

IP Flow Mobility based Offload in LTE Wi-Fi Interworking Scenario

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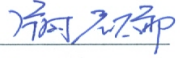
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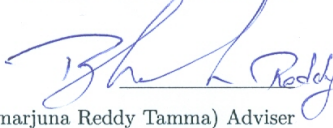
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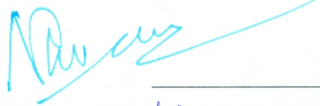
Approval Sheet

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Abstract

Mobile data traffic has seen an exponential growth in the past few years with the trend expected to continue. LTE as a standalone cellular network is unable to keep pace with the increasing traffic demands. In the meanwhile, wireless LAN has proven itself as an economical wireless access technology. 3GPP has thus been encouraged to standardize the integration of Wi-Fi networks with LTE. This opens up numerous opportunities to study data offloading and mobility management protocols. One of the newer offloading technique is known as IP Flow Mobility, where individual IP flows are migrated from one network to the other without affecting other flows belonging to the same IP session. In this thesis work, a framework has been developed on ns-3 which supports flow mobility between LTE and Wi-Fi. This framework is based on PMIPv6.

This flow mobility framework provides an opportunity to implement various algorithms to decide which network is used to serve which flows while trying maintain a balance between bandwidth utilization and user satisfaction. One such algorithm has been proposed here for a network consisting of LTE and Wi-Fi. This algorithm calculates a quality value for each flow on the network using parameters like flow type, SNR, velocity of the user, etc and tries to offload these flows onto either network based on the flow's quality value.

A simple simulation is carried out which validates the implementation of the framework, where a TCP flow is migrated to a Wi-Fi network from the LTE network based on the SNR of the Wi-Fi network. It also shows how the velocity of a UE affects the percentage of offload which can be achieved and how the flow's performance is affected by the offload.

Contents

Declaration	ii
Approval Sheet	iii
Acknowledgements	iv
Abstract	v
Nomenclature	vii
1 Introduction	1
1.1 Flow Mobility	2
1.2 Related Work	2
1.3 Overview of Our work	3
1.4 Thesis Outline	3
2 Mobility Management	4
2.1 Mobile IP	4
2.2 PMIPv6	5
3 LTE and 802.11: An Overview	10
3.1 LTE	10
3.2 IEEE 802.11 (Wi-Fi)	11
3.3 LTE Wi-Fi Integrated Architecture	11
3.4 Flow Mobility	15
3.4.1 PMIPv6 based Flow Mobility	16
4 Design and Implementation in NS-3	20
4.1 NS-3	20
4.2 PMIPv6 Support For LTE	20
4.3 Flow Mobility Support	22
4.3.1 Validation of Implementation	24
5 Simulation and Results	27
5.1 Simulation Setup	27
5.2 Results	28

6 QoS-based Flow Mobility Framework	31
6.1 Motivation	31
6.2 Related Work	32
6.3 Overview of Flow Mobility Framework	32
6.3.1 Flow Based Quality Function	34
6.3.2 QoS Based Flow Mobility Framework	34
7 Conclusions and Future Work	37
References	38

Chapter 1

Introduction

Mobile data traffic has seen an exponential growth in the past few years and the trend is expected to continue [1]. The major factor in this sudden increase has been the introduction of smartphones, tablets, apps etc. Cellular networks have continued to increase their capacity from 1st Generation to 4th Generation. The most popular and recent cellular standard known as Long Term Evolution Advanced (LTE-A) supports speeds of 1Gbps in downlink and 500Mbps in uplink [2]. However, the increase in user demand is far exceeding the increase in cellular network capacity. Cisco forecasts the growth of mobile data traffic at a rate of 66% Compounded Annual Growth Rate (CAGR) from 0.9EB (Exabytes) in 2012 to 11.2EB in 2017 as shown in Figure 1.1. It also predicts that the majority of the traffic would be generated by smartphones as shown in Figure 1.2.

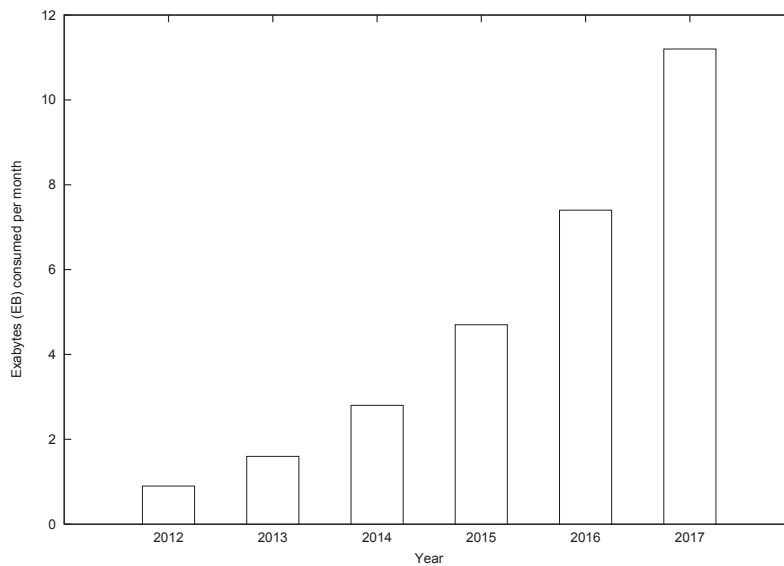


Figure 1.1: Mobile Data Monthly Usage Statistics [1]

In the meanwhile, IEEE has enjoyed great success with their wireless LAN standard 802.11. This offers greater speeds as compared to the cellular networks (802.11ac can offer phy data rates of upto 6.9Gbps [3] while compared to the 1Gbps in LTE-A) and has also found great penetration in

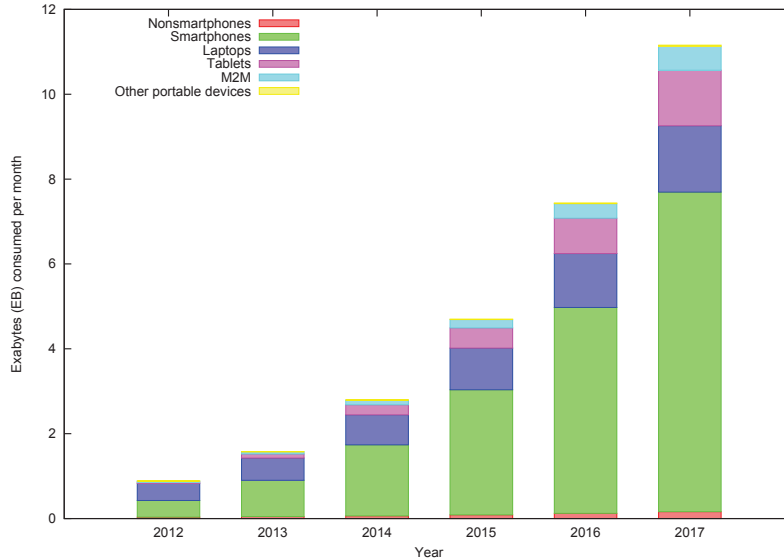


Figure 1.2: Mobile Data Device Usage Statistics [1]

the wireless domain. The other advantages offered by wireless LANs are their usage of unlicensed spectrum for communication (i.e. 2.4 GHz and 5GHz spectrum bands) and their ubiquitous presence in indoor environments like office buildings, malls, airports, homes etc.

As a result, the mobile network operators (MNOs) see selective offloading of traffic from the cellular domain into the wireless LAN domain as a viable solution to solve the data crunch.

1.1 Flow Mobility

3rd Generation Partnership Project (3GPP) [4] has recognized the importance of 802.11 WLANs (aka Wi-Fi networks) by defining standards for their integration into the Long Term Evolution (LTE) architecture. The standard supports various mobility management protocols like Proxy Mobile IPv6 (PMIPv6) [5], GPRS Tunneling Protocol (GTP) [6], Dual-stack Mobile IPv6 (DSMIPv6) [7] for the integration. Various mechanisms to offload traffic onto non-3GPP technologies have been proposed in the 3GPP standards. One of the newer offload mechanisms is known as flow mobility. In this instead of migrating all the flows over to Wi-Fi, only certain flows are routed over the Wi-Fi interface while keeping the rest of the flows over the LTE interface. This allows the MNOs to provision different policies for routing flows over either of the two interfaces, while trying to maximize the network capacity and meeting the Quality of Service (QoS) requirements of the applications.

1.2 Related Work

Most of the vertical handoff algorithms in heterogeneous networks involve moving all IP flows from one interface to the other. Generally a decision is taken based on certain parameters of each network like bandwidth, delay, jitter, etc. These parameters are used to calculate a score for each of the

available networks and based on the this score a network selection/vertical handoff decision is made. There are a class of algorithms like SAW (Simple Additive Weighting), WP (Weighting Product), TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), etc which fall under the Multiple Attribute Decision Making (MADM) approach [8] [9], which are based on this approach. Most of the parameters which are considered like packet jitter, packet delay, packet loss and cost per byte are static in nature i.e. their values are either part of technology standard or taken from real deployment scenarios (for example the value of delay is 100ms for LTE and 150ms for Wi-Fi). Therefore, these approaches provide a cost based method for selection of a network but the parameters considered are not realistic.

The introduction of flow mobility allows further optimizations and more parameters to use in the flow mobility decision making. It also provides more control as handoff can be performed for each flow separately. Wang et al. uses such an approach to extend the Dia algorithm [10] to enable offloading of flows onto either LTE, UMTS, WiMax and Wi-Fi networks [11]. The parameters considered included radio signal strength, available bandwidth of network, packet delay, packet loss rate and cost per byte. They have considered 4 types of flows (conversation voice, buffered streaming video, interactive gaming and TCP-base) and for each flow type they have assigned a different weight for each parameter. Even in this case except radio signal strength and available bandwidth the rest of the parameters are static in nature. Also their evaluation strategy considers the availability of one instance of each network which is not a typical case. As flow mobility is a relatively new area of research, most of the literature is concentrated on architectures for enabling flow mobility. There is not much literature on developing flow mobility algorithms for balancing of load in heterogeneous networks especially those consisting of LTE and Wi-Fi.

1.3 Overview of Our work

The work involves supporting flow mobility between LTE and Wi-Fi interfaces in ns-3 [12] using PMIPv6. The ns-3 simulator already provides a framework for LTE and Wi-Fi networks. A PMIPv6 implementation was available for ns-3 which was not merged into its mainline. This implementation is extended to support flow mobility and merged into the latest ns-3 (ns-3.19) and the correctness of the implementation is verified. Also an offload algorithm is proposed for balancing the load in a heterogeneous network consisting of LTE and Wi-Fi. However, the testing of the algorithm is not finished. A simple algorithm is implemented where certain flows are offloaded onto Wi-Fi based on the Signal to Noise Ratio (SNR) received from the Wi-Fi network.

1.4 Thesis Outline

The thesis is outlined as follows. Chapter 2 describes IP mobility management and PMIPv6. Chapter 3 gives an overview of LTE and Wi-Fi networks and then discusses the integrated LTE Wi-Fi architecture. Flow mobility is also discussed. Chapter 4 describes the design and implementation details of the flow mobility framework in ns-3. The simulation setup and results for the simple algorithm are discussed in Chapter 5. Chapter 6 presents the proposed flow mobility algorithm for flow based offloading. Finally, everything is concluded and future work discussed in Chapter 7.

Chapter 2

Mobility Management

Mobile IP solutions have become commonplace in wireless networks for supporting mobility. This chapter describes the concept of mobile IP. PMIPv6 is a network based mobility management protocol which has become quite popular. The details of the workings of PMIPv6 are presented below.

2.1 Mobile IP

Mobile IP is an Internet Engineering Task Force (IETF) standard communications protocol which allows Mobile Node (MN) mobility at the IP layer without the applications ever losing connectivity. The protocol allows the MN to move across different IP subnets while continuously maintaining connectivity to the Internet (or a private network). Transport layer protocols like TCP require the IP address to be the same for maintaining ongoing sessions and in the absence of Mobile IP it becomes impossible for such sessions to continue. Generally, these protocols are used in mobile wireless networks.

Each MN node has a fixed IP address called the Home Address (HoA), regardless of its current point of attachment (PoA) to the network. This registration is maintained by an entity known as the Home Agent (HA). As the MN changes its PoA, it is associated with a temporary Care-of Address (CoA) which identifies the MNs current location. The HA then maintains a mapping between the HoA and the CoA and redirects all IP packets received for the MN to its CoA using IP tunneling.

There are two broad categories of IP mobility management solutions:

1. **Host-based Mobility Management:** In this the MN is aware of the mobility i.e. the MN takes part in the mobility signaling. As a result changes are needed in the MN network protocol stack to support the same. Eg: MIPv4, MIPv6 and DSMIPv6.
2. **Network-based Mobility Management:** In this the MN is not aware of the mobility. All the signaling and tunneling is taken care of by the network entities based on certain Layer 2 (L2) triggers from the MN (e.g. Association Request message in case of Wi-Fi networks). This means that there are no changes required to the MN protocol stack. Eg: PMIP, PMIPv6 and GTP.

MIPv6 [13] has been a very stable protocol which has been standardized by IETF and is very popular. But, of late the trend has shifted towards the use of network-based mobility management

protocols. The major reasons for this shift are as follows:

- In the case of host-based mobility, changes are required to the MN protocol stack whereas there are no such requirements in the case of network-based mobility. This gives the operator flexibility to setup and modify their network without having to push any changes to MN.
- In the case of host-based mobility, as the MNs are responsible for the mobility signaling a lot of overhead is added to the already congested wireless access links.
- The signaling also causes additional consumption of limited MN battery power in case of host-based mobility.

This resulted in IETF actively looking for a network-based mobility management protocol for standardization.

2.2 PMIPv6

PMIPv6 is a network-based mobility management protocol standardized by IETF [5]. PMIPv6 has found its place in the telecommunication industry. It provides mobility management in a topologically localized domain known as the Localized Mobility Domain (LMD). PMIPv6 basically extends the MIPv6 protocol by extending the signaling messages and reusing some of the fundamental entities like Home Agent (HA) and Foreign Agent (FA). Unlike the MIPv6 where there are 2 addresses viz., HoA and CoA for a MN, in PMIPv6 it is ensured that the MN always has its HoA. Once a MN enters the PMIPv6 domain, the serving network ensures that the MN is always on its home network and can obtain its HoA. The PMIPv6 specification consists of 2 core functional entities:

- **Local Mobility Anchor (LMA):** The LMA extends the functionality of the HA in MIPv6. It is responsible for maintaining reachability state of the MNs and is the topological anchor point for all MNs Home Network Prefixes (HNPs). All packets destined to the MNs reach the LMA and it tunnels those packets appropriately so as to reach the respective MNs. It also receives all the packets originating from the MN via a tunnel from the MAG and routes them to the respective destinations.
- **Mobile Access Gateway (MAG):** The MAG performs the mobility management on behalf of a MN, and it resides on the access link where the MN is anchored. It is responsible for detecting the MN's movements to and from the access link and for initiating binding registrations to the MN's LMA. It is also responsible for emulating the MN's home link on the access link by advertising the HNP to the MN. All packets from the MN's reach the MAG, which then tunnels them to the LMA.

An LMD typically consists of one LMA and multiple MAGs. The MAGs could be supporting different access technologies. Figure 2.1 gives a brief overview of PMIPv6 along with some of the important terminology involved.

Figure 2.2 shows the messages involved in setting up an initial PMIPv6 session. The steps are detailed as follows:

1. The MN initiates a L2 attach with the access network (usually when it comes within the range of the access network) which is connected either directly or indirectly to the MAG (generally

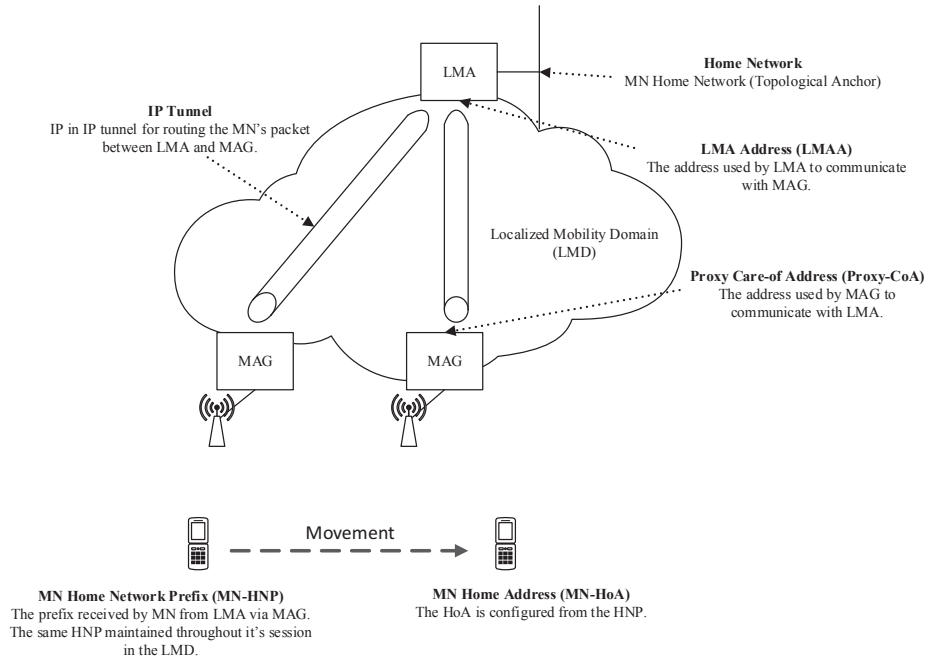


Figure 2.1: PMIPv6 Overview

the MAG is co-located on the same device of the access network to which the MN connects to. In case it is not then the access network needs to make the MAG aware of the connection).

2. The MN's identity (MN-Identifier) is retrieved based on the initial attach (generally from a AAA server) and the access authentication procedure is triggered. If the authentication is successful, then the MAG can obtain the LMA Address (LMAA) from the MN's policy profile along with certain other optional parameters like HNP(s), supported address configuration procedures, etc.
3. The MAG initiates the PMIPv6 connection by sending the Proxy Binding Update (PBU) message to the LMA (indicated by the LMAA). The PBU contains the MN-Identifier along with certain other parameters like HNP(s), Access Technology Type (ATT), Handoff Indicator (HI), etc. The MAG also enters these details into its Binding Update List (a table maintaining all the active MN's connected to it).
4. Once the LMA receives the PBU, it extracts the MN-Identifier and checks if the MN is already registered by looking in its Binding Cache (a table maintaining all the active MNs registered with it). If not the LMA creates a new Binding Cache Entry containing the MN details received in the PBU, also making note of the Proxy-CoA of the MAG. It then assigns it appropriate HNP(s) (either a new one from its IP address pool or the one requested by the MAG). It also sets up a bi-directional tunnel towards the MAG for the HNP(s) allocated. It then proceeds to send a Proxy Binding Acknowledgement (PBA) message to the Proxy-CoA of the MAG containing the MN-Identifier, the HNP(s) and certain other parameters.

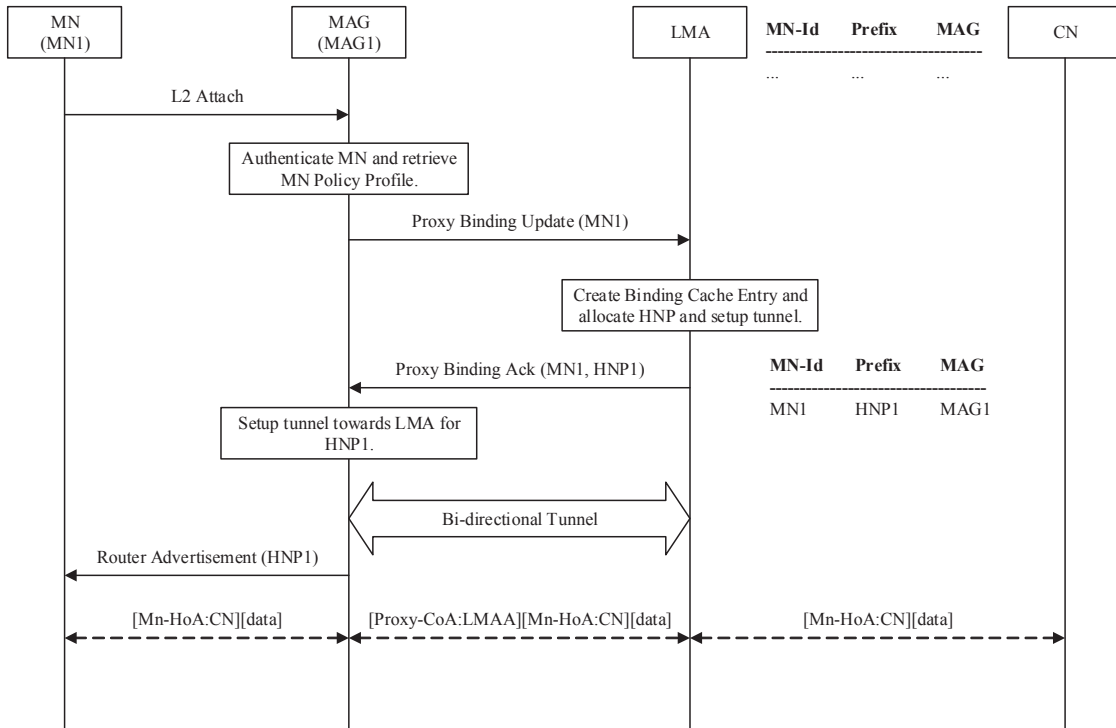


Figure 2.2: PMIPv6 Initial Attach

- Once the MAG receives the PBA, it extracts the MN-Identifier, HNP(s) etc. It updates its Binding Update List with these parameters (especially the HNP(s)). It proceeds to setup a bi-directional tunnel towards the LMA for the received HNP(s). After this the MAG then advertises the HNP(s) to the MN using IPv6 Router Advertisement (RA) messages.
- Once the MN receives the RA, it configures its IPv6 address based on the supported address configuration mode (Stateless or Stateful) as indicated in the MN's policy profile.
- Once the session is established the data can be transferred between the MN and Correspondent Node (CN). All the global packets from the MN are tunneled by the MAG towards the LMA and vice versa.

Figure 2.3 shows the process of handover in PMIPv6. The steps are detailed as follows:

- The MN detaches from MAG1 by making a L2 detach from the access network under MAG1. This event is then relayed to the MAG, MAG1.
- The MAG, MAG1 then sends PBU with a de-registration request. The PBU contains the MN-Identifier along with some other parameters.
- On receiving the PBU the LMA starts a timer to delete the Binding Cache entry for corresponding MN-Identifier. In case a PBU is not received before the timer expires, the Binding Cache Entry would be deleted and all the tunnels and resources allocated would be reclaimed.

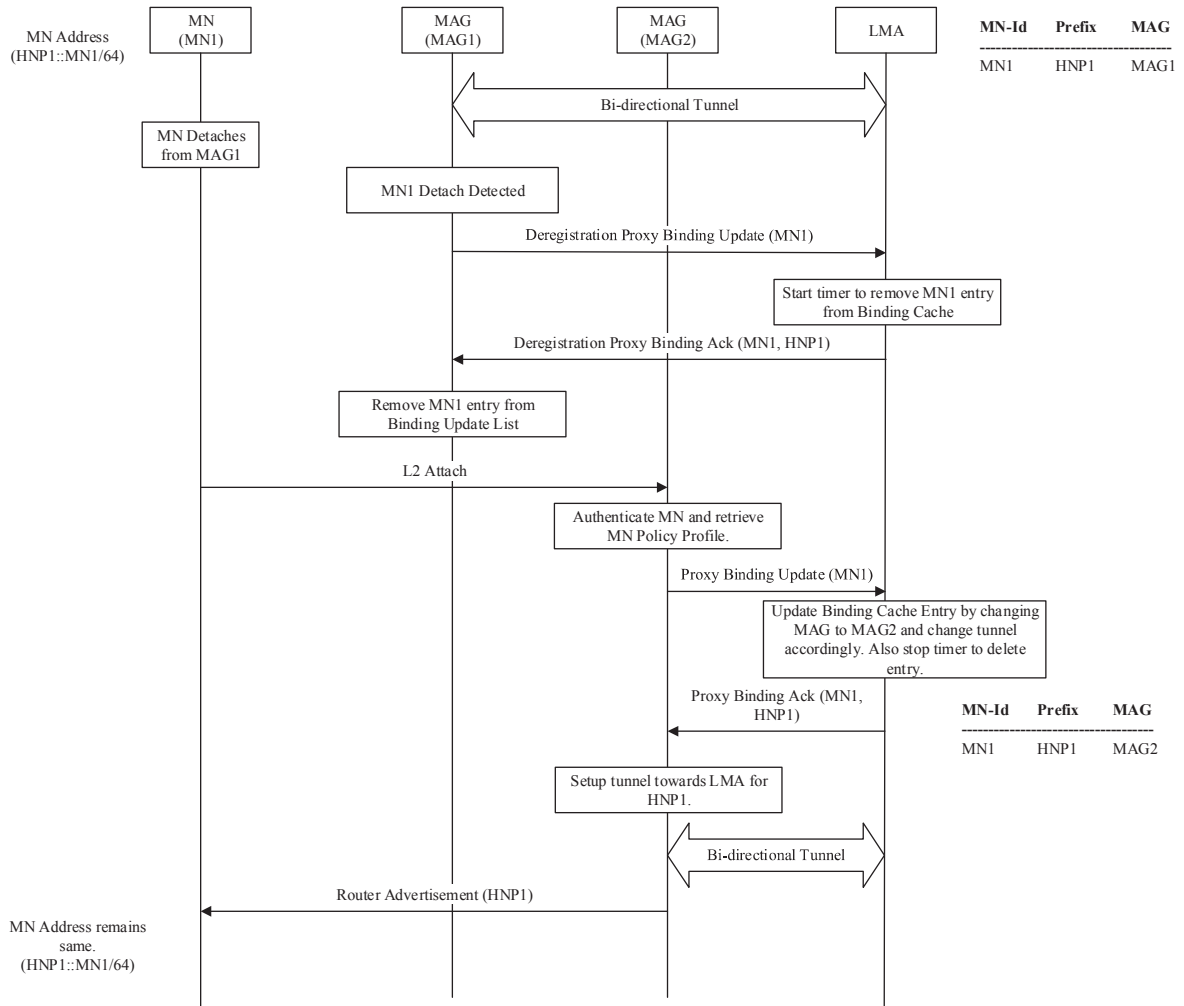


Figure 2.3: PMIPv6 based handover

The LMA also sends back a PBA containing the MN-Identifier and other parameters. During this time, any data packets received for the MN are dropped.

4. Once the MAG, MAG1 receives the PBA it deletes the entry for the particular MN-Identifier from its Binding Update List. The tunnels and resources allocated for the MN are reclaimed.
5. The MN then initiates a Layer 2 attach with the access network connected to MAG2. This causes MAG2 to create a PBU containing the MN-Identifier and certain other parameters and then sends it to the LMA.
6. On receiving the PBU, the LMA changes the Proxy-CoA in the Binding Cache Entry for the MN from that of MAG1 to that of MAG2. With that the tunnel and routing is also changed correspondingly. A PBA is created containing the MN-Identifier, the HNP(s) previously allocated and other parameters and sent to MAG2.

7. On receiving the PBA, MAG2 updates its state in the Binding Update List and sets up the tunneling and routing. The MAG, MAG2 then sends out an IPv6 RA with the same HNP(s).

Further details about the procedures can be found in [14].

Chapter 3

LTE and 802.11: An Overview

Cellular and WLANs are the two major types of wireless networks which are enjoying widespread penetration. 3GPP has had a major role to play in the standardization of various popular cellular networks like GSM, UMTS and LTE. IEEE has had similar success in the WLAN segment with their 802.11 standards. For a long time these two types of wireless networks have evolved independent of each other. But the increasing bandwidth demand of the users and requirement for seamless communication has made these networks coming together to solve these issues jointly. This chapter describes the latest 3GPP cellular standard LTE and the IEEE 802.11 standard. The LTE architecture provides procedures for integration of 802.11 based Wi-Fi networks. The last section discusses an offload strategy known as flow mobility.

3.1 LTE

In the past few years, voice communication has taken a backseat to the data requirements. The introduction of smartphones, tablets and the emergence of internet apps and multimedia have been reasons for this trend. GSM was the first cellular technology to gain widespread acceptance. It supported mainly voice calls and used circuit switching. This was considered the second generation (2G) of cellular communications. Later to support limited data services GPRS was integrated with GSM. UMTS which was standardized by 3GPP then came as a 3G technology by adding some extensions to GSM/GPRS, but it was clear that the completely new architecture was required to meet the increasing bandwidth requirements.

LTE was standardized by 3GPP to continue the evolution from UMTS. A System Architecture Evolution (SAE) was initiated at the same time as LTE development started which focused on a complete evolution of the core network architecture with support only in the packet-switched domain. This led to the development of the Evolved Packet Core (EPC), an IP based core network. LTE was designed from the start with the goal of evolving the radio access technology under the assumption that all services would be packet-switched. Together, LTE and SAE comprise the Evolved Packet System (EPS), where both the core network and the radio access are fully packet-switched. The target peak data rates for downlink and uplink in LTE Release 8 were set at 100 Mbps and 50 Mbps respectively for a 20 MHz bandwidth. The LTE release 8 was not exactly the 4G of cellular networks.

The work on LTE continued within 3GPP with new features being added with each release. ITU-R released a circular for IMT-Advanced which contained specifications which could be considered 4G. 3GPP made further enhancements to their existing LTE specification so that the requirements of IMT-Advanced are met by LTE-Advanced. Hence LTE-Advanced can be considered as a major step in the evolution of LTE and not as a new technology. LTE-Advanced could support speeds of 1Gbps in downlink and 500Mbps in downlink.[2]

3.2 IEEE 802.11 (Wi-Fi)

“The IEEE 802 LAN/MAN Standards Committee develops and maintains networking standards and recommended practices for local, metropolitan, and other area networks.”[15]. IEEE 802 has created a lot of standards for various types of networks within its umbrella. The IEEE 802.3 standard, more popularly known as the Ethernet, has found great success. It has been the most extensively used standard for deployment of wired LANs within enterprises, homes, offices, etc. In 1997, IEEE 802 began work for developing a standard for WLAN under the 802.11 family. Since then various standards have been developed under 802.11 of which the popular ones have been 802.11a, 802.11b, 802.11g and 802.11n. These standards most commonly use the 2.4 GHz and the 5 GHz frequency bands for wireless communication.

Since IEEE didn't mandate testing equipment for compliance with their 802.11 standard, a non-profit global organization named Wi-Fi Alliance was setup in 1999 comprising of various pioneer companies in the wireless network market. Their goal was to test the products developed to support the 802.11 standard and ensure compliance and thus promote the technology. Thus, all products (e.g. access points, laptops) which complied with the 802.11 standards could mark their products with the Wi-Fi logo.

Due to the standardization efforts of Wi-Fi Alliance, the Wi-Fi products gained great momentum in the market. In addition, the hassle free nature of wireless devices and the usage of unlicensed spectrum also made it simpler for users to just plug and play the devices. Thus it became commonplace in homes, offices, enterprises, malls, airports, etc. As of 2014 the most common and fastest form of Wi-Fi was the 802.11n, which offered speeds of up to 300Mbps. These Wi-Fi access points typically have a range of about 20 meters indoors and a range of about 100m outdoors.

The next version of 802.11 standard is 802.11ac. This builds on 802.11n by using wider channel bandwidth (80MHz or 160MHz), higher modulation schemes (256-QAM), and new radio technologies like Multi-User MIMO to improve the speeds. It works in the 5GHz spectrum and can deliver speeds of more than 1Gbps [3].

3.3 LTE Wi-Fi Integrated Architecture

The LTE architecture essentially consists of 2 parts:

- **Evolved Packet Core (EPC)** This includes the non-radio aspects of the LTE evolution. This was done under the term System Architecture Evolution (SAE). The resulting core network was an IP based packet-switched network which came to be known as the EPC network.

- **Evolved Universal Terrestrial Radio Access Network (E-UTRAN)** This includes the radio aspects of the LTE evolution. This includes the use of Orthogonal Frequency Division Multiple Access (OFDMA) in downlink and Single Carrier - Frequency Division Multiple Access (SC-FDMA) in the uplink. It also includes the radio protocol stack which involves the new physical layer, MAC scheduler for packet scheduling, Hybrid Automatic Repeat Request (HARQ) and various security and compression schemes.

Together these two are known as the Evolved Packet System (EPS) which is a completely packet switched system.

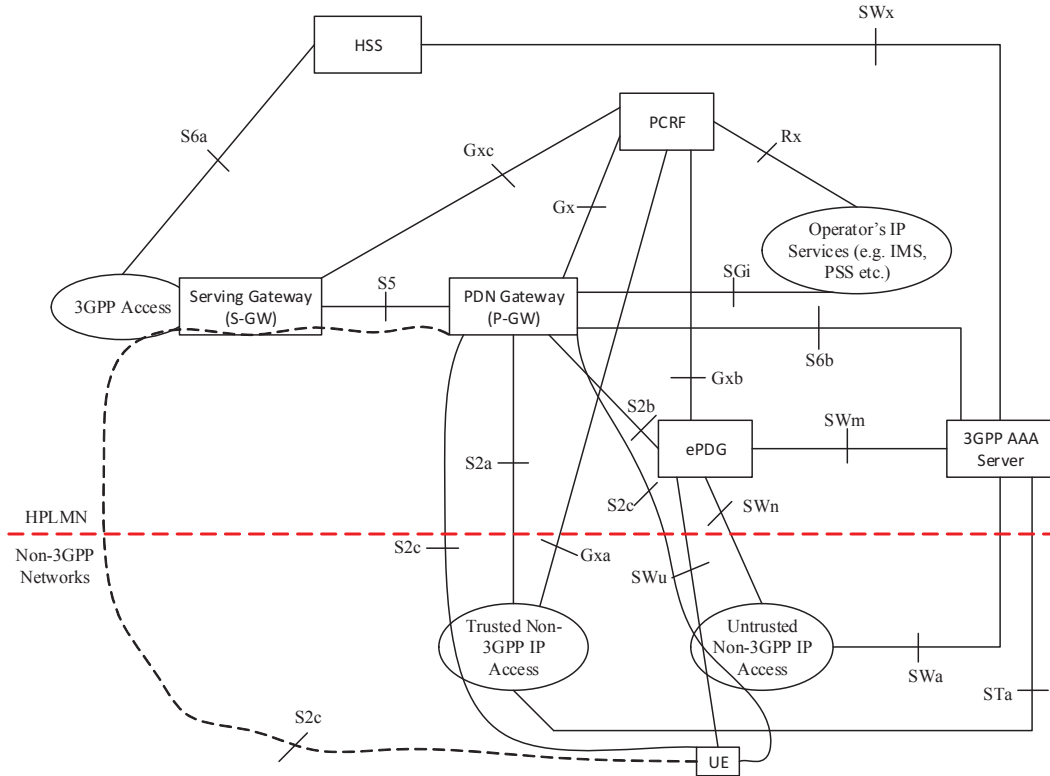


Figure 3.1: LTE Architecture (3GPP LTE Specifications [16])

The 3GPP LTE architecture is shown in Figure 3.1. Some of important entities are:

- **Evolved Universal Terrestrial Radio Access Network (E-UTRAN)** The E-UTRAN consists of Evolved NodeBs (eNBs) connected to each other via the X2 interface and to the EPC via S1 interface. The architecture is shown in Figure 3.2. The E-UTRAN is responsible for radio resource management, header compression, security, positioning and maintaining connectivity to the EPC. The E-UTRAN architecture is flat.
- **Packet Gateway (P-GW)** The P-GW is in charge of allocation of IP addresses to UEs, ensuring the fulfillment of Quality of Service (QoS) requirements of UE and charging. It also behaves as a mobility anchor to connect to non-3GPP technologies like Wi-Fi, WiMax, etc.

- **Serving Gateway (S-GW)** The S-GW behaves like a local mobility anchor by keeping track of UEs as they move between eNBs. All packets to and from the UEs are received by S-GW. It also behaves as a mobility anchor to connect to other 3GPP technologies like UMTS, CDMA2000, etc.
- **Mobility Management Entity (MME)** The MME is a control entity which does not process any data packets. It takes care of the signaling between the UE and the EPC.

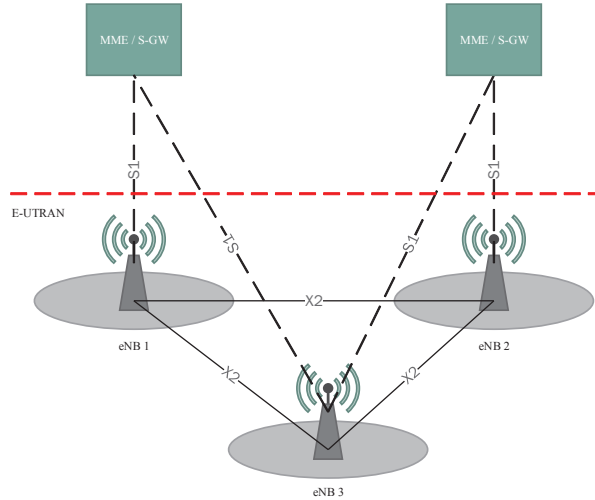


Figure 3.2: E-UTRAN Architecture (3GPP LTE Specifications [17])

The protocol stack of E-UTRAN is divided into 2 parts:

- **User Plane** This is used for exchange of data packets as shown in Figure 3.3. The protocol stack between the UE and the eNB consists of the sublayers: Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC) and Medium Access Control (MAC). The UE IP packets are exchanged between the eNB and S-GW using a tunneling protocol known as GTP. The protocol between the S-GW and P-GW can either be GTP or the PMIPv6.
- **Control Plane** This is used for the exchange of control packets as shown in Figure 3.4. The Non-Access Stratum (NAS) protocol is used for control signaling between the UE and MME. The radio sublayers remain the same as in case of the User Plane except for the Radio Resource Control (RRC) sublayer. The RRC layer is responsible for the establishing radio level configuration between the eNB and UE.

3GPP classifies the non-3GPP networks into two categories:

- **Trusted non-3GPP access** These access networks can directly connect to the EPC.
- **Untrusted non-3GPP access** These access networks can connect to the EPC using an entity known as Evolved Packet Data Gateway (ePDG). The ePDG is supposed to provide security mechanisms like IPSec for the connections established to the UEs.

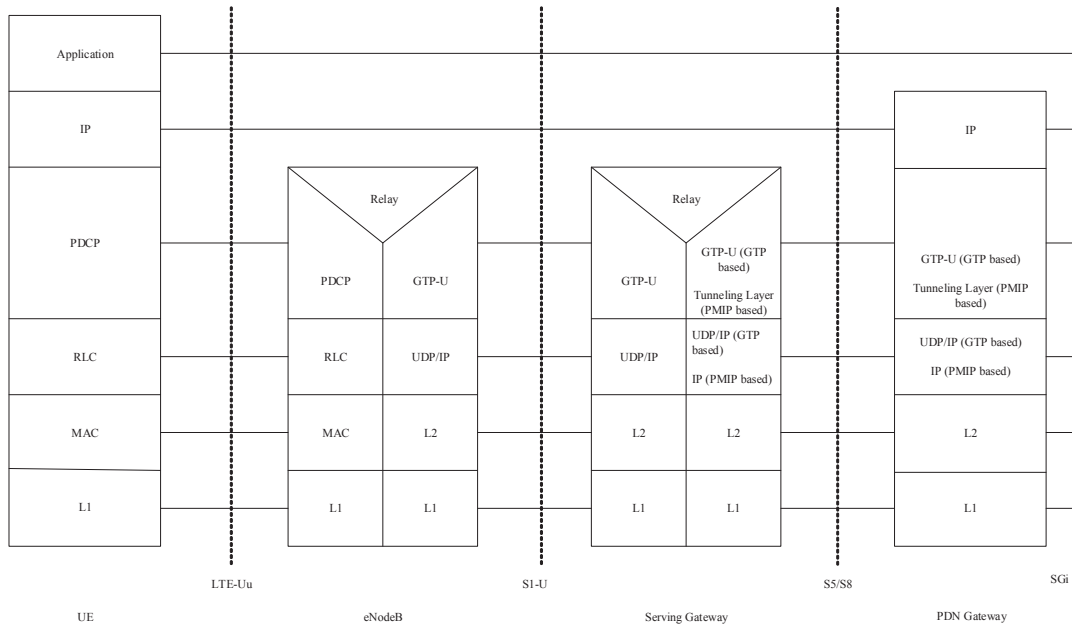


Figure 3.3: User Plane protocol stack (3GPP LTE Specifications [17])

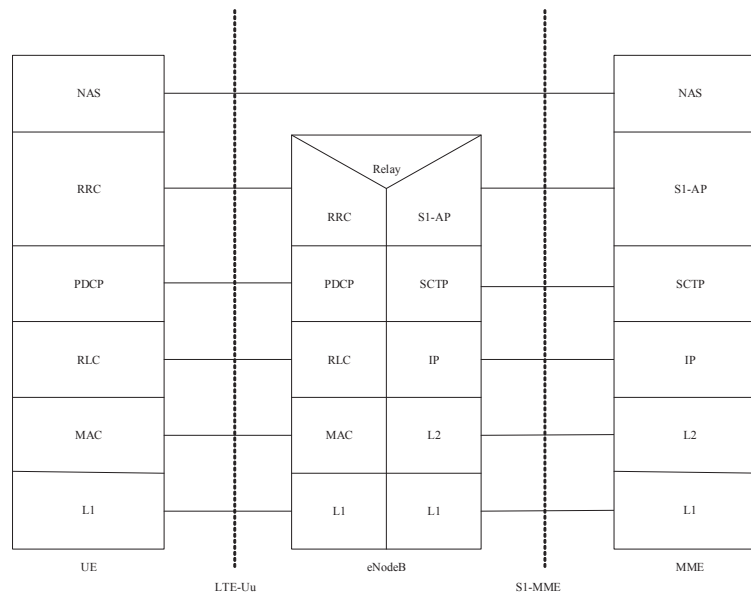


Figure 3.4: Control Plane protocol stack (3GPP LTE Specifications [17])

3GPP does not specify the access networks falling into each category. This decision left to the Mobile Node Operator (MNO). 3GPP defines 3 types of interfaces to connect non-3GPP technologies to the EPC:

1. **S2a** It provides mobility management support between the trusted non-3GPP access networks and P-GW. This interface supports either PMIPv6, MIPv4 or GTP based mobility management protocol. The protocol stack for the PMIPv6 based version is shown in Figure 3.5.
2. **S2b** It provides mobility management support between the ePDG and P-GW for the untrusted non-3GPP access networks. This interface supports either PMIPv6 or GTP based mobility management protocol.
3. **S2c** It provides mobility management support between the UE and P-GW for both the trusted and untrusted non-3GPP access networks. This interface supports the DSMIPv6 based mobility management protocol.

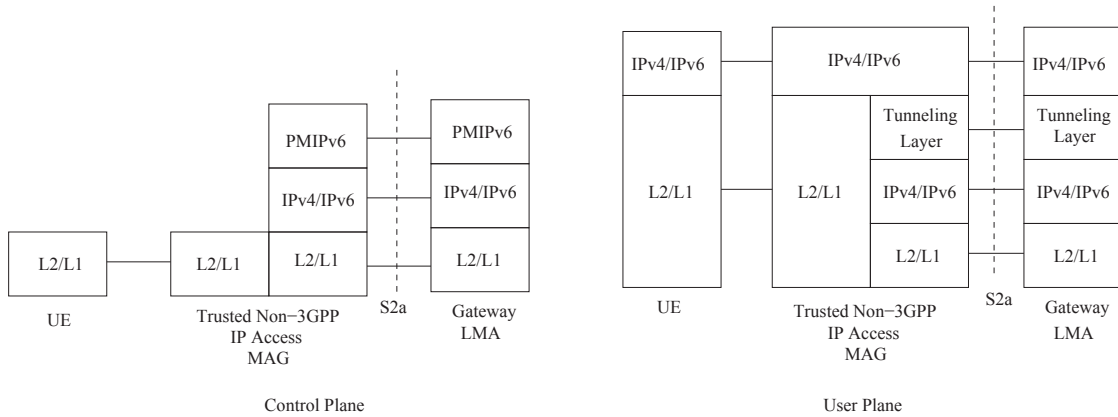


Figure 3.5: S2a protocol stack (3GPP LTE Specifications [16])

Further details about the roles of various entities, signaling, etc can be found in [18] [19] [16].

3.4 Flow Mobility

With the advent of smartphones, tablets, laptops, etc there has been an increased use of data based services. The proliferation of apps and the evolution of the Internet has also added to this data explosion. Currently most of smartphones and tablets come with two radio interfaces: cellular (3G/4G) and Wi-Fi. The users are almost always connected with the cellular network while connection to Wi-Fi is selected manually based on the availability of Wi-Fi access points (or hotspots). With multiple radio interfaces there is either a possibility of performing a vertical handover (moving all flows associated with one radio interface over to the other radio interface) or multihoming (simultaneously having flows go over both the radio interfaces).

Of late a new paradigm has emerged known as IP flow mobility, where a flow (typically identified by the 5 tuple <protocol, source IP address, destination IP address, source port, destination port>) can be seamlessly moved from one interface to the other without effecting other ongoing flows on either of the two interfaces. An example scenario for flow mobility is shown in Figure 3.6. UE initially involved in an online video chat with a voice component (VoIP) and a video component (conversational video) both of which are routed via 3GPP access. There is also a web browsing session and a video clip (non-conversational video) which are being routed via the non-3GPP access.

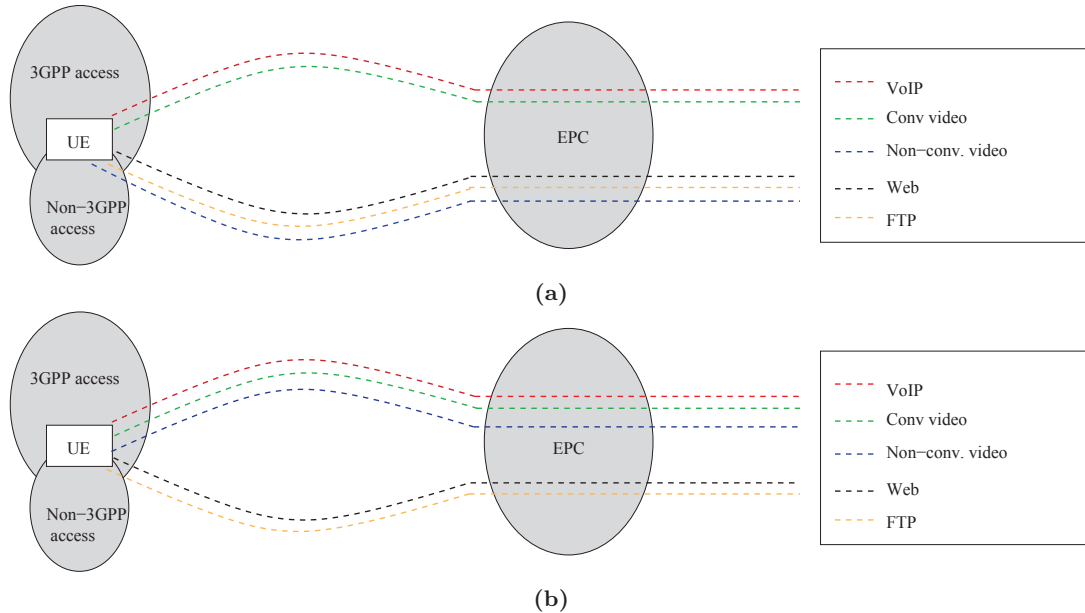


Figure 3.6: Flow Mobility Scenario: (a) Initial state of flows, (b) State after flow mobility [20]

In this example, once the FTP session is started over the non-3GPP access, it gets overloaded. Based on this a decision is made to move the video clip traffic to the 3GPP network. This movement doesn't affect any of the other flows. Some of the other use cases have been defined in [20]. The advantages of using flow mobility are as follows:

1. The higher bandwidth of the Wi-Fi networks can be used for those flows which are bandwidth hungry but don't have fixed QoS requirements like FTP downloads without having to move all flows over to the Wi-Fi access.
2. By moving some flows to Wi-Fi networks, the MNOs can reduce congestion in the 3GPP networks for other flows which have certain QoS requirements.
3. The operators can decide various policies based on parameters like flow type, subscription plan of the user, congestion, etc to provide the best service to the subscribers.

In [21] the authors discuss the extensions to MIPv6 and DSMIPv6 to enable flow mobility. IETF is currently working on standardizing the flow mobility solution for PMIPv6. A draft [22] has been submitted. In [23] the authors provide a survey of the client and networks based flow mobility protocols. The 3GPP specifications [20] and [24] discuss integration of flow mobility into the LTE architecture on the interfaces S2a, S2b and S2c. The specifications only provides the architecture for the integration, but the actual policies and parameters to be considered for triggering flow mobility is left to the MNOs.

3.4.1 PMIPv6 based Flow Mobility

There are two types of flows generally: inbound flows, flows which originate at the CN with their destination as the MN and outbound flows, flows which originate at the MN with their destination

as the CN. Usually there is a pair of flows (one inbound and one outbound) with their source and destination fields (IP address and port numbers) exchanged which represent a session.

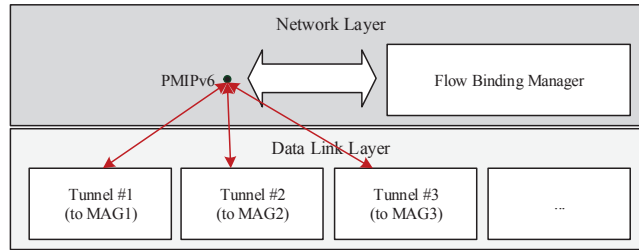


Figure 3.7: LMA Flow Mobility protocol stack [25]

The architecture of PMIPv6 is such that all the flows pass through the LMA. To handle flow mobility the LMA is tweaked slightly. The LMA is directly incharge of handling flow mobility for only the inbound flows. The LMA stack is shown in Figure 3.7. The Flow Binding Manager is responsible for deciding the MAG which should receive the packets of a particular flow (and thus indirectly deciding the interface). The Flow Binding Manager manages a structure known as the Flow Binding Table which contains the following fields:

- **Flow Identifier** This is an integer uniquely identifying an entry in the table.
- **Traffic Selector** Traffic selector [21] is used to identify if flows match the entry. The traffic selector contains the IP address, port numbers, protocol and some other fields. These fields can also include wildcard characters or a range of values for matching a number of flows.
- **Binding Id List** This contains an ordered list of access technologies and the corresponding binding cache entries and is used for selecting the outgoing MAG for the flow matching the entry.
- **Priority** This indicates the priority of the entry in the table. The entries in the table are matched in that order.
- **Type** It indicates whether the entry is static or dynamic. Dynamic entries have lifetimes, after whose expiration the entry is deleted. Static entries are never deleted.
- **Lifetime** This indicates the lifetime for the dynamic entries.

For every packet the LMA receives, the Flow Binding Manager checks its flow binding table starting with the highest priority entry and forwards the packet to the highest priority MAG having an associated binding cache entry (i.e. to the MN interface which is connected and having highest priority) as indicated in the binding id list. The initial entries (usually static in nature) in the flow binding table are generally filled using the MN profile and some fixed policies. The rest of entries (usually dynamic in nature) can be provisioned later based on certain policies.

The MN stack is shown in Figure 3.8. The MN consists of a Virtual Interface Layer between the Network layer and the Data Link layer which manages the addressing and the flow mobility on the MN side. The Network layer only sees one virtual interface [26]. All the actual physical interfaces are managed under this virtual interface. The Virtual Interface layer has a structure known as the Flow

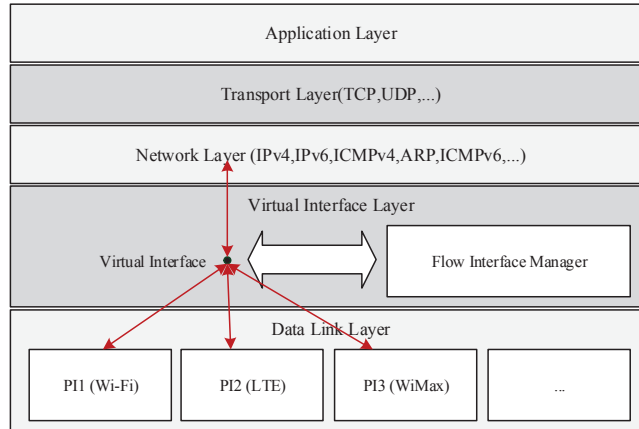


Figure 3.8: MN Flow Mobility protocol stack [25]

Interface Manager which manages the Flow Interface Table. This is similar to the Flow Binding Manager in the LMA. All the fields in this table are same as the flow binding table except for the binding id list. In its place there is the outbound interface list which contains an ordered list of interfaces in the MN. This list is used to determine the interface on which to forward the packet for a particular flow. The MN is in charge of selecting the interface for the outbound flows. The traffic selector in this list contains the reverse flow entries (flow having the source and destination fields exchanged). In addition, the Flow Interface Manager also keeps tracks of inbound flows for that MN. If the flow arrives on an interface which is not the expected one for that flow, then it assumes that the LMA has moved the flow over to the interface on which the packet arrived. It then changes the outbound interface list such that the reverse flow is sent over that interface. Thus, the LMA can indirectly control the outbound flows as well.

The signaling procedure for setting up of flow mobility using PMIPv6 is shown in Figure 3.9 [27]. The basic idea involves the sharing of Home Network Prefixes on the available interfaces. The role of LMA is played by P-GW and role of the MAG for LTE is played by S-GW. Following are the steps involved in moving a flow from LTE interface :

1. We assume that interface IF1 (LTE interface) of the MN already has a PMIPv6 session established and been assigned a HNP, HNP1. Also a flow, Flow1 is already being routed via that interface.
2. Once the interface IF2 (Wi-Fi interface) connects to its access network, MAG2 (Wi-Fi MAG) sends the PBU message to the LMA (with Handover Indicate (HI) as 1 indicating attachment over new interface). The LMA detects that the PBU is from a MN already having another interface attached. Therefore it sends a PBA to MAG2 (Wi-Fi MAG) containing 2 HNPs, HNP1 (which was already assigned to the LTE interface for that MN) and HNP2 (a new HNP for the Wi-Fi interface). On receiving the PBA, MAG2 (Wi-Fi MAG) advertises both the prefixes and MN configures both the HNPs, HNP1 and HNP2, on its interface IF2 (Wi-Fi interface).
3. The LMA also sends a Home Network Prefix Update Request (HUR) message to MAG1 (S-

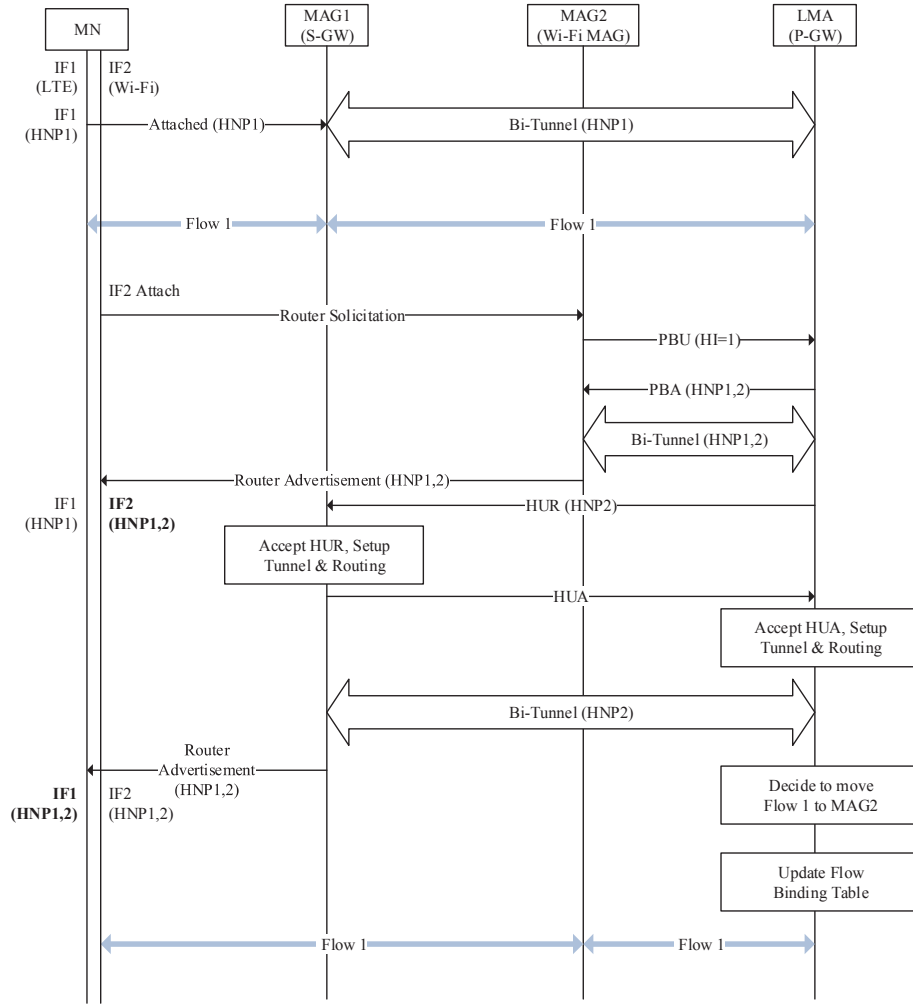


Figure 3.9: PMIPv6 Flow Mobility Signaling [27]

GW) containing the HNP, HNP2. Once MAG1 (S-GW) receives it, it updates its binding update list entry with HNP2 and sets up tunneling and routing for that prefix. It then sends a Home Network Prefix Update Acknowledgement (HUA) message to the LMA. On receiving the HUA, the LMA also sets up tunneling and routing for the prefix towards the MAG1 (S-GW) and updates its binding cache. MAG1 (S-GW) then begins to advertise both the HNPs, HNP1 and HNP2 to the MN.

4. Once this process is over both interfaces IF1 (LTE) and IF2 (Wi-Fi) on the MN have the IP prefixes HNP1 and HNP2 i.e. both interfaces can receive packets from either prefix (ensured by the virtual interface layer). The LMA can choose to move the flows between either of the two interfaces without any further signaling. All the LMA needs to do is change the binding list in the Flow Binding Manager for the flows which need to be moved.

Chapter 4

Design and Implementation in NS-3

NS-3 is an open source simulator which supports the LTE and Wi-Fi networks. Since ns-3 contains the implementations of both LTE and Wi-Fi, this was chosen to study the mobility between the two access networks. Flow mobility support was built into ns-3 using PMIPv6. This chapter gives an overview of the existing structure of LTE in ns-3 and how it is modified to support flow mobility. Finally, it describes how the implementation was validated.

4.1 NS-3

NS (Network Simulator) consists of the family of discrete event network simulators ns-1, ns-2 and ns-3. ns-3 is the latest version of these simulators and the only one being actively developed and maintained. It is free software licensed under GNU GPLv2. Its primary goal is to be used in research. ns-3's first version ns-3.1 was released in 2008 and since then with at least 3 releases every year, has now reached ns-3.20. It is written using C++ and Python.

ns-3 contains the implementations of both LTE and Wi-Fi. Hence this was chosen to study the mobility between the two access networks.

4.2 PMIPv6 Support For LTE

A PMIPv6 implementation was done by Choi et al. [28] for ns-3.8 and then later migrated to ns-3.12. This PMIPv6 implementation provided mobility support for Wi-Fi and WiMax networks. However, there was no vertical handover study performed. As this implementation was not merged into the ns-3 mainline, it wasn't available with ns-3.19 (the latest ns-3 version available at the time of our development).

We have merged the PMIPv6 implementation into ns-3.19 so that the latest versions of the LTE and Wi-Fi implementations could be used. The original ns-3 LTE architecture is shown in Figure 4.1. The existing implementation only supported IPv4 type EPC. Also the S-GW and P-GW functionality are merged into a single node. For supporting PMIPv6 on LTE there are two requirements:

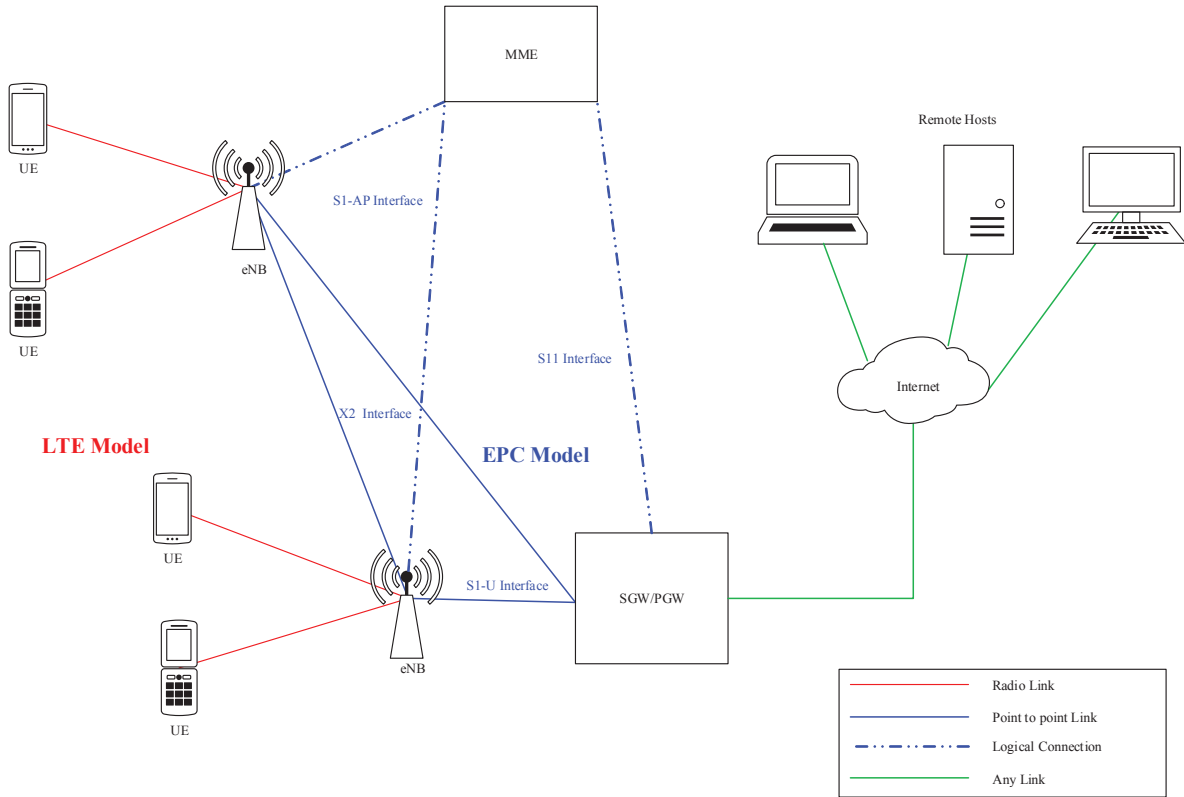


Figure 4.1: Original LTE Architecture in ns-3 (NS-3 LTE Design Documentation[29])

1. Build IPv6 support into existing LTE implementation.
2. Separate S-GW and P-GW into 2 different nodes and implement the PMIPv6 based S5 interface.

The LTE implementation is modified by us to satisfy these two requirements and the resulting LTE architecture is shown in Figure 4.2. The S5 attach procedure is started when the S-GW receives the S11 Create Session request from the MME. This is shown in Figure 4.3. The EpcMme sends the CreateSessionRequest to Epc6SgwApplication. The Epc6SgwApplication on receiving this calls the HandleNewLteNode on the Pmipv6Mag which begins the PMIPv6 signaling by sending out a PBU to the P-GW. The Pmipv6Mag also creates a BUL entry storing the IMSI of the UE and also the Tunnel Id of the default bearer. The Epc6SgwApplication responds back to the EpcMme with CreateSessionResponse. The Pmipv6Lma on the P-GW node on receiving the PBU responds by sending a PBA to the S-GW node which is received by the Pmipv6Mag. The Pmipv6Mag also sets the Ipv6 prefix information on Epc6SgwApplication by calling the SetUePrefix. The Pmipv6Mag then sets up a UnicastRadvd interface on the LteUnicastRadvd (for advertising Ipv6 HNP's). The LteUnicastRadvd then sends an Ipv6 RA to the UE via eNB by calling the Epc6SgwApplication SendRA which inturn calls the SendToS1USocket. Thus, the RA is tunneled from the S-GW to eNB and then forwarded to the UE.

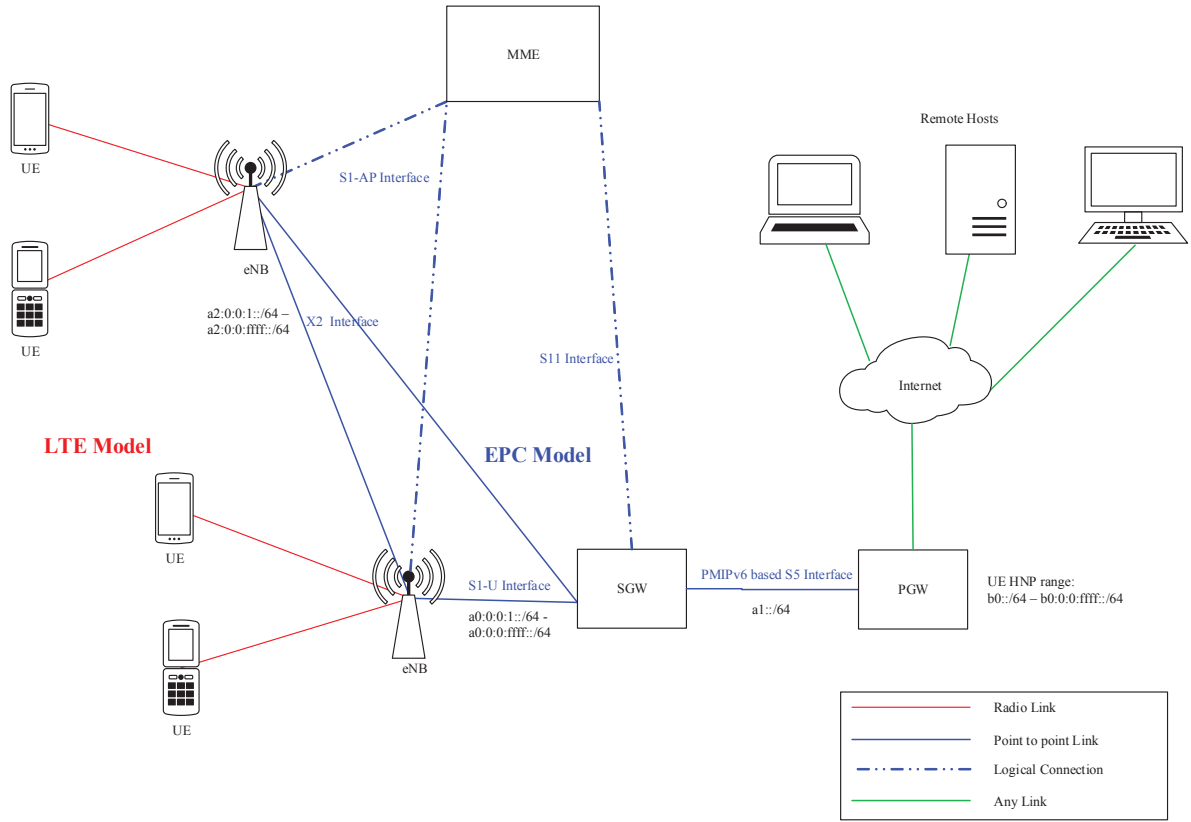


Figure 4.2: PMIPv6 based LTE Architecture in ns-3

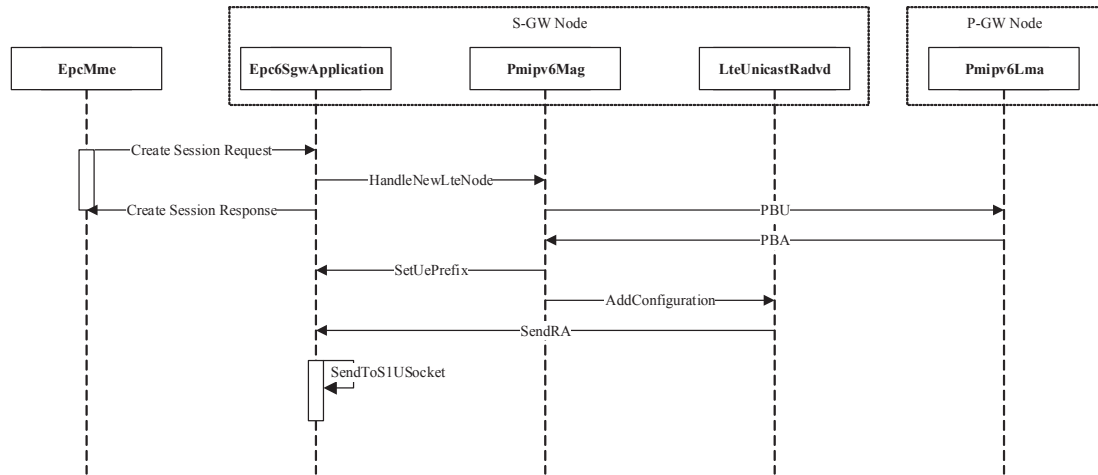


Figure 4.3: LTE Initial Attach Sequence Diagram

4.3 Flow Mobility Support

We have built Flow Mobility support into PMIPv6 for the access networks LTE and Wi-Fi. The flow mobility architecture was discussed in Section 3.4. The process of flow mobility signaling is shown

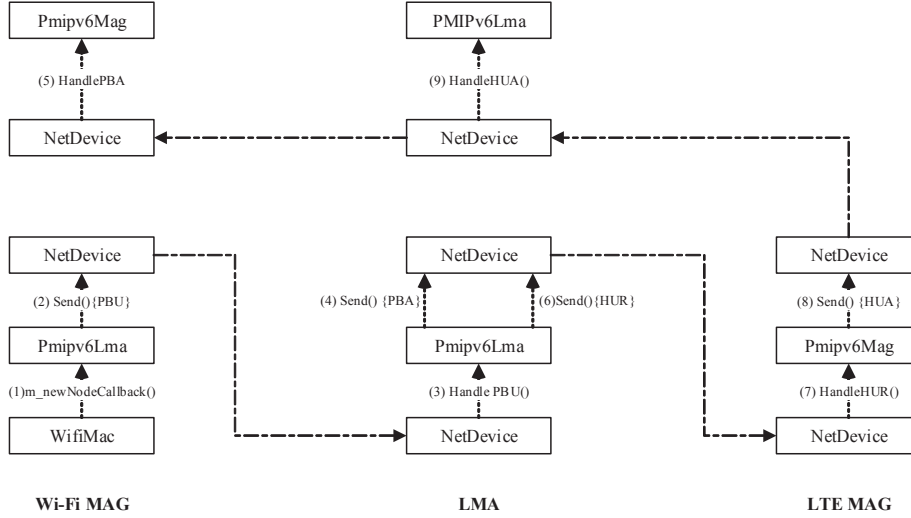


Figure 4.4: Flow Mobility Signaling in ns-3

in Figure 4.4. The assumption is that the UE has already connected with the LTE network and it newly attaches to a Wi-Fi AP. This WifiMac of the Wi-Fi MAG notices the new attach and notifies the Pmipv6Mag. The Pmipv6Mag sends out a PBU via Send (). When the LMA node receives the PBU, it triggers a call to the HandlePbu () in Pmipv6Lma. The Pmipv6Lma checks if the MN identified by the Mn-Identifier is already registered in its binding cache with a different attachment type. In that case, it sends PBA to the Wi-Fi MAG by including two Home Network Prefixes (HNPs), one which is assigned to the LTE interface and a newly allocated HNP. The NetDevice on the Wi-Fi MAG receives the PBA. This packet triggers the HandlePba () on the Pmipv6Mag which configures the HNPs. The Pmipv6Lma also sends a HUR to the LTE MAG (S-GW) which contains the newly allocated prefix. The NetDevice on the LTE MAG receives the packet which eventually triggers the HandleHur () on the Pmipv6Mag. The Pmipv6Mag processes the HUR by updating its Binding Update List with the newly sent prefix. It then sends a HUA to the LMA via the Send. When the LMA receives the HUA, HandleHua () updates the binding cache.

For enabling flow mobility the Flow Interface List and the Flow Binding List are implemented for the MN and the LMA respectively. The structure of these entities has already been discussed in Section 3.4. The Flow Binding Manager provides entries which are used to decide how the flows are routed. Figure 4.5 shows the routing of a packet from the CN to the MN. When the LMA receives a data packet it given to the Ipv6L3Protocol. This calls RouteInput () of the Ipv6ListRouting to determine the interface via which the packet is to be routed. The Ipv6ListRouting calls the RouteInput () for the Ipv6FlowRouting. The Ipv6FlowRouting is used to realize the Flow Interface List. The function LookupFlowRoute () is called to determine which interface of the MN should the packet be routed to. The packet is then sent via the TunnelNetDevice. This device encapsulates the packet in an Ipv6Header and sends it to the MAG. The MAG on receiving the packet checks if the packet is meant for it via the RouteInput (). Since the packet is destined for the MAG, the packet is received by the Ipv6TunnelL4Protocol. This then forwards the original packet on its interface towards the MN (LTE or Wi-Fi).

For the MN, a new routing protocol Ipv6UserFlowRouting is implemented. This included the

flow interface list and satisfied all functionality of the virtual interface. Both the WifiNetDevice and LteNetDevice which are installed on the UE are given same MAC addresses so that both configure same IP addresses given a HNP.

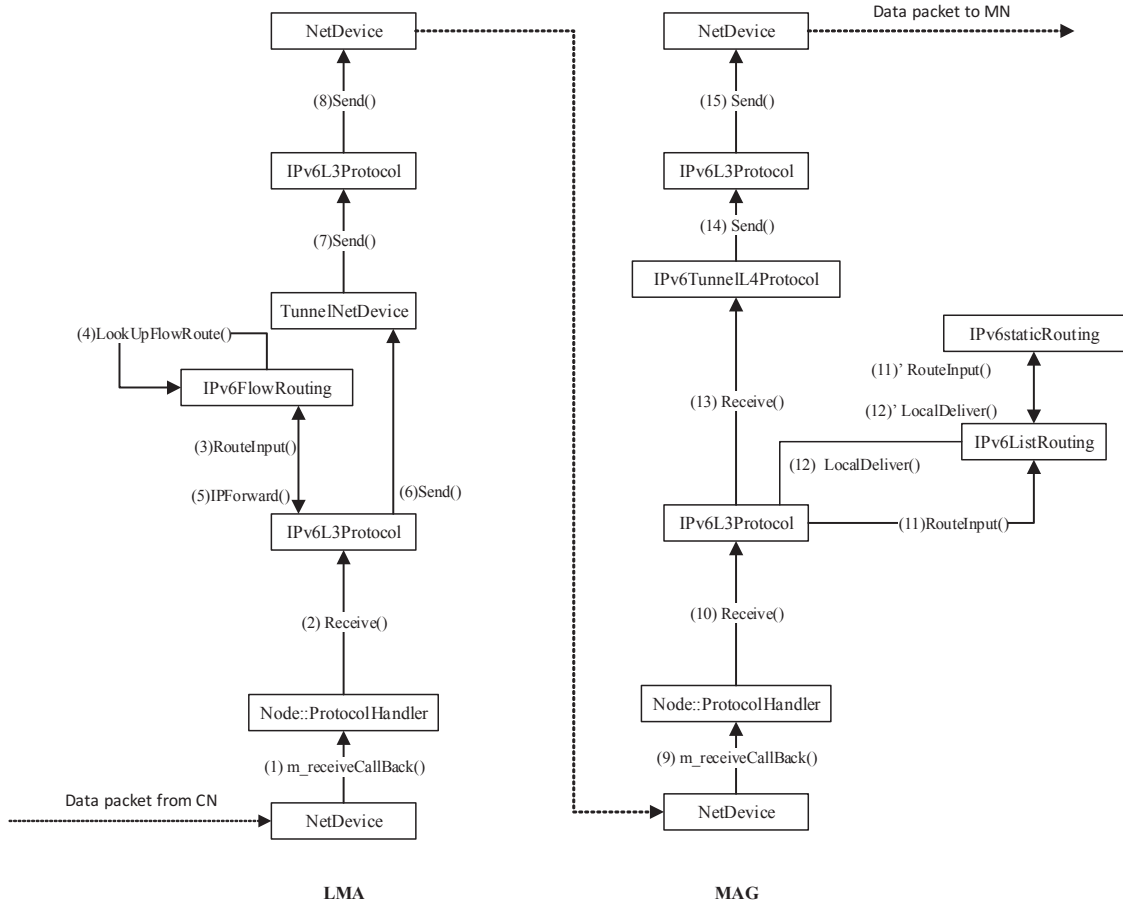


Figure 4.5: Flow Mobility Data Packet Processing in ns-3

4.3.1 Validation of Implementation

For validation the implementation a simple setup is considered as shown in Figure 4.6. The MAG functionality is co-located with the Wi-Fi AP. The UE moves towards the eNB with a velocity of 7 m/s. Initially 2 TCP flows are started from the CN to the UE (one with port 2000 and other with 2100). The flow binding list on the P-GW contains the following entries which are installed before the start of the simulation:

Flow Id	Priority	Traffic Selector	Binding Ids
2	15	(* , * , * , 2000 , TCP)	(LTE (8) , Wi-Fi (4))
1	10	(* , * , * , * , TCP)	(Wi-Fi (4) , LTE (8))

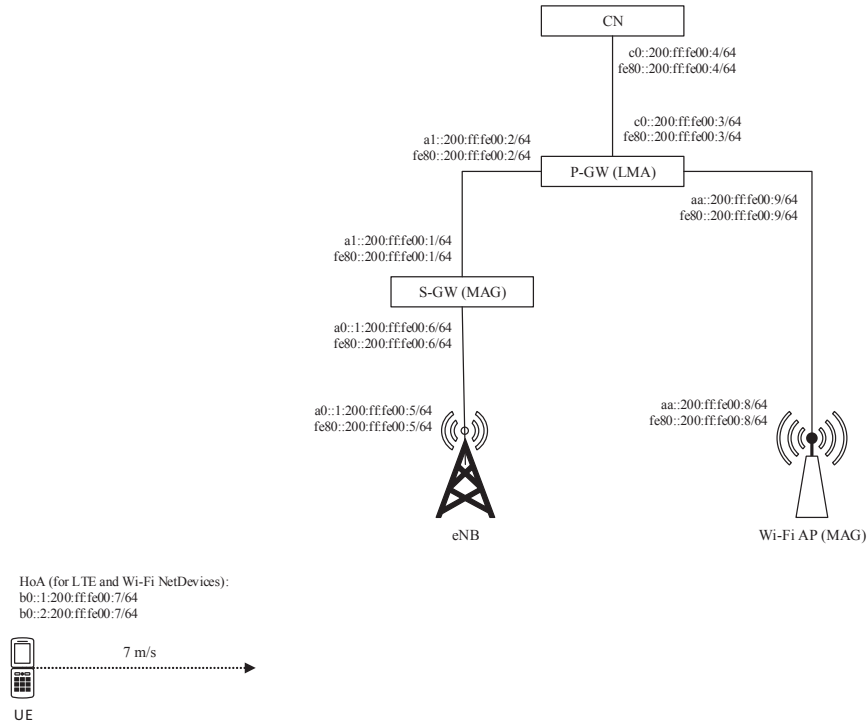


Figure 4.6: Simulation Setup for Flow Mobility Validation

The Flow Binding Table indicates that the TCP flow with destination port 2000 is routed over LTE if available and Wi-Fi if LTE connection becomes unavailable. All other TCP flows are routed the other way around with Wi-Fi having a higher priority than LTE.

When the simulation begins the UE is only within the range of the eNB (LTE) and hence attaches itself to the LTE network (The LTE interface of the UE gets assigned the HNP `b0:0:0:1::`). So, when the flows are started, both flows are routed over LTE as there isn't any available Wi-Fi connection. As soon as the UE comes within the range of the Wi-Fi AP, the MAG on the Wi-Fi AP begins the PMIPv6 signaling procedure. The Wi-Fi MAG receives the HNP `b0:0:0:1::` which was assigned to the LTE interface of the UE and also `b0:0:0:2::` which is the newly assigned HNP. The LMA sends HUR message to the S-GW with the prefix `b0:0:0:2::`, which the S-GW acknowledges using the HUA message. Once the Wi-Fi MAG is registered with the LMA, the flow with destination port 2000 is still routed over LTE while the other flow begins to be routed over Wi-Fi. The wireshark traces are shown in Figure 4.7 and Figure 4.8 which validates this process.

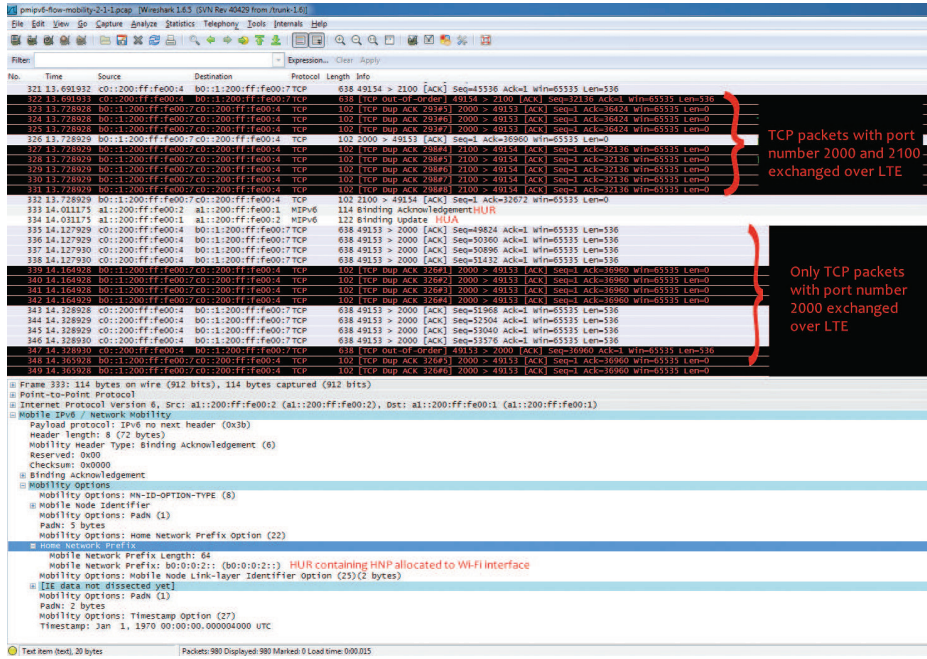


Figure 4.7: Wireshark trace for interface between P-GW (LMA) and S-GW (LTE MAG)

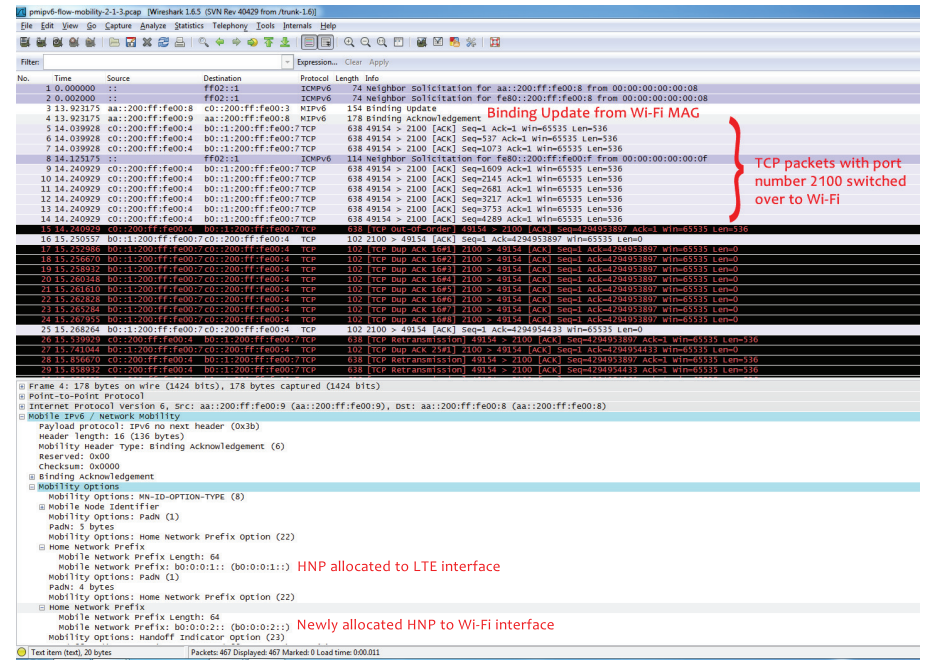


Figure 4.8: Wireshark trace for interface between P-GW (LMA) and Wi-Fi MAG

Chapter 5

Simulation and Results

5.1 Simulation Setup

The simulation setup consists of 1 eNB and 3 Wi-Fi APs deployed as shown in Figure 5.1. The range of these wireless stations are shown in dotted red lines. The UE is moving with along the path shown. The eNB is connected to the S-GW which inturn is connected to the P-GW via p2p links. Each Wi-Fi AP has the MAG functionality included in it. All these APs are also connected to the P-GW via p2p links. A CN is connected to the P-GW via a p2p link. 4 flows are started in the downlink from the CN to the UE after 10s. 3 of these flows are UDP flows with data rates of 80kbps, 400kbps and 500kbps respectively. The other flow is a TCP flow. The UDP flows are always sent over the LTE interface. The TCP is sent over Wi-Fi interface whenever the SNR of Wi-Fi becomes greater than 5dB, otherwise it is sent over LTE. Some of important simulation parameters are listed in the table 5.1.

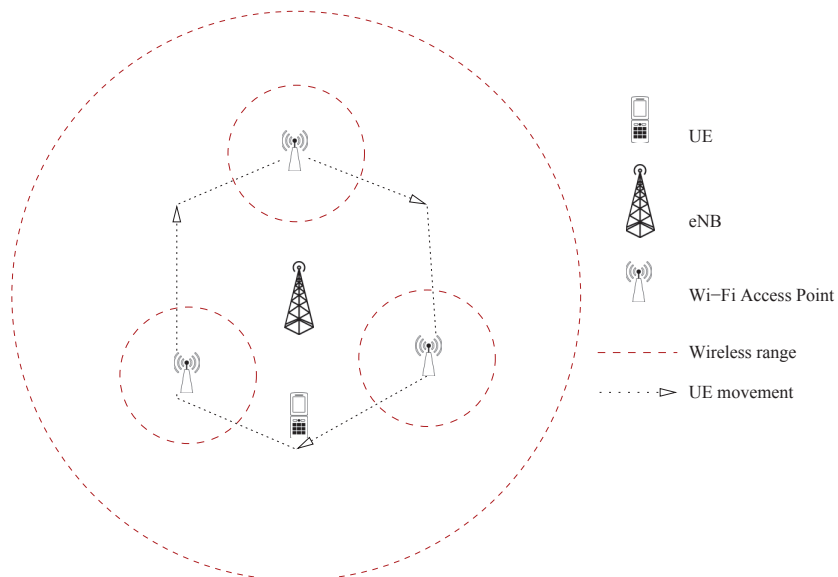


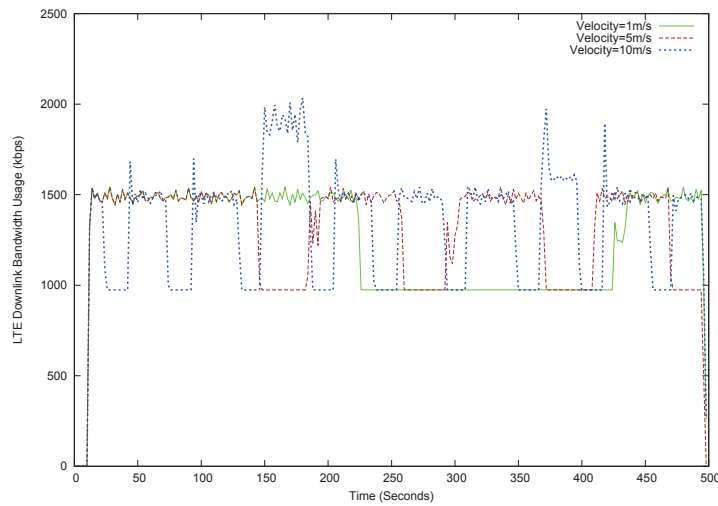
Figure 5.1: Simulation Setup

Table 5.1: Simulation Parameters

Parameter	Value
S1u delay (eNB and S-GW)	0ms
S5 delay (S-GW and P-GW)	5ms
S2a delay (Wi-Fi MAG and P-GW)	(10ms, 50ms, 100ms)
Internet delay (CN and P-GW)	(50ms)
LTE Scheduler	Proportional Fair Scheduler
Number of Resource Blocks (Downlink and Uplink)	25
Simulation Time	500s
Flow Start Time	10s
Flow End Time	485s
Velocity of UE	(1m/s, 5m/s, 10m/s)
Wi-Fi standard	802.11g

5.2 Results

Three experiments are conducted for observing various different metrics. For the first experiment, the simulation is run for all values of velocity, while keeping the all other parameters constant. The S2a delay is kept constant at 100ms. Then the LTE downlink bandwidth consumption is plotted against time as shown in figure 5.2. There is always a load of around 1000kbps on the LTE cell due to the UDP flows always being transmitted over LTE. Whenever a TCP flow is sent via LTE, then there are peaks in the graph where the bandwidth utilization increases to around 1500kbps. For higher velocity values the switch between the peaks happens faster due to the UE getting in and out of Wi-Fi coverage quicker than with lower velocity values. This graph clearly validates the working of flow mobility. It also shows reduction in load on the LTE cell due to flow mobility.

**Figure 5.2:** LTE Downlink Bandwidth Usage vs Time

For the second experiment, the simulation is run for all values of velocity and S2a delay. The TCP throughput is plotted against time as shown in Figure 5.3. The delay against time plot is also

shown. It can be noticed that the peaks in the throughput graph occur due to switching to the Wi-Fi interface. Every time an interface is switched there is a sudden drop in throughput, but it quickly picks up. For velocity 1m/s it is observed that the peak is maintained since the connection is maintained with Wi-Fi for a longer time. This can be attributed to the attainment of steady state in TCP. The delay values change based on the S2a delay for each graph. The higher throughput indicates that it was beneficial for the flow to shift to Wi-Fi.

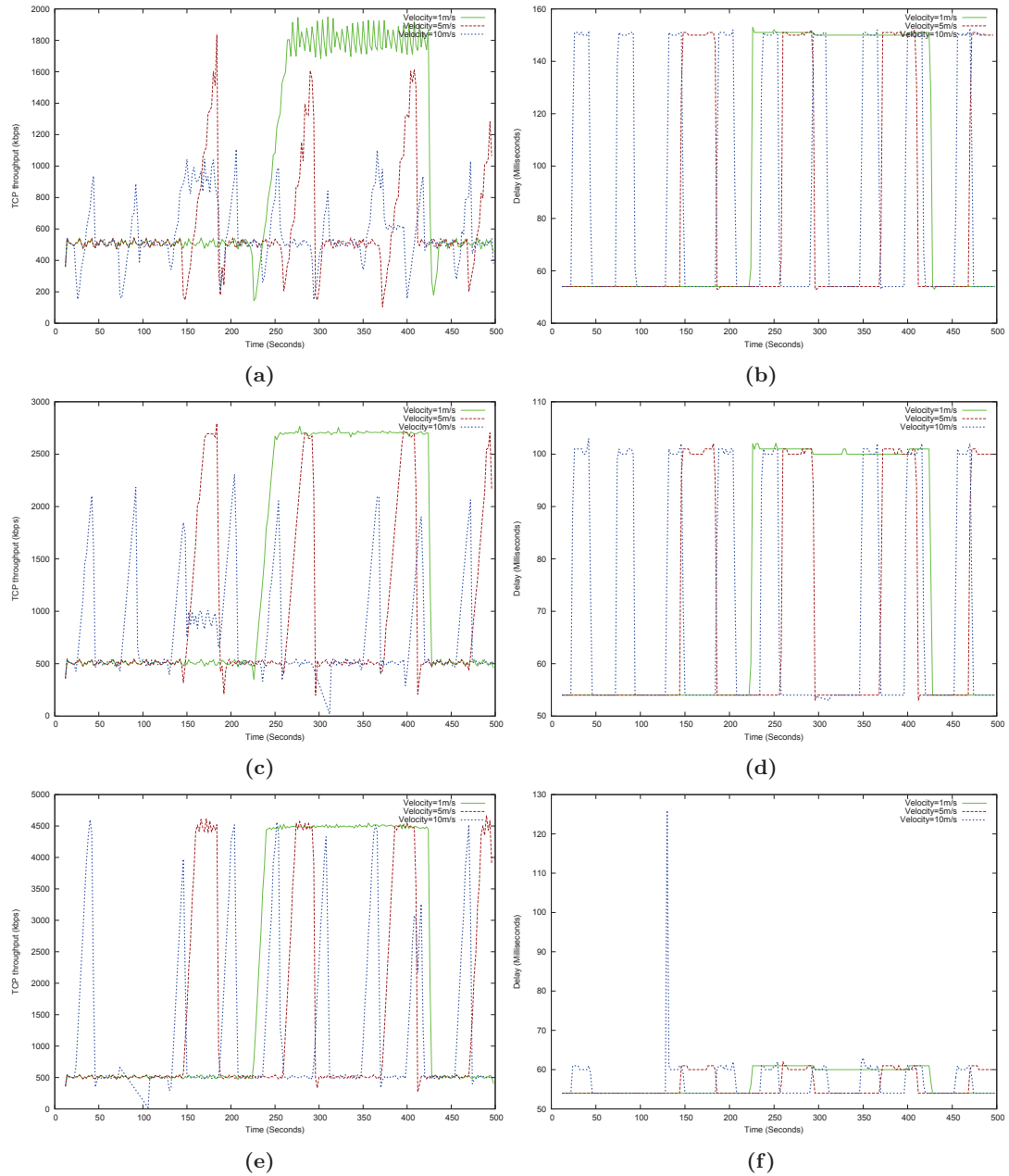


Figure 5.3: Results of experiment 2. The TCP throughput is plotted against time for S2a delay values of 100ms (a), 50ms (c) and 10ms (e). The Delay is plotted against time for S2a delay values of 100ms (b), 50ms (d) and 10ms (f).

The final experiment was also run by varying the velocity and S2a delay. For each S2a delay value the number of bytes sent over LTE and Wi-Fi was captured for each velocity. The results were averaged over 5 runs. The graphs are shown in Figure 5.4. It can be observed that for a given S2a delay the decreasing velocity higher number of bytes are sent over Wi-Fi. Also with decreasing S2a delay values a higher amount of data is offloaded onto Wi-Fi. This is due to higher TCP throughput over Wi-Fi with decreasing S2a delay values.

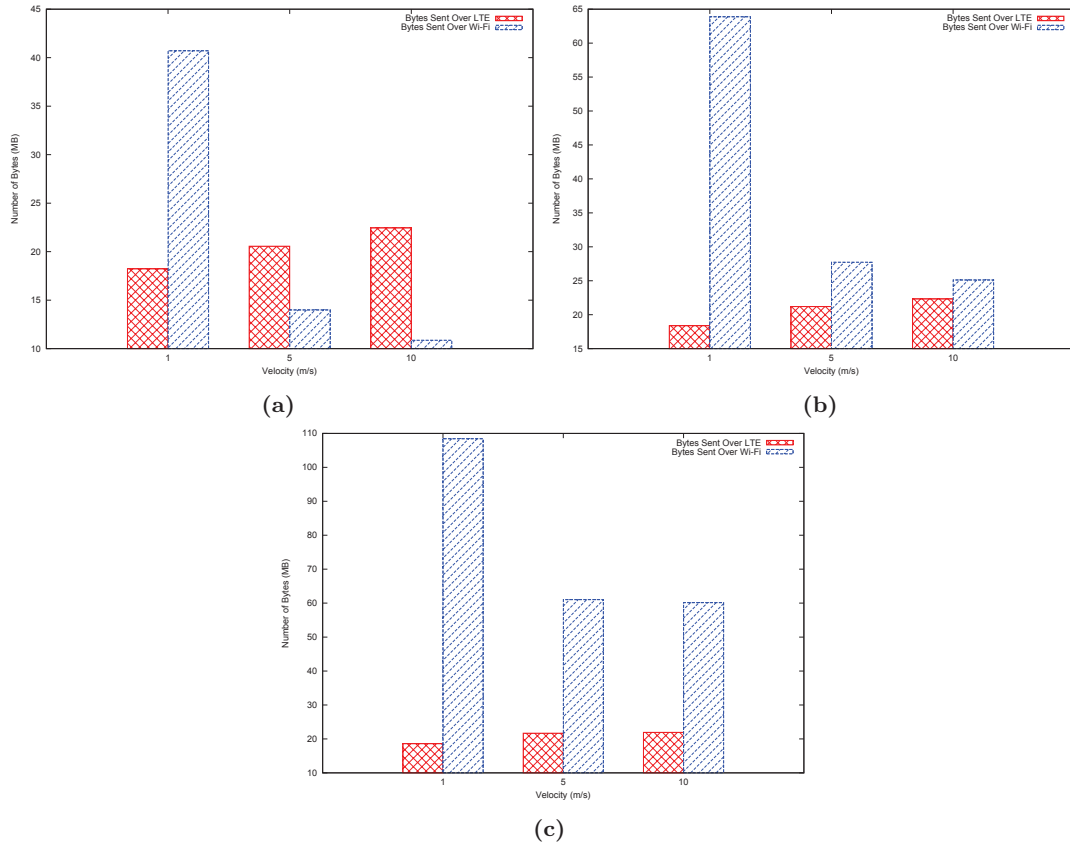


Figure 5.4: Results of experiment 3. The amount of bytes sent over LTE and Wi-Fi are shown for S2a delay values of 100ms (a), 50ms (b) and 10ms (c).

These experiments showed that velocity plays a major role in the amount of offload that can be achieved over Wi-Fi. The more amount of time a user stays within a Wi-Fi cell the higher is the amount of data that can be sent Wi-Fi. Also for TCP connections the S2a delay is an important factor for achieving better throughput. The working of flow mobility is also shown in these experiments where only a single flow is being migrated seamlessly between LTE and Wi-Fi without affecting other flows of the user.

Chapter 6

QoS-based Flow Mobility Framework

Most of the work in the heterogeneous networks has involved vertical handoff where all the flows belonging to an MN are assigned a network based on certain parameters. The flow mobility solutions provide an opportunity to offload traffic at the granularity of flows. This allows us to implement various algorithms to decide which network best serves a flow. This chapter discusses the motivation for using flow mobility, provides an overview of the parameters which can be considered for flow mobility and then finally proposes a new algorithm for flow mobility.

6.1 Motivation

The flow mobility solutions provide an opportunity to offload traffic from one network to another at the granularity of flows instead of entire traffic generated by the MN. Here we are considering the presence of 2 networks: LTE and Wi-Fi. Given the availability of these 2 networks the idea is to intelligently move certain flows onto either network so as achieve better throughput for them and improve the capacity of heterogeneous networks. Both the networks differ in their key characteristics. The LTE network provides better coverage but does not provide as much bandwidth as compared to Wi-Fi. Also, LTE provides QoS guarantees which is not the case with Wi-Fi.

The flows are generally categorized as follows:

1. Voice
2. Video streaming, interactive gaming
3. Web based like www, e-mail, chat, file sharing, etc.

The voice traffic has strict QoS (delay, jitter and a low bandwidth) requirements and is only suited to networks which provide a minimum QoS guarantee. The video streaming can be categorized as either conversational or non-conversational. Both types of video streaming have relatively high bandwidth requirements (100s of kbps to few Mbps). However the conversational video also has strict delay and jitter requirements. The conversational video streaming traffic is more suited to networks providing fixed QoS guarantees. However, it is possible to have conversational video streaming traffic over

a network which does not provide any QoS guarantees (delay, jitter or bandwidth) but has little to no congestion. The non-conversational video streaming traffic can be sent over any network as long as its bandwidth requirements are fulfilled. The Web based traffic is generally TCP based and can make do with whatever bandwidth is available to it (higher bandwidth providing a better user experience). We can therefore say that voice and conversational video streaming traffic is pretty much only suited to LTE and other forms of cellular networks whereas non-conversational video and web traffic can be sent over either LTE or Wi-Fi networks. The video streaming traffic can be sent over a Wi-Fi network if it can receive a minimum amount of bandwidth, but it is always better to have it over LTE network. The flows are classified into these categories using traffic selectors like source and destination IP addresses, ports, flow label (IPv6 header field), etc.

6.2 Related Work

Most of the vertical handoff algorithms in heterogeneous networks involve moving all IP flows from one interface to the other. Generally a decision is taken based on certain parameters of each network like bandwidth, delay, jitter, etc. These parameters are used to calculate a score for each of the available networks and based on this score a network selection/vertical handoff decision is made. There are a class of algorithms like SAW (Simple Additive Weighting), WP (Weighting Product), TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), etc which fall under the Multiple Attribute Decision Making (MADM) approach [8] [9], which are based on this approach. Most of the parameters which are considered like packet jitter, packet delay, packet loss and cost per byte are static in nature i.e. their values are either part of technology standard or taken from real deployment scenarios (for example the value of delay is 100ms for LTE and 150ms for Wi-Fi). Therefore, these approaches provide a cost based method for selection of a network but the parameters considered are not realistic.

The introduction of flow mobility allows further optimizations and more parameters to use in the flow mobility decision making. It also provides more control as handoff can be performed for each flow separately. Wang et al. uses such an approach to extend the Dia algorithm [10] to enable offloading of flows onto either LTE, UMTS, WiMax and Wi-Fi networks [11]. The parameters considered included radio signal strength, available bandwidth of network, packet delay, packet loss rate and cost per byte. They have considered 4 types of flows (conversation voice, buffered streaming video, interactive gaming and TCP-base) and for each flow type they have assigned a different weight for each parameter. Even in this case except radio signal strength and available bandwidth the rest of the parameters are static in nature. Also their evaluation strategy considers the availability of one instance of each network which is not a typical case. As flow mobility is a relatively new area of research, most of the literature is concentrated on architectures for enabling flow mobility. There is not much literature on developing flow mobility algorithms for balancing of load in heterogeneous networks especially those consisting of LTE and Wi-Fi.

6.3 Overview of Flow Mobility Framework

We consider a heterogeneous network where all the flows are expected to pass through the Packet Gateway (P-GW) regardless of whether they use LTE or Wi-Fi as the access network. A centralized

Flow-Tracker is installed on the P-GW which keeps tracks of all the active flows in the entire network. Along with the flows, it is also responsible for maintaining other information such as flow category, bandwidth consumed, MN to which the flow belongs. Apart from this it also maintains the the amount of traffic being served by each eNB and Wi-Fi AP.

Some of parameters which can be considered for flow mobility are as follows:

- **Flow Type** Whether the flow carries voice, video or web traffic. This is generally inferred using flow templates (containing port numbers, IP addresses, TCP/UDP etc).
- **Packet Delay** The average delay faced within the network.
- **Packet Jitter** The average delay variation faced within the network.
- **Packet Loss** The average packet loss rate faced within the network observed over a long period of time.
- **Signal Strength** The signal strength received from the network.
- **Bandwidth Usage** The amount of data sent by the flow.
- **Device Type** The type of device (laptop, tablet, smartphone or some other device) over which the flow is transmitted.
- **Subscription Plan** The plan which the user has subscribed.
- **Battery** The amount of battery remaining in the MN.
- **Velocity** The speed with which the MN is moving.
- **Available Bandwidth** The unused fraction of the total bandwidth (taken from the technical standard, for example 100Mbps for LTE) of the access network (eNB or Wi-Fi AP).
- **Wi-Fi AP location** Whether the Wi-Fi AP that is serving the flow is the home/office AP of the user generating the flow or a hotspot.

Some of these parameters device type, subscription plan, Wi-Fi AP location are static or semi-static in nature. These are kept track of using a user profile. The parameters signal strength, available bandwidth are access network based parameters and are retrieved by the Flow-Tracker from each eNB and Wi-Fi AP. The parameters battery and velocity should be retrieved from the UE via some non-standard protocol. Generally an estimation is used for velocity as it is difficult to retrieve the actual velocity. The parameters flow type and bandwidth usage are kept track at the P-GW itself by the Flow-Tracker. The parameters packet delay, packet jitter, packet loss values can be taken from the technical standard and actual deployment scenarios (and can be continually updated if needed). Some of these parameters are kept track of for both the networks LTE and Wi-Fi. For example, there will be two values of Signal Strength one each for LTE and Wi-Fi.

6.3.1 Flow Based Quality Function

A quality function Q is calculated based on these parameters for both LTE and Wi-Fi. $Q_{LTE f}$ and $Q_{Wi-Fi f}$ represents the network quality for the flow f for LTE and Wi-Fi networks respectively. It indicates the suitability of the flow for that particular network. Q_{if} is defined in Equation 6.1 for network i and flow f , where $(P_{ifk} \mid k = 1, 2, \dots, l)$ are the values for the l parameters in consideration.

$$Q_{if} = F(P_{if1}, P_{if2}, P_{if3}, \dots, P_{ifl}) \quad (6.1)$$

Since each parameter has a different level of importance, each of these parameters is associated with a weight to indicate the same. The weights are different for each network (LTE and Wi-Fi). Q_{if} is then defined for network i and flow f in Equation 6.2 where $(w_{ik} \mid k = 1, 2, \dots, l \text{ and } \sum_{k=1}^l w_{ik} = 1)$ (one weight value for each parameter for each network).

$$Q_{if} = F(w_{i1}P_{if1}, w_{i2}P_{if2}, w_{i3}P_{if3}, \dots, w_{il}P_{ifl}) \quad (6.2)$$

Since each parameter has a different unit the equation is normalized. This is done by dividing the maximum value of the parameter for all flows and all networks by the value of the parameter for the particular flow and network in consideration. Q_{if} is then defined for network i and flow f in Equation 6.3 for n networks and m flows such that $0 \leq Q_{if} \leq 1$.

$$Q_{if} = \sum_{r=1}^l w_{ir} \frac{P_{ifr}}{\max(P_{jkr}) \mid j = 1, 2, \dots, n \text{ and } k = 1, 2, \dots, m} \quad (6.3)$$

6.3.2 QoS Based Flow Mobility Framework

There are 2 utilization factors, L_1 and L_2 for an LTE cell (usually handled by an eNB) such that $L_1 < L_2$. For the purposes of this algorithm, congestion is being defined based on the amount of bandwidth being used by each cell. If the load of the LTE cell (amount of bandwidth being used up by an LTE cell) is below L_1 then the cell is considered to have relatively no congestion. If the load on the LTE cell is more than L_2 , then the cell is considered to be congested. The idea is to adjust the load on each LTE cell such that it stays within L_1 and L_2 . Similarly, an utilization factor W_1 is also associated with Wi-Fi (with each Wi-Fi AP). If the load goes beyond W_1 then the Wi-Fi AP is considered to be congested.

The framework consists of two algorithms, one for assignment of network to a new flow and the other for periodical load balancing of the existing flows. The function 1 is used for calculation of Q . Algorithm 2 is used for deciding the network to be assigned to a new flow. This algorithm runs on the P-GW. Since the Flow-Tracker keeps track of all flows, it knows whenever a new flow arrives. This algorithm assigns a flow onto the LTE network if the LTE cell to which the UE (to whom the flow belongs) is connected to has a utilization less than L_1 . It is also assigned on the LTE network if the UE does not have connection with a Wi-Fi network or if the flow is voice-based. In all other cases, Q_{if} is calculated for both LTE and Wi-Fi for the flow in consideration f . If $Q_{LTE f}$ is greater than $Q_{Wi-Fi f}$ by a threshold t ($0 \leq t \leq 1$), then it is admitted on the LTE network otherwise on the Wi-Fi network.

Every S_1 seconds, Algorithm 3 runs on the P-GW. This algorithm is used to manage the overall

Algorithm 1 Calculation of Quality factor of a network for a flow.

Input: Flow f
Input: Network n
Input: Parameters P ($p_1, p_2, p_3, \dots, p_l$)
Input: Weights W ($w_{kj}, k = \text{LTE, Wi-Fi}, j = 1, 2, 3 \dots l$)

- 1: **function** CalcQ(f, n)
- 2: list<FlowStats> $allFlows = \text{GetAllFlows}()$
- 3: **for** $i \leftarrow 1$ to l **do** ▷ Get maximum value of each parameter for normalization.
- 4: $PMax[i] = \text{GetMax}(P[i], allFlows)$
- 5: $Q_n \leftarrow 0$
- 6: **for** $i \leftarrow 1$ to l **do** ▷ Use Equation 6.3 to calculate Q .
- 7: $Q_n \leftarrow Q_n + W_{ni} \times \left(\frac{P[i]}{PMax[i]}\right)$
- 8: **return** Q_n

Algorithm 2 New Flow Network Assignment Algorithm

Input: Flow f which is to be newly admitted.
Input: Threshold t .

- 1: $ue \leftarrow \text{GetUe}(f)$ ▷ The UE information is retrieved based on the IP address of the flow
- 2: **if** $\text{GetUtilizedBandwidth}(\text{GetUeConnectedLteCell}(ue)) < L_1$ or (not $\text{IsConnectedWifi}(ue)$)
then ▷ $\text{GetUeConnectedLteCell}$ gets the eNB to which the ue is connected to.
 IsConnectedWifi checks if the ue has connection to a Wi-Fi network.
- 3: $\text{SetFlowOutInterface}(f, \text{LTE})$
- 4: **else if** $\text{GetFlowType}(f) = \text{VOICE}$ **then**
- 5: $\text{SetFlowOutInterface}(f, \text{LTE})$
- 6: **else**
- 7: $Q_{LTE} \leftarrow \text{CalcQ}(f, \text{LTE})$ ▷ Algorithm 1
- 8: $Q_{Wi-Fi} \leftarrow \text{CalcQ}(f, \text{Wi-Fi})$
- 9: **if** $Q_{LTE} > Q_{Wi-Fi} + t$ **then**
- 10: $\text{SetFlowOutInterface}(f, \text{LTE})$
- 11: **else**
- 12: $\text{SetFlowOutInterface}(f, \text{Wi-Fi})$

load of the heterogeneous network by reducing load on the overloaded cells by moving flows onto less uncongested cells. The algorithm performs three different checks:

1. The first check is made to find all the LTE cells which are underloaded. Then all flows which are currently being routed over the Wi-Fi which can be offloaded to the underloaded LTE cells are sorted based on the difference of their Q_{LTE} and Q_{Wi-Fi} values. Then each flow starting with the highest difference value is offloaded back onto LTE till L_1 utilization is reached for that cell.
2. The second check is made to find all the LTE cells which are overloaded. Then all flows which are currently being routed over the overloaded LTE cells are sorted based on the difference of their Q_{Wi-Fi} and Q_{LTE} values. Then each flow starting with the highest difference value is offloaded onto Wi-Fi until utilization for that cell falls below L_2 .
3. The third check is made to find all the Wi-Fi APs which are overloaded. Then all flows which are currently being routed over the overloaded Wi-Fi APs are sorted based on the difference of their Q_{LTE} and Q_{Wi-Fi} values. Then each flow starting with the highest difference value

is moved onto LTE (provided the movement doesn't overload the LTE cell) until utilization for that AP falls below W_1 .

Based on these checks the algorithm balances the flows such that there is maximum utilization of the heterogeneous network.

Algorithm 3 Load Balancer Algorithm

Input: L_1, L_2, W_1 utilization factors

```

1: for lteCell in GetAllLteCells () do
2:   lteCellUtil  $\leftarrow$  GetUtilizedBandwidth (lteCell)
3:   if lteCellUtil  $<$   $L_1$  then ▷ First Check
4:     list<FlowStats> allFlows  $\leftarrow$  GetFlows (LTE, lteCell)
5:     list<FlowStats> allFlowsSorted  $\leftarrow$  sort (allFlows, cmp = CalcQ (f, LTE) - CalcQ (f,
Wi-Fi)) ▷ Flows with greater LTE affinity as compared to Wi-Fi are moved first.
6:     for FlowStats fs in allFlowsSorted until lteCellUtil  $>$   $L_1$  do
7:       SetFlowOutInterface (GetFlow (fs), LTE)

8:   if lteCellUtil  $>$   $L_2$  then ▷ Second Check
9:     list<FlowStats> allFlowsSorted  $\leftarrow$  sort (GetAllFlows (LTE), cmp = CalcQ (f, Wi-Fi)
- CalcQ (f, LTE)) ▷ Flows with greater Wi-Fi affinity as compared to LTE are moved first.
10:    for FlowStats fs in allFlowsSorted until lteCellUtil  $<$   $L_1$  do
11:      SetFlowOutInterface (GetFlow (fs), Wi-Fi)

12: for wifiAp in GetAllWiFiAps () do
13:   wifiApUtil  $\leftarrow$  GetUtilizedBandwidth (wifiAp)
14:   if wifiApUtil  $>$   $W_1$  then ▷ Third Check
15:     list<FlowStats> wifiFlows  $\leftarrow$  sort (GetFlows (Wi-Fi, wifiAp), cmp = CalcQ (f, LTE)
- CalcQ (f, Wi-Fi)) ▷ Flows with greater LTE affinity as compared to Wi-Fi are moved first.
16:     for FlowStats fs in wifiFlows until wifiApUtil  $<$   $W_1$  do
17:       SetFlowOutInterface (GetFlow (fs), LTE) if flow movement doesn't increase LTE cell
utilization beyond  $L_2$ 

```

Chapter 7

Conclusions and Future Work

In this work flow mobility framework has been implemented in ns-3.19 using PMIPv6. It currently supports only LTE and Wi-Fi networks. The framework allows making flow mobility decisions on the LMA. A flow based offload algorithm is also proposed for reducing load on LTE by using Wi-Fi as the offload network. However the implementation of the algorithm is not completed. A simpler algorithm is shown as a proof of working of the framework in which web flows are migrated over to Wi-Fi networks if it is available. Otherwise all flows are routed via the LTE network.

As currently the flow mobility algorithm is not implemented, the future scope would be to implement the algorithm and monitoring various parameters like reduction in load of the LTE network, throughput and delay of each flow, etc. Currently ns-3 doesn't support a energy model for LTE. As battery is extremely important to an UE, an energy model can be implemented for LTE. Also other algorithms could be tried to improve the performance. Since flow mobility hasn't been standardized, one could still look at signaling solutions for supporting flow mobility. There is another case of offload where the Wi-Fi is co-located with femto cells.

References

- [1] C. V. N. Index. Global Mobile Data Traffic Forecast Update, 2012–2017, Cisco White Paper, Feb. 6, 2013.
- [2] E. Dahlman, S. Parkvall, and J. Skold. 4G: LTE/LTE-advanced for mobile broadband. Academic Press, 2013.
- [3] Cisco. 802.11ac - The Fifth Generation of Wi-Fi Technical White Paper .
- [4] 3rd Generation Partnership Project.
- [5] S. Gundavelli, K. Leung, V. Devarapalli, K. Chowdhury, and B. Patil. RFC 5213, proxy mobile IPv6 2008.
- [6] 3GPP. TS 29.274, Evolved General Packet Radio Service (GPRS) Tunnelling Protocol for Control plane (GTPv2-C) Stage 3, Release 12 V12.5.0 2014 .
- [7] H. Soliman, G. Tsirtsis, V. Deverapalli, J. Kempf, H. Levkowitz, P. Thubert, and R. Wakikawa. Dual Stack Mobile IPv6 (DSMIPv6) for Hosts and Routers. *draft-ietf-mip6-nemo-v4traversal-00.txt (Work in Progress)* .
- [8] P. N. Tran and N. Boukhatem. Comparison of MADM decision algorithms for interface selection in heterogeneous wireless networks. In Software, Telecommunications and Computer Networks, 2008. SoftCOM 2008. 16th International Conference on. IEEE, 2008 119–124.
- [9] N. Nasser, A. Hasswa, and H. Hassanein. Handoffs in fourth generation heterogeneous networks. *Communications Magazine, IEEE* 44, (2006) 96–103.
- [10] P. N. Tran and N. Boukhatem. The distance to the ideal alternative (DiA) algorithm for interface selection in heterogeneous wireless networks. In Proceedings of the 6th ACM international symposium on Mobility management and wireless access. ACM, 2008 61–68.
- [11] Q. Wang, W. Li, P. Yu, and L. Meng. IP Flow Mobility Trigger Mechanism in Heterogeneous Wireless Networks .
- [12] NS-3 Network Simulator.
- [13] C. Perkins and D. Johnson. J. Arkko,” Mobility Support in IPv6. Technical Report, RFC 6275, July 2011.
- [14] I. Soto, C. J. Bernardos, M. Calderón, and T. Melia. PMIPv6: A network-based localized mobility management solution. *The Internet Protocol Journal* 13, (2010) 2–15.

- [15] IEEE 802 LAN/MAN Standards Committee.
- [16] 3GPP. TS 23.402, Architecture enhancements for non-3GPP accesses Release 12 V12.4.0 2014 .
- [17] 3GPP. TS 36.300, Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2, Release 12 V12.2.0 2014 .
- [18] S. Sesia, M. Baker, and I. Toufik. LTE-The UMTS Long Term Evolution: From Theory to Practice. John Wiley & Sons, 2011.
- [19] 3GPP. TS 23.401, General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access, Release 12 V12.4.0 2014 .
- [20] 3GPP. TR 23.861, Network based IP flow mobility, Release 13 V1.8.0 2014 .
- [21] G. Tsirtsis, H. Soliman, N. Montavont, G. Giaretta, and K. Kuladinithi. Flow bindings in mobile IPv6 and network mobility (NEMO) basic support. *IETF RFC6089, January* .
- [22] C. J. Bernardos. Proxy Mobile IPv6 Extensions to Support Flow Mobility. *IETF draft-ietf-netext-pmipv6-flow-mob-08, work in progress* .
- [23] A. De la Oliva, C. J. Bernardos, M. Calderon, T. Melia, and J. C. Zuniga. IP flow mobility: smart traffic offload for future wireless networks. *Communications Magazine, IEEE* 49, (2011) 124–132.
- [24] 3GPP. TS 23.261, IP flow mobility and seamless Wireless Local Area Network (WLAN) offload Stage 2, Release 11 V11.0.0 2012 .
- [25] H.-Y. Choi, S.-G. Min, and Y.-H. Han. PMIPv6-based flow mobility simulation in NS-3. In Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS), 2011 Fifth International Conference on. IEEE, 2011 475–480.
- [26] T. Melia and S. Gundavelli. Logical interface support for multi-mode IP Hosts. *draft-ietf-netext-logical-interface-support-01 (work in progress)* .
- [27] T. M. Trung, Y.-H. Han, H.-Y. Choi, and H. Y. Geun. A design of network-based flow mobility based on proxy mobile IPv6. In IEEE conference on, computer communications workshops (INFOCOM WKSHPs). 2011 .
- [28] H.-Y. Choi, S.-G. Min, Y.-H. Han, J. Park, and H. Kim. Implementation and evaluation of proxy mobile ipv6 in ns-3 network simulator. In Ubiquitous Information Technologies and Applications (CUTE), 2010 Proceedings of the 5th International Conference on. IEEE, 2010 1–6.
- [29] NS-3 LTE Documentation, <http://www.nsnam.org/docs/models/html/lte-design.html#fig-epc-topology>.