Study on Network Selection Scheme for Wireless LAN Offloading in Cellular Network

セルラーネットワークにおける無線 LAN オフロードのためのネットワーク選択方式に関する研究

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Graduate School of Global Information and Telecommunication Studies
Waseda University

Wireless Communication Systems II

Nam NGUYEN

PREFACE

"The work presented in this dissertation was carried out at SATO Wireless Communication Systems Laboratory, Graduate School of Global Information and Telecommunication Studies, Waseda University."

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Summary

The astonishing growth of smart devices such as smartphones, tablets is generating huge demand for mobile data traffic in recent years since we are shifting from voice-centric homogeneous network toward data-oriented heterogeneous network. It is predicted that the demand for mobile data traffic will increase for 1000 times by 2020, and due to the blooming of Internet of Things (IoT), billions of household devices, sensors will be connected via mobile networks by then. The explosive increase of mobile data demand raises concerns over network congestion and degrading end user's Quality of Experience on existing cellular networks. Meanwhile, Wi-Fi (in this thesis, Wi-Fi will be used as the synonym term for Wireless LAN for abbreviation) is emerging as one effective mobile offloading data traffic solution for the problem since it utilizes unlicensed frequency bands causing minimum interference to the macro-cell. In addition, it is also a cost-effective compared to other small-cell technologies. For these reasons, more and more network operators are in favor of adopting Wi-Fi in large scale as the extended access network for their cellular network.

One of major challenges in Wi-Fi offloading is to provide a smooth and seamless experience for end-user such as seamless authentication and connectivity when roaming from cellular to available Wi-Fi access points (AP) and vice versa. Most of researches in the literature are concentrated on this issue. However, to the best of our knowledge, there is another issue concerning how the mobile terminal decides the right timing to make network switching decision and intelligently selects the most preferable point of service. Currently, this issue has not been resolved since conventional Wi-Fi roaming and decision selection scheme is mainly based on the Receive Signal Strength. In addition, as far as we concerned, with the existing standards, there is no explicit and standardized method to make Wi-Fi selection decision based on real-time traffic load of network condition and

user's required quality of service. This issue becomes important to the operators deploying Wi-Fi AP for offloading cellular traffic since the main objective is to improve the coverage and prevent network congestion for the macro-cell. For example, currently, there are many network operators such as AT&T US, KDDI Japan, deploying carrier grade AP in high density area to offload traffic and prevent congestion for cellular network. The mobile user can seamlessly roam to Wi-Fi and use cellular service. However, since mobile users are usually not aware of the availability of Wi-Fi AP, it is common that many of them might not switch their connection from cellular to Wi-Fi or the mobile terminals autonomously connect to suboptimal AP. As the result, the Wi-Fi APs are typically underutilized and the end-users might experience bad QoS due to overload or congestion.

In our first work, we first conduct an extensive survey on the state of the art of both 3GPP and IEEE standards related to interworking and interoperability between Wi-Fi and cellular network field. We address the aforementioned issue by proposing a cellular Wi-Fi roaming decision and selection scheme specifically for mobile offloading purpose. In the proposed scheme, we take advantage of related 3rd Generation Partnership Project (3GPP) and IEEE standards such as 3GPP (24.312 Access Discovery and Selection Function, ANDSF) and IEEE (IEEE 802.11u). By using ANDSF's selection policies and necessary network condition, the UE can autonomously decide the right timing to make cellular Wi-Fi roaming decision and selects the most relevant point of access. In addition, for evaluation, we develop our simulation model of 3GPP ANDSF as well as vertical handover in a heterogeneous network (HetNet) scenario. It is a high-level end-to-end system model from physical and application layer. It features typical HetNet scenario with vertical handover between WiMAX base stations and Wi-Fi APs, ANDSF entity, especially a connection manager running on each mobile node. During the simulation process, the ANDSF entity and the UE's connection manager entity run and interact corresponding to real-time network events. We compare the performance of proposed scheme with that of the conventional Wi-Fi selection scheme (based on the signal strength), which is adopted in most of nowadays smart devices. The simulation result showed that our proposed scheme can effectively steer the UE's traffic from cellular base stations to available Wi-Fi APs so that network resource utilization and per end-user experienced throughput is substantially improved. We also extensively evaluated the performance of the proposed scheme by varying the scheme's input thresholds i.e. the received signal strength and the load thresholds, which affect the number of mobile nodes roaming to Wi-Fi. We also pointed out the shortcoming of proposed scheme, which increases the number of handover between Wi-Fi APs.

In our second work, we extend the previous proposed scheme by considering end-user's on-demand QoS for Wi-Fi selection. We consider the requested throughput and remaining bandwidth of each AP candidate for selection decision. This allows mobile node filter out the AP candidate(s) that cannot provide the requested throughput or QoS in the selection process. We first propose a simple method to estimate real-time remaining throughput of Wi-Fi AP candidates prior to association process. The estimated remaining throughput is compared with the end user's requested throughput so that the irrelevant candidates are filtered out in advance. The new proposed scheme reduces the number of unnecessary handover to unqualified Wi-Fi AP, which are unable to provide requested throughput. In this work, we also discuss a trade-off between reducing the number of Wi-Fi handover and optimizing system for offloading data traffic.

Chapter 1

Introduction

1.1. Motivation

In recent years, the proliferation of smart devices (smart phones and tablets) and mobile Internet applications is generating huge demand for mobile data traffic. In addition, we are shifting from voice-centric homogeneous network toward data-oriented heterogeneous network (HetNet). It is predicted that mobile data traffic will grow more than 1000 times in next decades, and billions of devices will be connected due to the popular of Internet of Things [1]. However, the licensed frequency band of cellular network is considered expensive and limited. Therefore, increasing the number of macro-cell base stations and using different frequency band are no longer efficient methods to increase network capacity. Therefore, offloading data traffic from the cellular network using different access network is becoming a norm for network operators to deal with network congestion and improve end-user's Quality of Experience (QoE).

Offloading traffic is referred as using alternative network technologies for delivering data that is originally targeted for a network, e.g., using Wi-Fi to offload traffic from cellular network and vice versa. As far as we concerned, more and more network operators commit to adopt Wi-Fi as the extended access for their cellular network; unlike any other small cell technologies such as femto-cell and pico-cell, Wi-Fi utilizes unlicensed frequency band, which causes less interference to macro-cell. Besides, Wi-Fi can cut down the Capital Expenditure (CAPEX) since it is cheaper and easier to be deployed in different indoor environment such as airport, shopping mall or any other crowded area.

One of the main challenges in cellular Wi-Fi offloading is to provide a smooth and seamless experience for end-user when roaming from cellular to Wi-Fi APs and vice versa [2]. Most of the related researches in the literature are dealing with this area [3-7]. However, there is another issue concerning how the mobile node decides the right timing to make network switching decision and selects the most relevant point of service at anytime and anywhere. This issue needs to be addressed if the network operators want to intelligently steer the UE's traffic among available access networks so that the wireless network resource can be optimized.

As far as we concerned, 3rd Generation Partnership Project (3GPP) and IEEE, have been actively working on interworking issue between 3GPP cellular (3G/4G) and non-3GPP network (WiMAX and Wi-Fi). 3GPP proposed and ratified new network architecture and protocols namely, an All-IP Evolved Packet Core (EPC) architecture integrating with different access networks [8], a new entity so called Access Network Discovery and Selection Function (ANDSF) or TS 24.312 [9]. On the other hand, IEEE ratified a new enhancement for IEEE 802.11 specification to enhance Wi-Fi and cellular interworking known as IEEE 802.11u [10] or Hotspot 2.0 (HS 2.0) [11]. These standards are the key ingredients to make roaming from non-3GPP to 3GPP cellular network smooth and seamless. However, as far as we concerned, the issue of deciding the timing to make network switching decision and intelligently select relevant access point has not been addressed in existing standards. Since the key standards are continually updated, new enhancements are expected in future releases of TS24.312 [9] and IEEE 802.11u [10]. For example, in 3GPP ANDSF TS 24.312 [9], the role of ANDSF entity is to provide policies for discovering and selecting preferable access network as well as IP routing policies for multiple homing User Entity (UE). However, the ANDSF's policies are static and predefined by the network operators. Since there is no real-time network condition or measured information from UE taken into account, it can lead to undesirable network selection issue for UE. For example, if the suggested AP candidate is temporary overloaded or faraway, it might degrade end user's experienced QoS. On the other hand, the IEEE 802.11u [10] standard mainly concentrates on providing a seamless transition experience from Wi-Fi to cellular network. For facilitating Wi-Fi AP selection, it appends new quality indicator metrics such as the channel load, AP's downlink/uplink capability into the beacon of AP, which can be used for enhancing AP discovery and selection. However, this standard does not specify how the mobile node can exploit these metrics and selects the preferable point of service. Although the key enabler standards are available, how to take advance of these standards for intelligent network selection and handover decision in cellular Wi-Fi interworking network is out of scope of these standards.

1.2. Thesis contribution

The main contribution of this thesis is an extensive study of interworking issues in heterogeneous network, particularly, in Wi-Fi and Cellular data offloading. As far as we concerned, currently, there is no explicit method to make intelligent Wi-Fi selection based on access point traffic load and quality in the field of Wi-Fi cellular offloading. In our first main work, we propose a Wi-Fi handover decision and access point selection scheme specified for mobile data offloading. Our proposed scheme takes advantage of state of the art 3GPP (24.312 ANDSF) and IEEE (IEEE 802.11u) standards. By combining ANDSF's policies and necessary network condition metrics measured by UE, the UE autonomously decides the timing to make cellular Wi-Fi handover decision and selects the most relevant point of access anytime and anywhere based the load traffic of AP. However, there is a tradeoff between optimizing per-user's throughput and handover frequency between neighbor access points in our proposed scheme. Therefore, in our second work, we consider the UE's requested throughput and the remaining bandwidth of Wi-Fi for enhancing Wi-Fi AP selection decision. Therefore, we propose a simple method to allow the mobile node estimate the remaining throughput of Wi-Fi AP candidates before making handover decision. The idea is that, in reality, the mobile node may have different QoS at different time, the mobile node should decide to handover if only if the candidate AP can satisfy its requested data rate. By doing this, the number of unnecessary handover can be reduced.

From the beginning, we always pay attention to the practical implementation of the proposed scheme. Therefore, we extensively survey the latest IEEE and 3GPP standards and develop our scheme based on the ratified standards so that it can be applicable in future wireless network system. In this thesis, we also introduce our simulation model of 3GPP ANDSF [9] and vertical handover between Wi-Fi APs and macro-cell. Unlike related works, our simulation model is an end-to-end system model from application to physical layer. We also consider user's mobility and traffic model. During the simulation process, the ANDSF entity and the UE's connection manager entities interact with other nodes corresponding to real-time network events. our simulation model can be used for evaluation mobility and handover algorithms in heterogeneous network.

1.3. Organization of the Thesis

The rest of the thesis is organized as follows. Chapter 2 goes through the state of the art of the underline IEEE and 3GPP standards used in our proposal. In addition, in this chapter briefly reviews related work in the field of multiple access network discovery and selection. In chapter 3, we introduce our proposed network roaming decision and selection scheme for Wi-Fi Cellular offloading. In the proposed scheme, we consider the ANDSF policies, real-time network condition to assist the mobile node select the most relevant point of service. In chapter 4, we consider mobile node's requested throughput and the remaining bandwidth of access point candidates to enhance the proposed scheme in chapter 3. We first present a simple method to estimate the remaining throughput of a Wi-Fi access point prior to association operation. Subsequently, we use the estimated throughput of AP candidates and UE's requested data rate preference to enhance the proposed scheme in chapter 3. Finally, Chapter 5 concludes the thesis work and indicates future work.

Chapter 2

3GPP and IEEE Standard for Interworking Wi-Fi and Cellular Network

2.1. Motivations for interworking 3GPP and non-3GPP access technologies

- **Offloading 3GPP network – reducing the load on the cellular network**

The EPC architecture was designed to allow interworking between 3GPP and non-3GPP access technologies [8]. It provides a potential long-term solution to overcome the explosive growth of mobile data traffic [1] and macro-cell congestion by offloading 3GPP cellular data traffic to any available non-3GPP access network such as Wi-Fi, WiMAX etc. One popular solution for 3GPP offloading is to deploy small-cells within the macro-cell's coverage to increase the capacity as well as downlink and uplink throughput. However, small-cell technologies such as femto-cell or picocell raises macro-cell interference and cost-effective issues. On the other hand, Wi-Fi is emerging as an effective alternative since it utilizes unlicensed band, which causes minimum interference to macro-cell. Typically, Wi-Fi utilizes the unlicensed frequency band ranging from the 2.4 GHz and 5.8 GHz, which can mitigate the interfere with cellular network. In addition, it is also very cost-effective compared to small-cell technology such as femtocell and picocell. For these reasons, more and more network operators are adopting Wi-Fi for offloading cellular data traffic.

- **Coverage supplement for 3GPP**

Non-3GPP accesses technologies like Wi-Fi integrated with the 3GPP core network can deliver extended coverage for 3GPP access in area where macro-cell is unreachable. For example, in the indoor environment, usually, the macro-cell cannot puncture through obstacles such as thick wall or furniture. Therefore, the coverage of the macro-cell is greatly deteriorated in such environment. However, small cell technologies such as Wi-Fi has great advantage in indoor because it is easy to deploy and extend the wireless network coverage in indoor settings. In addition, Wi-Fi has cost effective advantage compared to cellular access technologies. For the same coverage, Wi-Fi requires much lower CAPEX [3], which is the one of the main incentives to use Wi-Fi for extending the coverage of 3GPP network.

❖ **Interworking between 3GPP macro-cell and Wi-Fi**

The interworking between cellular and Wi-Fi networks has to satisfy bellow requirements:

- Seamless IP session mobility and service when transferring between 3GPP and non-3GPP networks.
- Offloading traffic between Wi-Fi and 3GPP and vice versa.

For enhancing interoperability between two networks, the mobile node must detect the presence of available access networks in its vicinity as well as the operator's policies regarding network selection strategy.

Currently, the mobile node is not able to perform the appropriate selection because it has to make decision mainly based on the received signal strength (RSS). For this reason, a new EPC's entity was introduced in 3GPP Rel. 8 [9] known as ANDSF, which serves as an assistive node for macro-cell UEs to find and take advantage of non-3GPP networks.

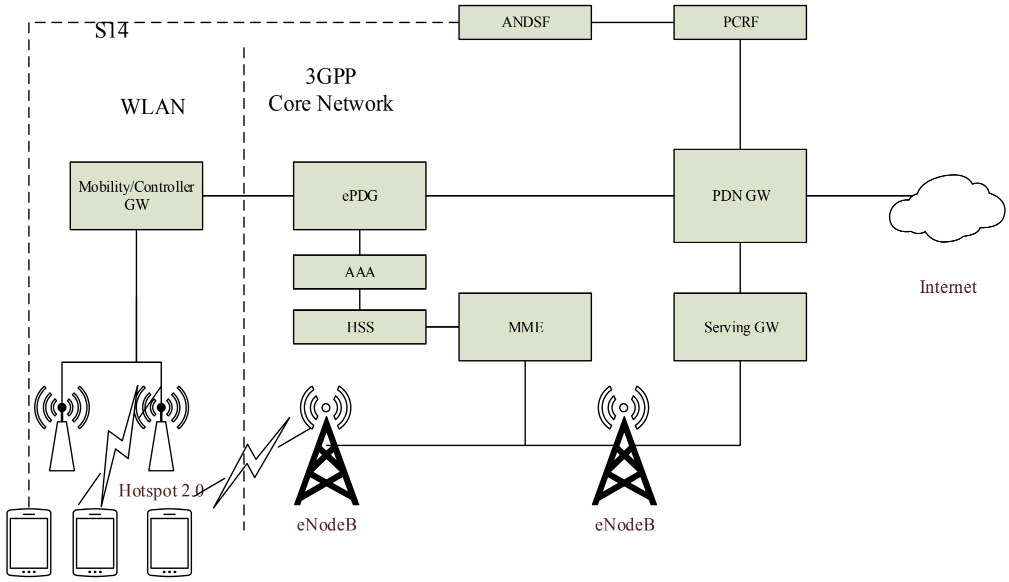

Figure 2. 1 EPS Architecture for non-3GPP Access integration

2.2. The 3GPP Evolved Packet Core

The 3GPP Evolved Packet Core (EPC) was first introduced in 3GPP release 8 providing an interworking platform between 3GPP and non-3GPP access technologies according to the 3GPP standard [8]. The EPC opens new opportunities for mobility and interworking across access network technologies. The interworking functionalities include access network discovery, authentication of the UE, QoS consistency and seamless handover.

The EPC is ratified as the core network architecture of 3GPP's state of the art access network, LTE/LTE-Advanced, it allows multitude of wireless access technologies to be interconnected. It is a realization of multi-access convergence in the 3GPP network supporting mobility and interoperation for any available access technologies. Along with the development of a ubiquitous IP management scheme such as Proxy IP, GTP, which provides a complete IP solution where streamed multimedia, data and voice can be delivered seamlessly to users at anytime and anywhere.

As it is specified in TS23.402 [8] the Evolved Packet System (EPS) introduced a heterogeneous network architecture, where multi-access technologies are connected to the

EPC. One fundamental change of EPC architecture is the capability of integrating non-3GPP access technologies such as WLAN, WiMAX into the EPC shown in Figure.2.1.

The EPC together with LTE known as EPS (Evolved Packet System) were released for providing higher data rate, greater flexibility for multi-access networks and all-IP network architecture. However, the interworking between access networks also becomes important and therefore mobile operators are also interested in introducing non-3GPP access technologies in EPS for following reasons such as:

- To on-load and offload macro-cell data traffic when it gets congested.
- To supplement to macro-cell in term of coverage and capacity.
- To increase the resilience for the network in case of disaster or power outage.

In addition, In the EPC, there is a new entity called Access Network Discovery and Selection Function (ANDSF), we will discuss in detail the role and the functions of this nodes in the next selection because it is the main component that we use in our proposal.

2.3.Access Network Discovery and Selection Function

The ANDSF is a new EPC entity defined in the 3GPP standard TS 23.402 [8] that contains necessary information to assist the mobile node in discovering and selecting available access network at its location and time of the day. The UE can exchange information with the ANDSF entity via the standardized S14 interface [8].

The ANDSF is located at the core network and interacts with other nodes of EPC of the network operator. The primary role of the ANDSF is to allow the network operators to assist the mobile nodes to discover and select non-3GPP access network anytime and anywhere.

The UE can obtain following set of information from the ANDSF:

- Intersystem mobility policy (ISMP).
- Access Network Discovery Information (ANDI).

- Inter system routing policy (ISRP).

MO-DM (Management Object Device Management) [9], a device management protocol standardized by the Open Mobile Alliance. The MO is a tree based structure, which is used to organize and manage aforementioned set of information ISMP, ANDI and ISRP.

❖ **Intersystem Mobility Policy ISMP**

The Intersystem Mobility Policy (ISMP) is a component of ANDSF management object. The ISMP indicates the availability of access network corresponding to UE's location Figure 2.2. UE's location can be identified by Macro-Cell ID of the base station, GPS information, or SSID of Wi-Fi AP etc.

The UE uses the ISMP, if it can only use one network interface at a time. In this case, the ANDSF can indicate imminent handover event to prepare the handover execution. The ISMP provides roaming preference policy to the mobile node so that it can decide which type of access is preferable at one particular location or time of day e.g. an ISMP may specify that Wi-Fi is more preferable to LTE at one particular location and specific time. The UE can decide the type of access network to connect based on this preference policy from ANDSF.

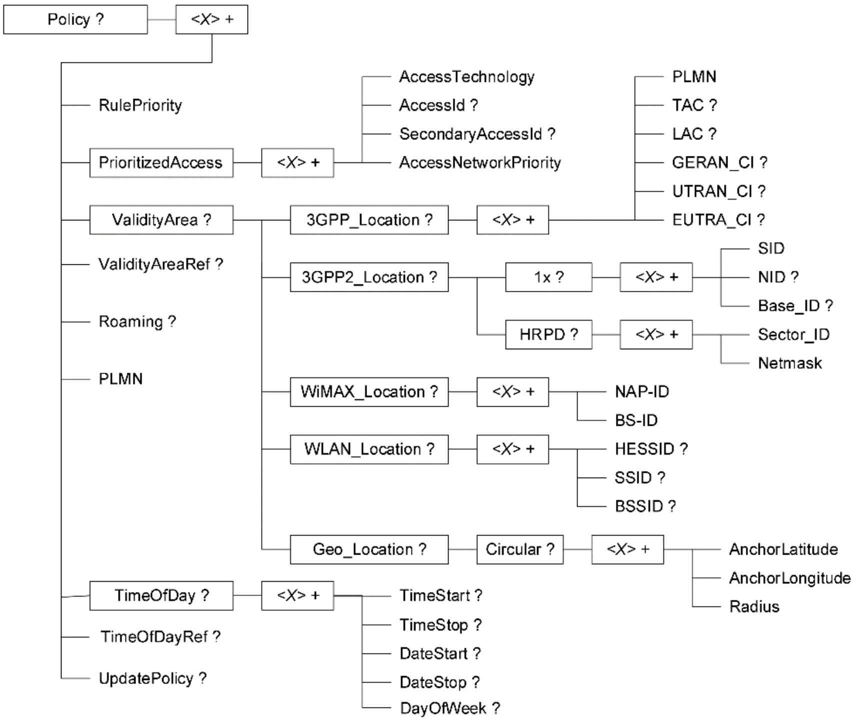

Figure 2. 2 Intersystem Mobility Policy[9]

❖ **Intersystem Mobility Access Network Discovery Information (ANDI)**

The figure 2.3 describes the ANDI node structure. ANDI specifies the available radio access technology which is near to the UE. The access network coverage area can be identified by the Cell-ID, Wi-Fi Service set ID (SSID) or GPS coordinates. In the conventional scheme, in order to detect available access network, the UE has to turn on all of its interfaces and regularly scans for available access network. This procedure will quickly drain the UE's battery. With ANDI, the UE does not have to turn on all of its interfaces and scans for available access network. When it moves to the area where the indicated access network is available, it can easily detect the present of access network. By using ANDI information, the UE's battery can be preserved. This is more efficient way to detect available access network at UE's side.

The UE can use pull mode to actively trigger the provision information process from the ANDSF entity via the dedicated interface S14. Conversely, the ANDSF node can also initiate the provision process by pushing the discovery information to UE using push mode. The provisioned information contains information of available access network or point of service at the UE's location. Upon received this information, the UE can either utilize or discard the information during discovery process.

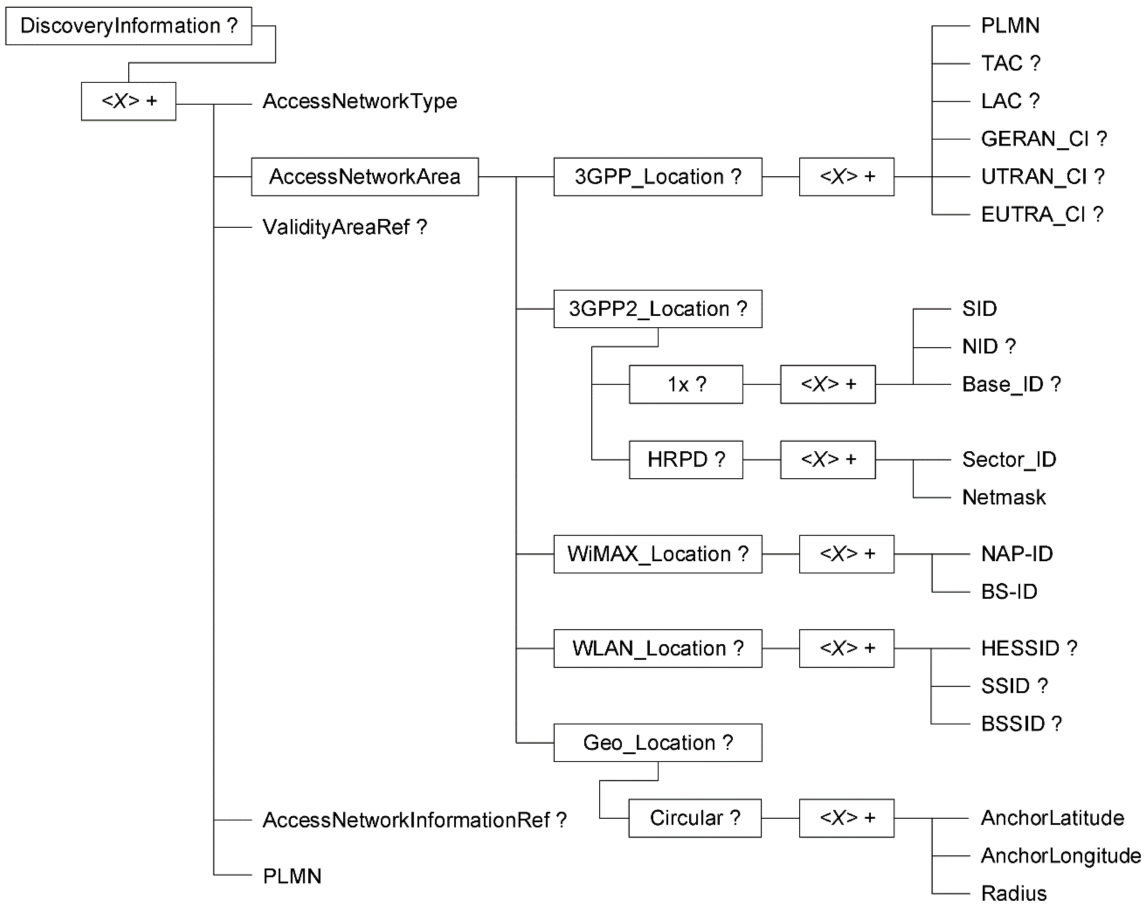

Figure 2. 3 Access Network Discovery Information [9]

❖ Inter system routing policy(ISRP)

Inter System Routing Policy (ISRP) contains information of data routing policies for multiple-homing UE, which can use multiple access interfaces simultaneously. ISRP provides the UE with necessary information about end-user's traffic routing preference via different interfaces. In other words, it specifies the traffic routing policies for different type of UE's data traffic. For example, ISRP can specify the user's VoIP traffic should route through LTE because of low latency and reliability while http, ftp traffic should be routed to Wi-Fi.

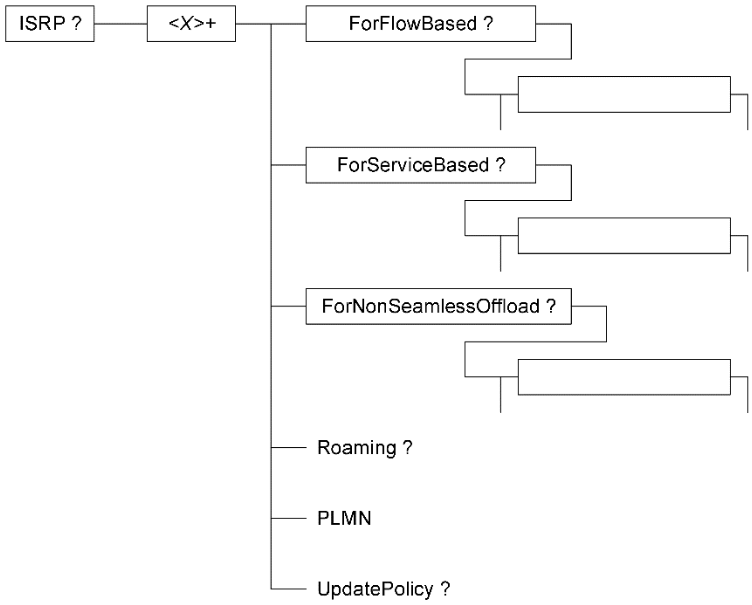

Figure 2. 4 Inter system routing policy [9]

The ISRP node is divided into 3 set of information:

- The first set of information (*ForFlowBased*) specifies the routing policy for each flow of data traffic to and from one particular target IP. In case of multihoming UE, the network operator can use this set of information to route different type of UE's traffic through different access networks.
- The second set of information (*ForServiceBased*) specifies the routing policy for each service or application in which the data packets can be routed via different interfaces at the same time. Therefore, the mobile node can bundle and take advantage of available access network in its vicinity to increase download/upload speed.
- The third set of information defines the traffic routing policies for interruption tolerated offloading. The UE can decide the preferable point of service among available access network. However, since the WLAN traffic is directly routed to PDN without passing through cellular data gateway, the session continuity and Quality of Experience (QoE) cannot be guaranteed in this case.

❖ WLAN Selection Policy

In 3GPP ANDSF TS 24.312 [9] Rel. 12, 3GPP has added new elements to allow the network operator to control over network selection for mobile offloading. The WLAN Selection Policy is set of information, which specifies the criteria for UE to select available Wi-Fi access point such as backhaul bandwidth, the load condition of the AP etc. The backhaul bandwidth or and channel utilization can be obtained directly from other standards (such as IEEE 802.11u, IEEE 802.11k, Hotspot 2.0 compliant AP).

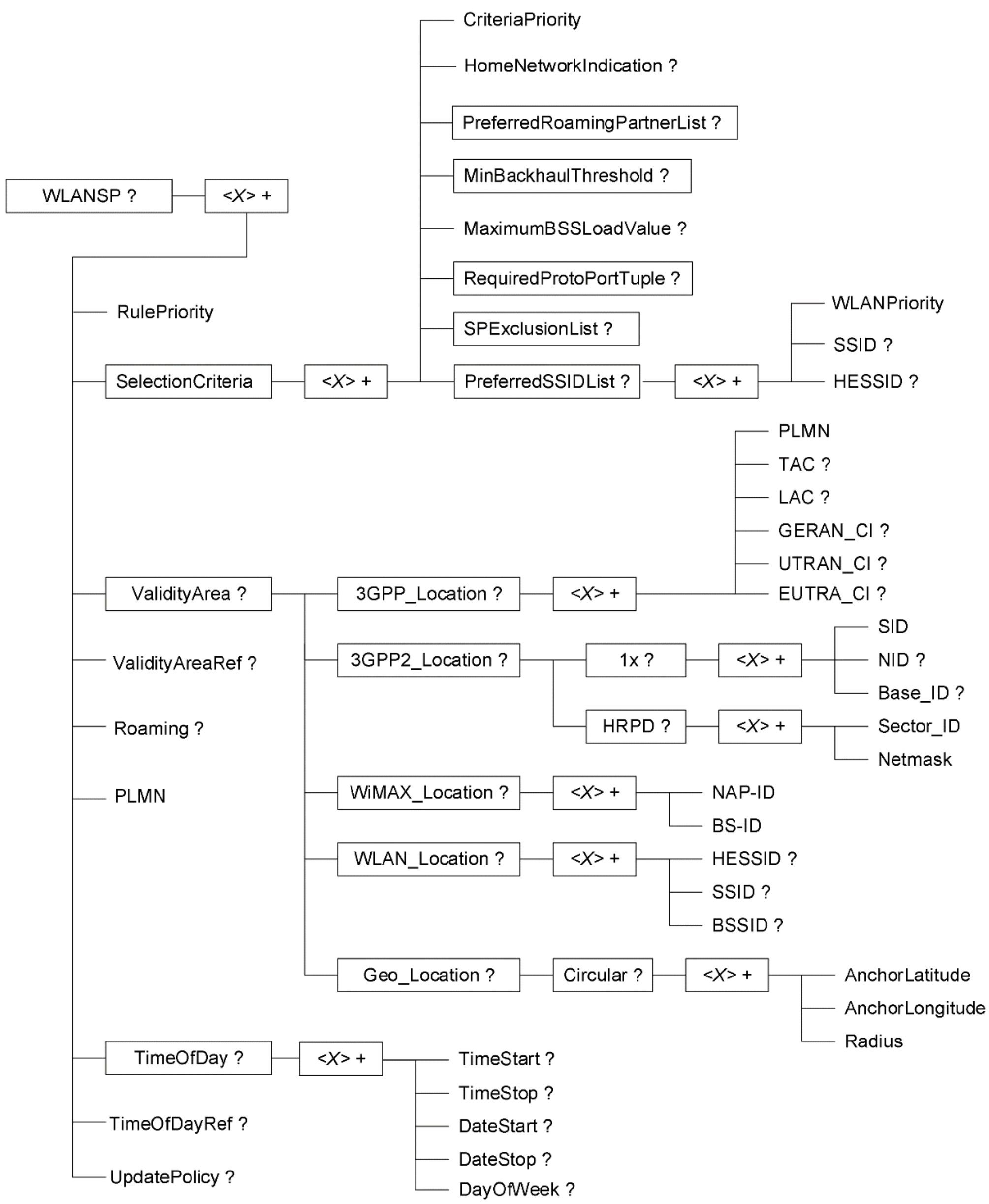

Figure 2. 5 WLAN Selection Policy [9]

The WLANSP Management Object can have a single or multiple WLANSP preference policy. In addition, each WLANSP policy may have one or more WLAN selection criterion defined in *ANDSF/WLANSP/<X>/SelectionCriteria* node including:

- *CriteriaPriority.*
- *HomeNetworkIndication.*
- *PreferredRoamingPartnerList.*
- *MinBackhaulThreshold.*
- *MaximumBSSLoadValue.*
- *RequiredProtoPortTuple.*
- *PreferredSSIDList.*
- *SPExclusionList.*

The UE obtains these selection criteria from ANDSF entity and uses them for selecting Wi-Fi AP.

2.4. IEEE 802.11u Standard

IEEE ratified an amendment for IEEE 802.11 standard to support Wi-Fi and 3GPP network interworking known as IEEE802.11u [10]. This amendment was aimed to make roaming between Wi-Fi and 3GPP network as smooth and seamless as roaming within 3GPP cellular network. Based on this amendment, Wi-Fi Alliance also released specification for the next generation of Wi-Fi AP also known as Hotspot 2.0 (HS2.0) [11] or Wi-Fi Certified Pass-point. Beyond the security authentication enhancement, the main feature of HS2.0 in release1 was to facilitate the Wi-Fi AP discovery and selection procedures of supported UEs. Therefore, the HS2.0 provides UE various type of network condition information (AP, backhaul load condition, authentication type, connection capacity etc.) prior to association through the Access Network Query Protocol (ANQP) and the Generic Advertisement Service (GAS). These additional network condition metrics are beneficial to UE when selecting preferable AP as well as providing seamless handover experience.

2.5. Related Work

- **Multiple Access Network Discovery and Selection**

In EPC architecture, the ANDSF is designated to deliver network selection policies from the operator for individual UE [8, 9]. Therefore, the operators can impose the policies to control when, where and which access network that the UE can connect. However, one of the most important aspects of dynamic network selection is to consider the real-time network conditions as the criteria for selection. The conventional Wi-Fi offloading strategy (adopted by most of smart device) is that Wi-Fi always has higher priority than 3G/4G cellular. As a result, the UE switches to Wi-Fi whenever AP is detected. Besides, Wi-Fi AP selection is simply based on the Receive Signal Strength (RSS) or SINR, thus the nearest AP is selected. However, as far as we concerned, RSS or SINR information alone is not enough to make intelligent Wi-Fi selection, especially in place, where there are collocated and overlapped APs. In such scenario, the selection scheme that is solely based on RSS can lead to bad quality of experience (QoE) for UE or network resource underutilization issue. Therefore, we need to consider other factors to enhance roaming and point of service selection decision.

In [15] authors highlighted technical challenges in heterogeneous wireless networks underlying seamless vertical handover. The authors also presented a detailed survey on the vertical mobility management process with a focus on decision-making mechanisms. Handover decision based on multiple inputs such as bandwidth, QoS, cost, UE’s velocity have been considered for years with complex system model and algorithms such as analytic hierarchy process (AHP), grey relational analysis (GRA) [12, 13]. However, the authors failed to describe how to implement their proposal in reality because some required inputs such as available bandwidth, cost of the service, UE's velocity, connection jitter, packet loss are not available or difficult to obtain with the existing standards.

In [16] 4GAmericas provided a comprehensive insight of the state of the art of the key enablers for integrating cellular network and Wi-Fi. It explained the possibility of combining the advantages of ANDSF and HS2.0 could resolve the problems of macro-cell and Wi-Fi roaming. However, there was no detail description, numerical evaluation such as simulations or experiment's result provided. In [14], authors examined the mobility between different access technologies in heterogeneous wireless networks and focused on the case of interoperability issue. The quality of the service of mobility, the time required for the handover and the packet loss during handover etc. are also extensively analyzed. There was 3GPP task group working on WLAN and 3GPP radio interworking at radio level. In [17], the authors tried to improve access network selection and traffic steering decision between 3GPP LTE network and WLAN. In their proposal, the cellular network provided additional Received Channel Power Indicator (RCPI) and/or (Received Signal to Noise Indicator) RSNI thresholds to the terminal so that it could make roaming decision to Wi-Fi when the LTE network condition was not favorable. In [18], the authors addressed solutions for Wi-Fi offloading in LTE cellular networks when demands exceeded the capability of the LTE access. For evaluation, the authors compared the performance of each access technology using different network performance metrics. In [19], the authors proposed a novel network-assisted user-centric Wi-Fi-offloading model for maximizing per-user throughput in a heterogeneous network. In the proposed model, the network collects network information, such as the number of users in Wi-Fi network and their traffic load. Subsequently, the network decided the specific portion of traffic to be transmitted via Wi-Fi network so that the individual user's throughput could be maximized by offloading more traffic to Wi-Fi. Through analysis, the authors investigated the effect of the Wi-Fi-offloading ratio on the per-user throughput. However, they did not consider user's mobility in their simulation model. In [20], the authors studied how much economic benefits can be anticipated thank to delayed Wi-Fi offloading method, by modeling the interaction between a single provider and users based on a two-stage sequential game. In this work, they first analytically proved that Wi-Fi offloading is economically beneficial for both the provider and users. Their main focus was to understand how and how much users and the provider obtained the economic incentives by adopting delayed Wi-Fi offloading and investigated the effect of different pricing and delay-tolerance. In [21], the authors investigated the performance improvement induced by adopting a hybrid cellular Wi-Fi communication architecture where the mobile users can be served by either the LTE eNodeB or a mobile Wi-Fi AP. In this proposed scheme, the mobile Wi-Fi APs are considered as relay entities that are wirelessly connected to the LTE eNodeB and share this broadband connection with other users over Wi-Fi tethering or Ad-hoc network (using Wi-Fi frequencies). Important performance metrics of the proposed hybrid scheme including the average bit error probability (ABEP), capacity and outage probability were theoretically studied.

❖ **Wi-Fi AP throughput estimation**

Several related works on Wi-Fi AP's data rate estimation found in the literature. In [36] Wi-Fi throughput was analytically discussed, however, the input parameters of the authors approach are difficult to obtain from the standard IEEE802.11 network. In [37], the authors discussed the issues in load balancing between IEEE 802.11 APs. However, the proposal based an assumption that Wi-Fi channel resource is distributed equally among all associated Wi-Fi mobile nodes. In [38], the authors also proposed a new Wi-Fi throughput estimation algorithm based on CSMA/CA and considered the traffic difference of each Wi-Fi device. However, this method is difficult to implement in practical system since it is required to estimate the channel occupancy ratio of every associated Wi-Fi UEs. As far as we concerned, there is no available tool or standardized method to obtain the channel occupancy of individual Wi-Fi station sharing the same channel. Besides, this approach did not allow Wi-Fi UE to estimate remaining throughput prior to associating with the AP or before selection process. Therefore, it is not suitable for a QoS based selection decision scheme.

Chapter 3

A Novel Cellular and Wi-Fi Roaming Decision and Selection Scheme

3.1. Motivation and Proposal Formation

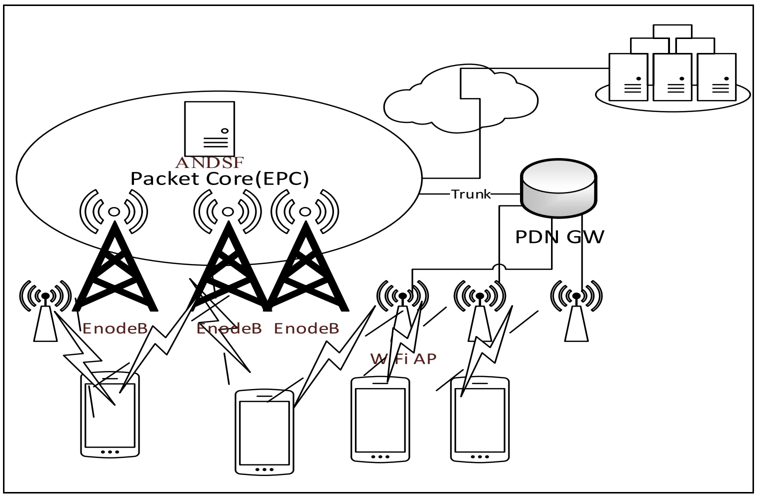

Figure 3. 1 Heterogeneous network scenario with LTE cellular and Wi-Fi interworking.

Since we anticipate that providing high-speed data service via multiple access networks will become common trend in near future, our assumed scenario is a heterogeneous network with cellular and WiFi coexisting. Our assumption scenario is described in Figure 3.1 applied to a 3GPP cellular network operator providing high-speed mobile data service via both cellular (LTE) and Wi-Fi networks. It also applies to the cellular operator and third party Wi-Fi service provider.

In Figure 3.1, the users freely transfer from macro-cell to Wi-Fi coverage and vice versa without any interruption. Conventionally, in order to detect available Wi-Fi APs, the mobile node needs to turn on Wi-Fi interface and passively search for available Wi-Fi AP. After detecting nearby Wi-Fi APs, the mobile node selects the target AP based on the signal strength. The AP candidate with strongest signal strength will be selected for target

AP. Currently, there is no explicit method to find non 3GPP access network and select the point of service based on the traffic condition or quality of service. This problem can lead to suboptimal network selection, which can degrade end-user's quality of experience (QoE). Therefore, in such scenario, the UE needs a mechanism to detect and select the most preferable point of service at anytime and anywhere so that it does not degrade the end user's QoE.

On the another hand, in order to increase the efficiency of Wi-Fi offloading, the operator need a way to instruct the UEs to offload some or all of their traffic through Wi-Fi AP based on the real-time network condition.

Therefore, in order to effectively offloading mobile traffic from macro-cell to Wi-Fi APs in heterogeneous network scenario in Figure 3.1, we need an entity from network side to regulate the cellular UEs when and where Wi-Fi roaming is possible. In addition, it should also provide rightful selection rules for UE. For instance, only authorized APs (AP belonged to operator or authorized provider who has roaming agreement) can be selected. For such scenario, the ANDSF [9] framework is a well-suited entity for this job since it is a 3GPP approach for assisting 3GPP mobile node detecting and selecting non-3GPP access networks. However, the drawback of ANDSF's policies is its static characteristic since there is no mechanism to frequently update the policies. As described in [9], for prioritizing AP in selection, the operator assigns AP with an integer number and the one with higher priority should be applied at first. However, since the condition of the network may vary dynamically from time to time, if the UE only relies on the ANDSF selection rule for selecting new point of service, it can lead to suboptimal selection problem (e.g. selected AP is too far away, or congested one). Therefore, it is also necessary to consider the real-time network condition metrics at the UE side when making handover decision. Among various network KPIs for network selection [12, 13] (such as bandwidth, delay, jitter, latency etc.), we consider the real-time load metric of Wi-Fi AP is one of the important factors for evaluating the link condition of AP. Whether this metric is high or low could greatly affect user's experience because the channel load of AP is correlated to the available bandwidth as well as delay or latency of the connection that the AP can offer. As far as we concerned, the channel load information was first defined in IEEE 802.11k, e [22] and later specified in the IEEE 802.11u or HS2.0 [11] specification. The UE can obtain this information via the beacon message from supported AP candidates.

For these reasons, our proposed scheme for dynamic Wi-Fi offloading is designed as follows:

- Taking advantage of ANDSF's ISMP selection policies to regulate the admission to access points, this requirement to prevent selecting unauthorized AP.
- Using ANDSF's ANDI to find the availability of Wi-Fi and cellular network anytime and anywhere.
- Using thresholds to control and select preferable AP candidate. E.g., a new defined item in ANDSF MO [9] called *MaximumBSSLoadValue* for AP load threshold and propose an additional selection criterion for signal quality condition so called *MinimumBSSRSSValue*.
- Considering the load condition of AP obtained from AP candidates (we assume that the Wi-Fi APs are either compatible with HS2.0 or IEEE 802.11k, u) to decide whether Wi-Fi offloading is relevant and which AP is preferable.

3.2. Wi-Fi Mobile Handover Procedures

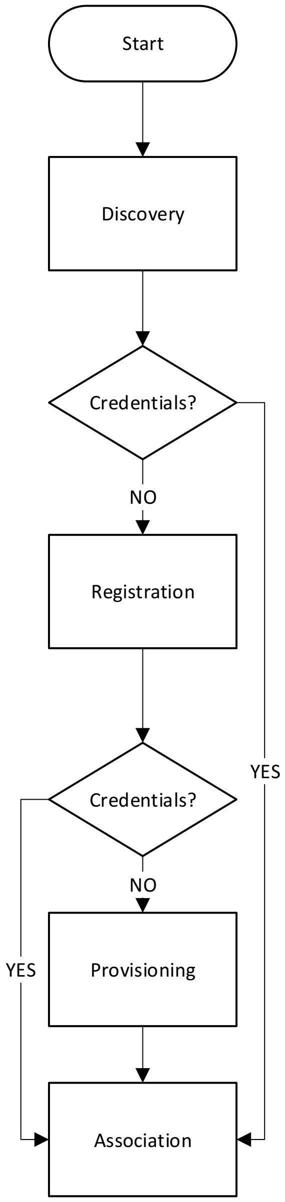

Figure 3. 2 Wi-Fi Terminal Basic Handover Procedures

In this section, we describe fundamental network discovery and selection procedures that a typical Wi-Fi terminal performs when connecting to a IEEE Wi-Fi AP. The main procedures are discovery, registration, provisioning and association as shown in Figure. 3.2. We will describe more detail about each procedure in the next sections.

3.2.1. The Discovery Procedure

In discovery procedure, the UE actively or passively scans for available AP by sniffing for a broadcasted short message known as the beacon message. The beacon message also conveys the information that allows the UE to detect whether the target AP supports IEEE 8021.11u or HS 2.0 or not. If the target AP supports IEEE 802.11u, it will perform an Access Network Query Protocol (ANQP) exchange to get more detail information of AP as well as network condition before the association process.

If there are several available AP candidates discovered in this process, the UE can select the candidates based on heuristic methods from input such as receive signal strength, network conditions (AP's load condition, backbone's load), or maximum supported data rate if it is applicable. These inputs can be obtained via IEEE 802.11u [10] and hotspot 2.0 [11]. However, the heuristic method to decide preferable target using these inputs is out of scope of IEEE 802.11u and hotspot 2.0. In this chapter, our main focus is to design a scheme to take advantage of these inputs for selecting the most preferable AP target anytime and anywhere.

3.2.2. The Registration Procedure

The registration process is performed by the end-user. It is the step in which the end-user registers the credential information with network operator such as contact information, payment method in order to obtain authorized account to access the network. In reality, this step can be performed via a web portal or when the end-user makes contract for using service with the network operator. The end-user can subscribe for specific service type, quality of service (QoS) at this step. The subscription and QoS is bound to end-user's profile. This process can be skipped and the UE can proceed to association process if it already has the authorized account to gain access to the network.

3.2.3. The Provision Procedure

The provision procedure is the next step after the UE completes the registration process to obtain authorized account. In this step, the UE installs necessary certificate, subscription, QoS profiles that is bound to its account information obtained in registration step. Upon provisioned with necessary profile, the UE instantly authenticates with the network without going throughput the registration and provision steps again when it accesses next time. The provision profiles can be Extensible Authentication Protocol (EAP) or EAP-Transport Layer Security (EAP-TLS)'s certificate used in HS 2.0 [10, 11]. Alternatively, the network operator can utilize STK SIM to provision UE, which is the same method adopted by cellular network operators.

3.2.4. The Association Procedure

The association process is the final step in which the UE performs authentication and negotiation procedure with the network with its authorized credentials and security settings.

In this step, the UE authenticates with the network operator's radius server such as Authentication, Authorization and Accounting(AAA) server using one of following EAP methods such as EAP-TLS, EAP-SIM, EAP-AKA, EAP-AKA (SIM, USIM), EAP-TTLS(User/Password).

3.3. IEEE 802.11u Beacon Message

In order to facilitate AP discovery and selection process, there are new network condition metrics added to the beacon message in IEEE 802.11u. The new elements are listed as following:

- Interworking element: This element contains information about supported services, type of access network (private or public network), venue specific information (Education, residence, Business) and HESSID (AP identifier).
- Roaming Consortium element.
- Country information element.
- Load metric: provides real-time network condition metric of the AP (number of associated UE, real-time channel utilization). This metric will be described in detail in the next section.

3.4. Real-time Channel Utilization Load for Wi-Fi Access Point

	Element ID	Length (5)	Station Count	Channel Utilization	Available Admission Capacity
Octets:	1	1	2	1	2

Figure 3. 3 IEEE 802.11u Beacon Message Frame

According to Hotspots 2.0 or IEEE 802.11u specification [11], the channel load metric of Wi-Fi AP is defined as one of the new QoS network metrics appending to beacon message of Wi-Fi AP Figure 3.3. This channel load metric is inherited from legacy standard IEEE 802.11k [22] ratified in 2008.

The channel load indicates the channel occupancy status of AP. If the load is too high, it can significantly degrade the end-user experience since it increases the contention probability among co-channel UEs. According to [22], the channel utilization or channel load, U_c is defined as the percentage of time, linearly scaled with 255 representing 100%, that the AP sensed the medium was busy, as indicated by either the physical or virtual carrier sense (CS) mechanism. By this definition, this metric indicates the real-time load status of radio channel.

$$U_c = Integer\left(\frac{t_{busy}}{T_M}\right) \times 255 \tag{3.1}$$

$$T_M = t_c \cdot t_b \cdot 1024 \quad (3.2)$$

The channel load is calculated by equation 3.1 the *Channel_Busy_Fraction*, t_{busy} is defined as the number of microseconds while the physical or virtual carrier sense mechanism in MAC layer keeps indicating busy channel status. The *Measurement_Duration* T_M represents the number of consecutive beacon intervals while the channel busy time is measured. T_M is calculated by (3.2), t_c is the channel utilization measured interval representing the number of consecutive beacon intervals during which the channel busy time is measured. t_b is the beacon period value in IEEE802.11-time unit (TU). One TU is 1024 microseconds. The AP regularly calculates its channel load metric every T_M (μs) and the UEs obtain this channel load metric either via beacon message or probe response message.

3.5. Access Point QoS Indicator

In our proposed scheme, we consider both the channel load and the RSS measured from the UE as the most significant metrics for selecting Wi-Fi AP. The access point QoS indicator was first presented in our paper [33] and revised in [34].

The **Receive Signal Strength** (RSS) or SINR is the most widely used metric for conventional handover (HO) decision since it is easy to measure and directly relate to the radio channel quality. With strong RSS, the AP can use high channel modulation and coding scheme and the bit rate becomes higher accordingly. Therefore, it is evident that strong RSS is preferable.

The **Channel Load:** as aforementioned, this metric indicates the real-time load condition of the AP operating channel. In a wireless network, if the load is too high, it will result in poor quality of service (low throughput, high packet loss or delay). This metric is even more important for Wi-Fi since Wi-Fi uses CSMA/CA for multiple access. The high channel load can result in high contention rate, which dramatically degrades active UE's throughput in the same channel. Therefore, lower load AP is preferable for good QoE.

$$\overline{RSS_i} = \alpha \cdot RSS_i + (1-\alpha) \cdot \overline{RSS_{i-1}} \quad (3.3)$$

$$APQI_i = w_r Log_2\left(\frac{\overline{RSS_i}}{RSS\_MIN_i}\right) + w_l Log_2\left(\frac{1}{\frac{\text{Channel\_Load}_i}{255}}\right) \quad (3.4)$$

With $w_r + w_l = 1$

Because the RSS and channel load have different unit and characteristics, we define a normalized metric, a cost function known as APQI (Access Point Quality Indicator) in order to make it easier to evaluate and compare the metrics between AP candidates.

Firstly, since each of above metric has different unit and characteristics, we have to normalize them. In equation (3.4), $\overline{RSS_i}$ is the mean value of RSS, which is calculated as (3.3) while the *RSS_MIN* is the minimum received signal strength of Wi-Fi receiver specified by the Network Interface Controller (NIC) vendor. Each vendor of Wi-Fi NIC has its own sensitive RSS value for the receiver. If the RSS is lower than this value, the data packet will be dropped. Therefore, the normalized term $\overline{RSS_i} / RSS\_MIN$ indicates how strong the received signal strength compared to its minimum value. We use binary Logarithmic function $\log_2(\overline{RSS_i} / RSS\_MIN_i)$ to reduce the impact of fluctuation of RSS input. By this definition, this value is independent to the vendor specified hardware specification and comparable among different vendor APs.

The *Channel Load* or *channel utilization* metric in Equation (3.3) is defined as the percentage of time when the UE sensed the channel was busy indicated by either the physical or virtual carrier sense mechanism [22]. This percentage is linearly scaled of integer range [1- 255] corresponded to 0 - 100% channel load. By this definition, the term $Channel\_Load_i / 255$ is the normalized value of the channel load (The $Channel\_Load_i$ is an integer number [1-255]). Here, we apply Logarithmic functions, $Log_2(\frac{1}{\frac{\text{Channel\_Load}_i}{255}})$ to reduce the rapid fluctuation of $Channel\_Load_i$ input and make it comparable with normalized RSS. The $APQI_i$ is the $APQI$ of ith AP defined as in (3.4). The first term represents the benefit of signal quality of the radio link between the UE and the AP while the second term represents the benefit of real-time channel load condition of AP. In Equation (3.4), the $APQI$ is inversely proportional to the channel load metric. It shows a trade-off between the signal quality and the traffic load metrics of AP candidate. The significance of each term is depended on the weighted values w_r, w_l , for link quality and the channel load or channel utilization respectively.

3.6. Proposal for Enhancing ANDSF WLANSP Management Object

The ANDSF standard defined various policies such as intersystem mobility, Access Network Discovery Information through the Management Objects (MO), which is a tree based structure. In the latest release 12 [9], a new leaf of ANDSF MO is added for WLAN Selection so-called WLANSP (WLAN Selection Policy). The WLANSP is a network-defined policies, which specifies how the mobile node should select an available WLAN access point. The UE can obtained the WLANSP information from the network operator which includes the following information:

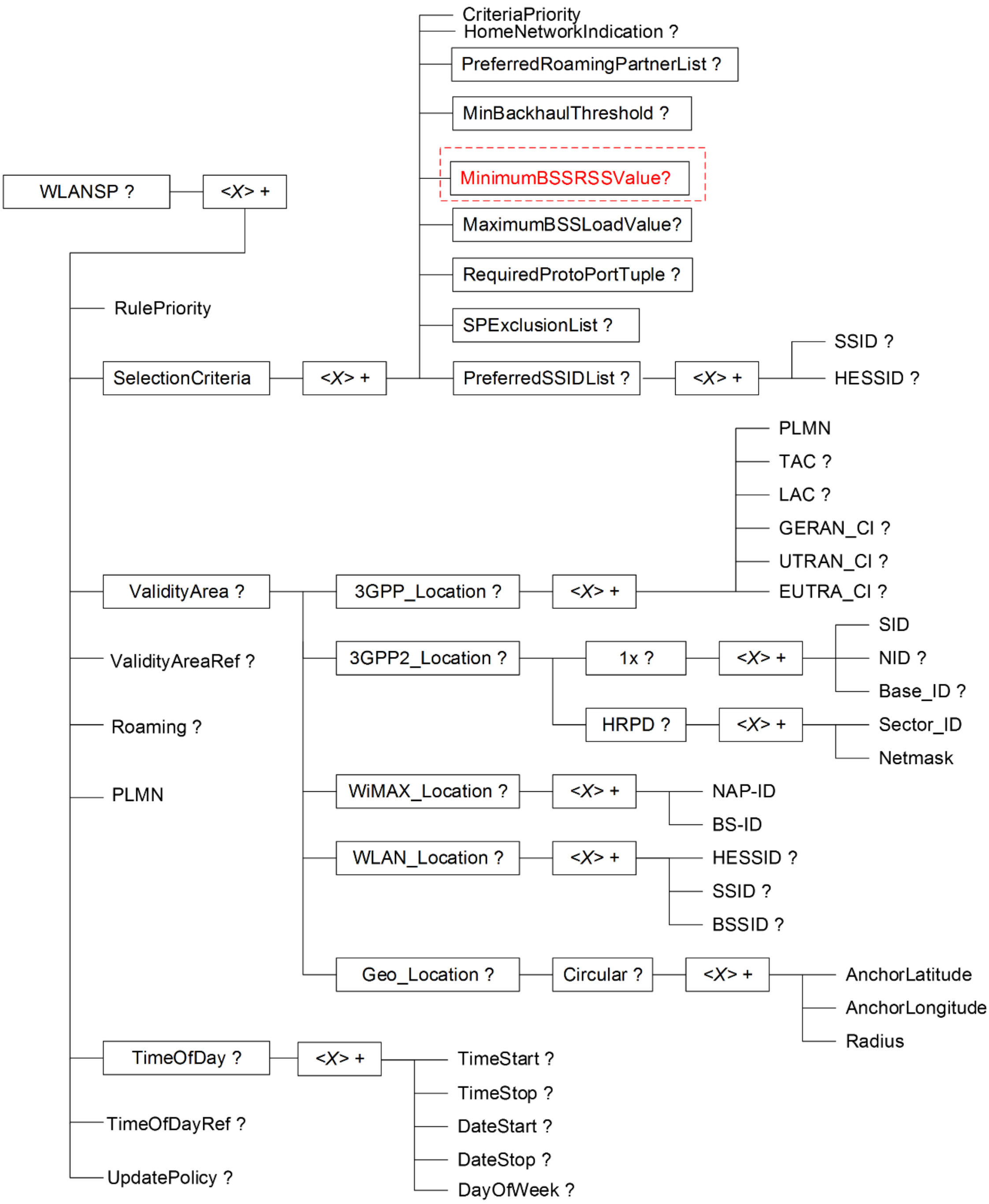

Figure 3. 4 Example of enhanced ANDSF OM for WLANSP.

- Validity rule which is the condition that indicated when and where the rule is valid. The validity rule can be the mobile node condition such as the cell-ID, time of days, Wi-Fi AP's SSID.
- Set of information for WLAN selection rule which specifies the criteria for selecting AP such as backhaul bandwidth, the load condition of APs.

The WLANSP's rule can have one or more WLAN selection criterion defined in *ANDSF/WLANSP/<X>/SelectionCriteria* node including following attributes:

- *CriteriaPriority.*
- *HomeNetworkIndication.*
- *PreferredRoamingPartnerList.*
- *MinBackhaulThreshold.*
- *MaximumBSSLoadValue.*
- *RequiredProtoPortTuple.*
- *PreferredSSIDList.*
- *SPExclusionList.*

The UE can obtain these selection rules and use them for Wi-Fi selection procedure. However, in our proposed scheme, for the sake of simplicity, we only consider the *MaximumBSSLoadValue* criterion for Wi-Fi AP selection because it serves as a load threshold in our selection scheme. If the load condition of AP candidate does not satisfy this threshold, it will be eliminated from the selection process. Therefore, this criterion is introduced in our scheme to pre-eliminated high traffic load AP candidates that do not provide good QoS. In addition, the threshold can also be used to control the number of UEs performing Wi-Fi offloading. For example, if this load threshold value is properly set, only certain number of UEs can roam to Wi-Fi, when the load traffic of AP still below that threshold. When the traffic load of APs is exceeded the load threshold, the rest of cellular UEs is not allowed to offload. In contrast, if the load threshold is increased, there will be larger number of UEs roaming to Wi-Fi. Therefore, network operator adjusts this threshold to control the percentage of cellular user roaming to Wi-Fi for offloading. We will evaluate the performance of the proposed scheme when varying the load threshold in the simulation section.

Apart from the load metric, we also consider the receive signal strength (RSS) as another important metric that can affect the UE's experienced QoS. If the AP is far away from the UE, it cannot sustain good QoS for the UE in spite of acceptable load condition. The reason is that the RSS is used to determine the modulation scheme in the physical layer between AP and UE. If the RSS is weak, the mobile node will use low coding scheme to reduce error and retransmission. Therefore, in our proposed scheme, we consider adding a RSS threshold to eliminate weak signal strength AP candidates. The signal strength threshold serves as the minimum signal level for ensuring acceptable QoS. Like the max load threshold, the operator can also utilize this threshold to control the number of Wi-Fi roaming UEs. For example, if the RSS threshold is high, only the UE(s) that is/are near to the AP can roam to Wi-Fi.

However, currently, such RSS threshold is not available in the ANDSF WLANSP MO. Therefore, we propose to append this selection policy node to the same OM leaf of *MaximumBSSLoadValue* in ANDSF WLANSP MO, *<X>/WLANSP/<X>/SelectionCriteria/<X>/MinimumBSSRSSValue so that this policy* can be distributed to UEs in a same manner. Figure 3.4 shows the tree based structure of ANDSF WLANSP element and an example of how the additional selection node is added to existing ANDSF MO standard. If *MinimumBSSRSSValue* node is not present or the node is present and empty, the UE will not evaluate the node. If it is available, the UE can use this information in our scheme for AP selection.

3.7. The proposed Wi-Fi roaming decision and selection decision scheme

Our roaming decision and selection scheme is a network assisted and UE driven scheme. The UE has a unique position, which allows it to receive both ANDSF's policies and the real-time network condition from AP candidates. Therefore, it is obvious to let the UE make the decision instead of any other entities in the network. The UE should decides timing for network roaming decision and selects the relevant point of service based on ANDSF's policies, UE's measured information, and channel load information from AP candidates. The proposed scheme is a decision-making procedure carried out by the connection manager (CM) of end user's device. In this thesis, the CM is a generic term referred as a system module or even an application that collect input from end-user, input from ANDSF and APs, and manage the mobile device's connection such as turn on/off access interface, routing end-user traffic via different interfaces. the CM decides whether cellular Wi-Fi roaming is relevant or not and which AP candidate is preferable for better QoS. In the proposed scheme, it is worthy to note that the channel load metric of Wi-Fi AP is required to decide the preferable candidate. However, it should not interfere with conventional homogenous cellular or Wi-Fi handover procedure.

Figure 3.5 illustrates the flow chart of proposed scheme:

STEP 1: The CM monitors the QoS of current connection. If the QoS is degrading (the data rate drops to certain threshold), running application or user's preference requests for better QoS, it will trigger the process to find better point of service.

STEP 2: The CM contacts the ANDSF entity at the core network to obtain the list of legitimate Wi-Fi AP and WLANSP selection rule corresponding to UE's location (Cell-ID of macro cell, or SSID or GPS location if applicable). The ANDSF entity returns a list of AP candidates that can be accessible from the UE's location. In addition, *MaximumBSSLoadValue*, *MinimumBSSRSSValue* thresholds are also obtained from ANDSF MO WLANSP.

STEP 3: By using AP discovery information from ANDSF, the UE needs to scan the surrounding to check whether the AP candidates are available because provisioned ANDSF's information may be out of date or unreachable from UE's location. By doing this step, UE eliminates unreachable AP and obtains the RSS and the channel load of each

AP candidate. This is the discovery process that we described in previous section. We assume that the AP candidates support either HS 2.0 or IEEE 802.11k, e. so that the real-time load and the RSS of each AP can be obtained from the beacon message or via ANQP protocol in case of HS.2.0

STEP 4: The CM obtains the list of APs that fulfil the load and RSS thresholds. The thresholds are specified by network carrier via ANDSF's Wi-Fi selection policies. As aforementioned, the MaximumBSSLoadValue are used to select Wi-Fi AP, if the load of AP is higher than this value, it will be eliminated. We introduce the load threshold in order to pre-eliminate unsuitable AP, which cannot guarantee a good QoS. The MinimumBSSRSSValue can serve as the RSS threshold to eliminate far away AP candidates.

STEP 5: If there is no the qualified AP after step 4, the UE will stay at the current network. The UE conducts the conventional homogenous handover procedure if it is favorable. If these are qualified APs available, the CM calculates the APQI metric (4) for each AP candidates. If the UE is using Wi-Fi, it will calculate the APQI of the associating AP. The AP with highest APQI is selected as the candidate for the next point of service. After deciding the preferable AP, the CM starts the handover procedure to selected AP.

STEP 6: if there is no better point of service, the UE will stay at the current network. The CM returns to the first step.

The pseudo code of our proposed scheme is shown as follows:

Algorithm Roaming decision and preferable AP selection

Input: Set the parameters: *RSS, RSS_Min, Channel_load*, *MaximumBSSLoadValue*, *MinimumBSSRSSValue,* w_r, w_l

Output: AP candidate.

1. **While** *(1)* **do {**
2.**if** QoS degrading trigger **then**
3.Obtain data from ANDSF entity

a. Obtain AP candidates Information (SSID, operating channel)
b. Obtain Load and RSS thresholds *MaximumBSSLoadValue*, *MinimumBSSRSSValue*

4. *qualified_AP_List=nil;*
***for** each* AP_i ***in** AP candidate List{*
a. Obtain information of available AP_i information from physical Layer,
b. Obtain RSS_i, calculate $\overline{RSS_i}$ Equation (3.3).
c. Obtain $channel\_load_i$ information.
d. **if** $\overline{RSS_i}$ *>MinimumBSSRSSValue &&* $channel\_load_i$ < *MaximumBSSLoadValue* ***then*** *qualified_AP_List add* AP_i
}
***If** qualified_AP_List is empty **then** return;*
5. Candidate_AP->APQI= *calculate* $APQI_1$ *using equation (5.4)*;
***for** each* AP_i ***in** AP candidate qualified_AP_List{*
calculate $APQI_i$ *using equation (3.4)*
if AP_i*->APQI> Candidate_AP->APQI **then*** Candidate_AP= AP_i;
}
6. if Candidate_AP !=current AP **then**
return Candidate_AP;
}

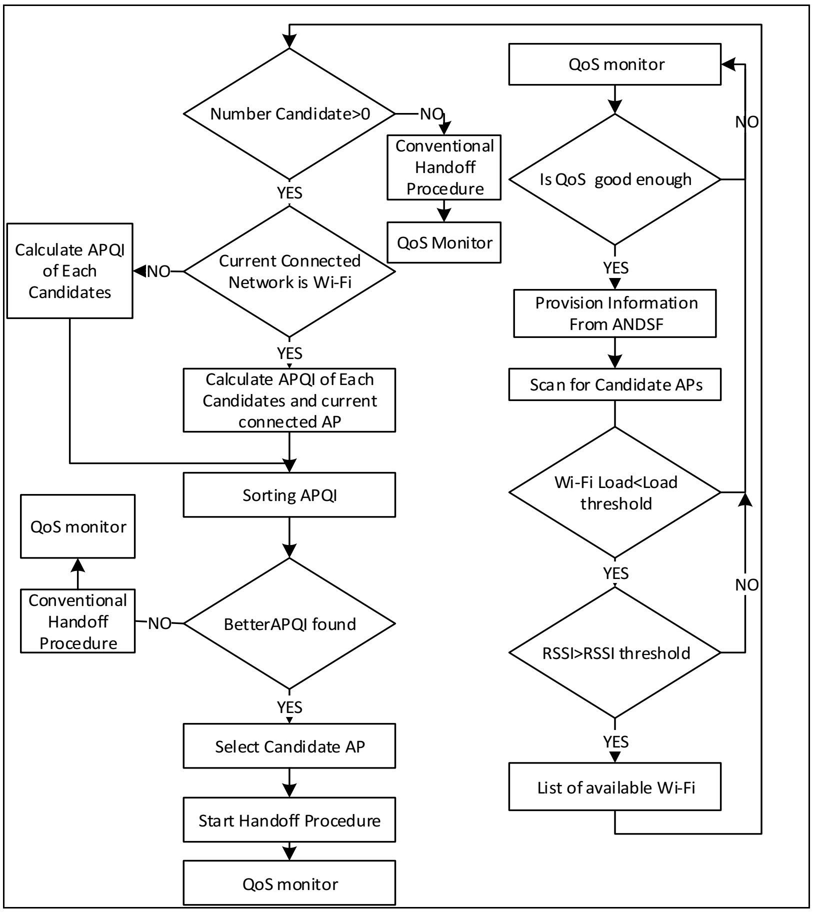

Figure 3. 5 Proposed roaming decision and Point of Service selection scheme

3.8. Simulation and Numerical Result

3.8.1. Choosing simulation tool

In order to evaluate the proposed scheme, we considered several tools such as Mathlab, Omnet++, ns-2, NCTUns. After throughout consideration, NCTUns was considered to be the best choice. For example, the ns-2, is a more complicated tool compared to the NCTUns since it requires creating the full simulation environment, such as mobile nodes, protocol stack, links, traffic, functionalities and so on. Omnet++ is an open source software but does support WiMAX and it would be needed to be created from beginning. And finally, Mathlab, it lacks the most components needed to create the simulation of heterogeneous networks. Another reason is that it has multi-interface mobile node which is a key functionality for the vertical handover. Last but not least, one of the key features of this software is that it allows running user-defined C/C++ application on the network node. In our simulation model, we take advantage of this feature to simulate the ANDSF entity and the connection manager (CM) for each UE node.

3.8.2. NCTUns Simulation Software

NCTUns is an open source simulation software developed by the National Chiao Tung University for communication networks [24, 25, 26, 27]. It can simulate varieties of popular wired and wireless network entities and protocols such as IEEE Wi-Fi 802.11a/b/g, ad-hoc networks, WiMAX IEEE 802.16 e/d/p, multiple-interface UE, GPRS, satellite and vehicular networks etc. However, one of the key features of this simulator software is that it allows running user-defined C/C++ application on the simulated node. In our simulation model, we take advantage of this feature to simulate the ANDSF entity and the connection manager (CM) for each UE node.

The main problem of this software is that it does not support handover between different access networks (vertical Handover). NCTUns supports mobile IP (MIP)for mobile node. However, IP mobility only supports within homogeneous network such as handoff between WiMAX base stations or between Wi-Fi APs.

One of the main reasons for choosing NCTUns for this research is that it allows running user's defined application on the mobile node. We use this feature to develop our model of ANDSF entity, CM for each mobile node.

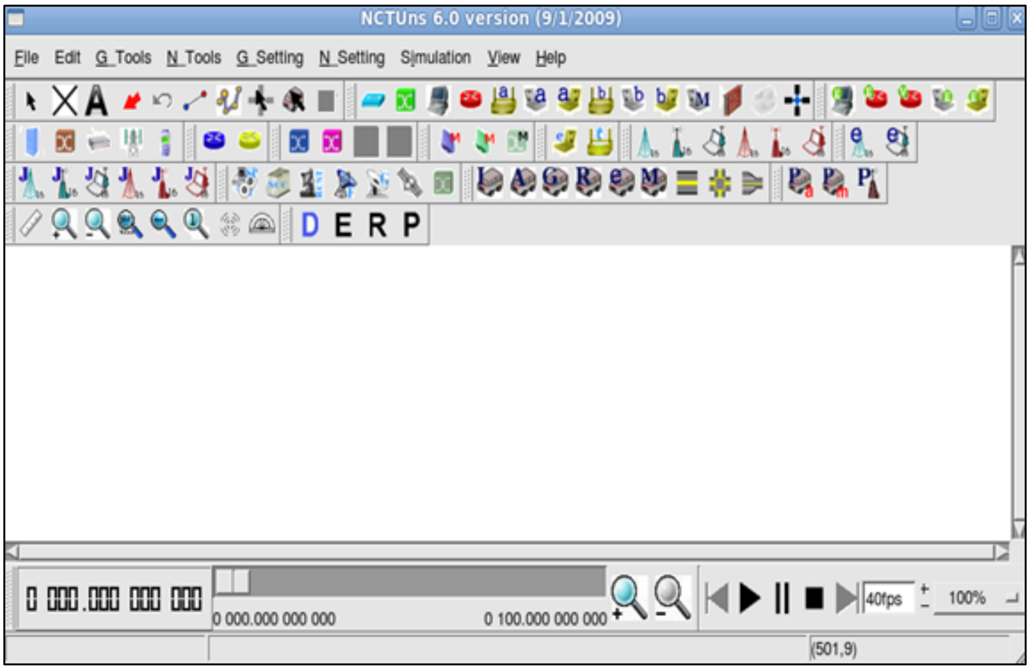

Figure 3. 6 NCTUns Simulation Graphic User Interface

NCTUns provides graphical user interface (GUI) showed in Figure 3.6 where all graphical network designing is done and simulation progress and numerical result can be observed. In general, the tool has 8 main components as following:

1. NCTUns provides a GUI interface, that make it easier for end-user to edit, modify, delete network scenario, simulation nodes, protocol modules, as well as simulation parameters, showing simulation result and other functionalities already mentioned above [25].

2. The second component of the NCTUns is the core simulation engine, which provides event scheduling and connects to all of modules, protocols [25].

3. The third component is the underlined algorithms, protocols and nodes modules, which are written by C/C++ programming language. and they are connected to simulation engine program via socket and dedicated tunnels.

4. The dispatcher program used for multiple simulation servers' management to scale up the simulation performance. Waits client connection via TCP port 9800 and waits coordinator connection vie TCP post 9810.

5. The coordinator program is another main component of NCTUns, it must run side by side with the simulation server. It registers itself with dispatcher to bundle with other coordinators to scale up simulation server. It serves as a simulation process unit. The dispatcher can freely select an available simulation server from the registered simulation server pool to perform a certain simulation task. In addition, messages exchanged between the simulation engine service and the graphic user interface are transferred via the coordinator [27].

6. The sixth component is the kernel patches that allows all of the simulation programs could run on the host operating system. The current version of NCTUns 6.0 runs on Fedora 12.

7. The seventh component is the protocol programs running at the top layer. For example, the routing program running on the host operating system exchanges routing messages and generates system routing tables [26].

8. The last component is user-level application programs. The NCTUns allows end-user's application or program to be executed on top of simulation nodes. This is the main feature that makes NCTUns stands out from other simulation software. in this research, we take advantage of this feature to develop the connection manager, which can run on a mobile

node to manage its connection and the ANDSF entity which can exchange information with the mobile nodes. We will further describe in more detail in the next section.

3.8.3. Simulation Model Setup

Although there are several adoptions of ANDSF [9] standard for commercial solutions for network selection in heterogeneous network [23], as far as we concerned, there is no simulation of ANDSF standard for academic studies. Therefore, in order to evaluate our proposed scheme, we developed a system model of HetNet with vertical handover (VHO), ANDSF entity/client and connection manager running on each mobile node. This system model was presented in our published papers [33-35]. The whole system model is developed by NCTUns 6.0, described in previous section. It can simulate varieties of popular wired and wireless network entities and protocols such as IEEE Wi-Fi 802.11a/b/g, ad-hoc networks, WiMAX IEEE 802.16 e/d/p, multiple-interface UE, GPRS, satellite and vehicular networks etc. However, one of the key features of this simulator software is that it allows running user-defined C/C++ application on the simulated node. In our simulation model, we take advantage of this feature to simulate the ANDSF entity and the connection manager (CM) for each UE node.

Our ANDSF entity (we call the ANDSF entity as ANDSF server in the simulation) model is a C program, which provisions information of available APs, load threshold, RSS threshold. The CM is also C program running on each mobile node executes our proposed scheme. It can obtain the RSS and the real-time channel load of AP candidate through MAC layer. The CM contacts the ANDSF server to fetch policies and thresholds via UDP socket. In addition, the CM can also obtain the RSS and the channel load of AP candidate from the MAC layer. As the simulation tool does not support IEEE802.11k, e or HS 2.0, we modify the MAC layer of the Wi-Fi AP node to append the real-time channel load information into the beacon message. In equation (3.1), the channel busy fraction is defined as the number of microseconds when the physical or virtual carrier sense indicates the channel is busy. In our simulation, we use the virtual carrier sense, Request to Send/Clear to Send (RTS/CTS) mechanism for detecting busy channel [22]. In [22] the default value of "*channelUtilizationBeaconIntervals*" in equation (3.1) is set to 50 and the beacon broadcast interval is 100 (ms).

The coefficients w_r and w_l are the weight values of RSS and channel load metric respectively used to calculate the APQI. In our simulation, we notice that if $w_r >> w_l$, the system performs much like conventional Wi-Fi selection based on RSS. In this case, the AP's load has less influence on Wi-Fi selection decision. Therefore, for the scope of this simulation, in order to increase the sensitive to channel load, we purposely set the weight of load slightly bigger than received signal strength we choose $w_r = 0.4$ and $w_l = 0.6$.

Although the simulator software supports multiple-interface mobile UE and horizontal handover within WiMAX or Wi-Fi, it does not support VHO between WiMAX BS and Wi-Fi AP. Therefore, we modify the source code of the simulation software to simulate the vertical handover between macro-cell (WiMAX IEEE 802.16e) and Wi-Fi IEEE 802.11a. It is worthy to note that our proposed scheme is proposed for 3GPP Cellular (LTE or UMTS) and Wi-Fi. However, the simulation software NCTUns version 6.0 [24] does not support LTE. Therefore, we have to use WiMAX instead of LTE for our HetNet model. Since our proposed scheme does not consider any metric from the macro-cell, using WiMAX instead of LTE for access network does not cause any difference in the simulation result. In addition, due to a problem related to Mobile IP protocol of the simulator, the simulation of VHO is not a seamless handover. Therefore, the UE's connection are interrupted when performing the VHO.

3.8.4. Simulation Model Description

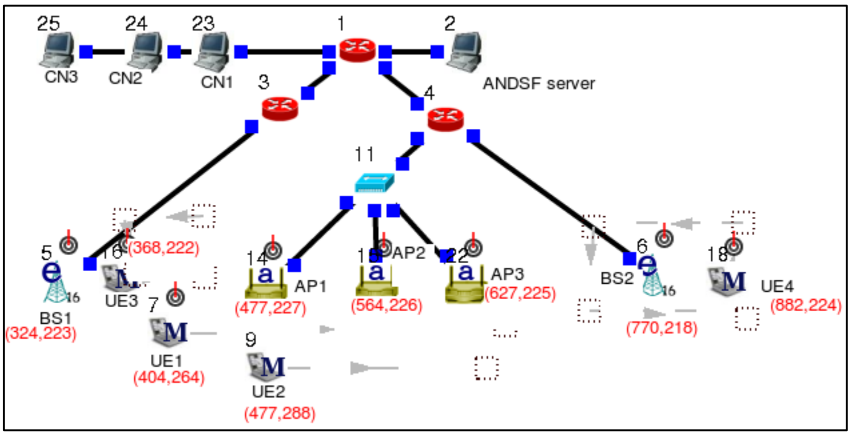

Figure 3. 7 Simulation scenario setup for HetNet with interworking WiMAX BSs, Wi-Fi APs, Multiple Interfaces UEs.

Figure.3.7 shows the screenshot of our simulation setup in the simulator and the simulation parameters are listed in Table 3.1. This setup is a typical Wi-Fi deployment scenario to offload traffic from cellular network as we described in previous chapter. We arrange a typical WiMAX-Wi-Fi interworking scenario with two IEEE 802.16e BS1, 2 (Node 5, 6), three 802.11a Wi-Fi AP 1, 2, 3 (Node 14, 15, 22) and four multiple wireless interface UE 1, 2, 3, 4 (Node 7, 9, 16, 18 consecutively) equipped with both WiMAX and Wi-Fi 802.11a interfaces. All of WiMAX BSs and Wi-Fi APs are interconnected via routers and switches, which is a simplified EPC architecture described in chapter 2. We simulate the typical movement pattern of UEs when they move from the coverage of WiMAX to Wi-Fi. During the simulation, the UEs 1, 2, 3 move from the coverage of BS1 toward Wi-Fi coverage area while the UE4 (node 18) moves around BS2. All of the UEs have a CM application embedded with our proposed scheme to monitor and manage their connectivity. The ANDSF server (Node2) resides at network side and it is reachable by all of UEs. The ANDSF communicates with the UE's CM to provide Wi-Fi AP candidates as well as load and RSS threshold. In order to simulate Wi-Fi roaming trigger event when QoS is not good enough, we randomly disrupt the WiMAX base station connection during the simulation.

At the beginning, the UEs are connected via WiMAX BSs; the UE1, 2, 3 (Node7, 9, 16) are associated with BS1 while UE4 (Node 18) is associated with BS2. At T=4 (s), The UEs start sending greedy CBR (Constant Bit Rate) traffic toward the Correspondent Node (CN), (Node 2, 23, 24, 25 in Figure 3.6. Figure 3.8 and Figure 3.9 show the incoming and outgoing throughput of BS1, 2. The throughput of BS1, 2 gradually increase and reach the maximum bit rate at 1975KB/s and 659KB/s respectively.

At T=10 (s), the CM of UE2 fetches information from ANDSF policies, which contains AP candidate1, 2, and 3 (Node 14, 15, 22). Subsequently, it scans the surrounding area to obtain the channel load and RSS of each AP candidate. The CM calculates the APQI of each AP according to (3.4). The UE2 picks AP1 because it has the highest APQI. The UE2 starts VHO procedure to AP1 at T=10s. As showed in Figure 3.8 and 3.11 the traffic of BS1 (red line) drops to 1316KB/s at T=11s while the traffic of UE2 is gradually rising at T=13s when the VHO is completed.

At T=12(s), the CM of UE1 (Node 9) detects the QoS of WiMAX BS degraded, it sends a request to ANDSF server to obtain the candidate list. The host returns the list of available AP1, 2, 3 (Node14, 15, 22). The UE1 carries out the same procedure as the UE2 to calculate the APQI of each AP candidate. The UE1 selects and starts VHO procedure to AP2 at T=12s. Figure 3.8 shows that the traffic of BS1 continual drops to 659.5KB/s at T=14s. From Figure 3.10, at T=16s, the traffic of UE1 starts rising when the handover procedure of UE1 is completed.

Table 3. 1 Simulation parameters

WIMAX		**Wi-Fi**
Technology	IEEE 802.16e	IEEE 802.11a
Coverage	1000 m	50 m
RX Thresh	-96 dBm	-82 dBm
Transmit Power	35 dBm	16.02 dBm
Bandwidth/QoS	5Mb/s	9Mb/s
Modulation scheme	OFDM 16QAM	OFDM 16QAM
Carrier frequency	2.3 GHz	5 GHz
channelUtilizationBeaconIntervals	NA	10
BS Number	2	3
Propagation channel	Two-ray ground	Two-ray ground
Channel Load threshold	NA	0.8
MS		
Node number	4	
Mobility movement	Straight line	
Multiple interface	WIMAX and Wi-Fi	
Speed	2-5 m/s	
Traffic parameter	Greedy CBR	
Miscellaneous		
Channel load broadcast interval	100 ms	
w_r	0.4	
w_l	0.6	
α	0.5	

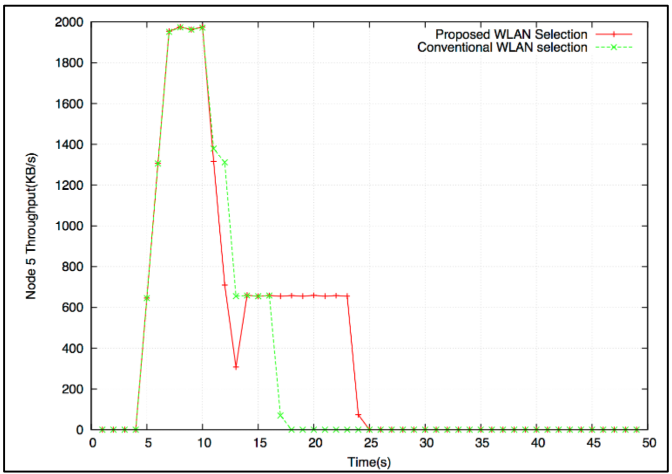

Figure 3. 8 The throughput of BS1 (Node5)

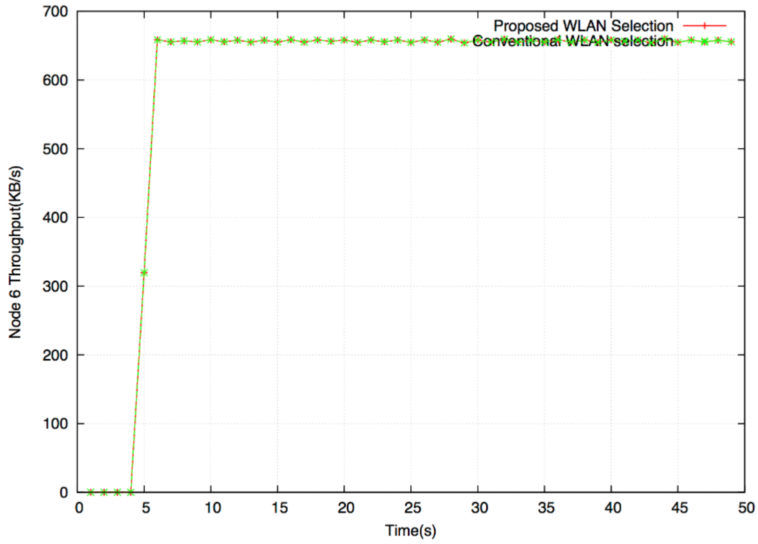

Figure 3. 9 The throughput of BS2 (Node6)

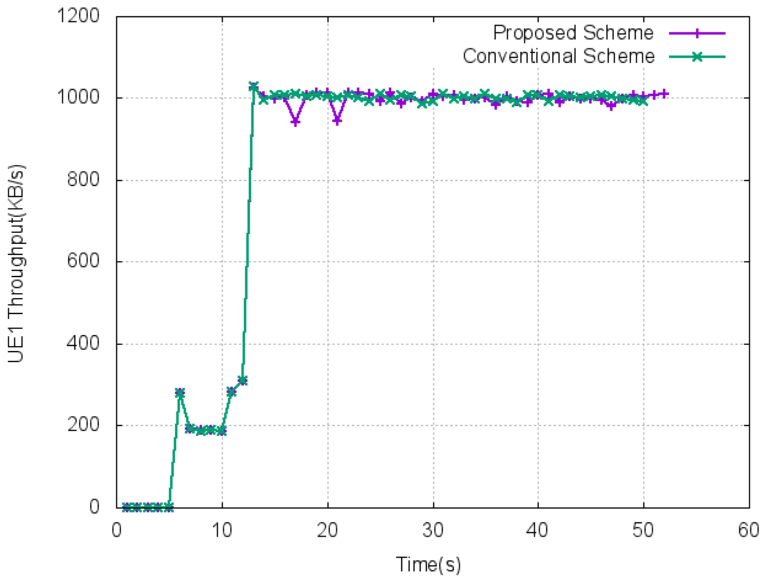

Figure 3. 10 The throughput of UE1 (Node 7)

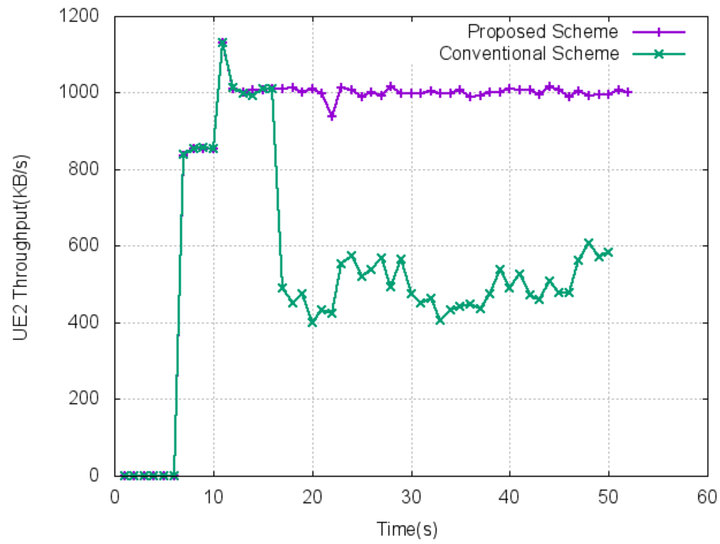

Figure 3. 11 The throughput of UE2 (Node 9)

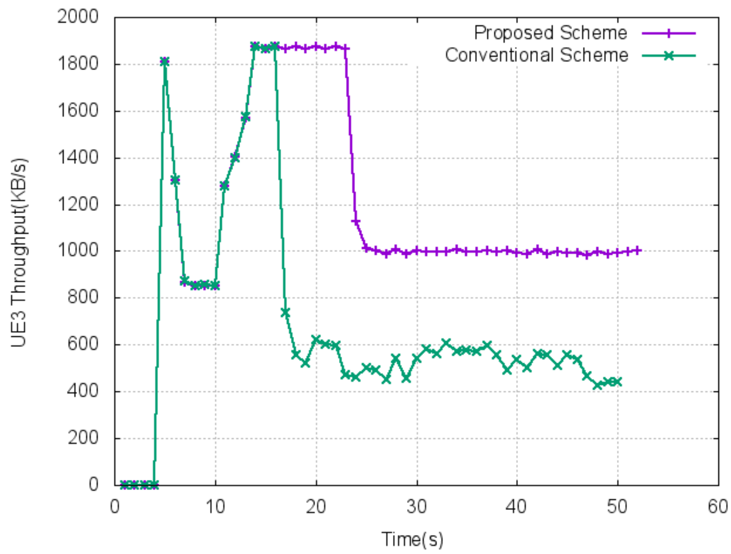

Figure 3. 12 The throughput of UE3 (Node 16)

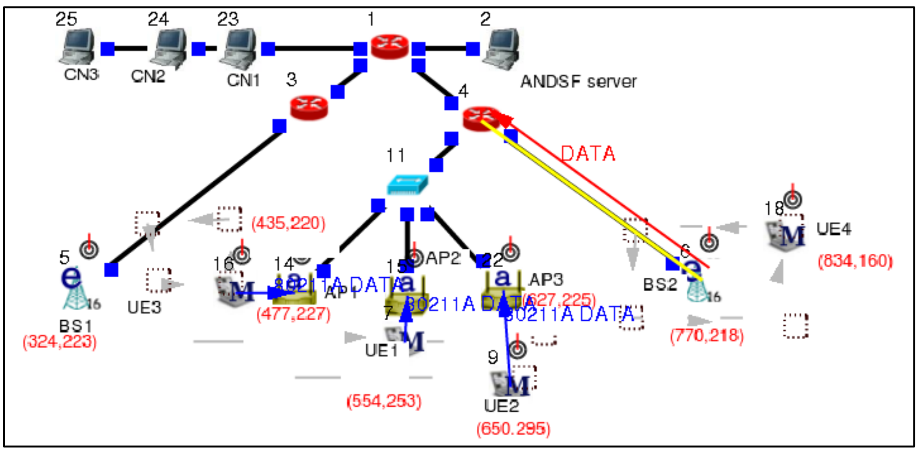

Figure 3. 13 Screenshot of simulator for proposed scheme at T=29s

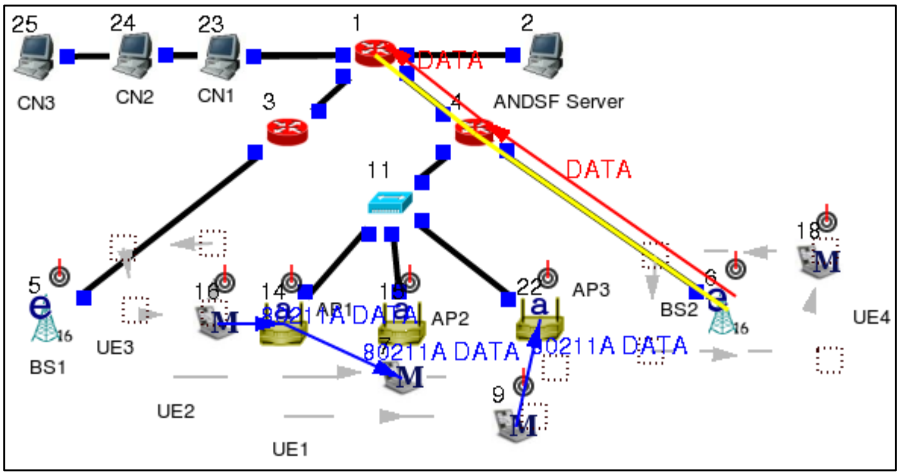

Figure 3. 14 Screenshot of simulator for conventional scheme at T=29s

At=15s the UE3 (Node 16) carries out the same procedure as UE1 and UE2. However, AP1, 2 are serving UE1, 2 and the channel load threshold is not satisfied. The UE3's CM decides to keep the connection with WiMAX BS1 since the specified APs are busy. As showed in Figure 3.8, from T=14s the throughput of BS1 remains at 650KB/s which is the traffic of UE3.

At T=20s, the UE1 moves closer to the AP3. The RSS of AP3 satisfies the RSS threshold. The UE1's CM decides to handover to AP3. Figure 3.10 shows the traffic of UE1 drops at T=20s.

At T=21s, The CM of UE2 calculates the APQI of each AP candidate. The AP2 becomes a better candidate for UE2 since it remains idle and closer to UE2. The UE2 decides to select AP2 as the target AP for handover. In Figure 3.11, the traffic of UE2 drops during that time.

At T=23s, the UE3 calculates the APQI for each AP candidate. The AP1 becomes the best candidate for UE3 this time because it is idle and satisfies both channel load and RSS threshold. The UE3's CM decides to switch the connection from BS1 to AP1. In Figure 3.8, the traffic of BS1 drops to 0KB/s at T=25s when all of UEs are transferred to Wi-F APs. In Figure 3.12, the traffic of UE3 gradually drops and stabilizes when handover process completes.

The UE4 moves back and forth around the BS2, however there is no available AP candidate at its location. Therefore, the UE4's CM decides to keep the connection with BS2 throughout the simulation.

Figure 3.13 shows the network connection status of UEs at T=25s after transferring from WiMAX BS1, each Wi-Fi AP serves one UE.

3.8.5. Simulation Result Discussion.

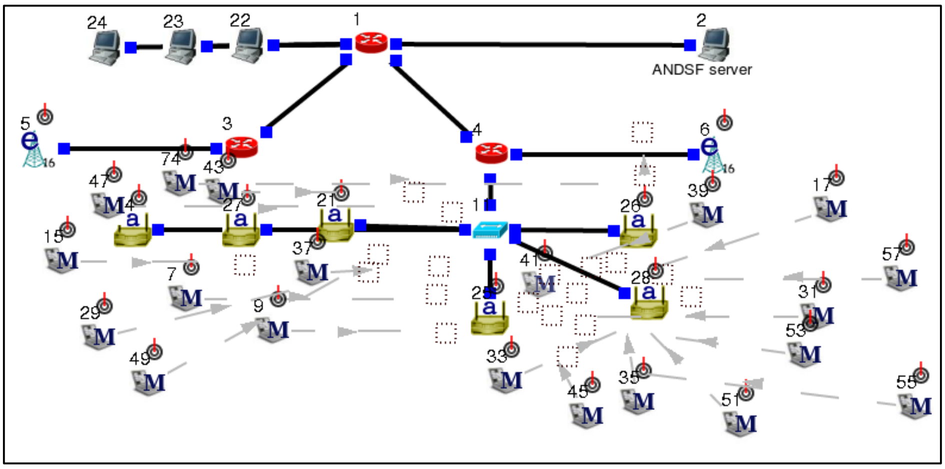

Figure 3. 15 Simulation setup with 20UEs and 6APs and 2 WiMAX BS.

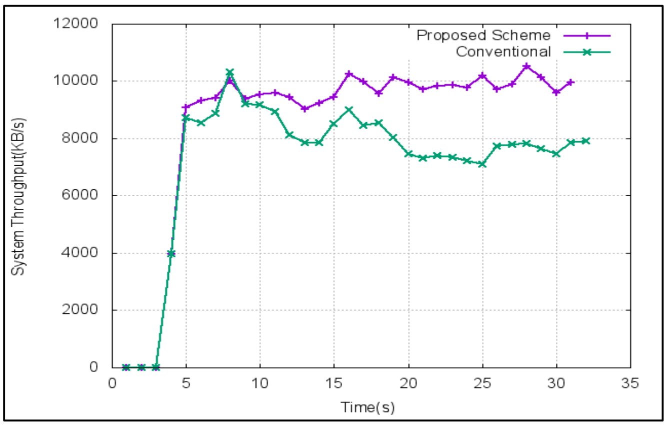

Figure 3. 16 System throughput comparison proposed scheme and conventional scheme

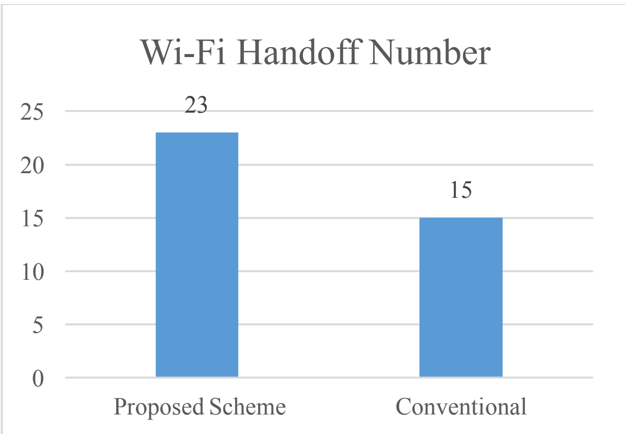

Figure 3. 17 Wi-Fi Handover Number Comparison between the proposed scheme and conventional scheme

In order to evaluate system throughput, we increase the number of mobile nodes or the density of mobile nodes during the simulation. The simulation setup is shown in Figure

3.15. The density of UEs gradually increases around Wi-Fi APs when the UEs move toward them. We compare the performance with that of the conventional Wi-Fi selection scheme. As aforementioned, in the conventional selection based on RSS or SINR, if there are several of available APs, the nearest AP (regardless of AP's load status) will be selected and the connection will remain until the signal strength becomes unacceptable (below RX sensitive threshold).

At the beginning, the UEs are connected via the macro-cell, WiMAX BSs; At T=4 (s), The UEs start sending greedy CBR (Constant Bit Rate) toward the Correspondent Node (CN), (Node 23, 24, 25 in Figure 3.15). Figure 3.16 shows the traffic of UEs rising at T=4s.

At T=7(s), the CM of UEs obtain discovery and selection policies from ANDSF, which contains AP candidates list, signal strength and AP's load thresholds corresponding to UEs location. Afterward, the UEs scan the surrounding area to obtain the channel load and RSS of each AP candidate. The AP candidates are evaluated based on their channel load and the received signal strength metrics. Only APs, which satisfy the load threshold and the signal strength threshold, are considered in the next steps. The CM of UEs calculate the APQI metric of each AP. The AP candidates are ranked by the APQI metric and the top AP is selected as AP candidate.

The numerical results show that the proposed scheme outperforms the conventional Wi-Fi selection scheme in terms of overall system throughput or average UE's data throughput. With the knowledge of the network conditions and selection policies, UEs can offload their traffic more efficiently. With our proposed scheme, the UE can proactively decide the right timing for making Wi-Fi roaming based on the policies from the network and UE's measured information. Furthermore, the UE can also dynamically select preferable AP (in term of load condition and radio link condition) when moving.

Therefore, the traffic of the macro-cells is offloaded and distributed among available APs. It increases the utilization rate of available APs since all of APs are utilized while one AP is left unused in conventional case. However, as shown in Figure 3.16, we are also aware that proposed scheme has a shortcoming, that increases number of handover between Wi-Fi. This shortcoming results from the fact that UEs switch to preferable AP to optimize their throughput. Because we do not consider UE's QoS preference as one input for AP selection, we assumed that the UEs always request for highest throughput as possible. The mobile nodes dynamically switch their connection to more preferable AP when it is on the move. However, in the conventional scheme, the mobile nodes only switch the connection when the RSS from associated AP becomes weak (lower than the *RSS_MIN*). Therefore, it is obvious that the proposed scheme increases the number of handoff between Wi-Fi APs. Increasing the number between Wi-Fi AP is not favorable because it might cause connection disruption to UEs. Therefore, we have a trade-off between the number of handover and maximum throughput for mobile node. This trade off issue will be considered in the next chapter.

3.8.6. The influence of signal strength threshold

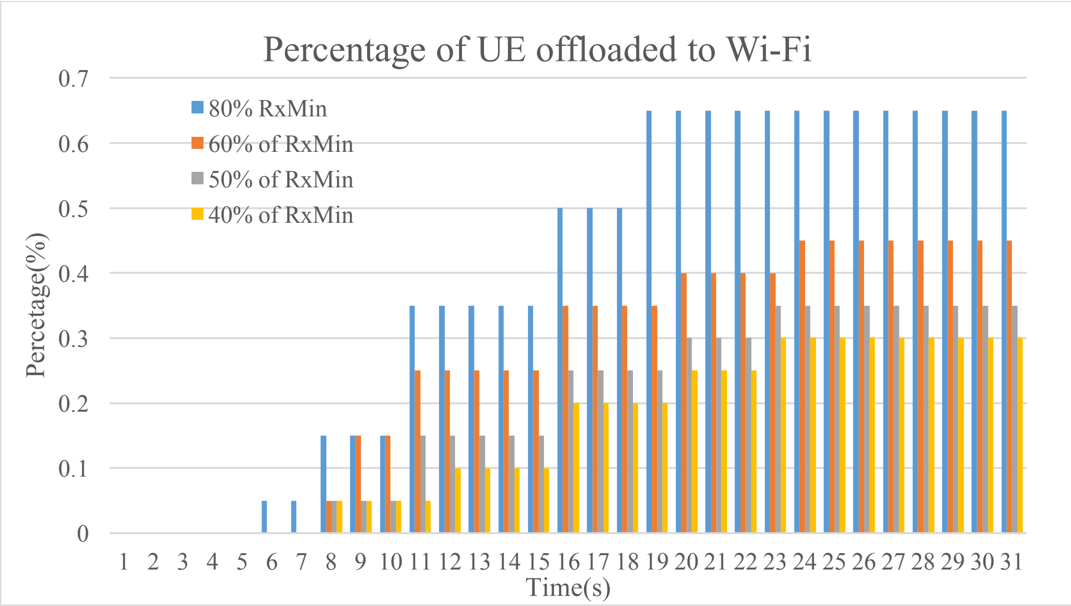

Figure 3. 18 The percentage of UE roaming to Wi-Fi

In this subsection, we evaluate the performance of proposed scheme by varying the received signal threshold. As shown in Figure 3.18, the signal threshold affects the number of users offloaded to Wi-Fi. When we set the received signal strength threshold for network discovery is 80% of minimum signal strength, it allows more macro-cell users roaming to Wi-Fi. Conversely, when the signal threshold is stronger, it limits the number of macro-cell user roaming to Wi-Fi. The weaker the signal strength threshold the more users will be offloaded to Wi-Fi. The mobile node is allowed to roam to Wi-Fi only if it found an AP candidate that satisfies the signal strength threshold. Therefore, during the simulation, the mobile nodes move toward the AP's coverage area, the number of users roaming to Wi-Fi is increasing accordingly. The signal strength threshold can be used by the network operators to control the percentage of macro-cell mobile nodes roaming to Wi-Fi. For example, when the macro-cell load is low while the load of access point is high, the mobile operator can adjust this threshold to reduce the number of mobile nodes roaming to Wi-Fi to prevent network congestion. In vice versa, when load of macro cell is high while the AP's load is low enough, the operators can decrease the signal strength threshold to encourage more users roaming to Wi-Fi.

3.8.7. The influence of the load threshold

In this subsection we evaluate the influence of the load threshold in our proposed scheme. It is obvious that the load threshold affects the number of mobile devices that allow to roam to Wi-Fi. The higher load threshold, the more AP candidates are satisfied for Wi-Fi selection. In this sense the load threshold is similar to signal strength threshold that we evaluated earlier. In this subsection, we vary the load threshold in our proposed scheme to see how it affects the system throughput.

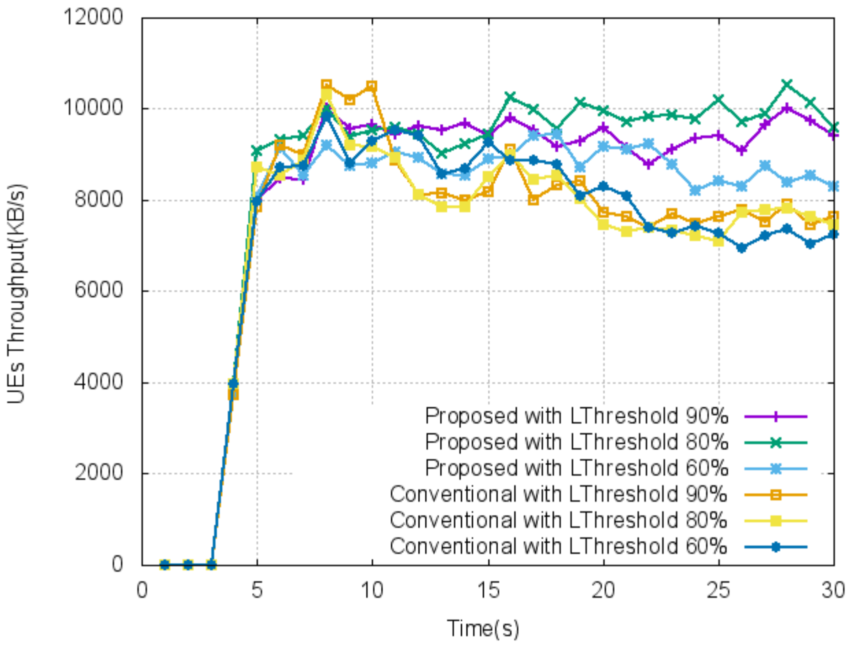

Figure 3. 19 The comparison system throughput when varying the load threshold

Figure 3.19 shows that when the load threshold is higher, more mobile nodes can roam to Wi-Fi. However, due to the fact that when the density of UE is getting higher, it can increase the contentions among UEs, which are served by the same AP at the same channel. These contentions result in negative effect that decreases the throughput of all mobile nodes sharing the same resource from the AP. Figure 3.19 shows that the system throughput when setting the load threshold to 90% is less than 80%. This declining tendency of overall system throughput when the mobile node's density gradually increases is caused by the contentions of UEs. In addition, we notice that when we decrease the load threshold to 60%, the system throughput also decreases accordingly. This results from the fact that the lower the load threshold, the less UEs roaming to Wi-Fi. This will decrease the utilization degree of Wi-Fi APs. Therefore, there is a correlation between the number of UEs and APs for maximizing per-UE's throughput and it is important to define a proper load threshold.

The load threshold affects the number of UEs that can roam to Wi-Fi in our proposed scheme. In Figure 3.19, the proposed scheme outperforms the conventional scheme when varying the load threshold. The proposed scheme allows the UEs to select preferable access point when they are on the move. Especially, when density of the UEs gradually increases on each AP, the proposed scheme can effectively optimize overall system throughput while the system throughput become saturated in conventional scheme. In the conventional scheme, the system throughput is less fluctuating when varying the load threshold limiting the number of Wi-Fi roaming UEs. By considering the load condition of AP, the proposed scheme outperforms the conventional scheme in both higher and lower UE density condition.

3.9. Conclusion.

In this chapter, we proposed a novel Wi-Fi roaming selection scheme for cellular data offloading. In our proposed scheme, we utilized the channel load metric, which is defined in IEEE802.11k as well as IEEE 802.11u for the proposed scheme. As far as we concerned, this channel load has not been considered in any related work. We defined a new metric, APQI, which was used to rank AP candidates based on their channel load status and signal strength. In addition, we utilized a series of signal level and AP load thresholds to eliminate unqualified candidates, which reduce the processing time and reduce unnecessary delay. We proposed to append signal strength threshold into the ANDSF OM WLANSP leaf so that UEs can easily obtain this information from ANDSF entity for network selection. In addition, we also considered the practical implementation of our proposed scheme. Therefore, we reviewed the state of the art in 3GPP and IEEE and developed our scheme based on the ratified IEEE 802.11 k, u [11, 22]and 3GPP TS 23.312 [9] standard so that it can be applicable in future wireless network. We also introduced our simulation model of ANDSF and vertical handover. Unlike previous related work, our simulation model is an end-to-end model from application to physical layer. We took into account user's mobility and realistic traffic model. During the simulation process, the ANDSF entity and the UE's connection manager entities behave and interact corresponding to real-time network events. By using this simulation model, we evaluated the proposed scheme in a typical heterogeneous network scenario with interworking macro-cell (WiMAX) and Wi-Fi.

Through our simulation, we demonstrated how the proposed scheme performs in a typical HetNet scenario with Wi-Fi APs and macro-cells. The result showed that our proposed scheme dynamically steered the UE's traffic from macro-cell and distributed to available Wi-Fi APs. As the result, both the overall system throughput and the utilization of available Wi-Fi APs were improved. We also extensively evaluated the performance of the proposed scheme when vary the received signal strength and the load thresholds. The received signal strength threshold affects the number of mobile nodes roaming to Wi-Fi. The lower the load threshold, the more number of macro-cell users can roam to Wi-Fi. The operators can adjust the receive signal strength to manage the percentage of macro-cell UEs roaming to Wi-Fi based on the load condition of macro-cell and Wi-Fi. The load threshold also has the same influence in term of controlling the number of UEs roaming to Wi-Fi. However, while the received signal strength threshold limits the mobile user access by the distance to the APs, the load threshold constrains the mobile node roaming to Wi-Fi by the load condition of AP. We also noticed there is a correlation between the number of mobile nodes and APs affecting the throughput performance. The load threshold and received signal threshold are the effective tools for network operators to control traffic going through macro-cell and Wi-Fi APs. The optimal values for these thresholds depends on the correlation between the number of UEs and APs as well as specific network condition and application. This issue is not in the scope of this thesis. We will consider it in our future work.

Finally, although we observed better user's experienced throughput compared to conventional scheme, the proposed scheme also increases the frequency of handover between Wi-Fi APs, which is not favorable for end-user. This is resulted from the fact that the proposed scheme allows the UEs selecting the most relevant APs in term of load condition and distances, which results in throughput improvement. When the mobile nodes move to new location, their optimal point of service also changes. This tradeoff between throughput improvement and number of handover will be considered in the next chapter.

Chapter 4

A Quality of Service Aware Handover Decision Scheme for Cellular Wi-Fi Offloading

4.1. Introduction

In the previous chapter, we proposed a Wi-Fi and cellular roaming decision and selection scheme for Wi-Fi Offloading. The proposed scheme is a network-assisted user driven mode in which the mobile node controls when and where to make handover decision based on the information from network (ANDSF's policies) and measured network condition information (Received Signal Strength or RSS and AP's channel load). The proposed scheme's performance was compared to that of conventional Wi-Fi selection scheme (Wi-Fi if covers and RSS based, which is used in most of nowadays smart devices) utilized in popular smart devices. The simulation result showed that our proposed scheme dynamically steered the UE's traffic from macro-cell and distributed to available Wi-Fi APs. As the result, both the overall system throughput and the utilization ratio of Wi-Fi APs were improved. The system throughput or per-UE's throughput was also increased accordingly. However, as we pointed out, there was a shortcoming in the previous work, which is originated from the fact that the scheme was designed for optimizing the overall system throughput or per UE. It increases the number of handover between access point in order to enhance individual UE's throughput when they are on the move. In the previous chapter, we assumed that the UEs always demanded for higher throughput. However, that is not necessary true in realistic scenario because the UE's requested throughput might vary from time to time. Obviously, it is not necessary to handover to the AP candidate if it cannot satisfy user's requested throughput. We consider this is unnecessary handover. In this chapter, in order to reduce the number of unnecessary handover, we consider the remaining throughput of the AP candidate and requested data rate of UE for the Wi-Fi AP selection decision scheme.

As far as we concerned, one of primary goals of future wireless network is to always satisfy user with on-demand traffic request rather than providing the highest throughput, it will make an impression of unlimited network resource to end-user and ease the burden of network operators at the same time. It is obvious that average user does not care about which access network is using as long as it can provide the desired quality of service. Considering the QoS for network selection is required to achieve this main goal of wireless network, which allows users to profit from always best connected (ABC) service.

In this chapter, we consider the user's QoS preference in the AP selection procedure. We utilize the requested data rate and remaining resource from the network for enhancing our previous proposed scheme. We first propose a simple method to estimate effective throughput or remaining bandwidth of a Wi-Fi AP prior to selection decision phase. In our estimation method, we employ the real-time channel utilization metric (specified in IEEE 802.11u, k [22] standards) to estimate the remaining throughput. The proposed Wi-Fi AP throughput estimation method was presented in [39]. Subsequently, we extensively evaluate the robust of proposed estimation method in case of non-occupied and full-occupied load condition of AP because the AP's resource allocation scheme behaves differently in these cases. Subsequently, the estimated remaining throughput of AP is adopted in the proposed scheme in previous chapter. In this chapter, we also conduct extensive simulation and analysis to evaluate the performance of the new proposed scheme and compare with that of proposed scheme in chapter 3.

4.2. Proposed Wi-Fi AP Throughput Estimation Method

In our new proposed scheme, the key issue is how to estimate the available bandwidth of AP before making Wi-Fi selection. The available Wi-Fi AP channel result is equal to the subtraction of total capacity and the total traffic load on that channel [38]. When the modulation and coding scheme are specified (determined by the signal strength from the node to the base station), we can estimate the total throughput of the AP. Therefore, the key idea of Wi-Fi throughput estimation is to obtain the utilization information of the channel and distribute this information to mobile node so that the mobile node can calculate the remaining throughput by itself. In this section, we develop our throughput estimation method by using an available element so called channel load or channel utilization in IEEE 802.11u AP beacon message [22]. The channel load element is described in detail in the previous chapter.

4.2.1. Estimation of Available Bandwidth of Wi-Fi AP

As far as we concerned, there are 2 main multiple access methods defined in IEEE 802.11 MAC: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). However, in the scope of this study, we only consider DCF due to its popularity. The DCF is the multiple access scheduling mechanism based on the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). In our proposed method, we assume that Wi-Fi AP's throughput is mainly influenced by the number of active Wi-Fi UEs (generating traffic), which utilize the common frequency band and the behaviour of Wi-Fi multiple access scheme (CSMA/CA) [35]. Our proposed method of estimating available bandwidth is described in following steps:

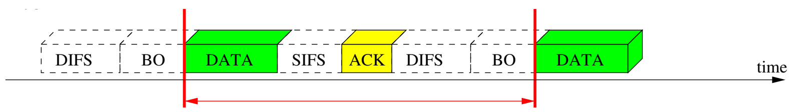

Figure 4. 1 DIF frame cycle

Step1: calculate the maximum theoretical throughput of AP, *MT,* which is referred from [35]. Figure 4.1 shows the example of a DCF cycle.

$$T_{DCF} = T_{DIFS} + T_B + T_{Data} + T_{SIFS} + T_{ACK} \quad (4.1)$$

$$MT = \frac{T_{data\_payload}}{T_{DCF}} = \frac{8.L_{data\_payload}}{T_{DIFS} + \frac{CW_{min}.T_{slot}}{2} + 2T_{PRE} + 2T_{PHY} + T_{OFDM}\left(\frac{22+8(L_{data\_payload}+L_{MAC\_overhead})}{N_{DBPS}}\right) + T_{SIFS} + T_{OFDM}\left(\frac{22+8L_{ACK\_frame}}{N_{DBPS}}\right)}$$

(4.2)

T_{DCF} is the transmission cycle of DCF (T_{DCF}); consists of DIFS time (T_{DIFS}), back-off time (T_B), data transmission time (T_{Data}), SIFS time (T_{SIFS}) and ACK transmission time (T_{ACK}). In equation (4.2), all of parameters are IEEE802.11 MAC layers specified except N_{DBPS} (Number of Bit per OFDM symbol) and $L_{data\_payload}$ (Length of Data Payload). For example, for IEEE802.11a, the MT can be calculated using (4.3). Therefore, the maximum theoretical throughput of IEEE 802.11a depends on the payload length or the average size of data packets and the modulation scheme used at the physical layer.

$$MT = \frac{8.L_{data\_payload}}{157.5 + 4\left(\frac{246+8L_{MAC\_overhead}}{N_{DBPS}}\right) + 4\frac{134}{N_{DBPS}}} \quad (4.3)$$

Step2: Calculate the available throughput *MT*

$$avT = \alpha.MT.(1-C_{load}) \qquad if\ C_{load} < 1. \quad (4.4)$$

$$avT = \frac{\alpha.MT}{N+1} \qquad if\ C_{load} = 1. \quad (4.5)$$

$0 < \alpha <= 1$, α is the adjustment coefficient for effective maximum throughput when considering the delay time and packets loss and retransmission. C_{load} is the normalized channel Utilization U_c [22], $C_{load} = \frac{U_c}{255}$. N is the total number of Wi-Fi devices associating with the AP. The available bandwidth of a link connection equals to subtraction of total channel capacity and the current traffic load over that channel. Therefore, we use equation

(4.4) to calculate the remaining throughput when the channel bandwidth is not saturated, which is the remaining of the bandwidth resource. However, when the channel is saturated ($C_{load}=1$), the associating Wi-Fi UEs will evenly share the whole channel resource of the AP [35]. Therefore, the estimated throughput can be calculated using Equation (4.5); the estimated throughput equals to the maximum bandwidth divided by the number of total associating UEs plus itself.

4.2.2. Evaluation of Proposed Throughput Estimation Method.

To evaluate the proposed available throughput estimation method, we have made a simulation model using the simulation software NCTUns 6.0 (shown in Figure 4.2). In our model, there are 5 UEs and 1 IEEE 80211a Wi-Fi AP and the simulation parameters are listed in Table 4.1. The UEs send UDP traffic to the corresponding node (CN). The UE1, 2, 4, 5 are active mobile node generating traffic while UE3 is in charge of estimating the available channel throughput using our proposed method. We evaluate the proposal method when the radio channel is in both non-saturated and saturated conditions.

We conduct two consecutive simulations to evaluate the proposed method. In the first run, the UE3 pays role as a dummy node, which does not send any traffic to the CN. However, it estimates the available bandwidth of the AP using the proposed method during the simulation. We refer the UE3's throughput in this case as estimated throughput. The second run, with same simulation parameters, the UE3 sends greedy UDP traffic toward CN. The throughput of UE3 is measured and compared to the estimated through in the former one. The all of parameters are kept identical so that the throughput of U1, 2, 4, 5 are the same and consistent in both cases. The Figure 4.3 shows the comparison of estimated and real throughputs when the channel resource is not saturated while Figure 4.3 shows the throughput comparison when the channel is in saturated condition. Table 4.2 and 4.3 show the root-mean-square error (RMSE) of the real and estimated throughput values using the proposed reference methods in [35]. The root mean square comparison shows the estimation error of proposed method is substantially lower than that of proposed one in non-saturated condition. In saturated channel condition, the proposed method shows the same result as the equal method. The simulation result shows our estimation method can achieve better estimation error both in non-saturated. In the next session, we use this method to estimate the remaining data rate of AP candidates to enhance Wi-Fi roaming decision and selection scheme.

We notice that Wi-Fi throughput is mainly affected by the average number of contending users and the packet size. Per-user Wi-Fi throughput is less fluctuated when Wi-Fi AP capacity is not saturated. As the AP reaches its maximum capacity, the throughput decrement tendency caused by the number of contentions, and the collision between UEs becoming more intensive. Hence, the per-user and network Wi-Fi throughput decreases and unstable in a high traffic load condition.

$$RMSE = \left(\frac{\sum_{i=1}^{N} (EMT_i - MMT_i)^2}{N} \right)^{1/2} \tag{4.6}$$

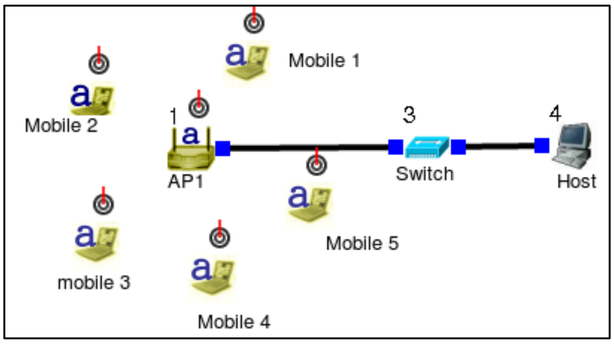

Figure 4. 2 Simulation five mobile nodes (Setup with STA), 1 IEEE802.11a AP

Table 4. 1 Simulation Parameters for proposed method evaluation

	Parameter
Technology	IEEE 802.11a
Coverage	50 m
RX Thresh	-82 dBm
Transmit Power	16.02 dBm
Bandwidth/QoS	12Mb/s
Modulation scheme	OFDM 16QAM
Carrier frequency	5 GHz

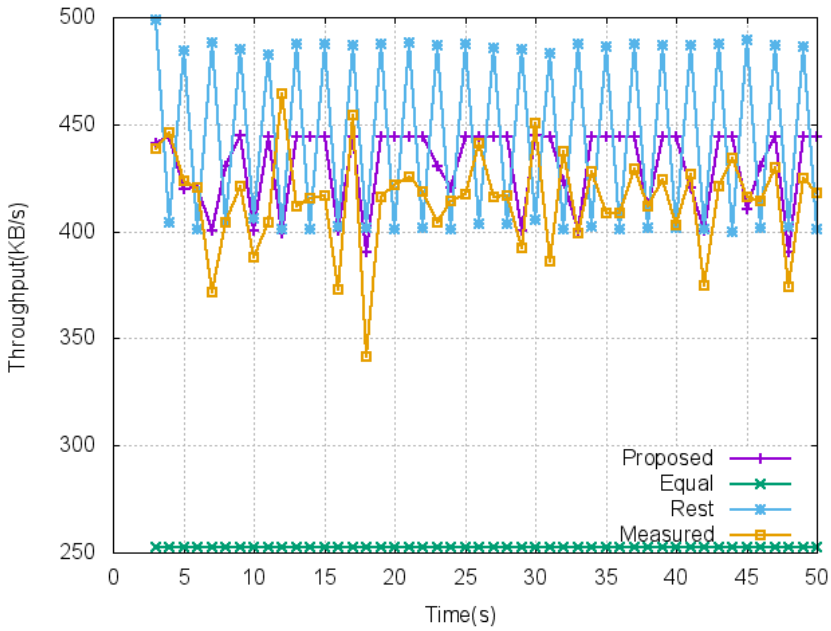

Figure 4. 3 Estimated VS Real throughput for mobile UE3 in non-saturated channel.

Table 4. 2 RSME Comparison of Proposed Method, reference methods in non-saturated condition

Method	**RSME**
Proposed Method	30.49
Equal Method	163.32
Rest Method	42.55

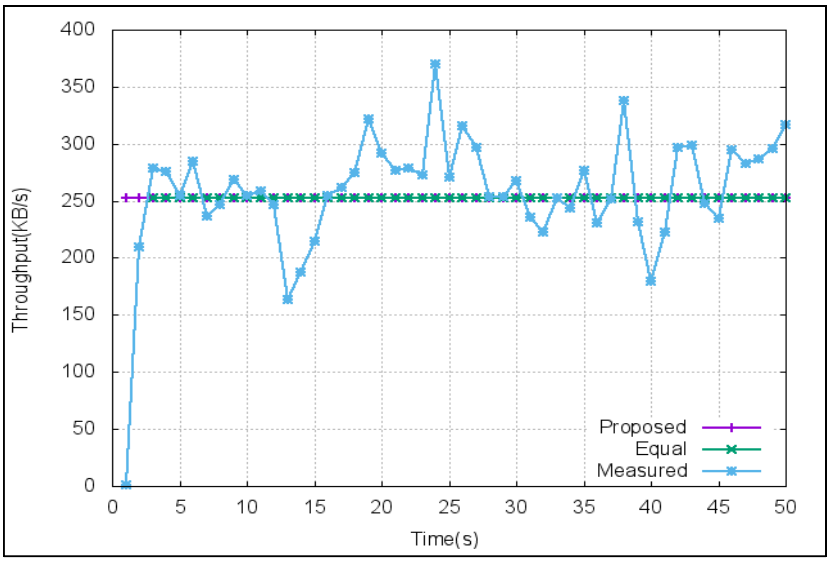

Figure 4. 4 Estimated VS Measured Throughput for mobile 3 in saturated channel.

Table 4. 3 RSME Comparison of Proposed Method, reference methods in saturated condition

Method	**RSME**
Proposed Method	37.88
Equal Method	37.88

4.3. New Proposed Scheme Description

In the previous chapter, the main objective of our proposed scheme is to help the UE select the most preferable Wi-Fi AP. In the acquiring data phase, the UE employs operator's selection policies from ANDSF entity to get the list of available access network. This information is used to facilitate the discovery of available legitimate access network and point of services. The UE can turn on available wireless interface to detect whether the AP candidates are in the range. This verifies the operators' policies and obtains RSS and channel load metrics in real-time because the operators' policy may be out of date and network condition can dynamically change from time to time.

For making an effective Wi-Fi selection decision, it is necessary to make sure the condition of the target networks be good enough to maintain acceptable level QoE. This can be done by setting suitable thresholds. In the previous proposed scheme, we already proposed to use received signal strength and the AP's load thresholds to pre-eliminate unsuitable AP candidates. The RSS and channel load thresholds could be set by network operators to control the load limit of AP and assure a certain level of QoS for each UE.

In this chapter, for considering end-user's on-demand QoS, it is necessary to make sure the condition of the target network good enough to satisfy end-user's on-demand QoS. we further enhance the previous proposed scheme in the previous chapter considering end-user's preference QoS namely, requested data rate because data rate is a primary metric when evaluating data service quality. Throughout the evolution of wireless technology, it is evident that the primary goal is to increase the capacity and data rate so that the network can carry more data on the same frequency band.

Table 4. 4 Throughput requirement for different service

Service	Required Throughput(kbps)
VoIP	64
E-mail, browsing	>512
Video Conferencing	174-320
Interactive gaming	85
Data	1000
Media stream	512
Video Streaming	2048
Peer-to-peer	500

Furthermore, each end-user's application might have different data rate requirement and it might vary from time to time and it is unnecessary to handover to the candidate AP if it could not satisfy user's desired throughput. For example, video streaming service requires 2Mbps data rate; VoIP requires 64Kbps for acceptable conversation quality etc. Therefore, in order to consider data throughput requirement and the remaining resource of AP candidate, in our new proposed scheme, we propose a new method, which allows the UE to estimate the available bandwidth of AP candidate prior to making selection decision. In case of the user's application requesting for a certain throughput requirement, the estimated available bandwidth of AP candidate must satisfy requested throughput. Otherwise, it should be filter out from the selection process.

Our new proposed scheme flow chart is shown in Figure 4.5.

STEP 1: The user's applications can explicitly request for a desirable data rate for running service. For example, video streaming service requires 2Mbps data rate; VoIP requires 64Kbps for acceptable conversation quality [34]. If the desired data rate is not set, the previous proposed scheme will be applied in selection decision procedure in step 6.

STEP 2: The CM monitors the QoS of current connection. If the QoS is degrading (the load of active connection exceeds allowed threshold, current connection no longer sustains the desired data rate) or running application requests for higher throughput, it will trigger the process to find alternative point of service.

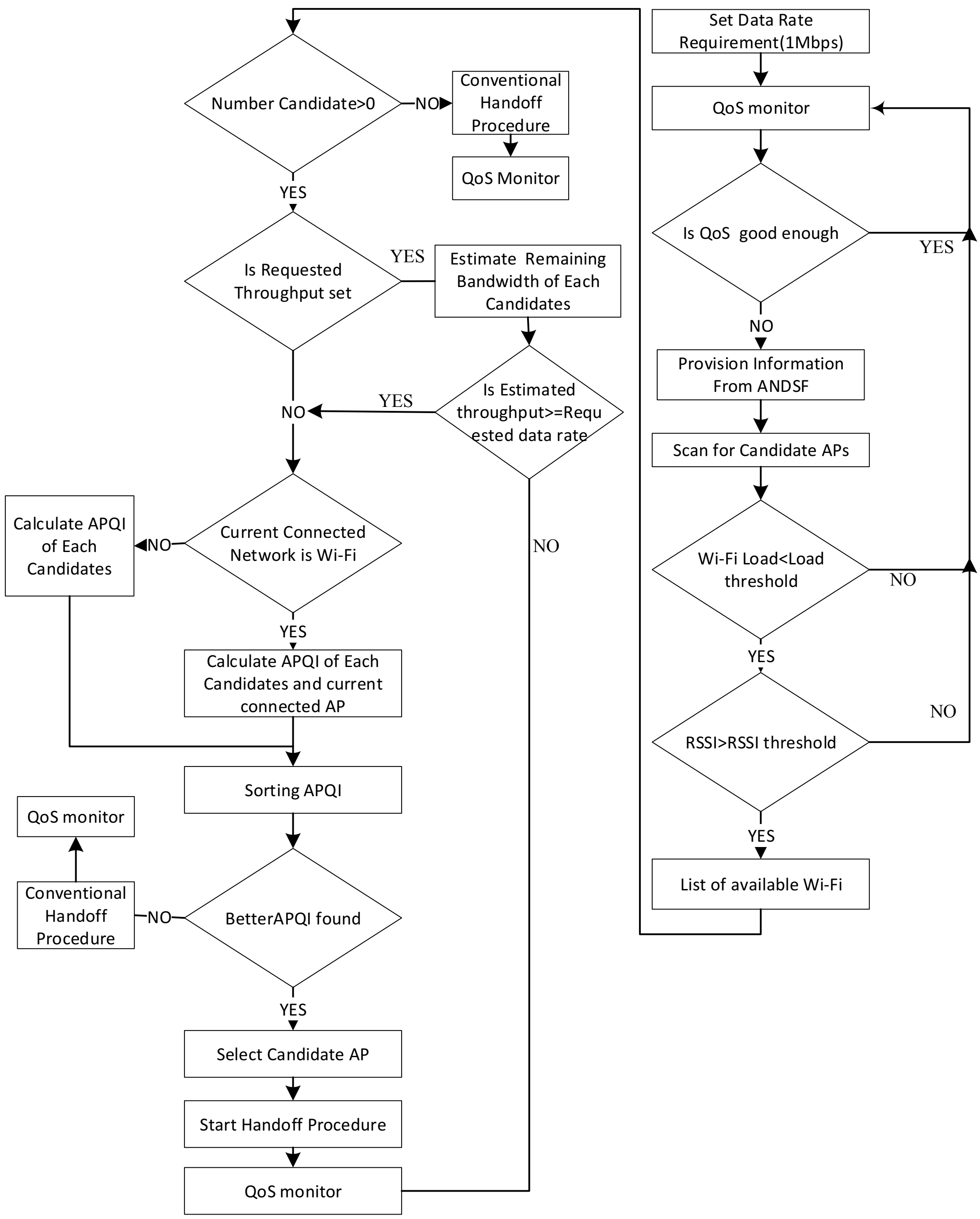

Figure 4. 5 Proposed Network Monitor and Wi-Fi Selection Scheme.

STEP 3: The CM contacts the ANDSF entity to fetch the list of legitimate Wi-Fi AP and selection rule corresponding to UE's location (Cell-ID of macro cell, or SSID or GPS location if any applicable). The ANDSF entity returns the list of AP candidates that can be accessible from the UE's location. At the same time, the channel load threshold and signal strength threshold (*MaximumBSSLoadValue*, *MinimumBSSRSSValue)* thresholds are also obtained.

STEP 4: Discovery process: the physical layer scans the surrounding to see whether the AP candidates are available or not. Although ANDSF's information indicates available access network and point of service, it may get out of date or the candidate is unreachable from UE's location. Therefore, by activating the corresponding interface and scanning, the CM eliminates unreachable AP and obtains necessary information of AP candidates, namely the received signal strength, load condition.

STEP 5: The candidates, which do not satisfy the load and RSS thresholds (*MaximumBSSLoadValue, MinimumBSSRSSValue*), are eliminated in this step. As aforementioned, we introduce the load and RSS thresholds in order to pre-eliminate far away or potentially overloaded AP and control the number of UEs can roam to Wi-Fi network.

STEP 6: If there is no qualified AP candidate in step 5, the UE will stay at the current point of service. The UE might conduct the conventional homogenous handover procedure if it is applicable. However, if these are qualified AP candidates available and desired data rate is set, the UE will calculate the available throughput of each AP candidate. The candidates are filtered by their estimated available bandwidth and the one that satisfy the requested data rate will be sent to next step for consideration as described in previous chapter. Otherwise, if the requested data rate is not set, the previous proposed selection procedure is applied to select preferable AP candidate. As described in chapter 3, the CM calculates our defined metric Access Point Quality Indicator (APQI) metric for each AP candidates. If the current connection is Wi-Fi, it will calculate APQI of the associated AP. The AP with highest APQI is selected as the candidate for Wi-Fi roaming. After deciding the preferable AP, the CM starts the handover procedure to selected AP candidate.

STEP 7: if there is no better point of service, the UE will stay at the current network and perform conventional network handover (if it is applicable). The CM returns to step one.

The pseudo code for our proposed scheme is shown as follows:

Algorithm Roaming decision and preferable AP selection

Input: the parameters: *RSS, RSS_Min, Channel_load*, *MaximumBSSLoadValue*, *MinimumBSSRSSValue,* w_r, w_l, *Requested_Data_Rate*.

Output: AP candidate.

1. **While** (*1*)**do {**

2.**if** QoS degrading trigger or new QoS level is requested **then**

3.Obtain information from ANDSF entity

a. Obtain AP candidates Information (SSID, operating channel)

b. Obtain Load and RSS thresholds *MaximumBSSLoadValue*, *MinimumBSSRSSValue*

4. *qualified_AP_List=nil;*

for *each* AP_i **in** *AP candidate List{*

a. Obtain information of available AP_i information from physical Layer,

b. Obtain RSS_i, calculate $\overline{RSS_i}$

c. Obtain $channel\_load_i$ information.

d. **if** $\overline{RSS_i}$ *>MinimumBSSRSSValue &&* $channel\_load_i$ < *MaximumBSSLoadValue* ***then*** *qualified_AP_List add* AP_i

}

If *qualified_AP_List is empty* ***then*** *return;*

If *Requested_Data_Rate is not nil* ***then***

// requested data rate is set, selection based on available bandwidth

for *each* AP_i **in** *AP candidate qualified_AP_List{*

calculate $AP_i -> EstimatedAvailableBW$ *;*

if(*Requested_Data_Rate>* $AP_i -> EstimatedAvailableBW$ *)* ***then*** *qualified_AP_List remove* AP_i*;*

}

}else{

//requested data rate is not set, previous proposed method is applied

5. *Candidate_AP->APQI= calculate* $APQI_1$ *[3.4];*

for *each* AP_i **in** *AP candidate qualified_AP_List{*

calculate $APQI_i$ *using [3.4];*

if AP_i*->APQI> Candidate_AP->APQI* ***then*** Candidate_AP= AP_i;

}

}

6. if *Candidate_AP*!=nil *and Candidate_AP !=current AP* ***then***

return Candidate_AP;

}

4.4.Simulation Setup

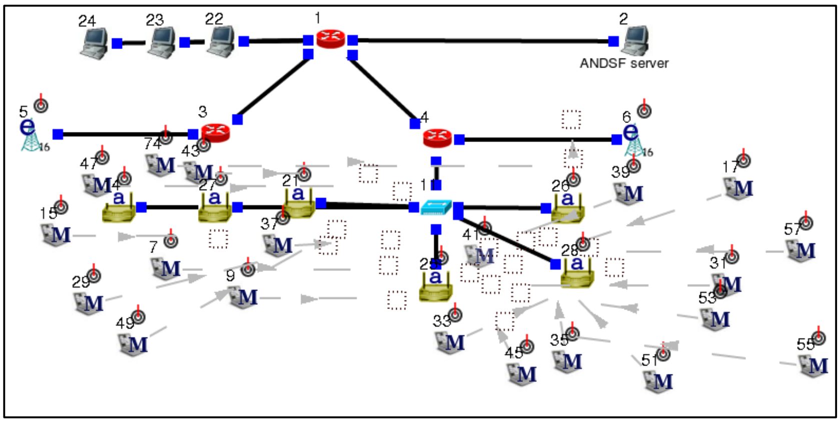

Figure 4. 6 Simulation Setup.

Table 4. 5 Simulation Parameter

WIMAX		**Wi-Fi**
Technology	IEEE802.16e	IEEE 802.11a
Coverage	1000 m	50 m
RX Thresh	-96 dBm	-82 dBm
Transmit Power	35 dBm	16.02 dBm
Bandwidth/QoS	5Mb/s	6Mb/s
Modulation scheme	OFDM 16QAM	OFDM 16QAM
Carrier frequency	2.3 GHz	5 GHz
channelUtilizationBeaconIntervals		10
BS Number	2	6
Propagation channel	Two-ray ground	Two-ray ground
Channel Load threshold	NA	0.8
	MS	
Node number	20	
Mobility movement	Straight line	
Multiple interface	WIMAX and Wi-Fi	
WiMAX Maximum guaranteed data rate	1000KB/s	
Wi-Fi Maximum data rate	6Mb/s	
Speed	0-5 m/s	
Traffic parameter	Greedy CBR 0-2Mbps	
Miscellaneous		
Channel load broadcast interval	100 ms	
Simulation time	30s	

Our simulation model setup is shown in Figure 4.6 and the simulation parameters are listed in Table.4.5. In this chapter, we use the simulation model described in previous chapter. Our system model includes two IEEE 802.16e BS 1, 2 (Node 5, 6), six 802.11a Wi-Fi AP1, 2, 3, 4, 5, 6 (Node 14, 21, 25, 26, 27, 28) and 20 UEs equipped with both WiMAX and Wi-Fi 802.11a air interfaces. The Wi-Fi APs are under the coverage of WiMAX Base Stations (BS) and overlapped Wi-Fi APs. We consider the typical movement patterns of UEs when they move from the coverage of macro-cell toward Wi-Fi available area. We evaluate the case when the density of UE gradually increases around Wi-Fi APs. All of the UEs have a CM application using our proposed scheme managing their connectivity. The ANDSF server (Node2) resides at network side and can be reachable by all of UEs.

4.5.Numerical Result and Discussion.

We evaluated the performance of the new proposed Wi-Fi AP selection scheme in the heterogeneous network model described above. We compared our proposed scheme with two references:

- **The previous proposed scheme:** Wi-Fi AP selection based on ANDSF's policy, AP channel load and received signal strength.
- **The conventional Wi-Fi selection scheme:** network-independent user-centric selection policy. In this scheme, Wi-Fi always has the higher priority than cellular and Wi-Fi selection is based on RSS/SINR. This scheme is simple and relatively effective in homogeneous network that makes it widely adopted in most of existing smart devices.

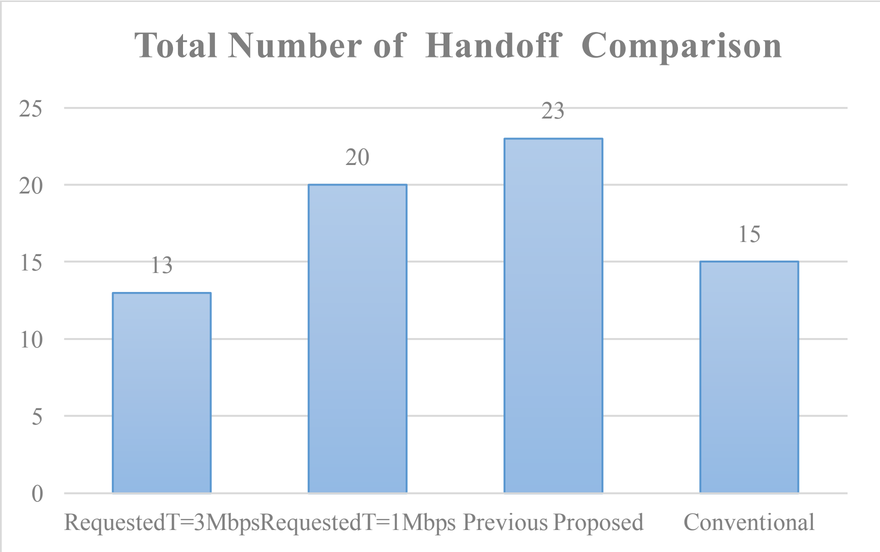

Figure 4. 7 Number of UEs transferred to Wi-Fi.

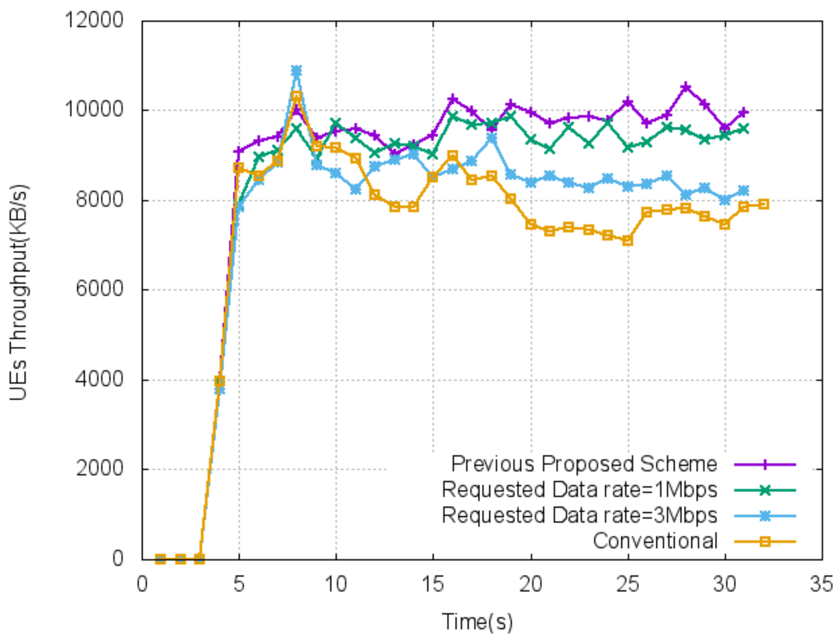

Figure 4. 8 UEs Throughput comparison between proposed method, previous proposed method, conventional scheme.

We consider the typical movement pattern of UEs when they move from the coverage of WiMAX toward Wi-Fi AP triggering Wi-Fi AP selection process. The density of UEs surrounding each Wi-Fi AP increases by time when UEs move toward them. We evaluate the performance of each method in the condition when the density of UE gradually increases around Wi-Fi APs.

At the beginning, the UEs are connected via WiMAX BSs;

At T=4 (s), The UEs start sending CBR (Constant Bit Rate) toward the Correspondent Node (CN), (Node 23, 24, 25 in Figure 4.6). Figure 4.6 shows the traffic of UEs increasing at T=4 (s). After that the CM of UEs fetch policies from ANDSF, which contains AP candidates list, signal strength and AP's load thresholds corresponding to UEs location. Afterward, the UEs scan the surrounding area to obtain the channel load and RSS of each AP candidate. The AP candidates are evaluated based on their channel load and the received signal strength metrics. Only APs, which satisfy the load threshold and the signal strength threshold, are considered in the next selection steps.

If the requested data rate is not set (in the first reference scheme), The CM of UEs calculate the APQI property of each AP, which is proposed in our previous chapter. The AP candidates are sorted by APQI metric and the highest APQI AP candidate is selected as AP candidate.

If the requested data rate is set, the CM of UEs will estimate the remaining data rate of each AP's candidate using Equation (4.4, 4.5). The CM selects the AP, which can offer the highest remaining throughput and satisfy requested data rate.

The requested data rate is user's preference and depended on required QoS of User application profile. In our simulation, we consider 4 cases:

- Case 1: we set the requested data rate as 1Mbps for low quality video streaming service, which is substantially lower than the maximum capacity of the AP.
- Case 2: we set the requested data rate as 3Mbps for high quality video streaming service.
- Case 3: The previous method in chapter 3.

- Case 4: Conventional user-centric Wi-Fi selection scheme.

The performance metrics are the total number of Wi-Fi handover and the system throughput.

Figure 4.7 shows the total number of cellular UEs that are offloaded to Wi-Fi during the simulation. The numerical results show that the conventional user-centric Wi-Fi selection scheme (case 4) has the worst performance in term of system throughput. As we notice, the new proposed scheme reduces the number of UEs that handover to Wi-Fi when set the requested throughput for each UE as 3Mbps. In this throughput based decision scheme, the proposed scheme takes into account a predefined data rate threshold, the UE selects the AP candidate that can satisfy its required data rate.

As we pointed out in previous section, the throughput of Wi-Fi AP is depended on the number of active associating UE. The higher number of associating UE can result in lower and unstable data throughput because the contention increases. Therefore, high number of UEs per AP may yield low bit rate per UE when AP's capacity is saturated. In such situation, it is preferable to limit the number of UE roaming to Wi-Fi.

Figure 4.8 show that the proposed scheme with 3Mbps requested data rate (case 2) outperformed the conventional (case 4) and previous proposed scheme (case 3) in term of reducing unnecessary vertical handover to Wi-Fi AP. The prior proposed scheme had the highest number of Wi-Fi handover because the UE constantly calculates and handovers to optimal AP candidate while it is on the move. Therefore, the UEs are dynamically transferred to preferable Wi-Fi APs when they are moving. However, the new proposed scheme considers user's on-demand throughput preference, it prevents UEs from selecting unfavorable AP candidate, which potentially could not sustain requested data rate. The higher the requested data rate is set, the less number of users can transfer to Wi-Fi AP.

The system throughput performance in case 2 is better than that of case 1 because with lower requested data rate more UE can transfer to Wi-Fi APs. The previous proposed scheme has the best performance in term of total system throughput because it does not limit the number of UEs roaming to Wi-Fi.

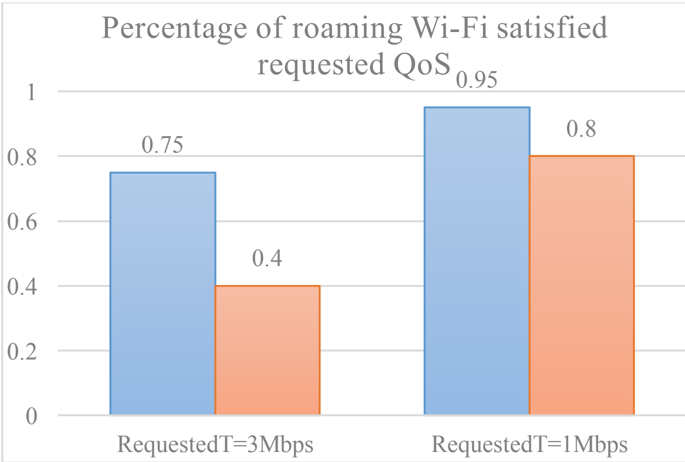

Figure 4. 9 The percentage of QoS satisfied UEs comparison between proposed scheme and the conventional scheme

We call the mobile node, which performs Wi-Fi roaming and experiences the data rate higher or equal to the requested data throughput as a satisfied Wi-Fi roaming UE. Figure 4.9 shows the comparison of the percentage of satisfied Wi-Fi roaming UE between the proposed scheme and the conventional one. When setting the number of requested throughput to 3Mbps, the percentage of satisfied UE is 35% higher than that of the conventional scheme. The reason is that the number of Wi-Fi offloaded UEs is higher in the conventional scheme. Since the Wi-Fi throughput is influenced by the number of mobile node sharing the same channel, the throughput becomes lower. Therefore, the percentage of UEs experiencing 3Mbps requested data rate is smaller. However, when the requested data rate is set to 1Mbps, more Wi-Fi offloaded UEs experience higher or equal to this data rate requirement. Therefore, the percentage of satisfied UE is higher than the former case. The proposed scheme achieves 15% higher than the conventional scheme.

The simulation result showed that the requested throughput effects the number of UE offloading to Wi-Fi. If the UE sets requested throughput to substantially high value, it will reduce the chance of offloading to Wi-Fi. Conversely, if the UE requests low data rate, it will increase the chance roaming to Wi-Fi network. As the result, the number of UE offloaded to Wi-Fi increases accordingly. It is worth noting that in the scope of this research, due to the limitation of the simulation software, we can only uniformly set the requested throughput to a specific value; that means all of UE always request for the same throughput value. Because the requested throughput can be autonomously decided by UEs, we need to randomize the requested data rate for each UE. This issue will be considered in our future work.

4.6.Conclusion.

In chapter, at first, we proposed a novel method to estimate remaining throughput of AP prior to association operation. The estimated remaining throughput of AP was used in the previous proposed Wi-Fi roaming and selection scheme. We assumed that UE can request different data throughput based on application. By considering UE's requested data rate, we could enhance AP selection decision in term of reducing number of Wi-Fi AP handover. By considering data rate threshold, the proposed scheme prevented UEs from selecting undesirable AP candidates, which could be unable to satisfy end-user's on-demand data rate. As the result, the unnecessary handover number was reduced. Our simulation results showed that the UEs throughput increased with a relevant UE's requested data rate value and reduce the number of Wi-Fi AP at the same time. It also showed that the requested data rate value set by UE could affect its chance to offload to Wi-Fi. Therefore, it affects the number of UE offloading to Wi-Fi as well as overall system performance and stability. This could be addressed by introducing some form of data rate negotiation and admission control. We will further consider this issue in our future work.

Chapter 5

Conclusion and Scope of the Future Work

5.1. Conclusion

In this thesis, we proposed novel cellular Wi-Fi roaming selection scheme for cellular data offloading in chapter 3. We utilized the channel load metric first defined in IEEE802.11k as well as IEEE 802.11u. As far as we concerned, this channel load has not been considered in any related work. We also defined a new metric, APQI, which was used to rank AP candidates based on their channel load status and signal strength. In addition, we utilized a series of signal level and AP load thresholds to eliminate unqualified candidates, which reduce the processing time and reduce unnecessary delay. For practical implementation of the proposed scheme, we extensively reviewed the state of the art in 3GPP and IEEE and developed our scheme based on the ratified IEEE and 3GPP standards so that it can be applicable in future wireless network. In this thesis, we also introduced our simulation model of ANDSF and vertical handover. Unlike related works, our simulation model is an end-to-end model from application to physical layer. We took into account user's mobility and realistic traffic model. During the simulation process, the ANDSF entity and the UE's connection manager entities behave and interact corresponding to real-time network events. By using this simulation model, we evaluated the proposed scheme in a typical heterogeneous network scenario with interworking macro-cell (WiMAX) and Wi-Fi. The result showed that our proposed scheme dynamically steered the UE's traffic from macro-cell and distributed to available Wi-Fi APs. As the result, both the overall system throughput and the utilization of available Wi-Fi APs were improved. In addition, we observed better user's experienced throughput compared to that of conventional scheme. We also extensively evaluated the performance of the proposed scheme when vary the received signal strength and the load thresholds, which affect the number of mobile nodes roaming to Wi-Fi. We also noticed a shortcoming of the proposed scheme in this chapter, which is originated from the fact that the scheme is aimed at optimizing the system throughput or per-user's throughput. Selecting optimal AP when UEs are on the move increases the frequency of handover between Wi-Fi APs. Because in realistic situation, each UE can have different data rate requirement depended on application, in chapter 4, we proposed an enhancement for the proposed scheme by considering UE's on-demand QoS and the estimated remaining resource of AP candidate. We proposed simple method to estimate remaining throughput of AP prior to association operation. The estimated remaining throughput of AP is used in the previous proposed scheme for AP selection process. By considering end user's requested data rate and estimated remaining throughput of AP, the new decision scheme prevented UEs from selecting undesirable AP candidates, which are unable to provide requested data rate. As the result, unnecessary handover number is reduced.

5.2. Scope of Future Work

In our future work, we will further enhance the proposed scheme and evaluate in more complex network scenario. In chapter 3, we noticed there is a correlation between the number of mobile nodes and APs affecting the throughput performance. In addition, the load threshold and received signal threshold are the effective tools for network operators to control traffic going through macro-cell and Wi-Fi APs. The optimal values for these thresholds depends on the correlation between the number of UEs and APs as well as specific network condition and application. We plan to consider this issue in our future work.

In chapter 4, our simulation results have shown that the requested data rate can affect overall system performance and stability. This can be addressed by introducing some kind of data rate negotiation and throughput threshold. In chapter 4, due to the limitation of the simulation software, we could only uniformly set the requested throughput to a specific value; that means all of UEs request for a same specified throughput value. Because the requested throughput can be autonomously decided by UEs, we need to randomize the requested data rate for each UE. This issue will be considered in our future work.

The current proposed scheme is designed for case when the mobile nodes can only use one interface at a given time. The mobile node selects the optimal radio access network to suit its requirement with considering load condition of the network, operator's preference policies. This can be referred radio level offloading. In our future work, we are planning to revise and extend the proposed scheme for multiple homing mobile nodes, which can use multiple wireless interfaces simultaneously. By routing different types of user's traffic via different interfaces such as cellular and Wi-Fi, we can further optimize traffic offloading at IP network level for different data application.

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Appendix A. List of Achievements

Category	
Articles in Refereed journals	○ **Nam Nguyen**, Mohammad Arifuzzaman and Takuro Sato "A Novel WLAN Roaming Decision and Selection Scheme for Mobile Data Offloading", Journal of Electrical and Computer Engineering, Vol. 2015, Article ID 324936, pp.1-15, 2015, doi:10.1155/2015/324936.
	○ **Nam Nguyen** and Takuro Sato, "A proposal to enhance cellular and Wi-Fi Interworking toward a reliable HetNet", The International Journal of Computer Networks & Communications, Vol. 8, No. 1, pp.1-18, January 2016.
International Conference Proceedings	○ **Nam Nguyen** and Takuro Sato, "A Novel Minimum Wi-Fi Throughput Estimation for Wi-Fi Offloading", International Conference on Simulation Technology, Toyama Japan, Vol. JSST2015, pp.108-113, October 2015.
	○ **Nam Nguyen** and Takuro Sato, "A Proposal for Dynamic WLAN Selection for Mobile Data Offloading in Heterogeneous Network", in Vehicular Technology Conference (VTC Spring), 2014 IEEE 79th, pp.1-5, May 2014, doi: 10.1109/VTCSpring.2014.7022792.
	Nam Nguyen, Battulga Davaasambuu and Takuro Sato, "Simulation of Dynamic Wi-Fi Selection for Mobile Data Offloading", the 33rd International Conference on Simulation Technology, Kitakyushu Japan, Vol. JSST2014, pp.12-13, October 2014, [*http://www.oishi.info.waseda.ac.jp/JSST2014_Abstracts.pdf*].
	Nam Nguyen and Takuro Sato, "Localization and Mobility Management Scheme for Heterogeneous Wireless Networks based on ANDSF", International Conference on Simulation Technology, Vol. JSST2012, pp.1-2. Kobe Japan, 2012, [*www.jsst.jp/e/JSST2012/extended_abstract/pdf/22.pdf*].

	Nam Nguyen, Zhenyu Zhou and Takuro Sato, "RLS for Link Trigger in Handover across Heterogeneous Wireless Networks", in Vehicular Technology Conference (VTC Fall), 2011 IEEE, pp.1-5, September 2011, doi: 10.1109/VETECF.2011.6092986.
National Conferences	**Nam Nguyen** and Takuro Sato, "Handover Prediction based on Recursive Least Squares Algorithm", IEICE Society Conference, Vol. 2011 BS-6, pp.82-83, Sapporo, Japan, September 2011.
Presentation at workshop Academic Meeting held by Study Group	**Nam Nguyen** and Takuro Sato, "WLAN Discovery and Selection for Mobile Offloading in Heterogeneous Network", Waseda-Hanyang IT Workshop, pp.1-5, Seoul Korea, November 2013. **Nam Nguyen** and Takuro Sato, "A Dynamic WLAN Discovery and Selection for Mobile Data Offloading in Heterogeneous Network", Waseda-KDDI Workshop, pp.1-5, Tokyo Japan, November 2013.
Others	Yanwei Li, Zhenyu Zhou, **Nam Nguyen** and Takuro Sato, "Game Theory Based Hybrid Access for Macrocell-Edge Users in a Macro-Femto Network", in Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th, pp.1-5, June 2013, doi: 10.1109/VTCSpring.2013.6692575. Battulga Davaasambuu, **Nam Nguyen** and Takuro Sato, "Context-aware Handover optimization for Wireless Mobile Base Station", International Conference on Simulation Technology, Vol. JSST2014, pp.1-2, Kitakyushu Japan, October 2014.