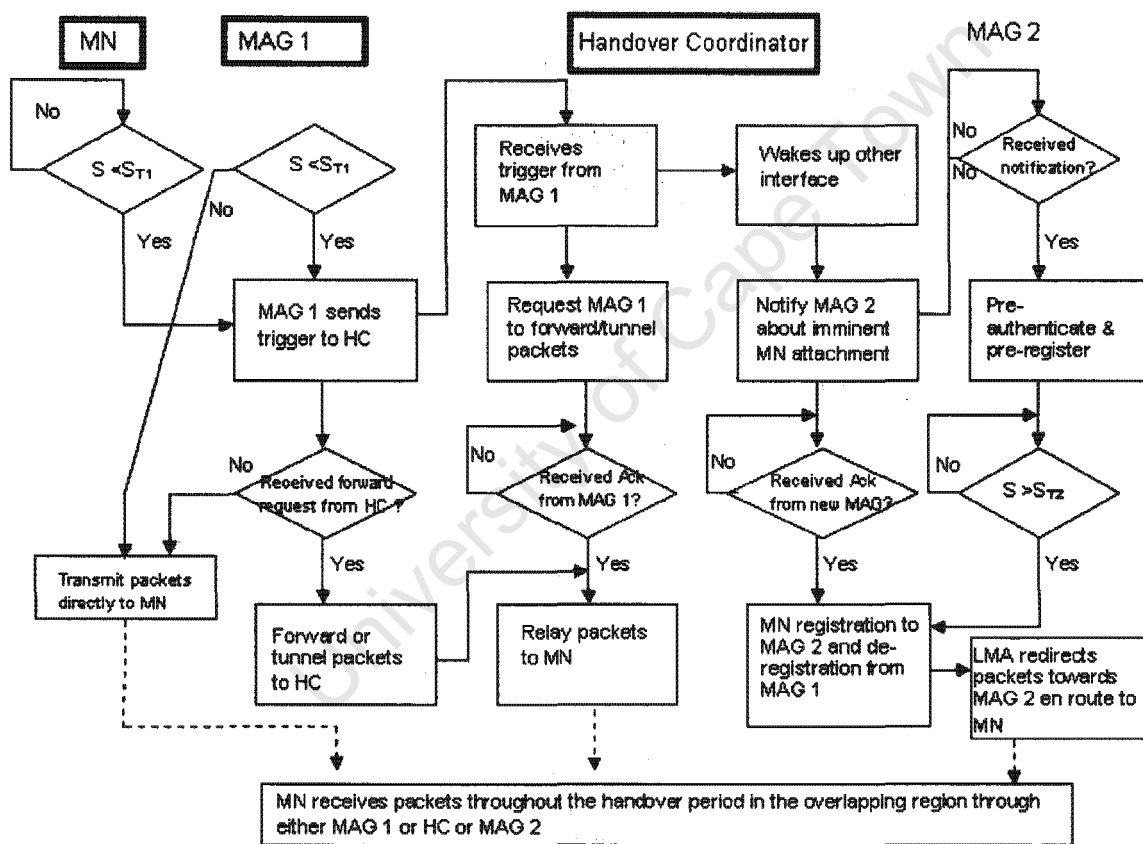


Figure 5-5 Handover algorithm for base-station-level HC.

To simplify the investigation of the handover performance of our proposed mechanism, we only considered unidirectional downstream flow of ongoing real-time communication.

However, since we use Constant Bit Rate (CBR) traffic over UDP for the simulation, as will be discussed below, the handover performance in the context of the upstream flow should be similar.

To simulate real-time traffic between the correspondent node (CN) and the MN we transmitted CBR traffic over UDP. As per PMIPv6, the CN communicated with the MN through LMA and the MAG. For simplicity and consistency in the handover performance investigation, the CBR packet size was fixed at 1000 bytes. The CBR packet interval was either 0.01 seconds or 0.001 seconds to simulate different multimedia traffic types, e.g., audio and video streams. It should be noted that these values were arbitrarily chosen for the purposes of simulation and proof-of-concept, and hence may not apply in real life scenarios.

We simulated the MN to move linearly from MAG 1's domain (WiFi) through the overlapping region (HC's domain) towards MAG 2's domain (WiMAX) then back to MAG 1's domain. This back-and-forth movement enabled vertical handovers to be experienced in both directions: WiFi-to-WiMAX and WiMAX-to-WiFi.

In order to evaluate the handover performance of our proposed mechanism (PMIPv6-HC), we compared it with that of PMIPv6 and FMIPv6 mobility protocols where the HC was not incorporated. We performed the handover simulations of these mobility management protocols in the same network topology and for the same types of traffic and network environment settings. The handover performances were evaluated in terms of packet loss, handover delay, and signaling overhead. The impact of various subsidiary and external parameters on the handover performance metrics was investigated.

5.2.2 Local Mobility Anchor (LMA) Logical HC Implementation

The implementation of logical PMIPv6-HC involved a slight modification of the LMA functionality source code to incorporate and interoperate with the developed HC entity. The following diagram illustrates the simulated network topology for this implementation.

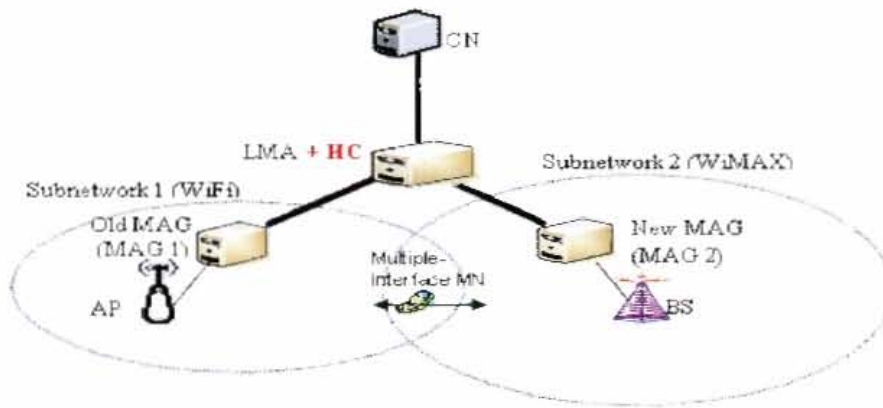


Figure 5-6 Simulation network topology of LMA logical PMIPv6-HC implementation.

The objective of the HC is to facilitate seamless handovers by reducing handover delay and packet loss without compromising signaling overhead in the air interface. Different tests were conducted on the above simulated network topology to investigate the handover performance.

Like in the previous simulation model, an MN was subjected to linear movement from subnetwork 1 to subnetwork 2 while having an ongoing real-time communication with a CN, which is fixed outside the PMIPv6 domain. The real-time communication was simulated with CBR traffic using UDP as the underlying transport protocol. Various external parameters such as the number of MNs simultaneously making handover, MN speeds, coverage range of overlapping region, etc. were varied to observe their effects on handover delay, packet loss, and signaling overhead. Many different simulation runs were conducted. In fact, we investigated 20 handovers, where in each handover the MN transits from subnet 1 (or subnet 2) to subnet 2 (or subnet 1). We then took the average of the performance metric (e.g. handover delay, packet loss, signaling overhead) under investigation, and presented it graphically against some specific variable external parameter. Ultimately, the handover performances of the different mobility management criteria were compared. Thus, each point in the graphs shown in the following chapter represents the average of 20 simulations.

We show and discuss the results of the simulations in the next chapter.

5.3 Summary

In this chapter we explained the simulation framework and implementation of our proposed handover coordination mechanism. We first gave a brief overview of the NS-2 network simulation environment, which we used for implementation, performance evaluation, and proof-of-concept of the proposed mechanism. The overview was particularly in terms of the simulator's wireless and mobility modeling capabilities. The design limitations in the implementation of a multiple-interface MN together with the relevant workarounds that we employed to mitigate these limitations were discussed. We also presented our simulated network topologies as well as mentioned the parameters that were used to investigate the handover performance metrics for the proposed system models.

Furthermore, we highlighted that our simulations are based on single-radio handovers. Thus, the multiple-interface MN can have both interface 'receivers' listening or receiving signaling messages from the respective networks. However, only one interface 'transmitter' sends signaling messages at a time.

The next chapter presents and analyzes the obtained results from the simulations of the two system models of the PMIPv6-HC and compares them with those obtained from PMIPv6 and FMIPv6.

Chapter 6 Handover Performance Results and Analysis

This chapter presents and analyzes the results obtained from the simulation experiments discussed in the previous chapter. The handover performance of PMIPv6-HC is evaluated by comparing with mobility management criteria that do not incorporate the HC, i.e., standard PMIPv6. The performance is also compared with fast mobility management criteria, i.e., the popular host-based fast handover protocol, FMIPv6.

The discussion of the handover performance results and analysis is divided into two sections, which correspond to the two types of system model implementations, i.e., base-station-level PMIPv6-HC and local mobility anchor logical PMIPv6-HC. The handover performances of these system models are compared individually with PMIPv6 and/or FMIPv6 performances. The evaluation and analysis focuses on performance metrics such as handover delay, packet loss, and signalling overhead. We simulated a few vertical handovers to both directions (WiFi-to-WiMAX and WiMAX-to-WiFi), whereby in each handover the MN transited from one subnet to the other. The evaluation and analysis is based on the downstream (CN to MN) traffic flow. However, since CBR traffic is used, we assume that the behavior will be similar for the upstream (MN to CN) traffic flow. The CN was kept stationary.

The following section (6.1) presents and analyzes the results obtained from the base-station-level PMIPv6-HC simulation while the next section (6.2) does the same for the local mobility anchor logical PMIPv6-HC.

6.1 Base-Station-Level PMIPv6-HC Performance Evaluation

Simulation runs were performed on the network topology shown in Figure 5-4 for all the different mobility management criteria (i.e., PMIPv6, FMIPv6, and PMIPv6-HC). Depending on the particular handover performance metric under investigation, various other relevant simulator or network settings as well as external parameters, which generally influence the behaviour of the metric, e.g., MN speed, number of MNs simultaneously making handover, overlapping coverage range, etc., were incorporated in the simulation environment to evaluate their impacts on that particular metric.

6.1.1 Packet Loss and Handover delay

IP layer handover delay, which our proposed mechanism addresses, is experienced when the handover procedures that facilitate successful MN handover at IP layer level are executed. During this handover, the MN is usually unreachable. Therefore, in-flight real-time communication packets are lost. Moreover, real-time communication transmission normally employs UDP, which by design lacks transmission control mechanism that guarantees delivery of packets to their destination. The packet loss and handover delay for PMIPv6-HC are compared with PMIPv6. Handover performance of FMIPv6 is provided in the next section.

In Figures 6-2 and 6.3, packet drop measurements are taken for a simulated real-time multimedia traffic with CBR packet interval of 0.01 s and 0.001 s, respectively. The results are for WiFi-to-WiMAX vertical handover, i.e., when the MN moves linearly from the WiFi network (MAG 1) to the WiMAX network (MAG 2) at a constant speed of 15 m/s. A similar graph profile was obtained for the WiMAX-to-WiFi handover. However, we do not show the latter graph to avoid redundancy.

Note that the PMIPv6-HC and PMIPv6 packet loss graphs are shown in the same figure for convenience and ease of comparison. It is also worth mentioning that in this thesis we use packet sequence number and packet identity (packet ID) interchangeably.

These figures show the time (vertical axis) at which the packets are dropped against the sequence numbers (horizontal axis) of these lost packets. The packets are dropped at MAG 1 when the MN detaches.

In Figure 6-2, packet drop at MAG 1 for PMIPv6 begins with packet sequence number 1385 at the time 10.30 s and continues with subsequent packets until packet number 1459, which is dropped at the time 11.10 s. The packets are dropped because they have been misrouted to the MAG 1 after the MN had already detached from it. This misrouted packet flow continues as long as the MN's routing or reachability state has not been deleted from MAG 1's binding cache entries, and the LMA routing state has not yet been updated with a new PCoA. The latter has only completed at time 11.10 s (shown in the extract below). From 11.11 s, the MN is able to

receive packets from MAG 2 starting with packet sequence number 1461. Consequently, the handover delay from the perspective of the MN occurred from 10.30 s to 11.10 s. There are therefore a total of 75 packets dropped at MAG 1 for PMIPv6. In contrast, the dropped packets for PMIPv6-HC are from sequence number 1438 to 1450 occurring at time of 10.83 s to 10.937 s, so that there are only 13 dropped packets. Thus, there is an 83% decrease in packet loss.

The value “_5_” in Figure 6-1 represents the MN agent, which receives (r) PBA from MAG 2 to complete binding registration.

```
+ 11.1010132 1 5 pba 68 ----- 0 1.0.0.250 4.0.0.250 -1 1460
- 11.1010132 1 5 pba 68 ----- 0 1.0.0.250 4.0.0.250 -1 1460
r 11.1010362 1 5 pba 68 ----- 0 1.0.0.250 4.0.0.250 -1 1460
r 11.1010375 _5_ AGT ----- 1460 pba 68 [0.0.0.0] ---- [4194304:250 16777216 250 31.0]
```

Figure 6-1 Extract showing binding registration completion at MAG 2

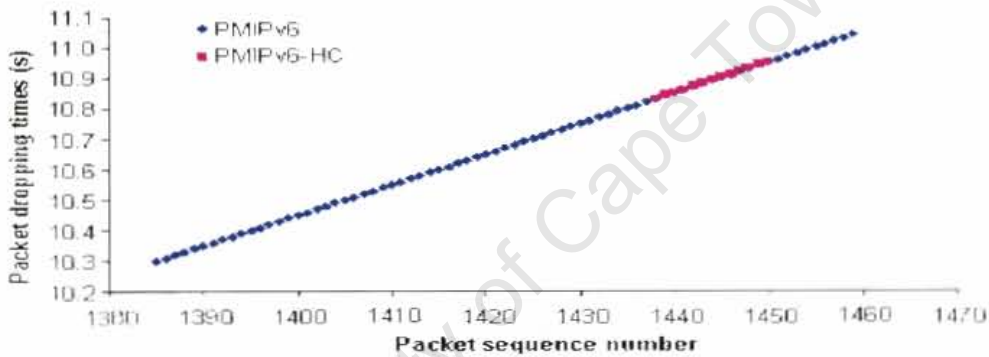


Figure 6-2 Packet dropping time vs. packet sequence number for CBR interval of 0.01 s.

It can be observed from the above figure that PMIPv6-HC starts the handover later than PMIPv6, i.e., at 10.83 s into the simulation and stops at 10.937 s. That is because the HC relays the packets from MAG 1 to the MN in the overlapping region. Thus, the MN continues communication with MAG 1 via the HC yet it has left the effective communication range of MAG 1.

On the other hand, the handover in the PMIPv6 scenario starts much earlier, i.e., at 10.30 s. MAG 1 starts dropping packets immediately the MN enters the overlapping region because the signal strength deteriorates at the cell edges. Moreover, there is no HC to extend the coverage by relaying the packets. Therefore, more packet loss is experienced in this scenario.

Handover delay is the time duration when the MN is unable to send and receive packets since detaching from the previous PoA (MAG 1) until attaching to the new PoA (MAG 2). From the above discussion, we can deduce that the handover delay for PMIPv6 is 0.8 s, which is the difference between 10.30 s and 11.10 s. In contrast, the handover delay for PMIPv6-HC is only 0.107 s, which is the difference between 10.83 s and 10.937 s. Thus, there was an improvement of 87% in average handover delay.

To determine the effect of the type of multimedia traffic on handover performance of the PMIPv6-HC and PMIPv6 mechanisms, we performed the same simulation as above but for a different CBR interval value. Thus, the handover performance graphs in Figure 6-3 below correspond to CBR packet interval of 0.001 s. The interpretation of the figure, axis, data points, and results in Figure 6-2 above applies to Figure 6-3 as well.

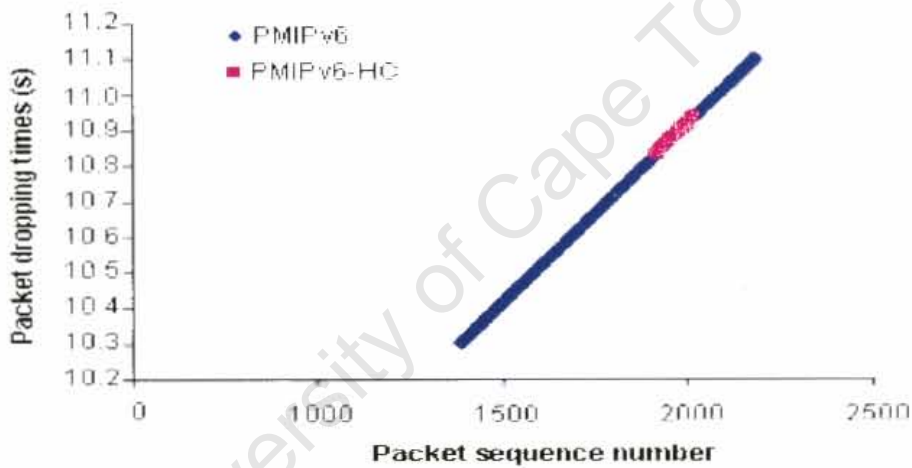


Figure 6-3 Packet dropping time vs. packet sequence number for CBR interval of 0.001 s.

Indeed, as observed in Figure 6-3, the CBR packet interval influences the handover performance in terms of the packet loss during handover. As expected, there is lower packet loss for a bigger CBR packet interval (i.e., low data rate multimedia traffic type) than there is for a smaller CBR packet interval (i.e., high data rate multimedia traffic type). We can observe though that handover still happens at the same time as for CBR packet interval of 0.01 s. However, the packet loss is now higher in both mobility management criteria because of the increased packet rate.

The PMIPv6 and FMIPv6 graphs are shifted downwards on the vertical scale by arbitrary constants to prevent them from appearing on top of each other. Thus, the topmost graph corresponds to the PMIPv6-HC scenario while the middle one corresponds to FMIPv6. The bottom graph corresponds to the PMIPv6 scenario. The graphs are obtained when the CBR packet interval was 0.001 s and MN speed was 15 m/s.

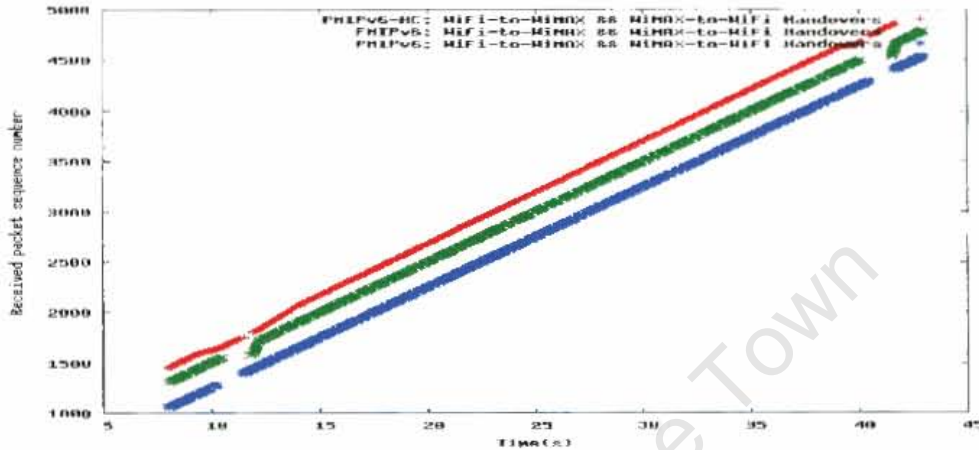


Figure 6-4 Handover delay for vertical handovers between WiFi and WiMAX.

The above diagram reiterates that the proposed PMIPv6-HC handover criteria perform better than PMIPv6 and FMIPv6 in vertical handovers. The handover delay and packet loss values are shown in Table 2. Communication packets are dropped during the discontinuities observed in the above figure. However, some packets are buffered in the candidate network in the FMIPv6 criteria.

It can be observed from the PMIPv6-HC graph that the gradient changes very slightly before a discontinuity. This slight change in gradient is due to the 'logical Layer 2 handover', whereby the packets to the MN are redirected and forwarded by MAG 1 towards the HC, which relays them to the MN traversing the overlapping region. Thus, the redirection and forwarding of packets momentarily decrease the packet arrival rate.

It can also be seen that the gradient of the FMIPv6 graph changes after a discontinuity. This change in gradient is due to buffered packets that are forwarded by the previous access router during the imminent start of handover. The packets are buffered in the new access router

and are delivered to the MN when it finally attaches. Thus, the buffered packets together with the real-time delivered packets momentarily increase the packet arrival rate. However, the buffer may overflow when the packet delivery rate is high and hence packets may be dropped.

Figure 6-5 below clearly depicts the corresponding packet losses incurred during the handover delays experienced in the Wi-Fi-to-WiMAX and WiMAX-to-WiFi vertical handovers observed in Figure 6-4 and summarized in Table 2. The packet loss (vertical axis) is shown against the respective mobility management criteria (horizontal axis).

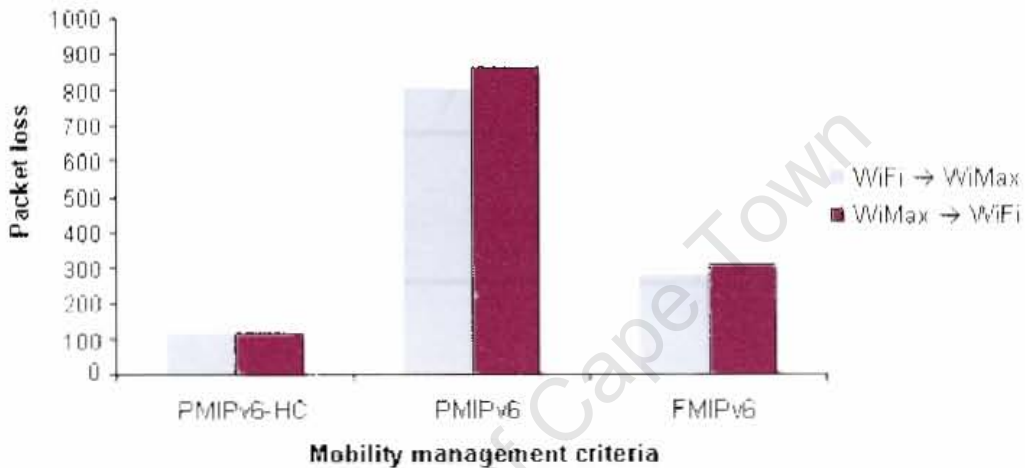


Figure 6-5 Packet loss in PMIPv6, FMIPv6, and PMIPv6-HC.

It can be observed from the above figure that the packet loss is slightly higher when the MN switches from the WiMAX network to the WiFi network in all the mobility management criteria. The respective values are given in Table 2 below. The increases in average packet loss are 8% for PMIPv6, 12% for FMIPv6, and 8% for PMIPv6-HC when the MN hands over from WiMAX-to-WiFi with respect to handover from WiFi-to-WiMAX. This behaviour can be attributed to the time-consuming process of channel scanning before attaching to a WiFi network. After all, all the channels are scanned before attachment in this wireless technology.

Table 2 below summarizes the differences in handover performances in the PMIPv6, FMIPv6, and PMIPv6-HC scenarios in terms of average handover delay and average packet loss during Wi-Fi-to-WiMAX and WiMAX-to-WiFi vertical handovers for CBR packet interval of

0.001 s.

Table 2 Handover performance comparison of PMIPv6, FMIPv6, and PMIPv6-HC

Handover direction	Handover Performance	PMIPv6	FMIPv6	PMIPv6-HC
WiFi→WiMAX	Handover delay (s)	0.80	0.56	0.107
	Packet loss	800	275	108
WiMAX →WiFi	Handover delay (s)	0.86	0.61	0.116
	Packet loss	861	307	117

PMIPv6-HC improves the average handover delay by 81% with respect to FMIPv6 in WiFi-to-WiMAX handover, with a corresponding decrease of 61% in packet loss. Likewise, the improvement in average handover delay is still 81% while the corresponding packet loss decreases by 62% in the WiMAX-to-WiFi direction.

6.1.2 Throughput

The throughput performance for PMIPv6-HC and PMIPv6 mobility management criteria was also investigated. In this thesis, we define throughput as the total number of bits of data received by the MN. The following graphs illustrate the throughput before, during, and after vertical handover from WiFi-to-WiMAX for both PMIPv6 and PMIPv6-HC scenarios. Figures 6-6 and 6-7 correspond to CBR packet interval of 0.01 s while Figures 6-8 and 6-9 correspond to 0.001 s. Furthermore, the graphs depict WiFi-to-WiMAX handover. We obtained similar graph profiles for WiMAX-to-WiFi handover. However, we do not present the latter graphs to avoid redundancy. The throughput (vertical axis) is plotted against the time (horizontal axis) when the MN receives packets. The discontinuity depicts the duration when the MN did not receive

packets because of handover.

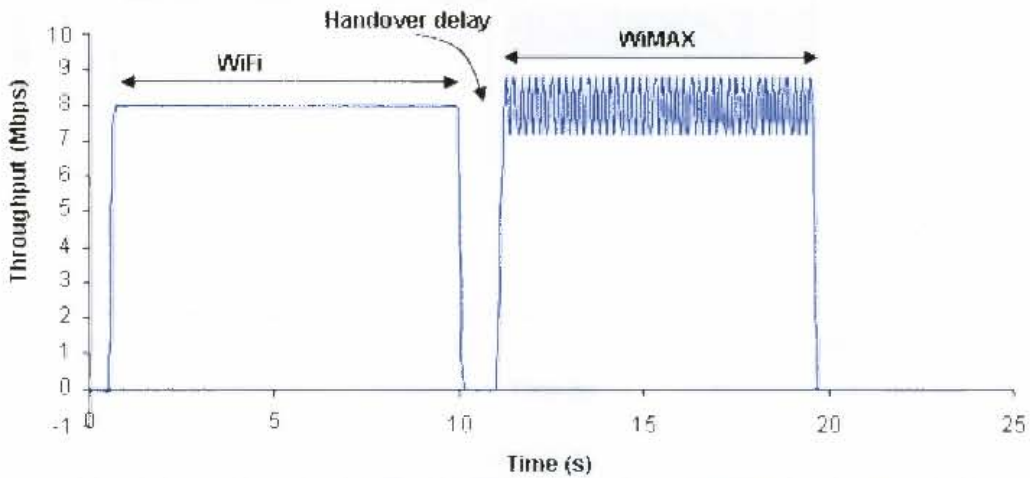


Figure 6-6 MN throughput in PMIPv6 scenario for CBR packet interval of 0.01 s.

As can be observed in the above figure, the MN first receives packets through MAG 1 in the WiFi network. The throughput is 8 Mbps. At 10.30 s the MN detaches from MAG 1 and hence the throughput drops to 0 Mbps because the MN is not receiving packets during the handover. The throughput remains at 0 Mbps until the MN attaches to MAG 2 at 11.11 s, where the throughput increases. The different throughput values in the two networks can be attributed to the respective properties and simulator settings of the wireless network technologies as well as the throughput measurement interval and CBR packet interval. The distance of the MN from the access point or base station also influences the throughput. **Appendix A** shows the throughput behaviour for different CBR packet intervals.

Figure 6-7 depicts the throughput behavior for the PMIPv6-IC criteria.

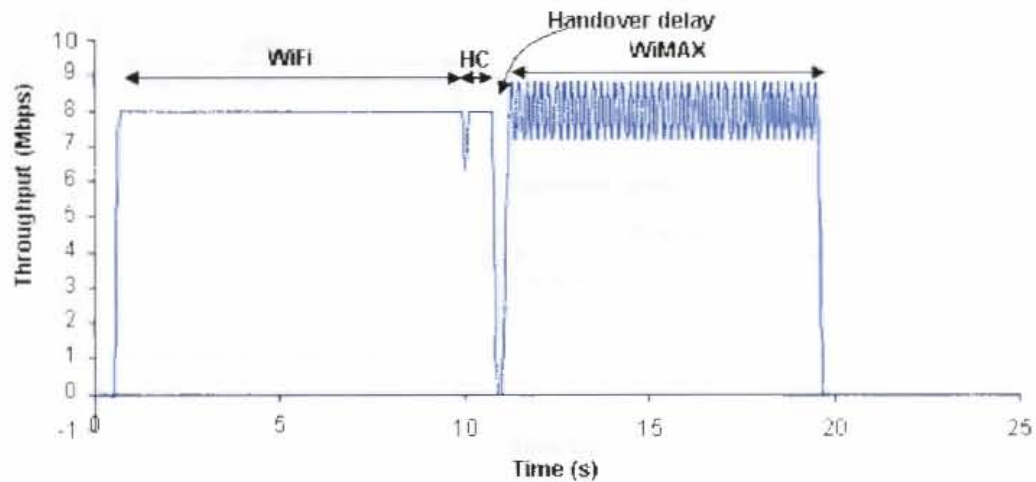


Figure 6-7 MN throughput in PMIPv6-HC scenario for CBR packet interval of 0.01 s.

We can clearly observe in the above figure that the HC improves the throughput performance in the overlapping region. In fact, the HC ensures that the throughput is maintained at the same 8 Mbps as long as possible through relaying the packets to the MN. This behaviour ensures ubiquitous continuity to ongoing communication. The spike observed at 10.3 s depicts the 'logical Layer 2 handover' when MAG 1 redirects packets towards the HC. As a result, with PMIPv6-HC the throughput drops to 0 Mbps only for a short period between 10.83 s and 10.937 s because of the relaying capability of the HC as well as the faster MN attachment at MAG 2. The oscillation when the MN is in the WiMAX region can be attributed to the low packet delivery rate to the MN due to the low data rate of WiMAX with respect to WiFi, yet the sending rate at the CN is kept the same.

Figure 6-8 depicts the throughput behaviour for PMIPv6 when the CBR packet interval is 0.001 s. The interpretation of the graph is the same as above. However, since the packet rate is higher, we observe a higher throughput, which averages 48 Mbps in the WiFi network. In contrast, the throughput averages 14 Mbps in the WiMAX network. As before, the throughput stays at 0 Mbps from 10.3 s to 11.1 s.

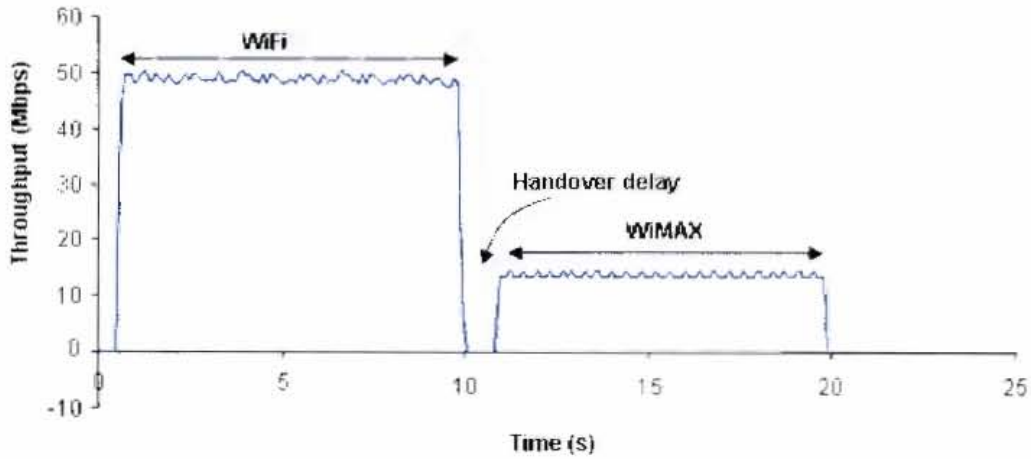


Figure 6-8 MN throughput in PMIPv6 scenario for CBR packet interval of 0.001 s.

Figure 6.9 below depicts the throughput behaviour for PMIPv6-HC when the CBR packet interval is 0.001 s. It can be observed that the throughput in the WiFi and WiMAX networks is the same as in PMIPv6. However, the HC improves the throughput in the overlapping region between 10.3 s and 10.83 s, where it is otherwise 0 Mbps without the HC. Yet with the HC the throughput falls to 0 Mbps only for 0.107 s, i.e., between 10.83 s and 10.937 s as depicted in the figure.

As already explained above, the spike at 10.3 s is the momentary drop in throughput when MAG 1 redirects packets towards the HC. It can also be observed from the diagrams that the packet interval affects the throughput, i.e., a long packet interval results in low throughput while a shorter packet interval results in higher throughput.

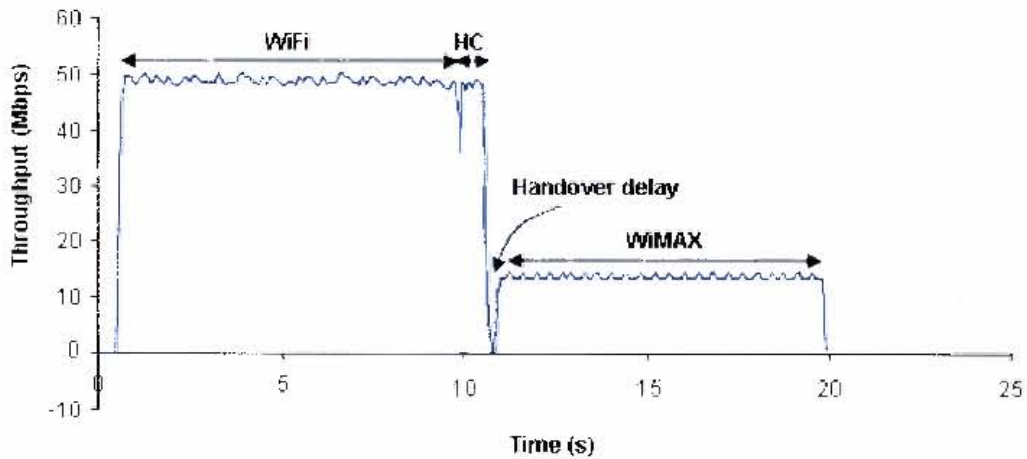


Figure 6-9 MN throughput in PMIPv6-HC for CBR packet interval of 0.001 s.

6.1.3 Signaling overhead

The impact on signaling overhead introduced by the PMIPv6-HC mechanism is minimal. Moreover, PMIPv6-HC is network-based and leverages PMIPv6 protocol. In fact, PMIPv6-HC slightly increases the sizes of the PMIPv6 signaling messages by piggybacking messages related to coordination. An example is a handover trigger signaling message to initiate the coordination, which is just a flag in a signaling message structure that already exists in PMIPv6 and is not significant. Other introduced signaling overhead includes the imminent MN attachment notification message, whereby the HC facilitates the handover coordination between the relevant entities in the heterogeneous wireless network. However, existing PMIPv6 signaling messages such as update PBUs are adequate to carry these coordination messages. The following figure depicts the average signaling overhead of our PMIPv6-HC relative to PMIPv6 and FMIPv6 for CBR interval of 0.01 s and MN speed at 15 m/s. The average signaling overhead (vertical axis) against the number of MNs simultaneously performing handover (horizontal axis) is shown for the respective mobility management criteria.

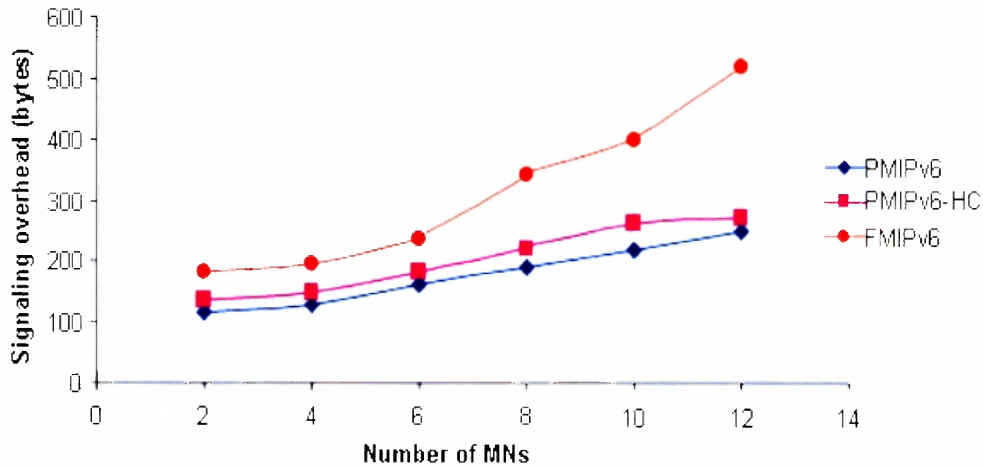


Figure 6-10 MNs simultaneously making handover vs. signaling overhead.

As observed from the above figure, the signaling overhead increases with the number of MNs simultaneously making handover for all the mobility management criteria. Clearly, PMIPv6-HC has slightly more handover signaling overhead relative to PMIPv6. However, the signaling overhead for FMIPv6 increases significantly as the number of MNs simultaneously making handover increases. In fact, FMIPv6 experiences more overhead than PMIPv6 and PMIPv6-HC. That can be attributed to the fact that more handover-related signaling is exchanged over the air between the MN and the access routers in FMIPv6, which is host-based.

Clearly, the increase in signaling overhead due to the increase in the number of MNs simultaneously performing handover implies that the handover delay and the packet loss will be affected in a similar pattern. More so, the relevant elements dealing with the handover procedures are overwhelmed by the signaling overhead, hence take longer to execute the respective procedures, which results in increased handover delay and packet loss. This behavior is investigated in the next section.

6.2 Local Mobility Anchor Logical HC Performance Evaluation

The simulation environment for the logical PMIPv6-HC mechanism is similar to that of the base-station-level mechanism discussed above. The parameter settings are varied accordingly to investigate and analyze the handover performance of the logical HC. The analysis investigated

the same handover performance metrics, i.e., handover delay, packet loss, and signaling overhead. However, this analysis has captured some aspects that are not necessarily captured in the base-station-level HC scenario. Consequently, the graphical representations of the handover performance evaluation are different. For example, in the previous analysis we have evaluated and depicted the handover performance of base-station-level PMIPv6-HC mostly against PMIPv6. Yet for the logical PMIPv6-HC analysis, we evaluate and depict all the performance metrics against the FMIPv6 scenario as well. However, the same FMIPv6 performance results can still be compared with the handover performance of base-station-level PMIPv6-HC. Furthermore, for consistency with the previous analysis, the following also provides graphical results related to the WiFi-to-WiMAX handover for performance evaluation. Note that we consider pedestrian to vehicular speeds in the simulations.

6.2.1 Handover Delay

Figure 6-11 below shows the handover delay (vertical axis) experienced at different MN speeds (horizontal axis) for the different mobility management criteria. The ongoing traffic has CBR packet interval of 0.01 s. As already mentioned, this particular diagram depicts the behavior in WiFi-to-WiMAX handover. Each point in the following graphs represents the average of 20 simulations.

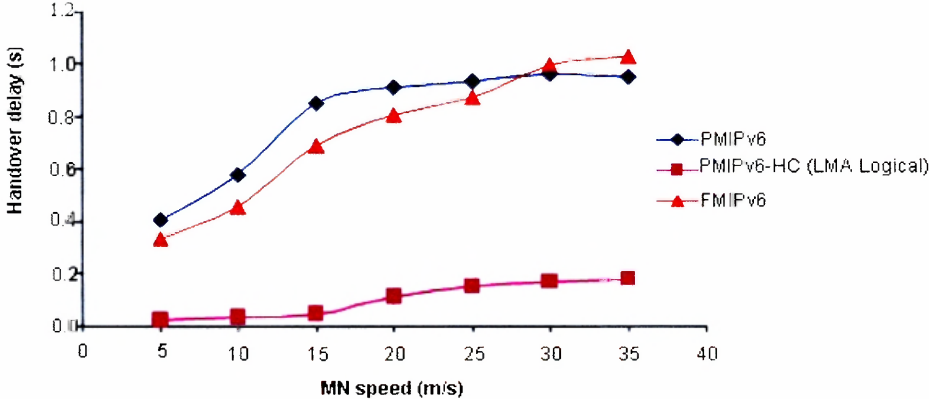


Figure 6-11 Impact of MN speed on handover delay.

It can be observed from the above diagram that the handover delay is smaller for low MN speeds yet increases with increasing MN speeds for all the mobility management criteria (PMIPv6, FMIPv6, and PMIPv6-HC). PMIPv6-HC performs better than all the criteria in all MN speeds. For MN speed of 5 m/s, the handover delay for PMIPv6 is 0.36 s, while for FMIPv6 and PMIPv6-HC it is 0.28 s and 0.05s, respectively. At higher MN speeds such as 35 m/s, the handover delay for PMIPv6 is 0.92 s, while for FMIPv6 and PMIPv6-HC it is 1.0 s and 0.18 s, respectively. Thus, in these extremes, PMIPv6-HC improves the handover delay by 86% with respect PMIPv6 at the low MN speed and 80% at the high MN speed. The improvement with respect to FMIPv6 is 82% at low MN and 82% at high MN speed.

Note that FMIPv6 performs better than PMIPv6 up to MN speeds of 28 m/s, after which PMIPv6 performs better. PMIPv6 performs poorly because it employs a reactive approach. The better performance of FMIPv6 in relation to PMIPv6 at lower MN speeds can be attributed to the predictive approach or anticipation technique. FMIPv6 assumes that detection of the new access router is well in advance of the actual handover, which works better at low MN speeds. Yet when the MN speed is higher, the signaling messages related to the anticipation of handover are lost over the deteriorated old link so that the anticipation technique is not reliable.

It can be further observed in Figure 6-11 that the increase in handover delay with increasing MN speed is not significant after 15 m/s for PMIPv6 and PMIPv6-HC. Yet the handover delay in FMIPv6 continues to increase significantly with MN speed. We can attribute this behavior in PMIPv6 and PMIPv6-HC to the network-based nature of the protocols in their mobility management. Thus, high MN speeds do not have a very significant effect on the handover delay since the MN is not involved in mobility-related signaling. The network elements (MAGs), which are responsible for mobility-related signaling, just need to detect the attachment or detachment of the MN irrespective of the contact duration. However, as the MN speed increases, the possibility of packet misrouting to the old path increases. Consequently, the handover delay increases slightly because the time for the high speed MN to receive packets via the new path is delayed (or postponed) since packets are misrouted to the old path.

On the other hand, the timely coordinated bicasting technique employed by PMIPv6-HC ensures that the MN node receives packets as soon as possible while in the overlapping region,

hence the low handover delays observed in the above diagram.

6.2.2 Packet Loss

Figures 6-12 and 6-13 show the packet loss (vertical axis) with respect to the MN speed (horizontal axis) for CBR packet intervals of 0.01 s and 0.001 s, respectively.

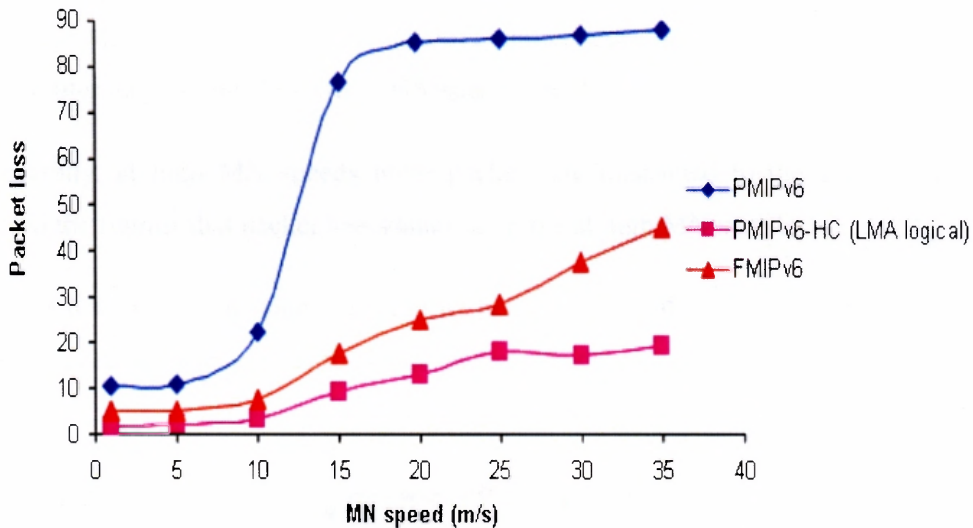


Figure 6-12 MN speed vs. packet loss at CBR packet interval of 0.01s.

It can be seen that PMIPv6-HC performs better than PMIPv6 and FMIPv6 in terms of packet loss at the various MN speeds. For example, at MN speed of 15 m/s the PMIPv6-HC decreases the average packet loss by 87% with respect to PMIPv6, and by 44% with respect to FMIPv6.

The performance of PMIPv6-HC with respect to FMIPv6 improves further as the MN speed increases, as can be observed from the figures. In fact, at MN speed of 35 m/s the PMIPv6-HC decreases the packet loss by 59% when compared with FMIPv6. Moreover, for FMIPv6, as the MN speed increases the packet loss continues to increase significantly. We can further observe that PMIPv6-HC and PMIPv6 packet loss behavior changes slightly with increasing MN speeds after 15 m/s and 20 m/s, respectively. Thus, at MN speed of 35 m/s the PMIPv6-HC decreases the average packet loss by 80% with respect to PMIPv6.

As already explained (Section 6.2.1), the small change in packet loss with high MN speeds in PMIPv6-HC and PMIPv6 can be attributed to the network-based nature of their mobility management. Similarly, the host-based nature of FMIPv6 mobility management incurs large packet loss as the MN speed increases. In FMIPv6, the mobility signaling might not complete on the old PoA's link at high MN speeds since some of the signaling might not reach the MN, hence packets may drop due to misrouting. Moreover, the MN might have left the old PoA's coverage already. In addition, the handover anticipation that FMIPv6 employs to detect a new access router may not be valid when MN speed is high.

Generally, at high MN speeds more packets are misrouted to the old path hence we observe from the figures that packet loss values are large at high MN speeds.

Figure 6-13 shows the same packet loss behavior as in the previous figure. However, it depicts more packet loss because of the faster packet rate delivery to the MN.

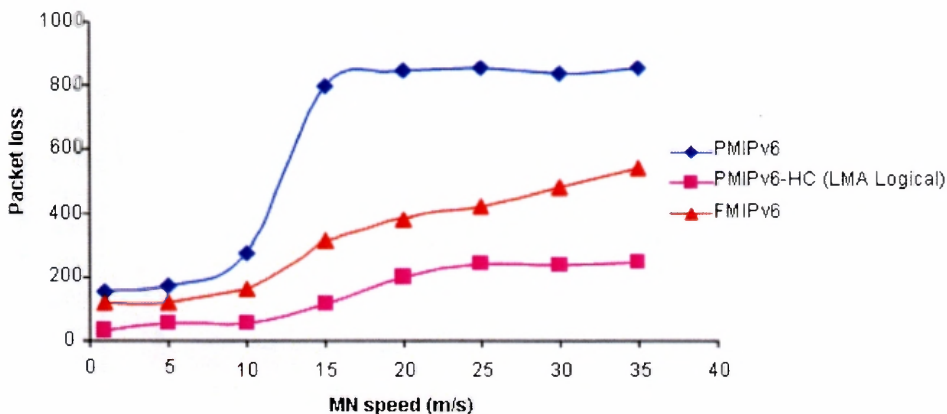


Figure 6-13 MN speed vs. packet loss for CBR packet interval of 0.001s.

Generally, we can observe that at lower MN speeds (pedestrian speeds), the packet loss is low in all cases. PMIPv6-HC provides the lowest average number of dropped packets. At low MN speeds, the mobility-related signaling completes the round-trip-times without any disruptions hence mitigating misrouting of packets. Therefore, packet loss is minimized at low MN speeds. As determined earlier, the type of ongoing multimedia traffic influences the packet loss rate as seen in the above figures.

The better performance of PMIPv6-HC is due to employing the bicasting technique, which cause packets to be simultaneously sent to both source and candidate networks to maximize the probability of packet reception at the MN in the overlapping region. Hence, packet loss due to misrouting is mitigated. PMIPv6, on the other hand, loses more packets because the MN can only receive packets from either the old or the new network at a time, hence does not receive sufficient packets in the overlapping region. Therefore, during the actual handover, the packets are misrouted and hence dropped.

Figure 6-14 shows packet loss (vertical axis) against CBR packet interval (horizontal axis) at fixed MN speed of 15 m/s. The figure reiterates that data rate influences packet loss during handover. As can be observed in the following figure, PMIPv6-HC improves the packet loss of PMIPv6 and FMIPv6 for all CBR packet interval values. Generally, as can be seen in the figure, for short CBR packet intervals the packet loss is high yet significantly decreases as the CBR packet intervals increase.

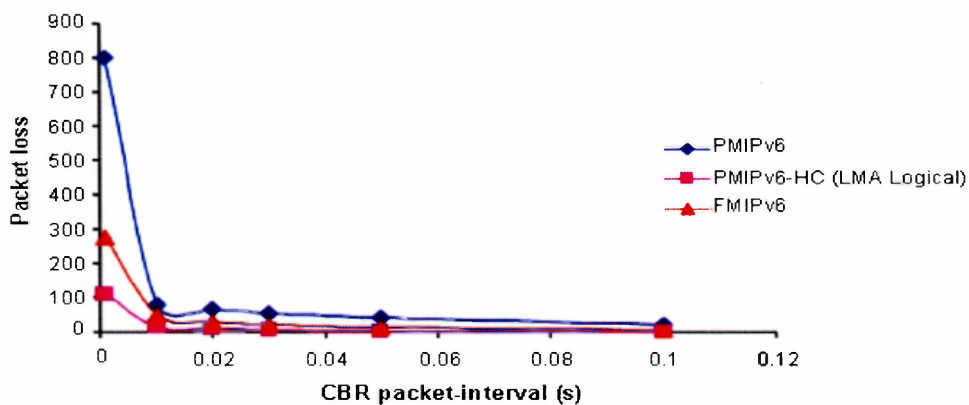


Figure 6-14 CBR packet interval vs. packet loss.

PMIPv6 loses 800 packets at CBR packet interval of 0.001 s. This packet loss reduces to 30 packets at CBR packet interval of 0.1 s. Similarly, for FMIPv6, 275 packets are lost at CBR packet interval of 0.001 s. This packet loss drops to 10 packets at CBR packet interval of 0.1 s. Finally, PMIPv6-HC drops only 108 packets at CBR packet interval of 0.001 s. This packet drop reduces to 0 packets at CBR packet interval of 0.1 s.

Ultimately, we can deduce from the above analyses that the incorporation of the HC decreases the packet loss in PMIPv6 while PMIPv6-HC performs better than FMIPv6. With PMIPv6, there is no coordination between detachment from old network and attachment to the new network, hence the MN disconnects abruptly from the old MAG and continues to lose packets until it finishes binding registration at the new MAG. With FMIPv6, exchanges of mobility signaling messages may not complete at high MN speeds hence more packets are lost due to misrouting.

6.2.3 Signaling Overhead

Figure 6-15 shows the impact on signaling overhead (vertical axis) with respect to the number of MNs simultaneously making handover (horizontal axis) due to FMIPv6, PMIPv6, and LMA logical PMIPv6-HC.

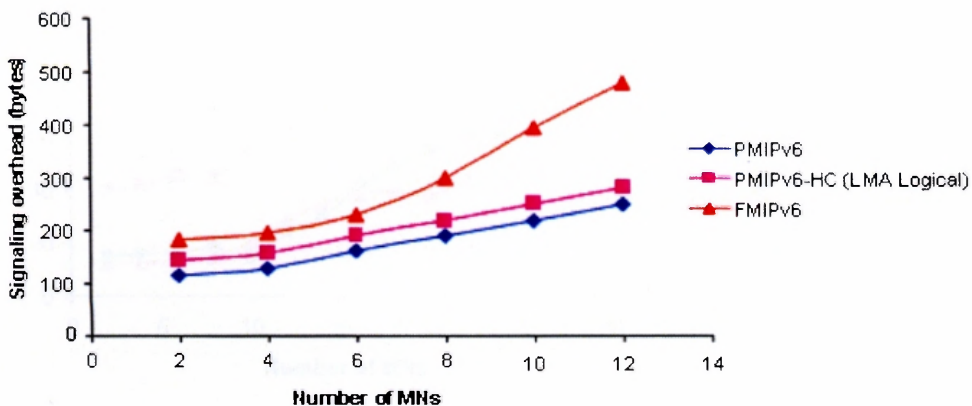


Figure 6-15 Number MNs simultaneously making handover vs. signalling overhead.

It can be seen in the above figure that PMIPv6-HC has a little more signaling overhead than PMIPv6. The increase in average signaling overhead with respect to PMIPv6 is about 13%, which is minimal trade-off in the context of the performance improvement achieved in handover delay and packet loss as discussed earlier. The above figure shows that the signaling overhead increases with the number of MNs simultaneously making handovers between the networks in all the mobility management criteria. In PMIPv6-HC, there are signaling messages sent by the HC to the respective MAGs and LMA before and during handover activities. This increased number

and size of update PBUs, where the handover-coordination-related information is piggybacked, increases the signaling overhead slightly. As already mentioned, this minimal signaling cost in PMIPv6-HC greatly enhances the handover delay and packet loss. In addition, the signaling overhead is still lower than in the popular mobility management protocol for fast handovers, FMIPv6.

6.3 Impact of number of MNs on packet loss and handover delay

The following diagrams, Figures 6-16 and 6-17, depict the results of the impact of the number of MNs simultaneously making handover on average packet loss and handover delay, respectively, for all the mobility management criteria for CBR packet interval of 0.01 s.

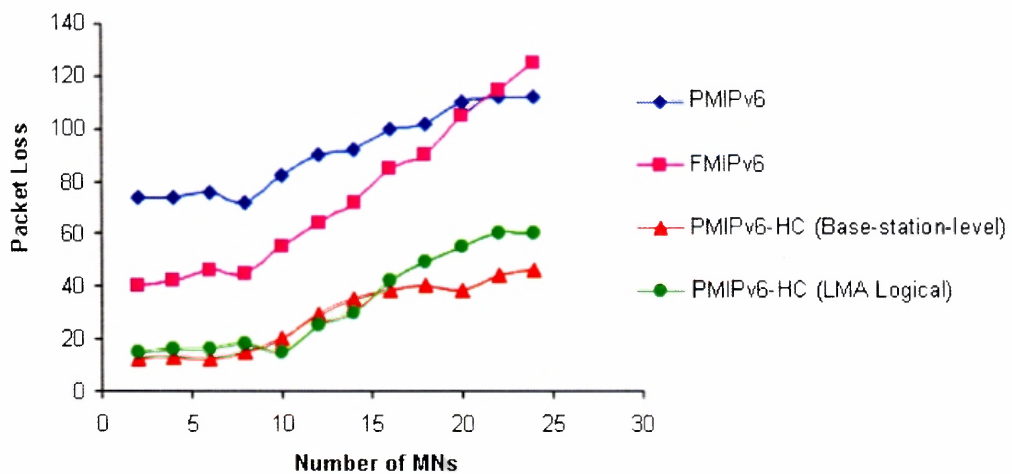


Figure 6-16 Impact of number of MNs on packet loss.

The MNs were simulated to move linearly across the overlapping region of the interworking networks at the same time hence triggering handover activities almost simultaneously. We can observe from the above figure that both PMIPv6-HC implementations perform better than PMIPv6 and FMIPv6. However, at a certain number of MNs, i.e., when there are more than 8 MNs simultaneously making handover, the packet loss suddenly starts to increase significantly in all the criteria. We can attribute this behavior to the saturation of the HC and the MAGs due to the increase in mobility-related signaling messages that must be handled at the same time. This scenario overwhelms the elements hence causes delays to the processing of

6.4 Impact of coverage range of overlapping region on packet loss and handover delay

The region of overlap between the heterogeneous wireless networks was varied to observe its effect on packet loss and handover delay for PMIPv6, base-station-level PMIPv6-HC, and LMA logical PMIPv6-HC mobility management criteria. Thus, we increased as well as decreased the overlapping coverage range and correspondingly initiated the MN's movement, which triggered the handover operations accordingly. The CBR packet interval was fixed at 0.01 s while the MN speed was maintained at 15 m/s. We define the coverage range of the overlapping region as depicted in the Figure 6-18.

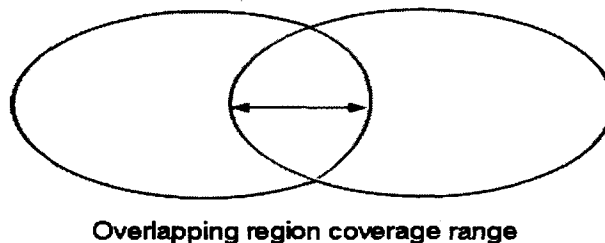


Figure 6-18 Definition of Coverage range of overlapping regions.

The following figure depicts the obtained results. The packet loss (vertical axis) is evaluated at different coverage ranges of the overlapping region (horizontal axis).

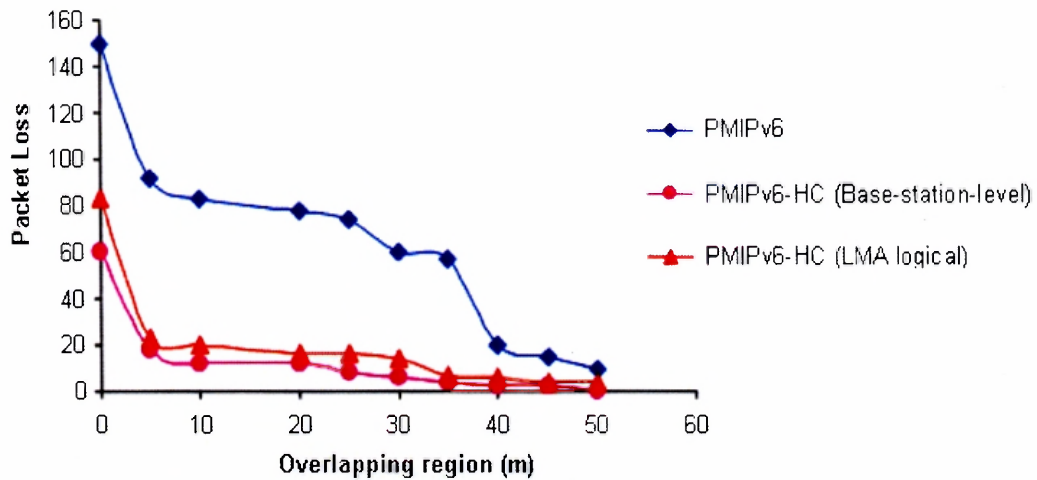


Figure 6-19 Impact of coverage range of overlapping region on packet loss.

We observe from the above diagram that indeed the coverage range of the overlapping region of the interworking wireless networks (note that the simulated coverage radius for WiFi was 50 m while the WiMAX coverage radius was 1000 m) influences the number of packet loss during handover. As the overlapping region coverage approaches zero (i.e., networks not overlapping) the number of lost packets increases significantly whereas as it expands, the number of lost packets decreases drastically. In other words, the longer the distance between the MAGs or access routers, the higher the packet loss is.

In the case of PMIPv6, the above behavior can be attributed to the fact that this protocol employs a reactive handover approach in its mobility management. Therefore, whenever a MN detaches from the currently attached MAG, packets start dropping until the MN fully attaches to the new MAG. However, as can be observed in the above figure, the coverage range does influence the degree of packet loss. For a constant MN speed there is more packet loss for smaller coverage and less for a wider coverage. In other words, the packet loss increases as the distance between the MAGs increases. An increase in distance between the MAGs corresponds to reduced coverage range of the overlapping region. Thus, when there is no (or very small) overlapping region coverage the MN experiences an abrupt disconnection hence the very significant packet loss observed in Figure 6-19. Likewise, when the MAGs of the interworking networks are very close to each other, i.e., the overlapping region is sufficiently large, the

multiple-interface MN is always detecting a strong radio signal and the network can complete handover procedures without the MN completely losing connectivity with the old network hence the packet loss decreases drastically.

The same reasoning applies for the graphs of the PMIPv6-HC mechanisms. However, in these cases, the HC coordinates and speeds up the handover processes hence quicker new network attachment and packet reception resulting in lower packet losses. For the base-station-level PMIPv6-HC mode, the performance is slightly better because the positioning of the HC ensures that the MN receives packets with reasonably good signal strength at the overlapping region (cell edges) since the HC relays the packets to the MN during handover. However, the same cannot be said with the LMA logical PMIPv6-HC mode. That is, even though multicasting maximizes the probability of packet reception at the MN in the overlapping region during handover, there is a critical point where the packets have insufficient signal strength from both the old and new networks. Thus, more packets are dropped in this latter approach. Therefore, the base-station-level PMIPv6-HC mode performs slightly better than the logical mode. However, the nature of the design of the base-station-level PMIPv6-HC mode is suited for small-scale interworking heterogeneous wireless networks as opposed to the LMA logical PMIPv6-HC which is suited for large-scale networks.

Figure 6-20 below shows the corresponding relationship between the handover delay (vertical axis) and overlapping region coverage range (horizontal axis).

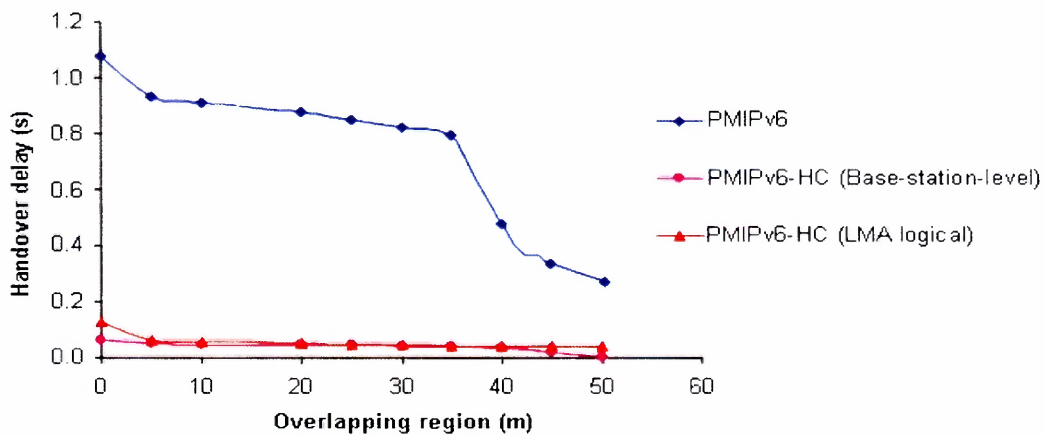


Figure 6-20 Impact of coverage range of overlapping region on handover delay.

The same explanation given earlier for the behavior depicted in Figure 6-19 applies in the above figure. As can be observed, both PMIPv6-HC perform better than PMIPv6 in terms of handover delay in all the overlapping region coverage ranges. We can observe though, generally, that the handover delay improves with increasing overlapping region coverage. The handover delay performance of the base-station-level PMIPv6-HC mode is slightly better than that of the logical mode. That can be attributed to the placement of the HC at the strategic location in the overlapping region where the actual handover occurs, so the HC shortens the distance to the new MAG hence the handover delay.

6.5 Single-radio handover vs. dual-radio handover – performance comparison

We also made simulations for dual-radio handover and compared the handover delay and packet loss performance with that of the single-radio handover as discussed above. This simulation is purely to compare the performance in the context of the utilization of the MN multiple (dual) interfaces during handover. However, we appreciate that dual-radio or multi-radio handovers are prohibitively complex and expensive in radio design due to the costly requirements, e.g., for radio frequency isolation and sharper filtering at the MN.

Dual-radio handover is where the dual-interface MN has the transmitters and receivers of the two interfaces active at the same time; thus, the respective interfaces transmit as well as receive signaling messages at the same time directly from the relevant detected networks. Thus, the MN uses one of the interfaces as the ‘target radio’ to prepare resources in the target network during handovers, while using the other interface as the ‘current radio’ to communicate with the current network.

The following results in Figure 6-21 are based on the LMA logical PMIPv6-HC design where we simulated a 50 m radius WiFi network interworking with a 1000 m radius WiMAX network. We evaluated the packet loss experienced for different coverage ranges of the overlapping region. The MN speed was maintained at 15 m/s throughout the simulation. The values in the following diagrams show an average of 10 simulations.

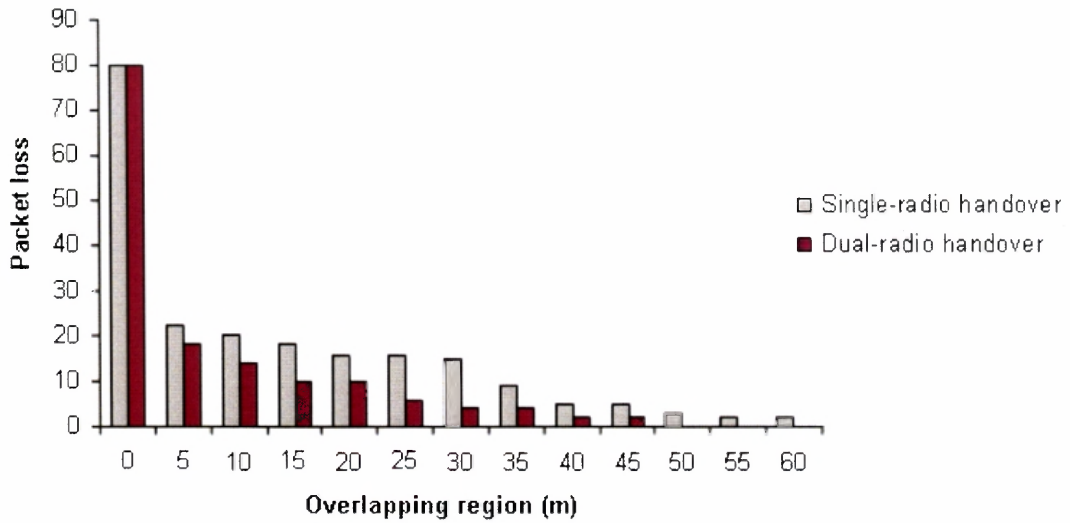


Figure 6-21 Coverage range in overlapping region vs. packet loss.

As can be observed from Figure 6-21, the dual-radio handover generally performs better than the single-radio handover and results in lower packet loss during the handover. However, when there is no overlap (0 m overlapping coverage range) between the interworking networks both single-radio and dual-radio handovers experience almost the same packet losses. That can be attributed to the fact that when the networks are not overlapping, ongoing real-time communication continuity is not achievable. However, as the coverage range becomes wider, i.e., the MAGs (i.e., access point and base station) get closer to each other, the dual-radio handover experiences lower packet loss. That can be attributed to the fact that as the MAGs get closer, the MN's new (target) interface transmitter signals the relevant network to initiate handover procedures and bicasting as soon as the MN's new interface receiver detects the network. Whereas, with the single-radio handover mode, the MN's new interface receiver detects the new network and the signaling goes via the MN's old interface transmitter through the old network to the HC to trigger the initiation of the handover procedures and bicasting, which takes longer. Consequently, the packet loss is more for the single-radio handover mode. The corresponding handover delay behavior is as shown in Figure 6-22 below. It is similar to the behavior shown in the above figure. After all, the disruption to ongoing communication is usually caused by handover delays which normally result in packet loss during the handover [109].

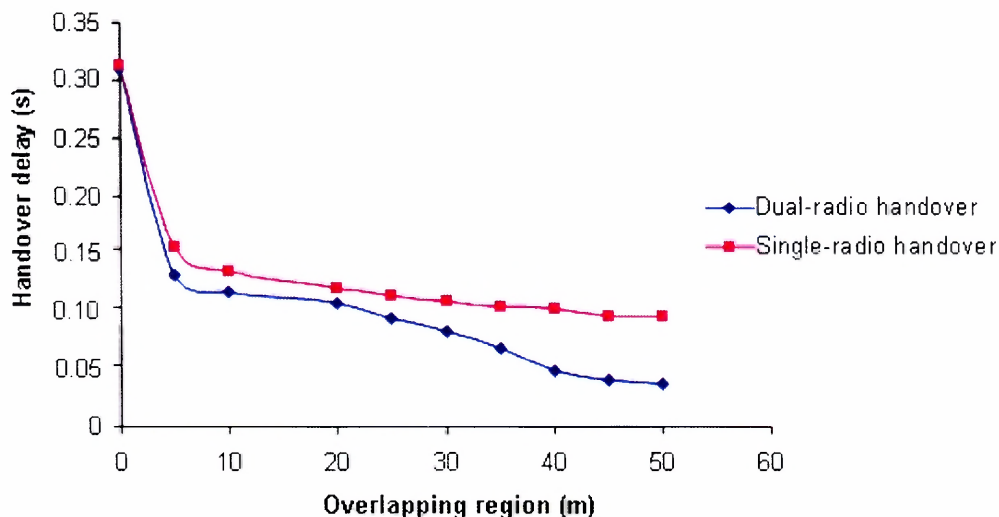


Figure 6-22 Coverage range in overlapping region vs. handover delay.

Figure 6-22 shows that indeed dual-radio handover performs better than single-radio handover. Moreover, with dual-radio the handover trigger message is sent directly through the new network immediately the new MAG detects the MN. This criterion is quick and efficient in the context of the handover solution. However, this dual radio handover mode, as already mentioned, introduces complexity in the MN design in terms of power consumption, frequency co-existence issues, etc. Also, synchronization at the MN in terms of harmonizing the same traffic flow that is received through different interfaces becomes a challenge.

6.6 Summary

This chapter has presented and analyzed the handover performance results obtained from the simulation of PMIPv6-HC, PMIPv6, and FMIPv6 mobility management criteria. The proposed PMIPv6-HC criteria, in the form of base-station-level PMIPv6-HC and LMA logical PMIPv6-HC, greatly enhance the handover performance between heterogeneous wireless networks. Thus, the handover delay and packet loss are reduced while the signaling overhead is kept to a reasonable minimal and is only slightly more than that experienced in standard PMIPv6.

We have shown that the packet loss, handover delay, and signaling overhead are influenced by external parameters such as the MN speed, CBR packet interval, number of MNs

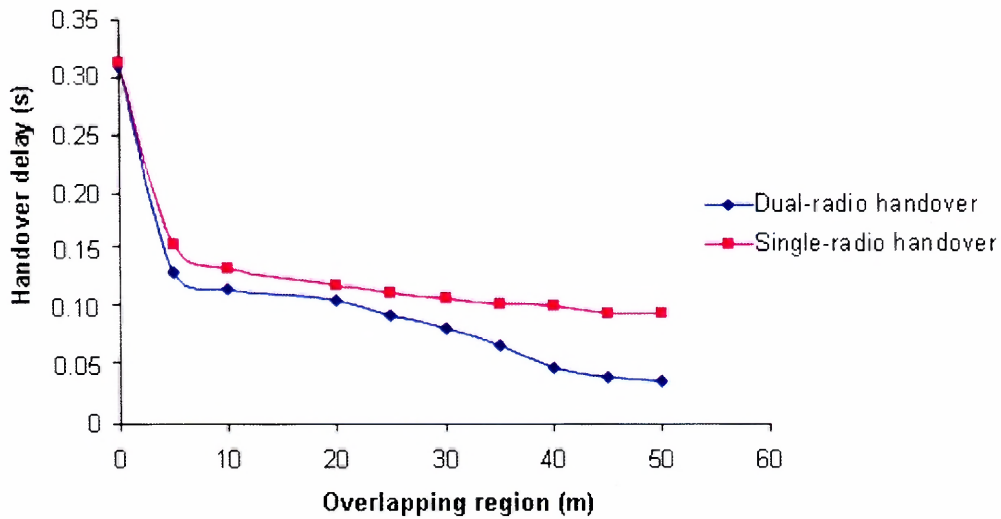


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Chapter 7 Conclusion and Recommendations for Future Work

Future wireless networks will coexist and combine resources over an IP-based infrastructure for ubiquitous connection support. In this heterogeneous wireless environment, mobility particularly vertical handover between the different access networks becomes topical. Thus, to support non-perceptible connection migration for active real-time communication between these heterogeneous wireless networks, seamless vertical handover mechanisms are necessary.

Various mobility management protocols have been proposed and standardized to support mobility across heterogeneous wireless networks but they cannot provide seamless handover in their current form. Many proposed seamless handover mechanisms in the literature leverage host-based and network-based IP mobility protocols to further improve the handover performance. However, the handover delay and packet loss are still too high for active real-time connections.

A network-based coordination design for seamless handover between heterogeneous wireless networks has been proposed in this thesis to further enhance the handover performance. The design employs ahead-of-time coordination of the initiation and preparation of the handover procedures between the involved heterogeneous wireless networks. Therefore, execution of the handover procedures happens in the background while the MN transparently continues with ongoing communication. Ultimately, the signaling steps during the actual handover are reduced, thereby reducing the handover delay and packet loss. Furthermore, the network-based nature of the mechanism ensures minimal signaling overhead in the air interface.

The summary of contributions of the thesis and directions for future research are presented in the following sections.

7.1 Summary of Contributions

This thesis proposes a seamless vertical handover mechanism to reduce handover delay and packet loss while ensuring minimal signaling overhead.

Since handover mechanisms have to leverage mobility protocols to improve handover performance, the common MIPv6-based protocols were mathematically analyzed to determine their respective performance models. The network-based PMIPv6 was discovered to be the most suitable leverage protocol.

The IEEE 802.21 MIH services were incorporated to leverage PMIPv6 mobility framework to further improve the handover performance. A performance model and simulation results show that the handover delay and packet loss are reduced by the IEEE 802.21-assisted PMIPv6 mechanism. However, signaling overhead is compromised.

A network-based seamless handover mechanism that leverages PMIPv6, known as PMIPv6-HC, is proposed to further reduce the handover delay and packet loss while maintaining minimal signaling overhead. This mechanism provides a common framework to handle seamless vertical handover in a coordinated manner between the source and target networks. It achieves seamless handover by coordinating the initiation and preparation of handover ahead of time between the involved networks. Simulation results have shown that PMIPv6-HC reduces handover delay and packet loss, yet maintaining signaling overhead to a minimal by increasing it very slightly.

Two system models of the proposed handover coordination design are presented; 1) a base-station-level HC implementation at the overlapping region of the interworking heterogeneous wireless networks and 2) a logical HC implementation at the Local Mobility Anchor (LMA) of the heterogeneous wireless network environment. The base-station-level HC design employs 'relaying' to ensure reduced packet loss as the MN traverses the overlapping region. The logical LMA HC design, on the other hand, employs 'bicasting' to ensure reduced packets loss. The network-based nature of the handover coordination mechanism ensures minimal signaling overhead in the air interface. Finally, the ahead-of-time coordination of the

initiation and preparation of handover procedures in the involved networks reduces the handover delay.

The two proposed PMIPv6-HC handover coordination designs introduce new handover processes which ensure that the MN continues with ongoing communication as real-time as possible even during the handover in the overlapping region. Consequently, packet loss, re-ordering, misrouting, and buffering problems often encountered in previously proposed solutions are alleviated. In effect, the handover delay and packet loss are reduced while the signaling overhead in the air interface is kept to a minimal.

7.2 Recommendations for Future Work

PMIPv6-HC does not necessarily address the context-aware network discovery challenge. Yet the IEEE 802.21 MIH services provide an important service that addresses this challenge. Consequently, it is recommended that future work considers incorporating this service or functionality in PMIPv6-HC. This enhancement will make PMIPv6-HC more advanced hence support network discovery and selection, which are very important in NGWN.

Another recommendation for future work is to enhance the scalability of the proposed handover coordination designs by allowing for distributed handover coordination architectures. This distributed architecture will help to prevent performance bottlenecks, e.g., in cases where the number of MNs simultaneously making handover is high. However, this enhancement to PMIPv6-HC must still maintain signaling overhead to a minimal while reducing handover delay and packet loss.

Quality of Service (QoS) capabilities to cater for QoS provisions as part of the overall handover coordination function is another important research area that is recommended for future work. These capabilities will enable the provision of resource reservation in the context of QoS for the ongoing real-time service after the handover process, hence ensuring consistent QoS attributes in the new wireless network.

Another aspect that requires future study is the overwhelming or overloading of the HC and the MAGs during handover events. In fact, many MNs may associate with the HC and need

services of the HC and/or MAGs at the same time, hence overloading these elements. Therefore, load balancing mechanisms to ensure efficiency and effectiveness of these elements, particularly in handling vertical handovers, are necessary.

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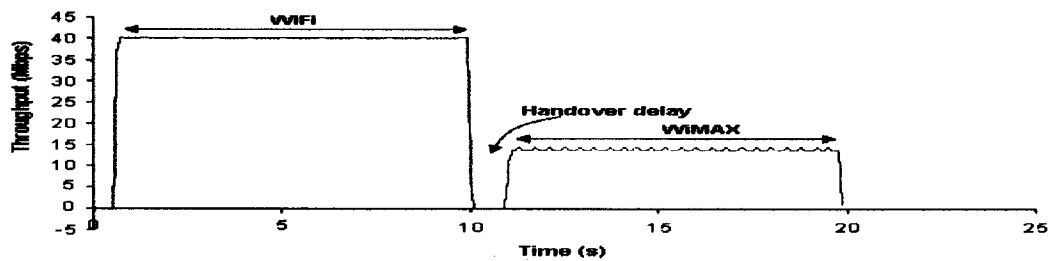
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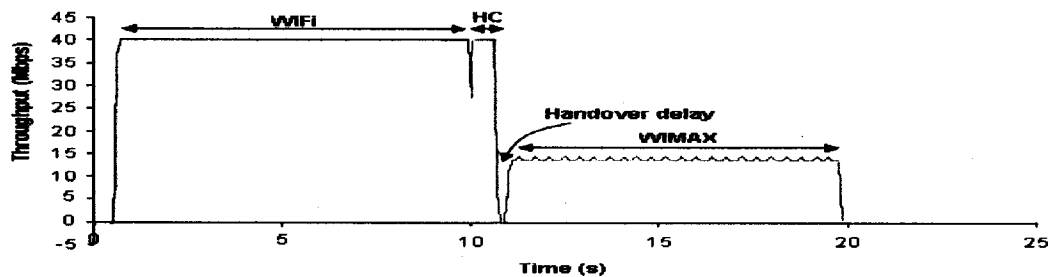
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Appendix A. Influence of CBR packet interval on throughput behaviour

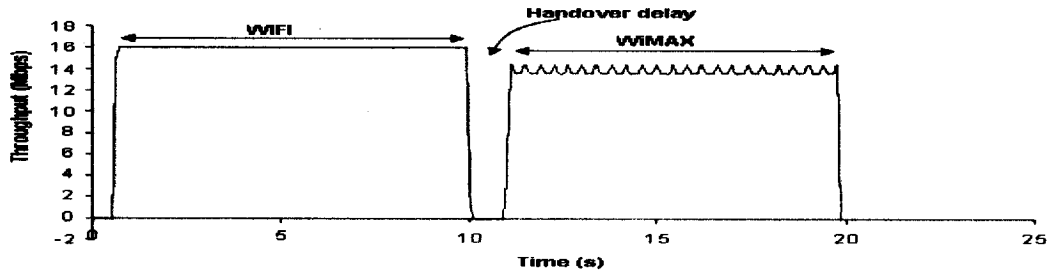
The following figures illustrate the influence that the CBR packet interval has on the throughput behaviour in WiFi and WiMAX network technologies before and after handover, respectively. The influence of the CBR packet interval in the following figures can be analyzed in relation to the throughput figures obtained in Section 6.1.2.



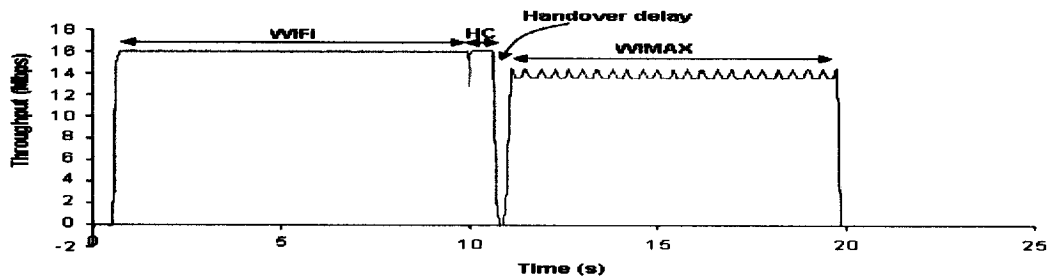
A 0-1 MN throughput in PMIPv6 scenario for CBR packet interval of 0.002 s.



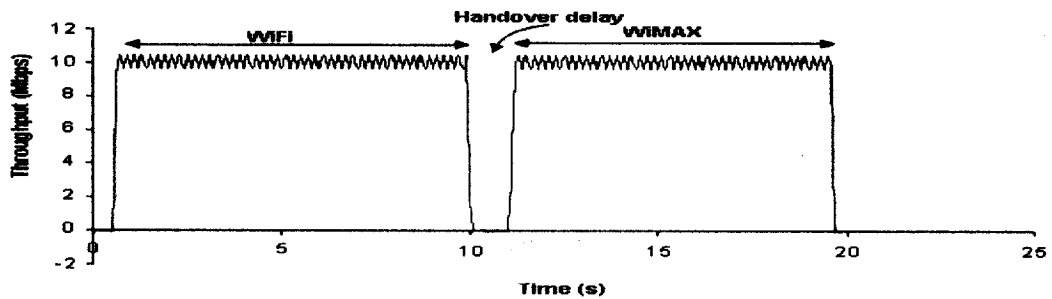
A 0-2 MN throughput in PMIPv6-HC scenario for CBR packet interval of 0.002 s.



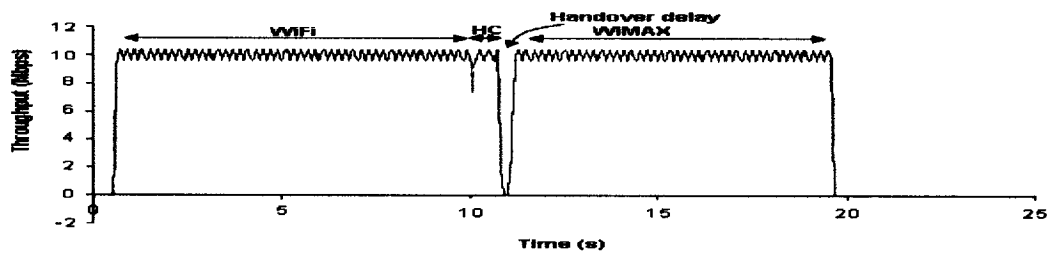
A 0-3 MN Throughput in PMIPv6 scenario for CBR packet interval of 0.005 s.



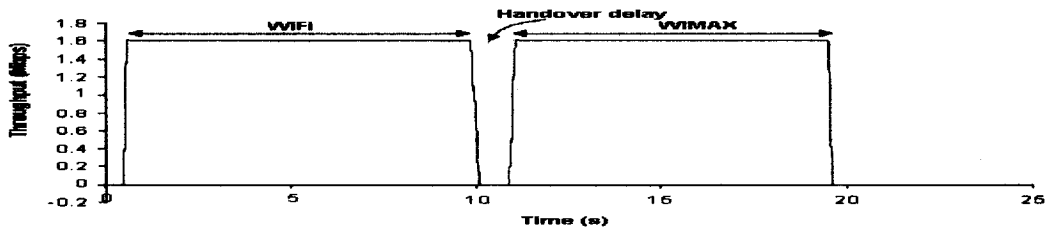
A 0-4 MN Throughput in PMIPv6-HC scenario for CBR packet interval of 0.005 s.



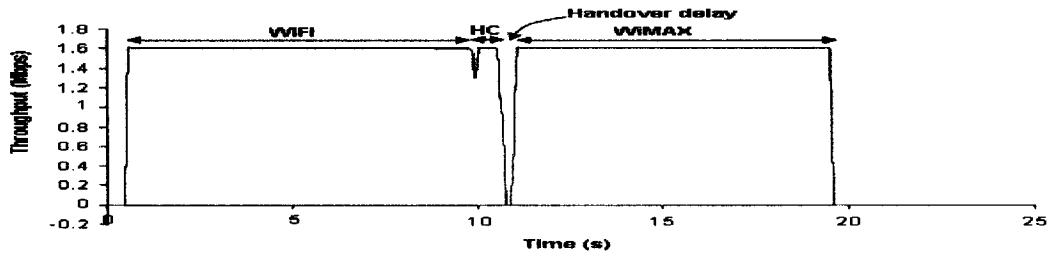
A 0-5 MN Throughput in PMIPv6 scenario for CBR packet interval of 0.008 s.



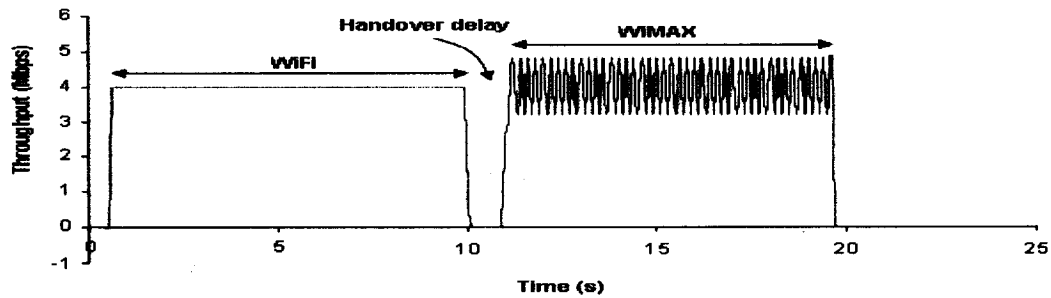
A 0-6 MN Throughput in PMIPv6-HC scenario for CBR packet interval of 0.008 s.



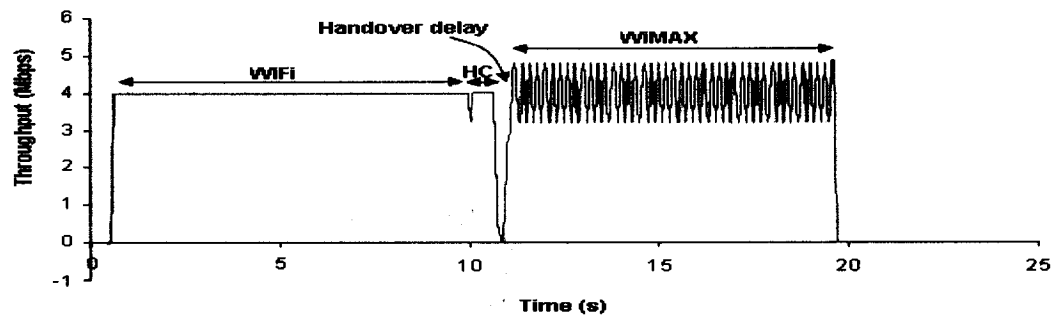
A 0-7 MN Throughput in PMIPv6 scenario for CBR packet interval of 0.05 s.



A 0-8 MN Throughput in PMIPv6-HC scenario for CBR packet interval of 0.05 s.



A 0-9 MN Throughput in PMIPv6 scenario for CBR packet interval of 0.02 s.



A 0-10 MN Throughput in PMIPv6-HC scenario for CBR packet interval of 0.02 s.