Efficient Handover Methods for Vehicle-to-Infrastructure Communications over Heterogeneous Wireless Networks

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To my lovely wife, kids,
parents and siblings

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

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Abstract

One of the key performance-limiting factors in achieving the Quality of Services (QoSs) in Vehicle-to-Infrastructure (V2I) communications over a heterogeneous network is the increased number of unnecessary handovers. In heterogeneous network environments, handovers consume a lot of network resources and consequently increase end-to-end network latency. Other factors affecting the handover performance are the traffic type and network loading. In this thesis, an efficient network selection method for handover is investigated. In the study, a multi-tier, multi-RATs heterogeneous network is considered. We first propose a novel algorithm for selecting the most suitable candidate network. We then propose a method for reducing the number of unnecessary handovers by considering the distance between the vehicle and the target Base Station (BS). The short-list of the potential target networks includes only those lying in the direction of movement and are determined based on the geo-location of both vehicle and the candidate network BSs. Certainly, the better network performance is achieved by reducing the scanning time of the candidate networks.

The surveyed literature has shown that the network load at the target network has a significant impact on the handover performance due to an increased handover drop probability. For example, a macro-cell BS could be regarded as a good candidate network for V2I communication due to the reasonable sojourn time, however, in the case, the BS is overloaded all handover requests are dropped. The integration of mobility and network information can further improve handover performance. A

network selection method that applies the knowledge of both mobility and network load information is proposed for further improving handover performance. The better performance is achieved by optimizing the parameters such as cell dwelling time, load index, and Received Signal Strength (RSS) values. The type of traffic such as safety-related applications that require stringent QoS requirements and the network usage-cost also influence the network selection for handover. The concept of multi-criteria decision making which combines cell QoS metrics and user budget is investigated and applied for developing an application- aware network selection for handover method. Five application profiles are proposed based on the QoS metrics and network usage monetary cost. It was observed that the QoS of V2I safety-related applications could be guaranteed once they are allocated to the appropriate application profile.

The thesis includes three main contributions. First, the scanning time of all available networks in the direction of movement is reduced by geo-locating both the vehicle and candidate network base stations. Second, by getting the knowledge of network information and vehicle mobility we further improved the system performance. Third, the overall network performance/utilization is improved by considering traffic type and network usage-cost. The thesis concludes with network design guidelines and deployment strategies for various practical network scenarios.

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List of Publications

Manuscripts relating to the this research project have been published in the following journal and academic conference proceedings:

1. E. Ndashimye, S. K. Ray, N. I. Sarkar, and J. A. Gutiérrez, "Vehicle-to-Infrastructure Communication over Multi-Tier Heterogeneous Networks: A Survey," Computer Networks, Elsevier, 2016.

2. E. Ndashimye, N. I. Sarkar, and S. K. Ray, "A novel network selection mechanism for vehicle-to-infrastructure communication," in Dependable, Autonomic and Secure Computing, 14th Intl Conf on Pervasive Intelligence and Computing, 2nd Intl Conf on Big Data Intelligence and Computing and Cyber Science and Technology Congress (DASC/PiCom/DataCom/CyberSciTech), 2016 IEEE 14th Intl C, 2016, pp. 483-488.

3. E. Ndashimye, N. I. Sarkar, and S. K. Ray, A Mobility-Aware Network Selection Method for Vehicle-to-Infrastructure Communication over LTE-A Multi-tier Networks Paper presented at the 31st International Conference on Information Networking (ICOIN 2017), Da Nang, Vietnam, January 11-13,pp.315-320.

4. E. Ndashimye, N. I. Sarkar, and S. K. Ray, A Network Selection Method for Handover in Vehicle-to-Infrastructure Communications in Multi-Tier Networks Paper submitted to the journal of Wireless Networks, Springer (First review, June 2018).

List of Abbreviations and Acronyms

3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
AHP	Analytic Hierarchy Process
ANDSF	Access Network Discovery and Selection Function
AP	Access Point
BS	Base Station
CA	Certification Authority
CAMs	Cooperative Awareness Messages
CMS	Co-operative Mobility Service
CN	Correspondent Nodes
CoA	Care of Address
CRLs	Certificate Revocation Lists
D2D	Device to Device
DENMs	Decentralized Environmental Notification Messages
DenseNets	Dense Networks
DHCP	Dynamic Host Configuration Protocol
DSMIPv6	Dual Stack MIPv6
DSRC	Dedicated short-range communication
DVB-H	Digital Video BroadcastingHandheld
EDCA	Enhanced Distributed Channel Access
EDR	Event Data Recorder
EPC	Evolved Packet Core
ETSI	European Telecommunication Institute
FMIPv6	Fast MIPV6
GeoWave	Geocaching WAVE
GPS	Global Positioning System

HA	Home Agent
HMIPv6	Hierarchical MIPv6
HSPA	High-speed Packet Access
HWN	Heterogeneous Wireless Access Network
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IP	Internet Protocol
ISO	International Standards Organization
ITS	Intelligent Transport Systems
LiDAR	Light Detection and Ranging
LMA	Local Mobility Anchor
LMD	Localized Mobility Domain
SLCs	Short-Lived Certificates
LTCs	Long-Term Certificates
LTE	Long Term Evolution
LTE-A	LTE - Advanced
MAG	Mobile Access Gateway
MANET	Mobile Ad Hoc Networks
MAP	Mobility Anchor Point
METIS	Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society
MIH	Media Independent Handover
MIPV6	Mobile IPv6
MIRON	Mipv6 Route Optimization for NEMO
MN	Mobile Node
MR	Mobile Router
NEMO	Network Mobility
NKW	Network
OBU	On-Board Unit
PANs	Personal Area Networks
PGW	Packet Gateway
PKI	Public Key Infrastructure
PMIPv6	Proxy MIPv6
POA	Point Of Attachment
QC	QoS Class Identifier
QoS	Quality of Service
QoSAL	QoS Abstract Layer
RAT	Radio Access Technology
RNC	Radio Network Controller
RO	Route Optimization

ROTIO	Route Optimization solution for nested mobile networks using Tree Information Option
RSB	Road Side Base station
RSS	eceived Signal Strength
RSSI	Received Signal Strength Indicator
RSU	Road Side Units
SAE	System Architecture Evolution
SDR	Software Defined Radio
SIM	Subscriber Identity Module
SLV	Secure Location Verification
SRC	Single Radio Controller
SSMMA	System Selection and Mobility Management Agent
TLMR	Top Level MR
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TPD	Tamper-Proof Device
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
USDOT	United States Department of Transportation
UTRAN	Universal Terrestrial Radio Access Network
V2I	Vehicle-To-Infrastructure
V2I-DHA	Distance-based Handover Algorithm for V2I communications
V2I-MoLoHA	Mobility and network Load-aware Handover Algorithm for V2I communications
V2I-MHA	Multi-criteria based Handover Algorithm for V2I communications
V2R	Vehicle-to-Roadside
V2V	Vehicle-To-Vehicle
VANET	Vehicular Ad-hoc Network
VoIP	Voice over IP
WAVE	Wireless Access in Vehicular Environments
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless LAN

Chapter 1

Introduction

Recently, there has been enormous growth in user demand for wireless services and applications due to the need for accessing information anywhere, anytime. This growth was accelerated by the development of the Apple iPhone and Android applications that came out in 2007 and 2008, respectively. Since then, the need for a system with higher data capacity has been inevitable [1]. Furthermore, the need for higher data capacity in wireless networks was exacerbated by the emerging vehicular network applications, namely, road safety, traffic management, and infortainment applications. Vehicular network applications require seamless connectivity for moving vehicles. Figure 1.1 presents a vehicular network. Vehicles communicate with each other in the form of an ad-hoc mode (vehicle-to-vehicle (V2V) communication) or connect to the Internet through fixed roadside infrastructure components (vehicle-to-infrastructure (V2I) communication).

While V2V applications are mostly designed for road safety, V2I applications benefit in-vehicle users who spend considerable hours in private vehicles or public transportation. Under the always-connected paradigm, the V2I network will provide in-vehicle users with ubiquitous network connectivity at all times. V2I communication is useful for on-road vehicular applications such as safety and security, efficient utilization of roads and intersections, infotainment applications, and payments.

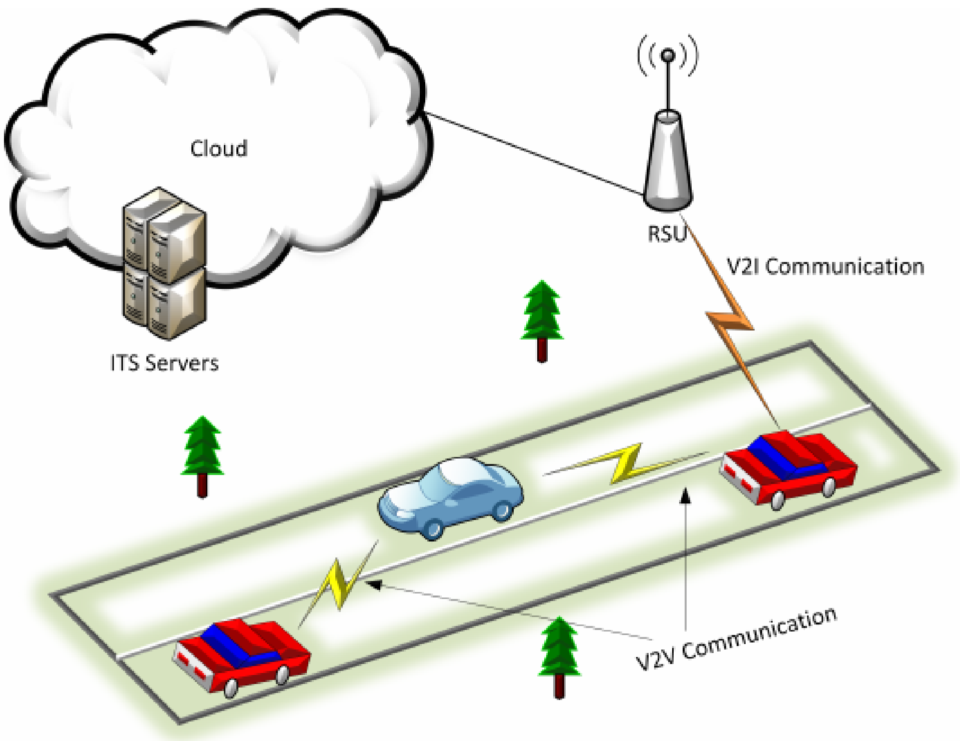

Figure 1.1: A typical V2V and V2I communications network configuration.

Despite these advantages of V2I applications, one of the challenges faced by V2I communications is providing a seamless connectivity to moving vehicles. Currently, available vehicular network infrastructures do not provide total coverage, thus preventing in-vehicle users from accessing internet content such as news and weather information continuously. Standardization efforts in vehicular networks have resulted in Wireless Access for Vehicular Environment (WAVE) protocol. The WAVE protocol integrates the IEEE802.11p at mac and physical layers; hence, its main limitation is linked to scalability issues [2]. On the other hand, the automotive industry has been building a fully featured vehicle On-Board Unit (OBU) that may integrate different communication technologies such as Wi-Fi, UMTS, LTE and WiMAX to solve the scalability issue and reinforce the communication systems of vehicles [3]. The multi-homing vehicle OBU will have different alternatives for communications; however, the primary challenge will be an increased number of frequent unnecessary handovers [4].

The research community has been making considerable progress towards the convergence of the different radio access technologies. Consequently, there are numerous proposals addressing heterogeneous networks in terms of handover management, procedures, and protocols. Furthermore, in addition, since 2008, in its Release 8, the Third Generation Partnership Project (3GPP) Group has introduced the Access Network Discovery and Selection Function (ANDSF) to enable a 3GPP compliant UE to discover non-3GPP access networks (e.g., Wi-Fi and WiMAX). In latter 3GPP Releases (1012) this has advanced to the extent of supporting the UE to discover, select and connect to both non-3GPP and 3GPP access networks (UTRAN, LTE, and HSPA).

1.1 Motivation

With the advancement of wireless technologies, mobile users demand ubiquitous internet connectivity anywhere and anytime. To achieve this, Fifth Generation (5G) wireless networks will have a seamless coexistence of multi-tier heterogeneous radio access technologies (e.g. LTE, Wi-Fi, WiMAX, IoT Low Power Wide Area Networks) [1]. There will be network densification with the macro-cells overlaying the plethora of heterogeneous small cells of different coverage areas (femto and picocells).

For effective vehicle-to-infrastructure (V2I) communication in an urban multi-tier heterogeneous network environment, vehicles on the move will need to perform fast and successful handovers between macro and small cell networks, and among the various small cell networks, to ensure seamless mobility and communication. Currently, there are various studies covering handover management over heterogeneous networks, but most of them were proposed for low-speed mobile users and most only take into account a few processes and parameters. This thesis presents QoS-aware handover algorithms developed to facilitate seamless handover activities for V2I communications over multi-tier, multi-RAT environments.

1.2 Research objectives

This research aims to identify relevant factors affecting the handover performance in V2I communications over multi-tier heterogeneous networks, thus offering a strong foundation to scientists interested in the vehicular network research area. Moreover, the primary objective of this thesis is to develop handover algorithms capable of managing different underlying radio access technologies by assessing diverse parameters from numerous sources. These parameters include node mobility, network availability and capacity, user profile and geo-location information to optimize the network selection process for a near future handover. The primary objectives of this thesis were to:

- Develop novel handover methods for efficient V2I communication over multi-tier, multi-RAT networks.
- Create a multi-interface mobile node in OPNET modeler that is used to test and evaluate the proposed handover algorithms.

1.3 Research methodology for investigation

The main objective of this thesis is to develop QoS-aware handover algorithms for V2I communication over multi-tier heterogeneous networks. To achieve this objective, both analytical models and simulations have been used to study system performance.

Figure 1.2 outlines the methodology adopted in this thesis. Both analytical and simulation models were used to develop three handover methods: (1) the distance based handover method (Chapter 4), (2) the mobility and network load aware handover method (Chapter 5) and the application-aware handover method (Chapter 6). The advantage of these three handover methods is that the best candidate network for a future handover is selected based on the combination of the knowledge about node mobility (e.g. speed and direction), some information about the candidate network such as network load and the QoS requirements (e.g. bit-rate, delay, and packet loss) of the on-going applications. This provides an optimized decision for network selection and facilitates reliable handover performance estimation. Furthermore, a customized mobile node that integrates multiple network interfaces is created (Chapter 5) for simulation set up and the performance study of these handover methods.

Given the characteristic of this research work, setting a real world experiment is highly expensive. Thus, computer simulation is used to analyze and evaluate the developed handover schemes. The OPNET (Riverbed) simulator [5], was used extensively as a primary tool for the simulation set up and performance evaluation. The OPNET modeler is selected due to its ability to support various wireless radio access technologies including cellular, WiMAX, and WLAN. Moreover, the OPNET is flexible in terms of creating different movement trajectories, which is a key requirement for V2I communications. Besides, MATLAB was used to evaluate the performance of the mathematical concepts of the designed algorithm (only in chapter 5). OPNET is a credible simulation tool, OPNET ranks at the third position among various simulation tools used in communication studies published in 2007 to 2009 [6]. Simulations were also used for validation of our proposals by comparing simulation results with conventional handover methods and related studies in the literature.

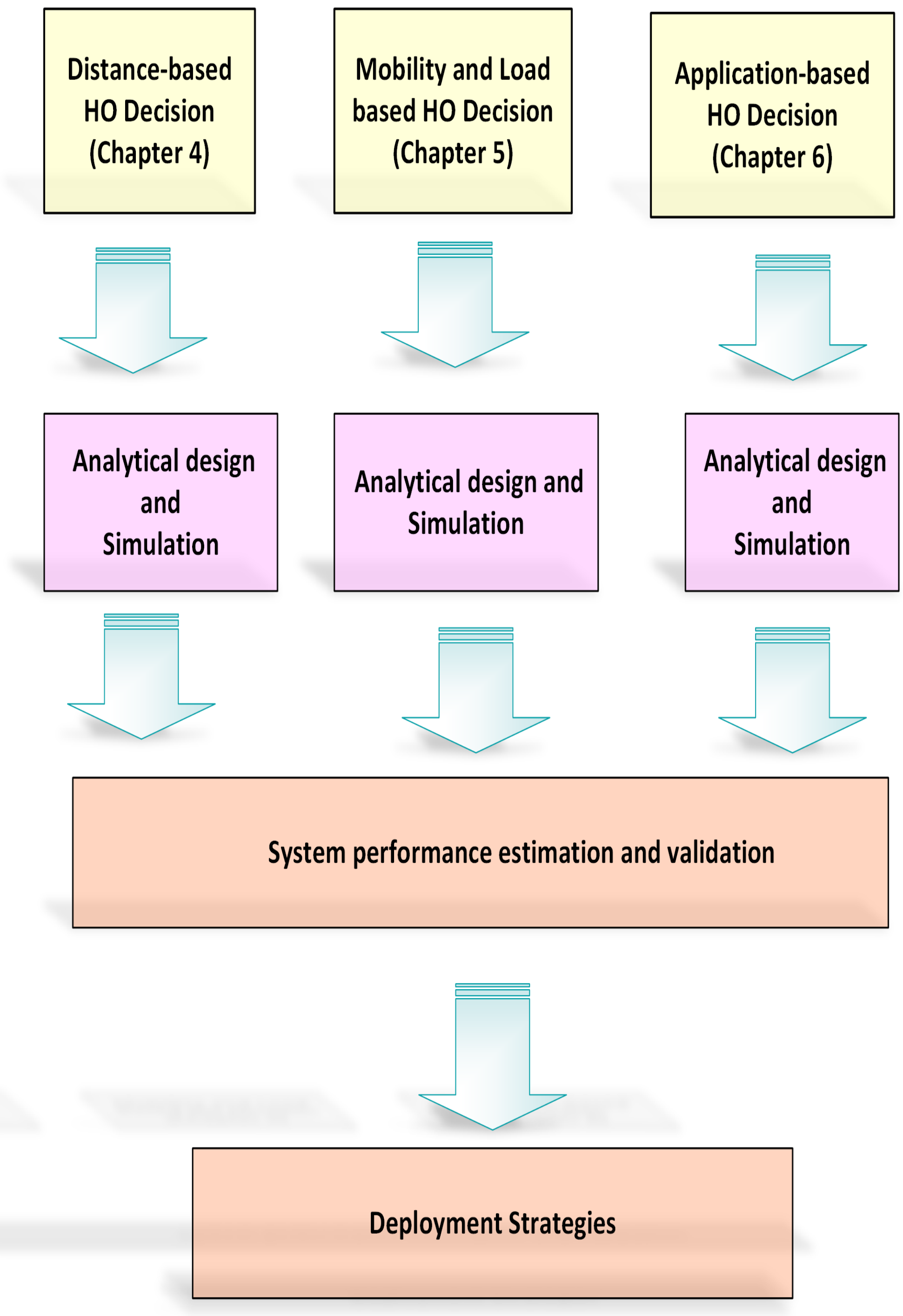

Figure 1.2: Block diagram of the adopted methodology.

1.4 Contributions and the structure of this thesis

The overall structure of this thesis is shown in Fig. 1.3. Providing a seamless and efficient connectivity for V2I communications over a multi-tier heterogeneous wireless network requires a basic understanding of different radio access technologies and V2I applications. Chapters 2 and 3 of the thesis present the background material for these areas.

Chapter 2 covers a detailed overview of wireless technologies (candidates to support V2I communications) and the viability to support V2I communications. Also in this chapter, V2I applications are introduced.

Chapter 3 provides a deep review of research issues in V2I communication over multi-tier multi-RAT heterogeneous networks. In a review, the existing vehicular network-related studies which include mobility management and data dissemination are investigated and were also published in [7]. Most of the identified key challenges are associated with mobility management and have led to the development of the novel handover approaches, the main contributions of this thesis.

The original contributions of the thesis are presented in Chapters 4 to 6, which are primarily concerned with network selection algorithms that are mainly designed to meet high mobility features of vehicular networks, particularly V2I communications. These algorithms are developed in a sequential and incremental method. Published papers associated with this work include references [8, 9]. This thesis includes three network selection methods. Each network selection method is associated with a particular handover algorithm. Consequently, in this thesis, the network selection method and the handover algorithm are used interchangeably. We proceed to describe these network selection methods briefly:

- **Distance-based Network Selection Method for V2I communications**

  Network selection is a key procedure for successful handover activities. Due to

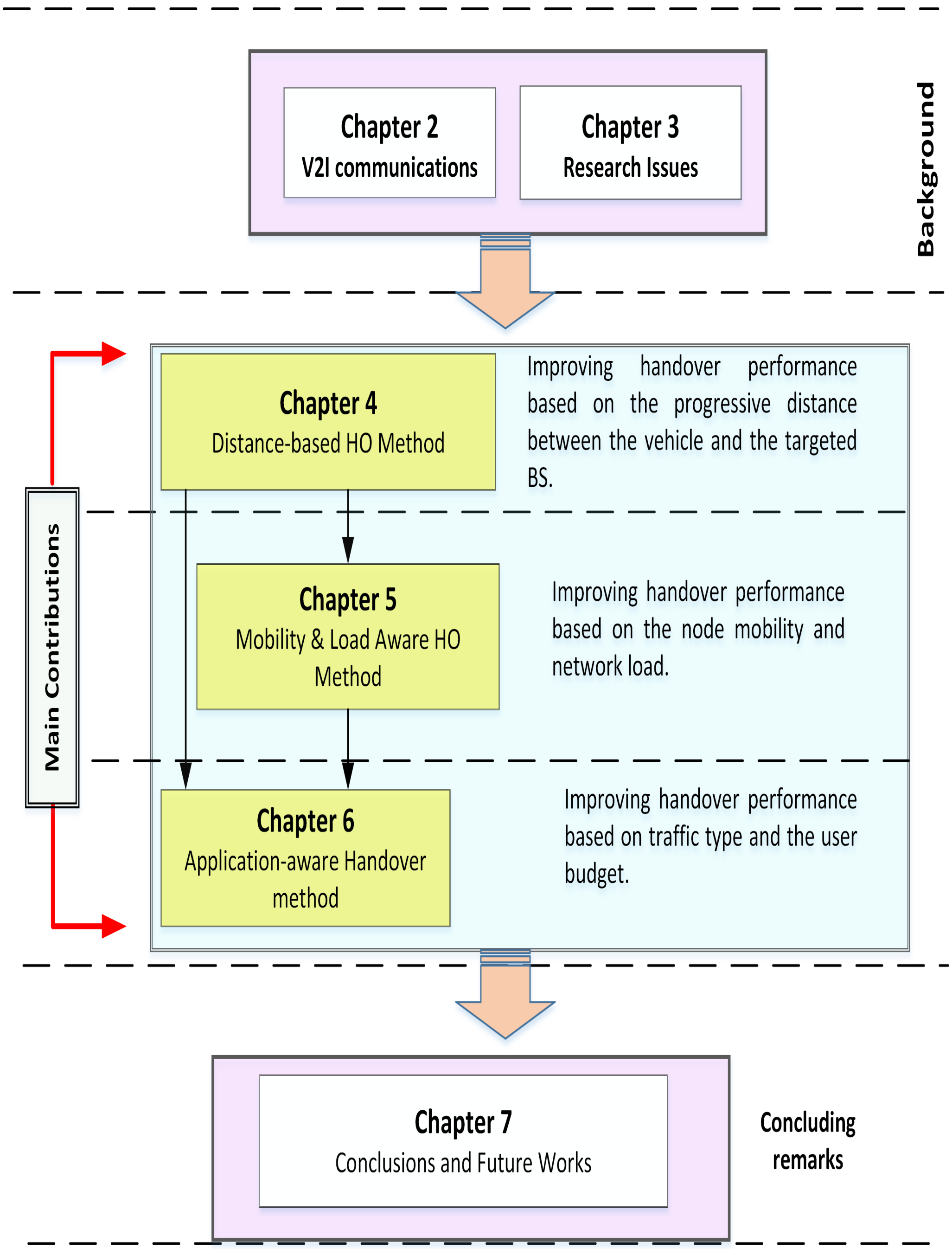

Figure 1.3: The structure of this thesis.

the high speed of vehicles, vehicular networks over the multi-tier heterogeneous wireless network will experience an increased number of handovers. The conventional/traditional handover procedure is based on the value of the received signal strength (RSS) measurements of the target network AP/BS measured by the UE (User Equipment). Due to the lack of information about the coverage area of the candidate networks, the vehicle is likely to select the target AP / BS with the highest RSS value, but this may not be so appropriate in terms of how much time the vehicle spends in its service area.

To enhance the network selection process, the proposed method pro-actively evaluates all candidate networks, first based on their geo-locations relative to the movement direction and secondly based their proximity to the vehicle trajectory (road). The shorter the distance between AP and the vehicles movement trajectory, the higher the selection probability of a candidate network. The contribution of this algorithm is twofold: it reduces the number of unnecessary handovers and it also improves the overall handover delays by limiting the number of candidates AP/BS to be scanned. The implementation of this method is detailed in Chapter 4 and the handover algorithm produced is named Distance-based Handover Algorithm for V2I communications (**V2I-DHA**).

- **Node Mobility and Network Load-aware Network Selection Method for V2I communications**

  This network selection method extends the idea proposed in V2I-DHA by considering both UE mobility and network resources available before sending a handover request. Moreover, this method considers both downward (vehicle switches its connectivity from a large scale to small-scale network) and upward (vehicle switches its connectivity from a small scale to a wide scale network) network selections. For downward network selection, the method considers the dwelling (residence) time (the time a UE spends within the coverage area of the selected BS/AP), the network load, which represents the capability of the target AP/BS to accommodate handed sessions, and the RSSI value of the target AP/BS. On the other hand, an upward handover is mandatory to prevent the UE from losing its ongoing connection as it moves out of the coverage area of the serving small cell AP/BS. This algorithm reduces the handover dropping probability, by limiting vehicles to select the candidates with an increased load. The implementation of this method is detailed in Chapter 5 and the handover algorithm produced is named Mobility and network Load-aware Handover Algorithm for V2I communications (**V2I-MoLoHA**).

- **Multi-Criteria Cell Selection Algorithm for V2I communication**

  This is an extension of its predecessor, V2I-MoLoHA. Once the filters in V2I-MoLoHA have filtered out inappropriate candidate networks, this algorithm applies the multi-criteria decision-making method to make sure that the candidate network is selected based on application requirements. The proposed method is expected to provide an improved network resource management due to the different user profiles defined based on various sets of criteria. Similar to V2I-MoLoHA, this method considers both handover directions: downward and upward network selection. Moreover, this method also considers network selection among small cells. While the previous algorithms can select the best AP/BS, regardless of how many network resources are required for the current applications, the key contribution of this network selection method is to improve the overall network resource management by enabling the mobile node to select a target AP/BS based on the traffic type of an ongoing application. The implementation of this method is detailed in Chapter 6 and the handover algorithm produced is named Multi-criteria based Handover Algorithm for V2I communications (**V2I-MHA**).

- The handover algorithms are coded and tested in OPNET modeler. Currently, OPNET modeler does not have any multi-interface nodes. Thus, we have contributed to the existing OPNET codes by customizing a traditional user equipment (UE) according to the developed algorithms. Moreover, Wi-Fi AP, LTE eNB and core network are enhanced to accommodate the new features of the proposed handover algorithms.

Finally, the thesis is summarized and concluded in Chapter 7.

Chapter 2

V2I Communications and Wireless Technologies

2.1 Introduction

In Chapter 1, the motivation for utilizing heterogeneous wireless networks to underlay V2I communications was presented. In a heterogeneous network environment, handover is the key challenge to provide a mobile user with a reliable and seamless connectivity. Hence, the primary objectives of this thesis were to identify the key factors that affect handover performance and to propose a system that can provide an acceptable QoS level when a user performs a handover activity. To achieve this objective, a brief review of wireless technologies and V2I communications is required, and is included in this chapter. In Section 2.2, the basics of wireless technologies are discussed. Also, this section includes a discussion of the viability of each presented technology to support vehicular networks. Moreover, the concept of multi-tier multi-RAT heterogeneous networks is presented.

Section 2.3 describes V2I communications applications and the possibility of supporting them in a multi-tier multi-RAT network environment. It also presents the key challenges related to the high mobility characteristic of vehicular networks. Section

2.4 discusses the research methodology adopted in this thesis. Finally, the chapter is summarized in Section 2.5.

2.2 Wireless Technologies

Wireless technologies have been advancing in terms of data rates, efficient spectrum management and the range of service areas as well as the number of supported users. With respect to the data rate, the wireless network has improved from a few Kbps up to Gbps nowadays. Moreover, to increase the communication range and to support an increased number of users, various mechanisms have been deployed including a multi-tier (also known as multi-layer) network architecture and an integration of multi-radio access technologies (Multi-RATs).

In this section, we will portray the essentials of the wireless technologies (Wireless fidelity (Wi-Fi), Worldwide Interoperability for Microwave Access (WiMAX) Advanced Long-Term Evolved (LTE-A)), candidates to support V2I communications.

2.2.1 Wi-Fi

Wireless Fidelity (Wi-Fi) is a technology for WLAN and Wi-Fi devices based on IEEE 802.11 standards. Wi-Fi has achieved a big market due to high market penetration; it supports a relatively high data rate and covers a short-range distance. The recent version, IEEE 802.11n, offers about 100Mbps, however, some studies have revealed its performance reduction due to interference [10]. Several studies confirmed the viability of the Wi-Fi technology to support moving nodes at the vehicular speed. On the other hand, its short-range transmission resulting in frequent transmission interruption becomes a big challenge, particularly when vehicles are moving at high speed. [11]

discussed the use of WLANs (IEEE 802.11) to support vehicle-to-infrastructure communications. The author focused on the innovations in the legacy 802.11 handover procedures. Throughout this research, some experiments were done to prove the arguments of the researcher. Though WLANs APs are widely distributed, the challenge is the handover latency between APs compared to the time a vehicle node will spend in its range. To overcome this challenge, the physical layer of the Wi-Fi protocol has been modified resulting in the two well-known vehicular network standards DSRC and WAVE that are discussed in the subsequent sections.

- **Dedicated Short Range Communication (DSRC)**

DSRC has been developed and standardized in the USA [2] and is derived from the IEEE 802.x family using licensed spectrum at 5.9 GHz with seven channels of 10 MHz bandwidth (5.850-5.925 GHz). This is half of the bandwidth used in IEEE 802.11a. Among the seven channels, two at the ends are reserved for special uses; one in the centre is the control channel (CCH) limited to safety applications, and the rest are service channels (SCH) available for both safety and non-safety usage. It is worth noting that the regional (USA, Japan and Europe) standardization of DSRC was slightly different in terms of selected radio frequencies, allocated bandwidth, number of channels, data transmission rate, and coverage. The details of the DSRC specification can be found in [12].

- **WAVE**

As previously mentioned, DSRC is derived from IEEE 802.11a. The major modification was made at the physical layer, where the authentication process was suppressed to speed up the network discovery and selection processes. However, DSRC suffers from multiple overheads inherited from the MAC layer and this fact makes it difficult to provide the fast data exchange compulsory for vehicular networks [2]. To address this issue, the American Society for Testing and Materials (ASTM) working group, ASTM 2313, migrated the DSRC effort to IEEE802.11p WAVE, which integrates both the MAC and physical layers [2]. WAVE defines two classes of devices: OBU and RSU. The former is essentially used as a stationary device, while the latter is used as a mobile device. WAVE uses Orthogonal Frequency Division Multiplexing (OFDM) to divide the signal into a number of narrow band channels. In the WAVE stack, the access media and physical layers are derived from IEEE802.11a, while the operational functions and channel planning are handled by IEEE 1609 standards [13] IEEE P1609.1 defines resource management, IEEE P1609.2 works on security, IEEE P1609.3 works at the network layer and IEEE P1609.4 defines a standard for the media access control extension sub-layer (Layer 2) that defines interfaces between these multiple applications and communication stacks that interface with ASTM 2213-02 (IEEE 802.11a). Despite the efforts invested in improving WAVE functions to meet the high-speed and dynamic topology changing nature of vehicular networks, a recent study in [14] has listed various challenges requiring further research. That list includes latency and capacity requirements for safety applications, security, and scalability, to mention a few.

2.2.2 WiMAX

Worldwide Interoperability for Microwave Access (WiMAX) or IEEE 802.16 is designed to solve IEEE 802.11 short-range transmission and to deliver a high data rate to end-users. Theoretically, WiMAX covers a large geographical area, up to 50 km, and, to deliver significant bandwidth to end-users, up to 70 Mbps theoretically. The first release of WiMAX was in 2004 and it was only to support fixed broadband wireless communications. The second release named IEEE 802.16e or mobile WiMAX was released in 2005 [15]. Mobile WiMAX can support high speed nodes up to 160 km/h and guaranteed services for data, voice, and video, even for non-line-of-sight transmissions [16]. WiMAX works with many bands: 2.3 GHz, 2.5 GHz and 3.5 GHz and it can use any available spectrum from 1.25 MHz to 28 MHz. While WLAN uses a contention-based channel access mechanism, WiMAX has got a scheduling algorithm for which the subscriber nodes need to compete only once for initial entry into the network; after that, they are allocated an access slot by the BS [17]. Various papers have proved WiMAX viability to support vehicular networks [15, 18]. The author of [18] confirmed that WiMAX technology could be used to connect moving vehicles on highways to peers at home or in office.

2.2.3 LTE & LTE-A

Mobile data growth was accelerated by the development of the Apple iPhone and Android applications that came out in 2007 and 2008, respectively. Since then, the need for a system with higher data capacity was inevitable [1].To cope with those changes in mobile data demand, Long Term Evolution (LTE) was designed in a project named 3GPP (Third Generation Partnership Project) founded by a collaboration of national and regional telecommunication standard bodies [19]. Initially, the effort of 3GPP produced a system named Universal Mobile Terrestrial Systems (UMTS), which was an evolution from the GSM system. UMTS itself was an advancement from the GSM frameworks.

The Figure 2.1 presents the architecture of the LTE system. While the UMTS and GSM systems deploy both circuit switching (CS) to handle voice application and packet switching (PS) for data communication, the LTE system deploys the evolved packet core (EPC) to distribute all types of information (voice and data) to the UE using the packet switching technologies. The Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) handles the EPCs radio communication with the UE, and the

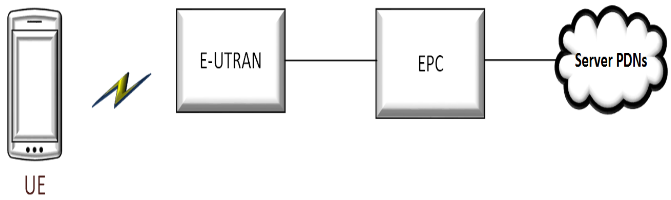

Figure 2.1: The system architecture of LTE.

mobile terminal is named user equipment (UE).

The LTE system was required to provide an improved data rate, reduced end-to-end latency, wider coverage area and mobility support. With respect to data rate, the target was to deliver 100 Mbps in the downlink and 50 Mbps in the uplink; however, these requirements were eventually exceeded, the developed LTE system delivering 300 Mbps and 75 Mbps peak data rate in downlink and uplink, respectively [1]. In terms of latency, LTE provides considerably less end-to-end delay due to the reduced amount of communicating equipment required in the core network. Also, LTE is optimized in terms of cell coverage and mobility, it can support a wider cell size up to 10 km and the mobile nodes can speed up to 350 km/hr over LTE networks [1].

Motivated by the exponential increase of mobile data traffic demand and International Telecommunication Union (ITU) requirements, the cellular network technologies have been upgrading over time from the second generation Global system for mobile (GSM) up to the current Long Term Evolution Advanced (LTE-A) [1]. While the specifications of the regular LTE system are well defined in 3GPP Release 9, LTE-A is defined in 3GPP Release 10 and this is an upgraded version of LTE technology which increased the peak data rates to about 1Gbps in the downlink and 500Mbps in the uplink. LTE-A utilizes a higher number of antennas to increase the data rates and provide carrier aggregation features. Table 2.1 compares LTE and LTE-A based on selected key specifications.

Table 2.1: LTE Vs LTE-A.

Specifications	**LTE**	**LTE-A**
Standard	3GPP Release 9	3GPP Release 10
Bandwidth	supports 1.4MHz, 3.0MHz, 5MHz, 10MHz, 15MHz, 20MHz	70MHz Downlink(DL), 40MHz Uplink(UL)
Data rate	300 Mbps Downlink(DL) 4x4MIMO and 20MHz, 75 Mbps Uplink(UL)	1Gbps Downlink(DL), 500 Mbps Uplink(UL)
Theoretical Throughput	About 100Mbps for single chain, 400Mbps for 4x4 MIMO. 25% of this is used for control overhead	2 times than LTE
Modulation schemes supported	QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM
Access technique	OFDMA (DL),DFTS-OFDM (UL)	Hybrid OFDMA(DL), SC-FDMA(UL)
Carrier aggregation	Not supported	Supported

- **LTE-A for V2X**

There are more than 30 studies in the anticipated LTE release 14 [20]. LTE-V2X is one of them. LTE mobile networks are fast becoming the preferred mode of communication between vehicles and roadside infrastructure. With respect to V2I communication, LTE offers superior network capacity, higher coverage, and greater mobility support but suffers from higher latency in comparison to 802.11p with an increase in network load [21]. Moreover, to facilitate the availability of real broadband for end users even in areas of high vehicle density, the deployment of small LTE base stations forming microcells is required on top of the existing LTE infrastructure that can be used to provide V2I communication through LTE-enabled vehicular on-board units (OBU) or smartphones [21]. One such example of LTE OBU is QUALCOMM Snapdragon X5 LTE modems for vehicles. In terms of LTE-V2X standardization, LTE device-to-device (LTE-D2D) has paved the way for V2X communication and 3GPP SA1 started Rel-14 LTE-V2X SI from February 2015 with support from a significant number of companies [22]. Hybrid approaches combining LTE and 802.11p can also be suitable for V2I communication as proposed in [23].

2.2.4 Multi-tier, multi-RATs heterogeneous networks

The evolution of 4G technology has made it possible to integrate non-3GPP technologies, including Wi-Fi and WiMAX, into the 3GPP designated Evolved Packet Core (EPC) eventually providing access to packet data networks (PDN). Moreover, this integration is also known as a heterogeneous network. A heterogeneous network uses a variety of radio access technologies and different cell formats, each having different functionalities, capabilities, and constraints [24]. The concept of heterogeneity can be defined either in terms of various network sizes (or cell sizes) or in terms of coexisting wireless networks using different radio access technologies (RATs). The actual term multi-tier is utilized to portray the different sizes with BSs/APs of various transmitting power, capacity (supported number of subscribers) and BS/AP density [25]. As illustrated in Figure 2.2, the biggest level cell is named the macro-cell and its cell coverage area provides the widest range. The macro-cell is found in most rustic regions and can be situated along major highways. The next relatively smaller size cell is named the micro-cell, also known as a small cell [1]. It is mostly utilised in populated areas including shopping centers, It is mostly utilized in populated areas including shopping centres, industrial places, and large office structures. The smallest cell is the femtocell. The femtocell is an indoor low power BS used to provide radio access in a relatively small area such as an individual office or home. Moreover, Wi-Fi cells also belong to the microcell type due to their limited transmit power area. Furthermore, a network environment, which integrates multiple radio access technologies (RATs) of various cell sizes, is referred as a multi-tier, multi-RAT network.

Recently, LTE-Advanced [25] has introduced the concept of multi-tier networks where small cells are overlaid on the macro-cells in order to overcome the challenges related to network resource management and coverage gaps. The study in [24] has mentioned the effectiveness of such BS densification methodology to enhance network performance in terms of capacity, coverage, spectral efficiency, and power consumption. However, increasing the number of small cells introduces the following challenges [24]:

- **Co-tier interferences** : due to unplanned small cells deployment and lack of coordination between different tiers.
- **Handover** : due to small coverage distance, mobile users frequently move in or out of coverage area, resulting in a high number of handovers with an increase in ping-pong effects.
- **Back-hauling**: the key challenge is to design the back-haul network to connect

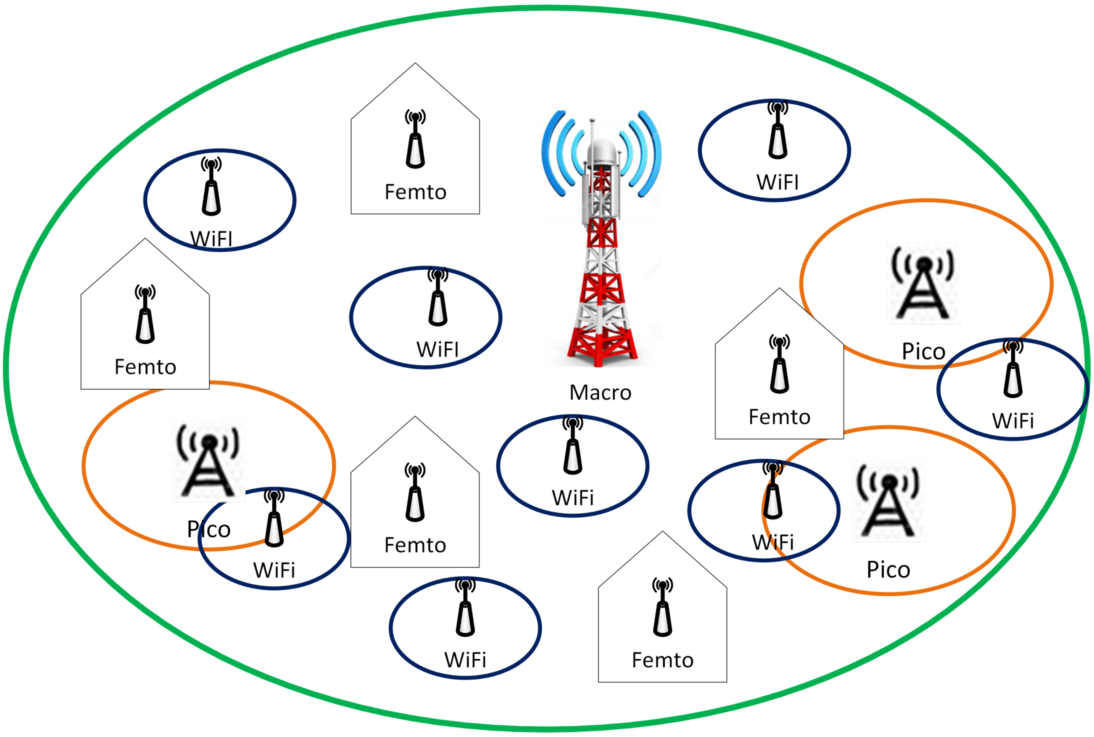

Figure 2.2: Multi-tier, multi-RAT network environment.

complex topologies of the various types of coexisting cells.

Besides, LTE-Advanced architecture [26] includes heterogeneous networks, known as HetNEts that combine conventional outdoor cell towers with the newer concept of small cells located on buildings or even light poles. Also, to take advantage of unlicensed spectrum, in its releases 13 and 14, the 3GPP project introduced the LTE- WLAN aggregation (LWA) standard that anticipates the integration of LTE and Wi-Fi technologies in the same mobile devices and the device can be configured to utilize both the LTE and Wi-Fi links simultaneously [27].

The deployment of multi-tier, multi-RAT networks is fueled by the cellular network as an instrument to meet the higher increase of data demand. The main advantages of deploying small cells include solving network capacity issues, eliminating dead zones present in macro-cell coverage areas, and better throughput, to mention a few. Small cells solve network capacity issues by offloading macro-cell base stations where the unlicensed Wi-Fi is integrated with cellular technologies for offloading purposes. Secondly, small cells are deployed in areas of poor coverage such as cell edge or indoor areas. The distance between the user and small cell base station is relatively small and this translates into the higher signal quality that leads to better throughput. Further- more, deploying small cells reduces the number of macrocell towers which consume high power, and thus they are environmentally friendly as they provide a cleaner signal at less transmitting power. However, small cell deployment has met various challenges from a technical perspective. The increased number of small cell base stations leads to frequent handovers, particularly for medium to high-speed mobile nodes. Most of these handovers result in handover failure due to the limited coverage area of the small cell BS and thus implies an increased number of packet drops that may affect the service quality of the on-going communication sessions. Moreover, multi-tier networks require some optimized engineering mechanism to eliminate interference since small cell BSs are deployed by users in arbitrary locations.

Needless to mention, network operators need innovative techniques to handle ever-increasing data demands. The precipitous growth in IoT will create an exponential increase in data demand which cannot be met with todays network capacity. In order to provide the necessary coverage for IoT, small cells must be densely deployed on a wide-scale basis, and this calls for a new innovative network selection mechanism, which will optimize handover management in multi-tier, multi-RAT network environments. The following subsection discusses two standard mechanisms, which were developed to facilitate network selection in a heterogeneous wireless network environment composed of various access technologies.

2.2.5 Network selection standards

To facilitate fast and seamless handover in an area with overlapping multi-RATs, two standard protocols were independently proposed by IEEE and 3GPP: Media Independent Handover (MIH) proposed by IEEE and Access Network Discovery and Selection Function (ANDSF) proposed by 3GPP [28]. Both MIH and ANDSF are utilized for providing a mobile node with rich information about neighbouring cells for a fast handover.

- **Media Independent Handover (MIH)**

The MIH (IEEE 802.21) protocol defines procedures and methods to facilitate neighbourhood network discovery, as well as the selection and handover activities between heterogeneous networks [29]. MIH lists all available radio access technologies in the vicinity along with their operator ID, security mechanisms; cost, QoS, capabilities (such as emergency services) etc. This protocol was primarily defined to support handovers between IEEE 802.x networks and cellular technologies, which are the main candidate V2I communication underlying network technologies [30].

The MIH defines three main services: Media Independent Event Service (MIES), Media Independent Information Service (MIIS) and Media Independent Command Service (MICS). While the MIES detects the changes on the lower layers, the MIIS allows the MIH to discover its network environment by gathering information that the upper layers use to make decisions. This information includes the location of neighbouring PoA, operator ID, roaming partners, cost, security, QoS, PoA capabilities, and vendor-specific information, among others. Finally, the MICS allows the MIH client to take control over the lower layers through a set of commands. The MIH client decides to switch from one PoA to another based on the information gathered by these three services. The primary design principles of the MIH standard are defined in [31].

Concerning V2I communications over heterogeneous networks, MIH will not only provide a list of available RATs, but also the relevant information to enable the vehicle to select the appropriate target network [32]. However, the MIH function in its current form will not assist the vehicle with providing a prioritized list of candidates RATs (e.g., those RATs lying in the future vehicle direction). Consequently, the vehicle will spend much time scanning all available candidate RATs, while only a few of them could be potential candidates to which, the vehicle may handoff to, in the near future. This may result in increased overall handover latency, which implies more packet loss, and affects the required service quality. Thus, the current MIHF needs modifications to fit V2I communication requirements.

- **Access Network Discovery and Selection Function (ANDSF)**

The Third Generation Partnership Project (3GPP) Release 8 has introduced the Access Network Discovery and Selection Function (ANDSF) entity within an Evolved Packet Core (EPC) of the System Architecture Evolution (SAE) for 3GPP compliant user equipment (UE) to automatically discover and select the most suitable underlying wireless access network based on certain priorities and policies that are predetermined by network operators. Although, ANDSF was introduced primarily to discover non-3GPP access networks (e.g., Wi-Fi and WiMAX), in latter 3GPP Releases (10-12) [33], this has advanced to the extent of supporting the UE to discover, select and connect to both non-3GPP and 3GPP access networks (UTRAN, LTE and HSPA) UE [34]. ANDSF protocol makes network transitions seamless for end users and network traffic manageable for service providers. Unlike traditionally preferred roaming lists (applied on the 3G network) which were static, ANDSF is a HetNEt solution which determines the most appropriate network to select based on rules evaluation and operator objectives [35]. ANDSF provides not only a list of networks that may possibly be in its service area but also suggests a network priority list, to the UE [34].

The ANDSF server is able to interact with it through the OMADM (Open Mobile Alliance Device Management) protocol over the S14 interface in the 3GPP EPC [33]. This interface supports both push and pull data communication methods [36].

For efficient communication between the ANDSF client and the ANDSF server, ANDSF protocol consists of various ANDSF management objects. Among these objects, three are frequently used: the UE location management object (UEL-MO), Network Discovery Information (NDI) Management Object (NDI-MO), and ISMP Rules management object (ISMP-MO). The UEL-MO dynamically monitors and reports the devices actual network location to the ANDSF server. This enables the optimal usage of heterogeneous network resources, as well as improving the user experience by enabling the best connection at any moment or any location. The NDI-MO contains access and location information which expedites the connection to the desired network. However, NDI information does not specify when or how the device should use the network. Finally, the ISMP-MO defines the policy rules for the device to discover, select and establish a connection into a network using guidance such as validity conditions and access priority [37].

- **MHI Vs. ANDSF**

Unlike the MIH protocol, ANDSF provides UEs with a list of networks that may possibly be in its service area, along with their geographical coordinates, which may enable the mobile node to pre-select and store potential target networks, to which it may likely handoff to in the near future. Consequently, with respect to V2I communication of heterogeneous wireless networks, we consider that ANDSF must be taken into account while designing a vertical handover architecture.

The objective of this thesis was to develop novel network selection mechanisms suitable for high-speed mobile nodes, such as vehicles. The following sections discuss the viability of HWN to support V2I applications.

2.3 V2I Communications

As was stated in the introductory chapter, in V2I communication, vehicles exchange data or connect to the Internet through fixed roadside infrastructure components, called Road Side Units (RSU). The RSUs, connected to the backbone IP networks, communicate with the vehicle on-board units (OBU) to receive and transmit different on-road information (e.g., on-road traffic calculations, accident warnings etc.) from and to nearby vehicles as they pass by [3]. Based on the type of transmitted information, V2I communications define three main applications that are discussed in this section. Furthermore, the viability of the integrated multi-tier, multi-RAT heterogeneous networks to support V2I communications is discussed and the related challenges are presented in Chapter 3.

2.3.1 V2I Applications

Vehicular network applications include both safety and non-safety-related applications. Safety applications may include driver assistance and road hazard warning applications. The non-safety applications could be road traffic management, remote vehicle diagnostics, air pollution monitoring, and onboard comfort and entertainment [2]. These applications are supported through V2V and/or V2I communications using various underlying wireless technologies. The V2I applications and related use case examples are discussed next.

2.3.2 Safety-related applications

These applications provide drivers of vehicles with information about different hazards and situations they generally cannot see. These applications include hard safety (time-critical) and soft safety (less time-critical) applications [38]. While the former

Table 2.2: V2I safety applications.

Type of Application	Brief description	Potential benefits
SWIW/OVW [39]	This application warns drivers about severe weather conditions that may impact travel conditions	The driver takes extra care to avoid any weather-related accidents
RSZW [39]	RSZW increases the vehicles driver awareness about the posted speed limit in reduced speed zones and changed roadway configurations.	Avoids any possible accidents for pedestrian or infrastructure destruction at work zones
RCVW [39]	RCVW is designed to warn drivers about railroad crossing locations	Avoids any possible crash between a vehicle and train
SVW [39]	SVW increases vehicle's driver awareness about stop-sign locations	No Stop-sign violation

aim to avoid imminent hazards/crashes and minimize damage when crashes become unavoidable (mainly supported by V2V Communications), the later primarily enhance driver safety awareness without requiring any instantaneous reactions. In V2I safety-related applications, achieving the required low latency which generally varies from under 100ms, is the typical challenge [39]. Thus, V2I communications are expected to support soft safety applications, which include intelligent traffic signs, weather conditions, construction zones and traffic congestion. The study in [39] has explored various cases of V2I road safety applications, which are summarized in Table 2.2. Additional work on V2I safety applications can be found in [40].

2.3.3 Traffic efficiency and management applications

These important applications aim to improve the management of traffic on the roads by providing users with traffic assistance and by updating local traffic information. A vehicle or RSU collects information about traffic conditions, passes this information to other vehicles either directly or through a remote server, enabling them to choose an alternate route, which optimizes the travel time. Speed management (e.g., regulatory contextual speed limit notification and greenlight optimal speed advisory) and co-operative navigation are the primary examples of traffic management applications [41]. Typical actions in response to traffic management messages would be to proceed with caution or to take an alternative route to avoid the dangerous conditions ahead.

2.3.4 Entertainment and personalized applications

These applications may help to extend internet access to the moving vehicle so that passengers may continue working on their office work while on the move. Passengers are not only able to access different web applications, but also applications relating to VoIP, video, multimedia streaming, navigation and localization services [42]. Examples of such applications include searching for the nearest gas station or looking for the nearest McDonalds restaurant. These applications do not usually suffer from stringent communication constraints, like restricted latency or packet loss, although high data throughput may be occasionally required. The effectiveness of these applications depends on the capability of V2I communications underlying network technologies. While the WAVE enabled RSUs to provide reduced latency for V2I communications, the development of cellular technologies has extended their capabilities to provide reduced latency for safety applications [43]. The study in [44] has shown that the recent version of Long Term Evolution (LTE) provides low transmission latency, very high data rate ($> 100Mb/s$) and it can tolerate high mobility. Both of these features are imperative for road safety applications. Radio Access technologies (RATs) such as Wi-Fi, WiMAX, 3G and 4G networks can work cooperatively to support these applications.

2.3.5 QoS requirements of applications-based on V2I communications

Different vehicular network applications require a different quality of services. Safety related applications, which include driver assistance and road hazard warning applications, are highly delay-sensitive. Safety messages must be delivered to neighbourhoods within 100ms [41]. The non-safety applications, which comprise road traffic management, remote vehicle diagnostics, air pollution monitoring, and on-board comfort and entertainment, do not usually suffer from stringent communication constraints like restricted latency or packet loss, although high data throughput may be occasionally required. Moreover, the passengers on board are not limited to some real-time applications such as video conferencing and VoIP, which requires less end-to-end latency and jitter. Table 2.3 summarizes one-way end-to-end latency requirements and the traffic characteristics of delay-sensitive applications defined by ITU [45].

2.3.6 V2I in multi-tier, multi-RAT environment

WAVE (IEEE 802.11p/1609) (discussed in Section 2.2) is currently the primary standard to support vehicular networks. However, its main weakness lies in intermittent connectivity, especially during low vehicle density (during non-peak traffic hours or on rural roads where vehicles are far apart). The WAVE protocol can be used for V2I communication if RSUs are ubiquitously deployed along the roads. However, that may incur high infrastructural costs. The best way forward is the incorporation of the WAVE protocol in heterogeneous RATs such as Wi-Fi, WiMAX, 3G and 4G

Table 2.3: Latency requirements for delay-sensitive applications.

Applications	**Latency Requirements (ms)**	**Traffic characteristics**
Safety applications	Critical safety ≤ 100 Safety warning ≤ 100	Event-Driven Periodic
Video Conference	preferred: ≤ 150 acceptable 150-400	continuous traffic
VoIP	preferred ≤ 150 acceptable: 150-400	continuous traffic
Game	action: ≤ 80 Interactive: ≤ 250	continuous traffic

cellular networks to support V2I communications [17]. As shown in Figure 2.3, the WAVE-enabled RSU is located at road intersections for relaying and broadcasting communication traffic. Because RSU setups are expensive, they cannot be deployed throughout the road. Consequently, numerous researchers have suggested the use of heterogeneous networks for V2I communications [17, 42, 43, 46].

As was discussed in the previous section, the future generation of heterogeneous networks integrates different access technologies characterized by various cell sizes which add a number of opportunities and challenges associated with the inter-system handover. Smaller network deployments, with reduced distances between receivers and transmitters, provide an efficient solution to scarce radio resources by improving spectral reuse and link quality. V2I communication can enjoy the following benefits from networks with smaller cell sizes: improved quality of received signal due to a reduction of the distance between transmitter and receiver, and ubiquitous coverage at certain points of interest like road intersections and bus stops. On the other hand,

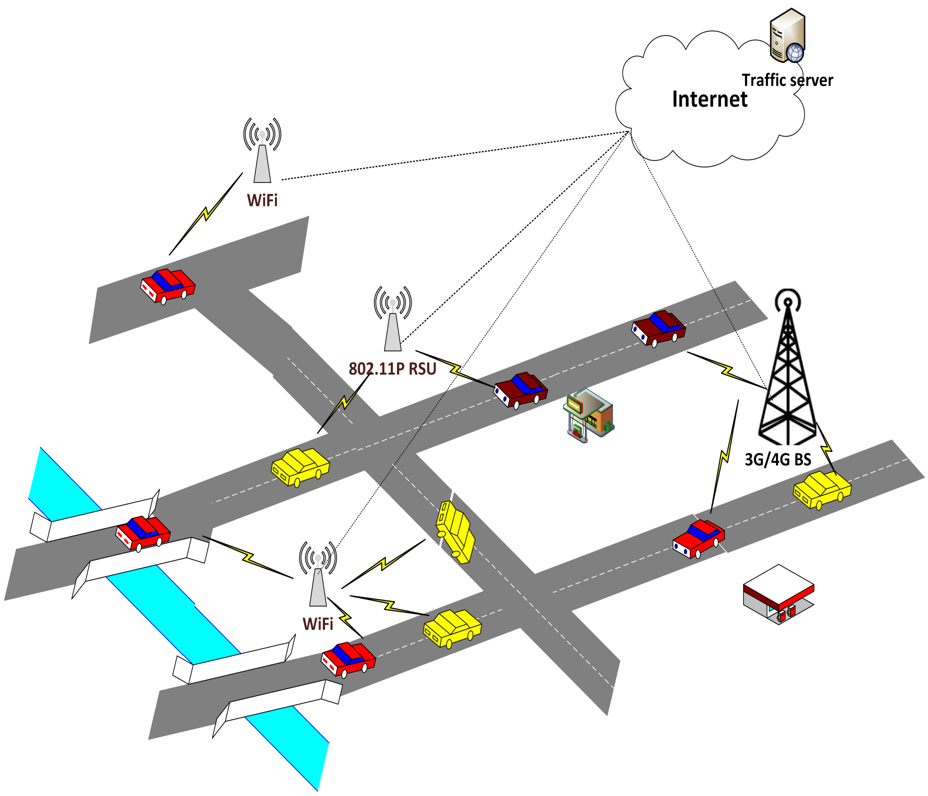

Figure 2.3: Integration of WAVE protocol and evolving RATs to support V2I communication.

vehicle speed will be a problem for multi-tier networks. For a vehicle moving at high speed in a multi-tier network environment having multiple low coverage underlying cells, it will lead to unavoidably frequent handovers, thereby increasing the chances of ping-pong activities. For example, in the scenario shown in Figure 2.4, multiple small cells are deployed under the coverage area of an overlaid macro-cell to boost the traffic capacity and communication link quality, especially at the edge of the macro-cell.

A vehicle moving within such a networking environment will have to cross the coverage areas of all these cells, which may even be governed by different service providers. Such movements may result in multiple handovers from macro to pico or pico to femto or femto to macro with the considerable possibility of increasing ping-

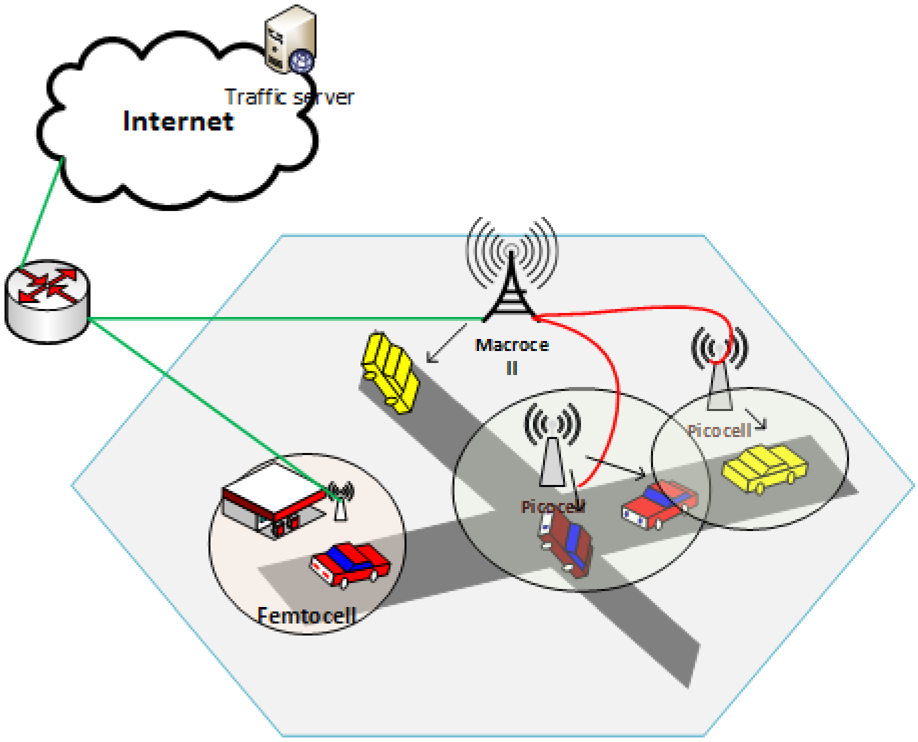

Figure 2.4: V2I communication in a multi-tier scenario. Green lines represent backhaul, red lines represent macro-to-pico-cell communications and arrows show wireless links.

pong effects. These effects not only waste valuable network resources but also hamper the handover performance. Under such circumstances, the communication system in the vehicle will have to decide whether the best choice is to connect to the macrocells BS or to a picocell/femtocells BS. By connecting to a picocell/femtocells BS, the transmission distance between the vehicles OBU and RSU (picocells BS) is relatively small, resulting in improved link quality. From the point of view of achieving high link quality, vehicles located at the cell edges are better off connecting to available small cell BSs. However, as the travelling duration under small cell coverage areas is relatively less, a vehicle will frequently switch cells performing unwanted handovers, which may lead to packet losses. These unnecessary handovers become a potential challenge for real-time applications. In the context of such situations, one may suggest the use of small cells only for delay tolerant applications and moving the delay sensitive application users from small cells to the macro-cell. For instance, a vehicle under the coverage of a small cell may download and cache more bandwidth-hungry data, e.g. delay tolerant multimedia data, such that passengers can keep using the cached data when the vehicle moves out of small cell coverage areas. On the other hand, for delay sensitive on-going real-time applications (e.g., VoIP, on-line gaming and video conferencing), it is beneficial for the vehicle to stay connected to macro- cell BSs. While Table 2.4 presents the notable features of candidate RATS to support V2I communication, Table 2.5 shows different technologies used in different proposals. As it can be seen from Table 4, apart from DSRC (IEEE 802.11p) dedicated for vehicular communications, LTE was the most proposed to support V2I communication.

The decision to switch to an available small cell or remain connected to the macro-cell may also require a multi-parameter (e.g., speed, coverage, and data rate) based algorithm. This algorithm would calculate the time required to cross the cell coverage area, then compare that computed time with the estimated handover latency, and finally, make the decision based on the computed results. In this context, it is also worth noting that small cells are more beneficial to fixed or nomadic network users rather than to high-speed mobile users traveling in vehicles.

2.4 Adopted Handover Performance Approach

The primary factors that affect service quality of V2I communications over the multi-tier multi-RAT heterogeneous networks are associated with handover activities due to

Table 2.4: Wireless technologies for on-the-road communications.

Feature	**Wi-FI**	**802.11p**	**UMTS**	**LTE**	**LTE-A**
Channel width	20 MHz	10 MHz	5 MHz	1.4, 3, 5, 10, 15, 20MHz	Up to 100 MHz
Frequency band(s)	2.4 GHz, 5.2 GHz	5.865.92 GHz	7002600 Hz	7002690 MHz	450 MHz4.99 GHz
Bit rate	6-54 Mb/s	327 Mb/s	2 Mb/s	Up to 300 Mb/s	Up to 1 Gb/s
Range	Up to 100 m	Up to 1 km	Up to 10 km	Up to 30 km	Up to 30 km
Coverage	Intermittent	Intermittent	Ubiquitous	Ubiquitous	Ubiquitous
Mobility support	Low	Medium	High	Up to 350 km/h)	Very high (up to 350 km/h)
QoS support	EDCA	EDCA	QoS classes	QCI	QCI
V2I support	Yes	Yes	Yes	Yes	Yes
V2V support	A-hoc	Ad-hoc	No	No	D2D
Market penetration	High	Low	High	Potentially high	Potentially high

Table 2.5: Wireless network technologies used for V2I communications.

Proposals	**DSRC**	**Wi-FI**	**WiMAX**	**UMTS**	**LTE & LTE-A**
Multi-RAT based V2I [6]	-	X	X	X	-
LTE for Vehicular network [42]	-	-	-	-	X
Vehicle safety communications [30]	X	-	-	-	X
WiMAX-based V2I [15, 18]	-	-	X	-	-
WAVE [2]	X	-	-	-	-
Hybrid HTE & WAVE [23]	X	-	-	-	X
LTE-V2X [22]	-	-	-	-	X

high mobility characteristic of vehicular networks. Consequently, the performance of a typical handover mechanism can be measured with respect to the handover latency, the number of handovers as well as handover failure probability. This section depicts methods for QoS performance adopted in this thesis.

It would be very costly to actually implement a realistic multi-tier multi-RAT heterogeneous network and get a smart vehicle with OBU embedded with multiple RAT interfaces. Thus, this research will adopt computer simulation to test and evaluate the performance of the proposed handover approaches for V2I communications over multi-tier heterogeneous wireless networks. Moreover, simulation methods provide means of varying different network metrics leading to a generalization of the research findings.

Various simulators have been surveyed including OPNET (Optimized Network Engineering Tools) Modeler which is widely used as a simulator tool for modelling telecommunications networks [5], RUNE (Rudimentary Network Emulator) which is a number of MATLAB functions that together make it possible to simulate a cellular radio network [47] and VeinS (Vehicle in network Simulation) which is an open source framework for running vehicular network simulations [48]. Both OPNET (Riverbed) and MATLAB will be used for system performance evaluation. While OPNET is used to study the performance of the whole network, MATLAB is used to evaluate the performance of the mathematical algorithms primarily owing to the ease of integrating Google Map with it. The proposed methodology is appropriate for my work, which is supported by key network researchers [6, 49].

In this thesis, the performance evaluation is presented for all proposed handover algorithms, presented in Chapters 4, 5 and 6. While all proposed handover methods are simulated in the same network environment (integrated LTE-A and Wi-FI technologies), it is considered that for each algorithm a multi-interface mobile node (vehicle OBU) is modelled according to the proposed network selection approach.

Furthermore, the effectiveness of the proposed algorithms is evaluated in comparison with the performance of the conventional handover scheme that select the target network based on received signal strength and one handover method selected from the existing related studies.

2.5 Summary

This chapter discussed different radio access technologies that are candidates to underlay V2I communications. While Table 2.4 presented the notable features of candidate RATs to support V2I communication, Table 2.5 showed different technologies used in different proposals. As can be seen from Table 2.5 , apart from DSRC (IEEE 802.11p) dedicated for vehicular communications, LTE was the most favoured technology proposed to support V2I communication. Besides, it is now believed that V2I applications will be supported by heterogeneous multi-RAT networks to provide vehicles with a ubiquitous connectivity anywhere, any time. However, the primary challenge of V2I communication in multi-RAT environments is the occurrence of frequent vertical handovers due to the high mobility of vehicles. Deployment of a system selection and mobility management agent (SSMMA) on both vehicles and networks was proposed as a solution to handover issues [17]. The existing handover approaches for multi-tier heterogeneous networks are reviewed in Chapter 3. Also, the challenges which may arise by applying those approaches for V2I communication scenarios are discussed.

Chapter 3

V2I Over Heterogeneous Networks: a Review

3.1 Introduction

Chapter 2 has discussed different technologies that could be utilized to underlay V2I communications. In addition, the interoperability of these technologies, also known as a heterogeneous network was discussed. A primary objective of this thesis is to optimize handover decision in multi-tier heterogeneous wireless network (HWN) in terms of reducing handover latency as well as the number of unnecessary handovers. To achieve this objective, a clear understanding of the existing related studies is required. These studies are reviewed in perspective of different challenges in supporting V2I communications over HWNs. This chapter explores challenges related to handover processes such as detecting available networks, selecting and connecting to an optimal network as well as maintaining acceptable QoS for an ongoing session during handover.

3.2 Efficient Network Discovery

In the near future, the world will experience the commercial deployment of 5G networks constituting heterogeneous multi-tier, multi-RAT networks that will support V2I communication-based diversified services. Maintaining effective QoS and Quality of Experience (QoE) for those services will require the fast and efficient discovery of available underlying networks by vehicles [46]. While moving from one location to another, vehicles will need to cross a number of heterogeneous small networks and, due to their very high-speed of movement, vehicles may quickly move in and out of the coverage areas of underlying networks performing handover activities. Ensuring seamless network connectivity requires faster and seamless vehicular handovers with the underlying network systems. Thus, more network discovery time implies more overall handover delay and deteriorated communication performance, which includes packet loss and potential session disruptions. Therefore, the efficient discovery of underlying networks is one of the key challenges in V2I communication over 5G networks.

Potential Research Solutions: A considerable number of research activities have been carried out in this context. In addition to MIH [29] and ANDSF [33] discussed in 2.2.5, this subsection discusses notable solutions proposed to improve network discovery process including Hotspot 2.0 and some other studies available in the literature.

The emerging industry initiative, the Hotspot 2.0 introduced by the Wi-Fi Alliance uses the IEEE 802.11u standard to improve the users experience of Wi-Fi roaming [50]. Hotspot 2.0 aims to assist Wi-Fi devices to automate the process of underlying network discovery, selection, authentication, registration and connection to the most suitable and available Wi-Fi hotspots in the region. In the context of V2I communications, this could make Wi-Fi technology a suitable underlying network, once ubiquitously deployed. However, most of these approaches consider multi-mode or multi-SIM UEs, which are more expensive.

In addition to different standard solution [34, 46] that facilitate the UE to effectively discover neighbour networks that are available in its vicinity, numerous researchers invested effort in developing various approaches, which improve the network discovery procedure in terms of energy and time that the UE spends during the network discovery phase [51–53]. To minimize the power consumed by the UE while scanning neighbouring cells for a future handover, a recent study [51] applied graph theory to devise a network scanning mechanism which limits the potential candidate networks to only those share cell boundaries with the serving cell. Thus, the UE can save some energy by only scanning a few BS/APs. Additionally, this approach reduces the overall handover latency due to a reduced number of candidate BSs to be scanned. Similarly, the authors of [52] proposed an approach that considers the use of UE mobility state estimation for small cells discovery in multi-layer networks. This goal was achieved by prolonging the measurement periods which resulted in infrequent measurements of small cells.

While energy is a critical issue for normal ad hoc networks, with respect to V2I communications, vehicles provide continuous power supply, therefore; power is not considered a constraint in vehicular networks. Also the study in [53] utilised the historical movement pattern, current path and digital map to predict the next movement direction, hence the best candidate network is selected from those located in the movement direction. The direct drawback of this mechanism is that the UE should keep the database of previously visited AP/BSs which requires significant storage capacity, and increases the equipments price.

On the other hand, network discovery activities are more challenging when mobile terminals or UEs are equipped with single access technology interfaces. In [54] a new Hybrid Unit (HU) located at network access points is proposed. In this study, two

Table 3.1: Main approaches for network discovery with strengths and limitations.

Approaches	Strengths	Limitations
MIH [46]	Supports heterogeneous handover between 802.x and cellular networks	Does not advise the best network
ANDSF [34]	Improves seamless connectivity between non-3GPP UEs and the 3GPP network. Beneficial to V2I communication	Congestion in core network due to high data rate from non-3GPP UEs
Hotspot 2.0 [50]	Improved handover latency between Wi-Fi cells, suitable for V2I communication once ubiquitously deployed.	Limited to Wi-Fi APs only
Cooperative architecture [54]	The new node, HU coordinate WLAN and WiMAX interoperability.	High delays for real-time applications
Energy based [51–53]	Proposed network discovery mechanism which improves the usage of UE battery	Not directly applicable in V2I communications.

networks (WiMAX and WLAN) are involved and the HU does the network selection between the two. A software defined radio (SDR) platform to coordinate between different wireless accesses technologies in vehicular networks is proposed in [55]. Table 3.1 lists the main approaches for network discovery.

3.3 Underlying Network Selection

Selecting the most suitable available network technology is important for maintaining a satisfactory QoS for an ongoing communication. Optimal selection of underlying networks in the case of V2I communication in a heterogeneous multi-tier environment is always challenging and depends on various parameters, such as: the received signal strength indicator (RSSI), the speed and movement direction of the vehicle, network bandwidth and traffic load, delay, usage cost, etc., to name a few. RSSI is by far the most commonly used selection parameter for a suitable underlying network. Direction and speed of the moving vehicle are also considerably important. Each radio access technology has a maximum mobility limit that it can handle. For example, theres no point for a high-speed vehicle moving at over 120km/h on a free-way to even consider scanning short-ranged Wi-Fi networks or pico-cells with small coverage as that would lead to another network selection very quickly. Similarly, there is no point in considering underlying networks lying in the opposite direction of its movement trajectory. Apart from these, a few other influencing factors include: network bandwidth that varies with types of on-going applications and their requirements, network traffic load to determine the accommodation capability of users, the initial delay that defines the required setup time for a new connection, and usage costs since users would prefer the lower cost when the available networks offer an equivalent QoS.

Potential Research Solutions: Considerable contributions have been made towards proposing different solutions for selecting the appropriate underlying network for a V2I communication. This subsection discusses various approaches that are frequently used in the literature to devise network selection algorithms.

Two mathematical theories, namely: game theory and MCDM or multi-criteria decision making have been applied by a number of researchers for proposing an efficient decision for selecting the suitable network handover in a heterogeneous network environment. Game theory deals with strategic decision-making when multiple agents (players) have conflicting interests or goals [56]. In V2I communication, a vehicle generally tries to select a suitable network offering acceptable QoS and the lowest usage cost. The possibility of multiple vehicles selecting the same underlying network always exists, which may result in poor performance owing to network congestion. This is because the demand for vehicular communication bandwidth will be higher than the traffic handling capacity of the roadside infrastructure. As a potential solution to problems like these, a game theoretic selection of RSUs is proposed in [57] to ensure that all vehicles receive identical resources from the available road side base stations (RSBs). Apart from bandwidth allocation, game theory has been used to analyse various conflicts which may rise in vehicular networks. Refer, for instance, to [58].

On the other hand, MCDM algorithms shall provide a good solution as multiple parameters (network condition, application requirements, user preferences, etc.) are combined in a decision matrix which is the first step for any chosen MCDM algorithm. While MCDM algorithms consist of various techniques, two of them, TOPSIS (technique for order preference by similarity to an ideal solution) and AHP (Analytical hierarchy process) have gained a lot of importance in the network selection process [59]. Both techniques rank available networks based on multiple parameters, like network traffic load, vehicle speed, type of service, etc., and then, the highest-ranked network is selected. Concerning V2I communications, these techniques could be used to combine information acquired during the network discovery phase to wisely rank all available candidate networks based on current application requirements [60]. Here, each network metric is assigned a weight depending on its influence over the vehicles handover decision. One criticism of most of these mathematical theories is linked with required UE computing capacity, which involves high power consumption and enough storage capacity. However, for V2I communications, this problem could be technically solved since the vehicle nodes are not constrained by power supply and storage capacity compared to typical mobile nodes.

Apart from the mathematical theories discussed above, a few other network selection techniques suitable for V2I communication in HWNs were also proposed. Generally, the unique characteristic of the vehicular network is high mobility. Thus, an efficient network selection for V2I communications should take into account vehicle speed, a direction of movement as well as the residence time in the service area of the selected network [61–64]. The authors of [61] have proposed a location aware network selection technique, which selects the proper target network based on estimated residence time under the service area of the selected network. Similarly, the mechanism proposed in [64], the vector of motion is defined and it is used to suggest the potential candidate networks based on direction of movement. The main weakness with both techniques is that the resource availability is not checked before network selection, which may result in an increased handover drop probability. To overcome this weakness, the authors in [65] proposed a network selection mechanism, where the UE initiates handover based on the estimated gain in throughput which may be achieved by handing off to the target network. Also the study in [62], proposed a network access index function, where the important influential factors are: data rate, a direction of movement and vehicle residence time. While the mechanism itself could be efficient in terms of selecting the best target network, the overall handover delay maybe increased by the processing time due to the proposed complex network selection process.

In the context of resource management, most of the UEs served by a macro-cell BS will not handover to small cells as long as the serving cell reference signal is higher than the configured threshold value. Consequently, the small cell resources remain underutilized while macro-cell BSs are overloaded. This problem could be solved by forcing some UEs in the service area of small cells to handoff to the small cell BSs. This can be achieved by adding a positive bias value to the received power signal from the small cells [66]. Thus, more UEs are actively pushed to the small cell service area, though they dont provide the strongest down link signal strength. However, this approach could not be suitable for V2I networks as it may introduce ping-pong effects for high speed vehicles, for which the best choice is connecting to macro-cell BS. The notable proposed approaches for network discovery are summarised in Table 3.2.

Table 3.2: Main approaches for network selection approaches strengths and limitations.

Approaches	Strengths	Limitations
Game theory [56–58]	Network selection based on user satisfaction	May increase handover latency due to processing due to much processing time
MCDM [59, 60]	Network selection based on multiple network parameters	-
Speed adaptation [67]	High-speed vehicles connect to Macro-cell and low speed vehicles to Micro-cells	Overlooks resources availability which may result in handover dropping or blocking
Mobility Based [61,63, 64]	Selecting potential target networks based on direction of movement	
Resource management [65, 68]	Network selection based on the estimated gain in throughput	May introduce ping-pong effects for high speed vehicles
Power signal [66]	more UEs are actively pushed to the small cell service area	May introduce ping-pong effects for high speed vehicles

When considering vehicular mobility, the direction of movement and the coverage area of candidate networks, should be given more weight than other decision parameters such as received power signal and available bandwidth, while deciding an appropriate target network to hand-off to. Thus, this thesis introduced new network selection methods that considers both vehicle mobility and direction information.

3.4 Performing Fast Seamless and Reliable Handovers

According to a recent report from the renowned Gartner Inc., by 2020, there will be around 250 million connected vehicles on the road worldwide with some kind of wireless network connections in them [69]. Presumably, most of these vehicles will maintain connections with the roadside infrastructure and perform frequent vertical handovers on the move from one underlying network to another. To maintain the QoS and QoE for an on-going communication, vertical handovers need to be fast, seamless and reliable. Vertical handovers are associated with challenges such as high handover delays, packet losses (or even call disruptions) and frequent ping-pongs resulting in unsatisfactory service quality.

In 5G heterogeneous environments with a mix of macro-pico-femto cells and different technologies (UMTS, HSPA, WiMAX, LTE, and Wi-Fi), these challenges are likely to be topped up by issues such as frequent unwanted handovers and, at times, wrong handover choices. The handover time needed to complete a successful vertical handover activity can be quite significant. This depends on the degree of compatibility of the networks, the handover procedure followed, and the volume of signalling messages exchanged between the mobile devices and the base stations of the current serving (target) networks by the roadside. If the handovers are not fast enough and the delay is more than the pre-set threshold, it may lead to packet losses and even disruption of on-going high-speed multimedia communications (i.e., not seamless any more).

The occurrence of an increased number of frequent unwanted handovers is likely to happen because of the presence of multiple smaller cells lying on the movement path of a vehicle. This could be a significant problem in urban or semi-urban areas. In multi-tier, multi-RAT heterogeneous environments, for a moving vehicle to choose a not so appropriate (i.e., wrong) target roadside network for handover is likely to hamper mobility performance and may lead to ping-pongs, packet losses and even call drops. To avoid such situations, performing a reliable handover is necessary [70]. Barring a few stray initiatives, the concept of handover reliability has not attracted much research attention and it is widely open.

Potential Research Solutions: A number of interesting research solutions to the above-discussed V2I handover issues had been proposed by the research fraternity, out of which the notable ones include the concept of a single radio controller (SRC), Layer-3 mobility and cross-layer based handovers, handovers based on the movement prediction of vehicles, fast cell selection (FCS) and the concept of macro-assisted small cells, known as phantom cells. Given the low cost of wireless transceivers, the vehicle OBU shall be embedded with more than one radio interface, to enhance the performance of the network by allowing more parallel transmissions in different frequencies [17]. However, the interoperability of different radio access technologies remains an important area of research. In 2013, Huawei introduced the Single Radio Controller (SRC) entity for unified radio resource and traffic management in a multi-RAT environment. This unified controller entity, consisting of integrated RNC/BSC/Wi-Fi controller functionalities, not only facilitates heterogeneous handovers but also reduces the vertical handover latency by minimizing the handover signalling overheads. This is because, in the case of inter-RAT handovers, the SRC directly changes the radio interface of RATs without involving the backbone core network in the handover procedure, thus resulting in fast handovers [71]. Similarly, the 3GPP has standardized the intra-RAT handover procedures for LTE systems in its Release 9-12 [72, 73]. However, whether the standardized procedures can adequately manage inter-RAT selection process and handovers in 5G multi-RAT dense networks (DenseNets) without degrading the performance has not yet been tested. For example, the LTE X2-interface does not support handovers between LTE and non-3GPP technologies and the Packet Gateway (PGW) in the 3GPP Evolved Packet Core (EPC) backbone network manages those inter-RAT handovers. It is not clear how the 3GPP backbone EPC will function in a multi-RAT heterogeneous environment to facilitate seamless handovers between LTE (and other 3GPP technologies) and non-3GPP technologies (e.g., WiMAX/Wi-Fi). Recent simulation studies performed by a 3GPP study group have shown that mobility performance of user equipment moving at high-speed across heterogeneous multi-tier networks (mix of small and macro cells) small cell environments is poorer compared to pure macro-cell environments [74].

On the other hand, a fast handover can be performed by minimizing layer-3 latency. A typical approach is proposed in [75] where a vehicle leaving the network passes its IP address information towards the back vehicles entering the cell coverage, relative to the travel direction. This mechanism relies on the VANET multi-hop communication mode. Its key weakness is using the normal DHCP when the distance between both vehicles is too long to pass an IP address. Moreover, this mechanism cannot work with the standard mobile IPv6, since MIPv6-based mobility management systems require each mobile node to have a direct link to the internet gateway to get a valid IP address. In recent years, a few cross-layer handover approaches have been proposed to reduce the vertical handover latency [32]. In these approaches, the layer 2-handover information is used to trigger the layer 3 handover activities in advance resulting in a vehicle to resume IP connectivity with the target network faster. In heterogeneous V2I communication, cross-layer handovers are likely to reduce the packet loss during the inter-handover gap. From the previous discussion (3.3), it can be seen that a fast handover may also be achieved by predicting the movement of the vehicle [76]. The proposed approach determines the next AP to which the vehicle may likely handover in near future, by probabilistically analysing the vehicles current movement. While this approach could speed up the handover process, the study would have been more interesting if it had included mechanisms to avoid ping-pong effects that may cause communication instability. To achieve a stable communication in multi-tier networks, authors in [77, 78] applied the concept of macro-assisted small cells also known as phantom cells. This idea of phantom cells involves splitting control (C-plane) and user planes (U-plane) such that the C-plane of the UE in small cell is managed by a macro-cell BS and the small cell only provides the U-plane. In the context of V2I communication, phantom cells are identified as key technics to enhance handover activity performed by vehicles while moving in and out of coverage since the control signals overhead (negotiation between serving and target eNB) is completely removed for all handover activities are done by the macro-cells BS. Also the normal hysteresis (time-to-trigger) used in conventional handovers can be removed to further provide a fast and reliable handover. However, the implementation of phantom cells is still a challenge due to the required low-latency connection (e.g., optical fiber) between the macro and phantom cells. In the same way, based on FCS (fast cell selection) mechanism, the UE may be enabled to decide which cell in its active set is going to send data in the next transmission time interval (TTI) [79]. While FCS has been originally designed for UMTS handover, authors of [79, 80] applied FCS mechanism to select the best cell for LTE (-A) multi-tier networks. Fast cell selection is a solution tailored for mobility in multi-tier networks and thus it could be an efficient solution for vehicular networks. Further improvements have been proposed in [81] for interference management. This is done by applying a coordinated multi-point (CoMP) strategy, where the UE in multi-coverage region selects a cell with a better link quality. Table 3.3 compares the main approaches proposed to perform fast handovers, based on their strength and limitations.

Table 3.3: Main approaches for performing fast handover with strengths and limitations.

Approaches	Strengths	Limitations
Single radio controller (SRC) [71]	Achieves multi-RAT network synergy. V2I applications can benefit from improved handover latency	SRC failure affects entire heterogeneous network communication
Cross-layer handover [32]	Layer-3 handover is prepared during Layer-2 handover. Improves handovers for high-speed vehicles in small cells environment	Network load is not considered
Mobility prediction [76]	Predicts the future location based on the current movement direction. Thus, handover activities can start in advance.	The approach does not consider the residence time under the target network. Hence, Ping-pong effects may rise.
IP passing [75]	Fast layer-3 handover	Depends on vehicles density
Phantom cells [77, 78]	The macro-cell BS manages the C-plane of UEs in small cells, and thus removes handover control signal overhead	A low-latency connection is required between macro-cell BS and a phantom cell.
FCS [79, 80]	The UE decides which cell in its active set is going to send data in the next transmission time interval (TTI)	The UE must send an uplink signalling to the BS to indicate the selected sector from which the network should direct its data transmission.

Successfully maintaining the quality of on-going communications for users in high-speed vehicles moving through urban 5G multi-tier, multi-RAT dense network environments is a significant challenge. The provision of fast, seamless and reliable vertical handover activities is the key to achieve an effective in-vehicle communication with the diverse roadside base stations. The proposed concept of SRC is promising as it significantly reduces inter-RAT handover latency by minimizing the handover signalling overhead. However, the failure of the SRC entity may lead to a disruption of the whole network. In a way, the multi-RAT handover requires a session context update. To optimize such handovers, the in-vehicle OBU preferably needs to select and establish a link with the target network for handing off before releasing the link with the current serving network and notifying the backbone core network to update the routing of the data packets from the current network to the target network [82]. The handling of ping-pong activities owing to the presence of a huge number of small cells adds a new dimension to multi-RAT handover issues. When trying to optimize the mobility performance in multi-tier heterogeneous network environments, a trade-off always exists between the number of handover failures and ping-pong activities [83]. The high-speed of vehicles (with user equipment and OBUs) makes the situation more complicated.

3.5 Maintaining Effective Quality of Service (QoS)

In V2I communication, services can have different requirements in terms of bandwidth, latency, error rate, delay variation, etc. depending on the type of application running. For example, an on-going video conferencing session requires more stringent bandwidth than non-delay sensitive applications involving simple best effort non-detrimental traffic. Such requirements need to be ensured, regardless of the chosen underlying networks when a vehicle moves from one place to another [84]. In multi-RAT environments, effective QoS mapping mechanisms need to ensure that on-going sessions are not disrupted and the QoS of communication is not degraded when vehicles switch underlying networks. Moreover, the availability of adequate resources to maintain the same level of QoS for the on-going session in the new network is critical. The core QoS challenge in a multi-RAT, multi-tier environment is, therefore, to formulate a proper resource reservation and management mechanism for networks specifically for V2I communication.

Potential Research Solutions: QoS oriented research for V2I communication is primarily focused on differentiated services (DiffServ), resource provisioning based on application requirements, QoS mapping techniques, and IP based QoS provisioning. As pointed out in section two, V2I communication applications include delay-sensitive and delay-tolerant applications. To ensure the service quality of either type, a DiffServ-based QoS design could be used to maintain acceptable service quality for V2I communications in a multi-RAT environment [85]. The proposed approach considers the communication between two groups of vehicles located in the service area of two distant Wi-Fi (IEEE 802.11p) cells that are overlaid by an LTE macro-cell. To maintain an acceptable service quality for various applications, a Policy Provisioning Module (PPM) is used to handle different priority requirements of the multicast sessions coordinated by the MBMS feature of LTE. Although this approach could solve WAVEs intermittent connectivity, it requires the willingness of the LTE operator to upgrade the existing LTE technology to integrate the proposed PPM module. In addition, the service quality highly depends on resource availability in the new network to accommodate the ongoing sessions after the handover is done. In this context, one can argue that handover mechanisms that do not take into account the availability of adequate resources in the target network effectively increase the probability of handover failure or call drops.

While various parameters can be used to monitor network load such as actual free bandwidth and packet transmission end-to-end delay of the target network, the authors in [86], have devised a QoSaware vertical handover algorithm, where the beaconing frequency adaptation module is deployed to monitor the IEEE 802.11p interface buffer. Once the buffer threshold value is exceeded, the handover to LTE is triggered. Though the proposed approach showed interesting results, the study makes no attempt to address the issues of handover stability linked with ping-pong activities, which affect the service quality due to unsuccessful handovers causing high packets loss. To overcome this problem, the study in [62] proposed an access network index function, where factors influencing network selection decisions include the movement direction of the UE and the available bandwidth at the target AP/BS. Despite various approaches proposed to improve V2I communication in a heterogeneous environment, seamless integration of different network technologies remains the key challenge (discussed in Section 3.1). In recent years, researchers have proposed few loose and tight coupling based integration techniques [87–89] aiming to effectively map the QoS traffic between the source and target networks after a vertical handover activity. In tight coupling integration, both data and signalling traffic originating from non-3GPP networks are transferred through the 3GPP networks [87]. Although, tight coupling-based integration mechanisms could provide solutions to the centralized control problems, they are not very efficient in terms of supporting scalability in V2I communication. In cases where the network traffic hugely increases with the increase in the number of vehicles, high speed non-3GPP (e.g., WLAN) RSUs shall receive high traffic from vehicles and this traffic is fed into the 3GPP network resulting in network congestion. On the contrary, in loose coupling architectures, each underlying RAT would independently implement its relevant protocols and QoS classes and all networks are interconnected via gateway nodes [88]. With this type of architecture each network functions relatively autonomously resulting in a simple and cost-effective implementation. However, handover execution time may increase due to the enhanced requirements of handover signalling between gateway nodes [89]. Thus, in the context of V2I communication, loose coupling-based schemes could only be suitable for delay tolerant applications, due to increased handover latencies. On the other hand, the common part of all existing and future heterogeneous wireless networks is the IP protocol. Thus, the IP layer could be the best location to deploy QoS mechanisms for the unified multi-RATs technology. In such an environment, the QoS requirements could be analysed per packet-basis to make an efficient decision of selecting a suitable RAT. That type of approach is proposed in [90] and extended in [91]. In both papers, an adaptive cross-layer QoS module is proposed and it works as an additional entity at the IP layer. The mobile node, continuously, collects QoS parameters (end-to-end delay, bit error rate, packet loss etc.) from all available RATs, and store them in the proposed module. Before any transmission of an IP packet, this database is used to select the wireless technology, which fits well with the required QoS for the on-going service. While the approach proposed in [90] is only applicable for UE that uses a single interface at a given time, the authors extended the study in [91], where the new approach enables the so called 5G mobile terminal (5GMT) to simultaneously access different wireless networks at the same time for a given multimedia service. Although this approach seems promising in terms of providing required QoS over heterogeneous RATs, the direct drawback is the required updates in the existing standard IP protocol. In addition, this approach could introduce an increased end-to-end delay due to the additional adaptive QoS processing which makes it not suitable for V2I communication, particularly for time-critical safety applications. The main approaches for QoS provisioning in V2I communications are compared in Table 3.4.

Table 3.4: Main approaches for QoS provisioning With strengths and limitations.

Approaches	Strengths	Limitations
Multi-criteria-based [62]	Less handover drop probability due to UE mobility and BS load based network selection	-
Tight Coupling [87]	Seamless connectivity	Traffic from high data rate Non-3GPP RATs will make the 3GPP network congested.
Loose coupling [88]	Independent RATs are connected via gateways	High handover latency due mobility signalling traversing long distance
DiffServ-based QoS [85]	Seamless connectivity	LTE upgrade is required
Resource-based [86]	Lower number of vertical handovers	It may increase ping-pong effects, since coverage area is not considered.
IP-based QoS provisioning [90]	Integration of a new module at the IP layer, which selects the RAT based on QoS requirements	The new module calls for changes in the existing standard IP layer.

3.6 Summary

In this chapter, we identified and discussed four key research challenges for V2I communication over heterogeneous multi-tier and multi-RAT network environments. Most of the challenges are related to mobility management, including, network discovery and selection, fast and reliable handover and maintaining an acceptable QoS during handover activities.

Sections 3.2 and 3.3 discussed the primary issues along with related research proposals in network discovery and selection for V2I communication over multi-tier heterogeneous networks. Despite the research advancement in network discovery, there is a need for minimizing the network discovery time for the relevant underlying networks to which the vehicle intends to connect with. In the context of network selection, a non-optimal network selection method may degrade the handover performance. In spite of the existing research advancements, considerable scope still exists in terms of proposing an efficient and intelligent network selection mechanism supporting QoS and QoE. On the other hand, Section 3.4 reviewed the key issues with vertical handover in heterogeneous multi-tier, multi-RAT environments, namely, frequent ping-pong activities and carrying out handovers to non-optimal networks. With respect to QoS requirements in V2I communication, Section 3.5 revealed necessity for designing standardized mechanisms to satisfy the QoS requirements in the heterogeneous network scenario without hampering the performance of on-going communications. The work done in this thesis focused on these four key challenges by proposing three new network selection methods, suitable for V2I communications. Next in Chapters 4, a distance-based network selection method for handover is presented.

Chapter 4

Distance-Based Fast Handover Method for V2I Communications

4.1 Introduction

In Chapter 3, a review of the handover decision approaches was presented. The primary objective of this thesis is to speed up overall handover activities and thus improve the quality of service for on-going applications during handover. This is achieved by enabling the mobile terminal (MT) to start handover procedure well in advance before a handover request is initiated. This chapter presents a simple but effective distance-based handover algorithm for V2I communications (V2I-DHA) which minimizes the number of unnecessary frequent handovers for a vehicle OBU crossing a multi-tier multi-RAT network. Although there were previous studies [70, 92] on improving handover management for heterogeneous wireless networks, the approach taken in this thesis considers not only the coexistence of different radio access technologies but also multi-tier feature that is already deployed for a cellular network such as LTE-A. The chapter starts by introducing the idea behind the V2I-DHA algorithm and the key contributions to handover management in a multi-tier multi-RAT network. The previous related studies are discussed in 4.3 while Section 4.5 gives the details of the algorithm. Section 4.6 presents performance study. Experimental setup and simulation results are presented and discussed in Section 4.7 and the chapter is summarised in Section 4.8.

4.2 Discussion

In a multi-tier heterogeneous wireless network environment, selection of the candidate network for handover is a complicated and time-consuming process. Whenever a vehicle on the move from one location to another decides on a handover, it has to select the candidate network from a considerable list of available nearby networks. This list is formed based on the RSS values received from neighbouring cells. These cells include those that are either not located in the vehicles movement direction or for which the crossing time is not sufficient for handover activities. Thus there is a high probability that handover may be carried out to a not so appropriate network which results in handover failure.

Figure 4.1 illustrates a scenario where a vehicle is moving from across a multi-tier heterogeneous network environment in the direction of the arrow. The macro-cell cellular network overlays the multiple micro-cell networks of limited coverage that are installed as road-side units (RSU). However, the micro-networks provide higher bandwidth and are relatively more cost-effective than the macro network. As it can be seen from this figure, RAT_3 is out of the direction of movement and the visiting time of the MT in the service area of RAT_1 is too small compared to RAT_2. In this situation, the traditional RSS-based cell selection will try to initiate a handover request to both RAT_1 and RAT_2; however, both handover trials will eventually fail due to the speed of movement. Generally, failure in handover affects the service quality of the on-going sessions, particularly delay-sensitive applications such as VoIP and video conferencing. Moreover, unwanted frequent handovers consume network resources due to an increased number of exchanged handover messages between MT, serving BS and the target BS.

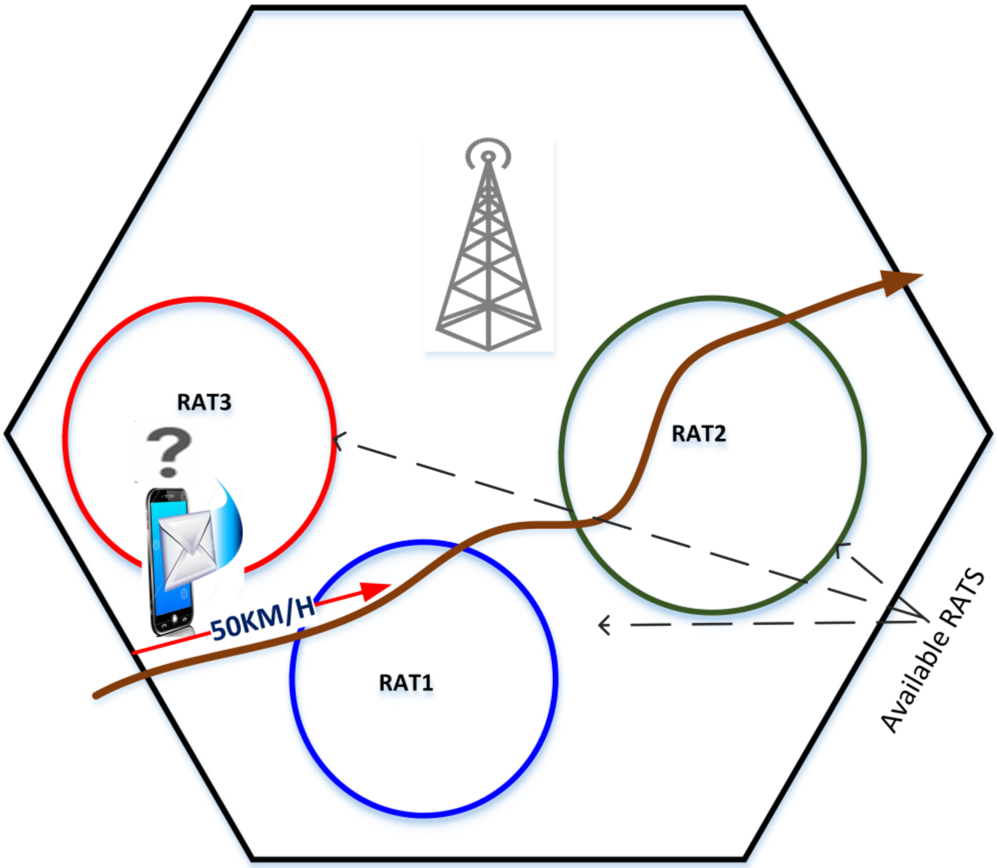

Figure 4.1: Cell association challenges in a multi-tier heterogeneous network.

In this chapter, we present a simple but effective distance based network selection algorithm that enables the MT to pro-actively evaluate all candidate networks and the handover request is sent to the most promising candidate network. The term vehicle OBU represents the wireless communication device embedded in the vehicle that exchanges messages with on-road BSs, also know as roadside units (RSU).

4.3 Previous Work

A considerable network selection schemes to improve the performance of handover in HWNs have been proposed and notable solutions have been proposed in the relevant literature. This section, for brevity, discusses only a selected set of literature (Sections 3.2 and 3.3) that is directly related to the network selection algorithm proposed in this chapter.

Guo at al. in [61] proposed a mechanism to improve the performance of handover in an HWN comprising WiMAX and WiFi RATs. The idea is to include neighbouring network information in the $WiMAX\_MOBNBRADV$ message, periodically sent to the mobile terminal and thus the latter selects the target network based on the value of the cell coverage radius. Similarly, the handover scheme in Mobile WiMAX is proposed by Ray et al. in [70], where the geographical position of the neighbouring base station and the direction of mobile terminal are used to determine a short list of potential candidate networks, from which the best candidate is selected based on two criteria: orientation matching and received signal strength. The main weakness with both techniques is that the resource availability is overlooked, which may result in increased handover drop probability.

Xie et al. [62] designed a handover mechanism that combines multiple parameters to decide the most appropriate target network for a near future handover. Instead of RSS-based network selection used in traditional handover, the best target is selected based on data rate, the direction of movement and the vehicle residence time.

Jeong et al. [92] designed a handover method that would prevent unnecessary macro-to-femto handovers in a multi-tier LTE network. This approach applies positioning technology to monitor the node for predicting the future mobility pattern that is used to optimize the handover decision. Similar approaches are found in [93], where the proposed network selection mechanism is based on UE navigation information.

Furthermore, the micro-cell HeNBs are prioritized for traffic offloading [94].

Li et al. in [95] investigated the challenges that affect handover decisions procedures in an LTE macro-femto multi-tier network environment. The weakness that most of the existing approaches have in common is the assumption of a simple network layout, and most analytical models consider the distance between the UE and the access point as a straight line instead of considering the spherical form of the Earth [36].

4.4 The Concept of V2I-DHA

This fast network selection algorithm is conceived based on the following key ideas:

- At any time, the vehicle OBU is able to get its current geo-location based on GPS devices

- At all times, all types of small cell networks are always overlaid by a wide network (e.g macro cell) and all small cell access points (SAPs) communicates their geographical coordinates to the ANDSF (Advanced Network Discovery and Selection Function) server located in the core network [96]. Thus, the vehicle (MT) is able to get the geographical location information of neighboring small cells from the ANDSF server.

- The ANDSF server interacts with the ANDSF client, which is running at the vehicle OBU, through OMA-DM (Open Mobile Alliance Device Management) protocol over the S14 interface. This interface supports both push and pulls data communication mechanisms.

- The ANDSF request is only sent once when the vehicle moves to the service area of another macro-cell network. (the vehicle OBU interacts with the ANDSF server once in a macro-cell network).

4.5 Proposed Network Selection Method

The proposed V2I-DHA algorithm described in this chapter differs from the various related proposals described in Section 4.3. The key difference is based on a pro-active network selection process that reduces the overall handover latency. The design of V2I-DHA was motivated by the key idea that in a cellular network, a mobile node can receive information about the geographical locations of neighbouring cells base stations (BSs) from the ANDSF server located in the core network [33]. As discussed in Section 2.2.5, policies and parameters obtained from the ANDSF server. The proposed method applies the ANDSF concept and utilizes its key feature of providing some network selection information.

In this thesis, we have proposed to extend the functions of the ANDSF server by including one more feature of collecting geolocation information of all the small cells located in the service area of a macro-cell BS. The ANDSF server can get this information through small-cell gateways. With the knowledge of the physical location of the nearby cells, proportionally less time is spent in scanning activities. Many studies have highlighted this aspect of using the ANDSF concept for handover performance improvement [36, 37].

In V2I-DHA, a vehicle with a multi-mode OBU (having multiple RAT interfaces) travelling across the multi-tier multi RAT networks of macro-cells and small cells is able to self-determine the most appropriate target network for a potential handover based on the calculated network selection probability. This probability is calculated based on two parameters: (a) the proximity factor which estimates the geo-distance from the target candidate AP physical location to the trajectory of movement and (b) the distance factor that estimates the remaining distance for the vehicle to reach the coverage area of the target candidate network.

Figure 4.2 illustrates a scenario where a vehicle is moving from point A to point B in the direction of the arrow. The macrocell network overlays the multiple microcell networks of limited coverage that are installed as roadside units (RSU). However, the micro-networks provide higher bandwidth and are relatively more cost-effective than the macro network. The proposed technique seeks to avoid selecting a candidate network AP, which is either not lying in the direction of the vehicle or does not offer enough time to complete the handover when the vehicle is crossing it. In the scenario presented in Figure 1, we assume that the vehicle is currently under the coverage of the macro network at point A. When it starts moving towards point B, the vehicle OBU sends an ANDSF query to the ANDSF server (which may be accessed via macro-cell eNB) inquiring the coordinates of available candidate APs in its vicinity. The ANDSF query also contains the vehicle location and direction so that the ANDSF server response contains only APs available in the vicinity of the vehicle.

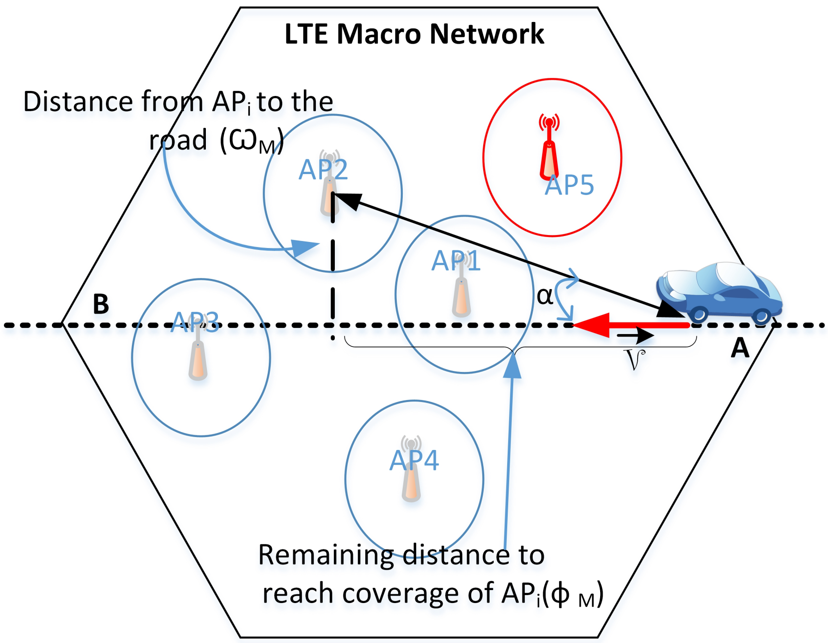

Figure 4.2: Vehicle moving across multiple APs.

4.5.1 Proximity factor (ω_m)

The parameters, ω_m denote the geo-distance between the physical location of the target candidate SAP to the trajectory of movement for the vehicle.

Let $N = AP_1, AP_2, AP_3, ..., AP_m$ be the set of all of the nearby micro-cell APs received from ANDSF server. For a faster and efficient handover process, out of all the APs in set N, the vehicle needs to select only the potential candidate (a) whose coverage area with respect to the speed of vehicle is considerable and (b) whose the distance to the vehicle current location is sufficient to finalize the selection before entering its coverage area.

As it can be seen from the Figure 2, We estimate the distance between the AP and the road as:

$$\omega_m = d_i * \sin\alpha \tag{4.1}$$

where d_i is the geo-distance between the current geo-location of the vehicle and the geo-location of the target candidate AP_i. Given the spherical form of the earth, this geo-distance is calculated by using the haversine formula (14), which is a function to calculate the great-cycle distance between any two points on the earth.

Let (Lat_v, Lon_v) and (Lat_{APi}, Lon_{APi}) denote the coordinates of vehicle and candidate AP respectively. We also denote latitude separation by Δ_{lat} and longitude separation by Δ_{lon}.

The geo-distance, d_i is calculated as follows [15]:

$$\begin{aligned} haversine(\frac{d}{R}) = haversine(\Delta_{lat}) + \cos(Lat_v)* \\ \cos(Lat_{APi}) * haversine(\Delta_{lon}) + \sin\alpha \end{aligned} \tag{4.2}$$

where the angles are in radians and $R = 6371km$ [15], is the radius of the Earth. Furthermore, the haversine function is given by:

$$haversine(\delta) = \sin^2(\frac{\delta}{2}) \tag{4.3}$$

Thus (1) can be written as:

$$\begin{gathered} haversine(\frac{d}{R}) = \sin^2(\frac{\Delta_{lat}}{2}) + \cos(lat_v)* \\ cos(lat_{APi}) * \sin^2(\frac{\Delta_{lon}}{2}) \end{gathered} \tag{4.4}$$

the distance d can be derived from equation 4.3, and can be derived as follows:

$$d = 2R\sin\sqrt{\sin^2(\frac{\Delta_{lat}}{2}) + \cos(lat_v) * \cos(lat_{HeNB_i}) * \sin^2(\frac{\Delta_{lon}}{2})} \tag{4.5}$$

In Equation 1, α is the angular movement and it is the angle between the vehicles line of sight with the candidate AP/BS and the direction of the vehicle. This angle can be estimated by sensor systems such as 10-DOF [11]. We have assumed that the small networks shape is a circle. This implies that the closer the candidate AP/BS is to the vehicles movement trajectory, the more time the vehicle spends visiting that network. Thus, the greater the value $\omega_m \approx 0$, the better the candidates network and the probability that an access point AP_i is added to the candidate's RAT list can be formulated as follows:

$$P(AP_i)select = \begin{cases} 1, & \omega_m = 0 \\ \frac{\omega_m}{R}, & 0 < \omega_m < R_c \\ 0, & \omega_m \geq R_c \end{cases} \tag{4.6}$$

whereR_c denotes the coverage area radius.

To accommodate vehicles moving at different speeds, we define ω_{th} to indicate the minimum coverage distance for a vehicle traveling at a given speed category (slow, medium and high). In this context, the value of ω_m is always higher than ω_{th} and less than the SAP radius as indicated by equation (4.7)

$$\omega_{th} < \omega_m < R_c \tag{4.7}$$

4.5.2 Distance factor (ϕ_m)

The distance factor, ϕ_m, gives us the estimated remaining distance for the vehicle to reach the coverage area of the target candidate network. ϕ_m can be calculated as:

$$\phi_m = d(AP_{m-V}) * \cos\alpha \tag{4.8}$$

Obviously, the higher the value of ϕ_m, the more time the vehicle gets to finalize the selection of the candidate AP before it enters the coverage area of the target network. Once that is done, the vehicle can then immediately initiate the handover process with the target candidate AP on entering its coverage area. Successful early selection of the candidate AP (network) for handover cannot only facilitate the betterment of the overall handover performance by reducing the handover latency, but also reduce the chances of a failed handover. Lastly, the parameter ϕ_{th} indicates the minimum threshold distance from the vehicles current location to the coverage area of the target network that is required to enable the vehicle to successfully complete the selection process. Equation (9) implies:

$$\frac{\phi_{th}}{v} \leq \tau \tag{4.9}$$

where τ represents the time required for completing selection process.

Before proceeding with algorithm implementation, the main steps that the vehicle OBU performs to select the suitable target network for V2I-DHA are presented in Figure 4.3 and are as follows:

1. Self-estimates the suitable target network for a near future handover based on calculated network selection probability.

2. determines its need for a handover based on RSS level received from both the serving and the target cell BS/AP.

3. requests the serving cell to hand it to the selected Target cell (network assisted handover) or self-performs a handover (depending on radio access technology).

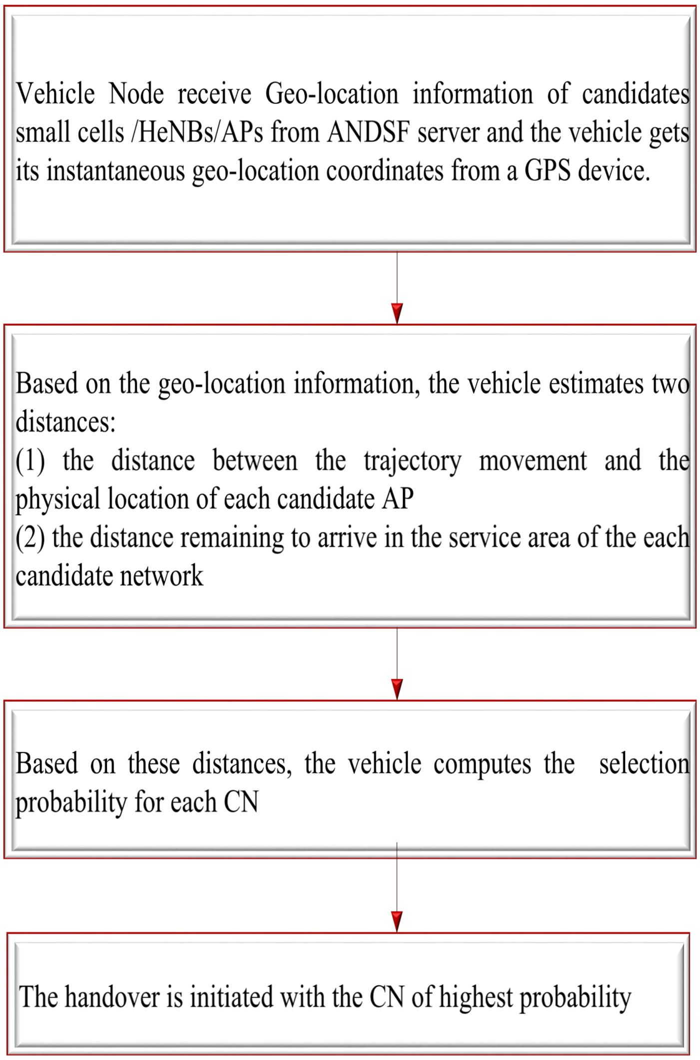

Figure 4.3: Network selection algorithm (V2I-DHA).

4.6 Performance Study

4.6.1 Introduction

The concept of the proposed network selection algorithm was presented in the previous section. In this section, we present the modelling and simulation of V2I-DNSA.

In order to evaluate the performance of V2I-DNSA, we have developed a heterogeneous network environment in OPNET modeler The simulation environment consists of Long Term Evolution-Advanced (LTE-A) and WLAN LTE-A and WLAN technologies. Also, this chapter presents an inclusive comparative analysis with the conventional RSS-based handover method and other related studies, that show the performance of the proposed network selection methods.

4.6.2 Why OPNET modeller?

OPNET Modeller (also known as riverbed modeler) is a simulation software package, highly designed for studying communication networks, protocols, and devices as well as applications. This software applies discrete event simulations (DES) and allows users to investigate different behavior and analyze the performance of systems models. OPNET modeler integrates various network technologies and protocols, including, wired, and wireless systems. The actual communication networks are modelled by utilizing its user-friendly graphical editors which are built on the object-oriented paradigm of C++ that allows the creation of objects and classes [5, 97]. OPNET was chosen as a simulation tool for this thesis due to its credibility and it was available to us at AUT during the duration of this study. In addition, OPNET modeler supports a range of various network access technologies and communication applications including delay-sensitive such as voice and video conferencing, delay-tolerant applications such as FTP and HTTP and many more. Moreover, in some cases, we have performed a few MATLAB simulations to support our proposed analytical design concepts.

4.6.3 OPNET modelling domain

V2I-DHA is implemented in the OPNET modeler software, commercial version 18.0. The OPNET modeler comprises three hierarchical models: network model, node model, and the process model. All codes are executed at process model. As is shown in Figure 4.4, the process model deploys state machines to define various simulation events which are presented as a C++ programming. The OPNET coding can be edited and Microsoft Visual studio makes the debugging process easier than OPNET interface. The proposed handover algorithm involved various modifications at both node and network access systems, particular Marc and network layers. The details of the main modifications are explained in the following subsections. More details about OPNET configurations are appended in Appendix A.

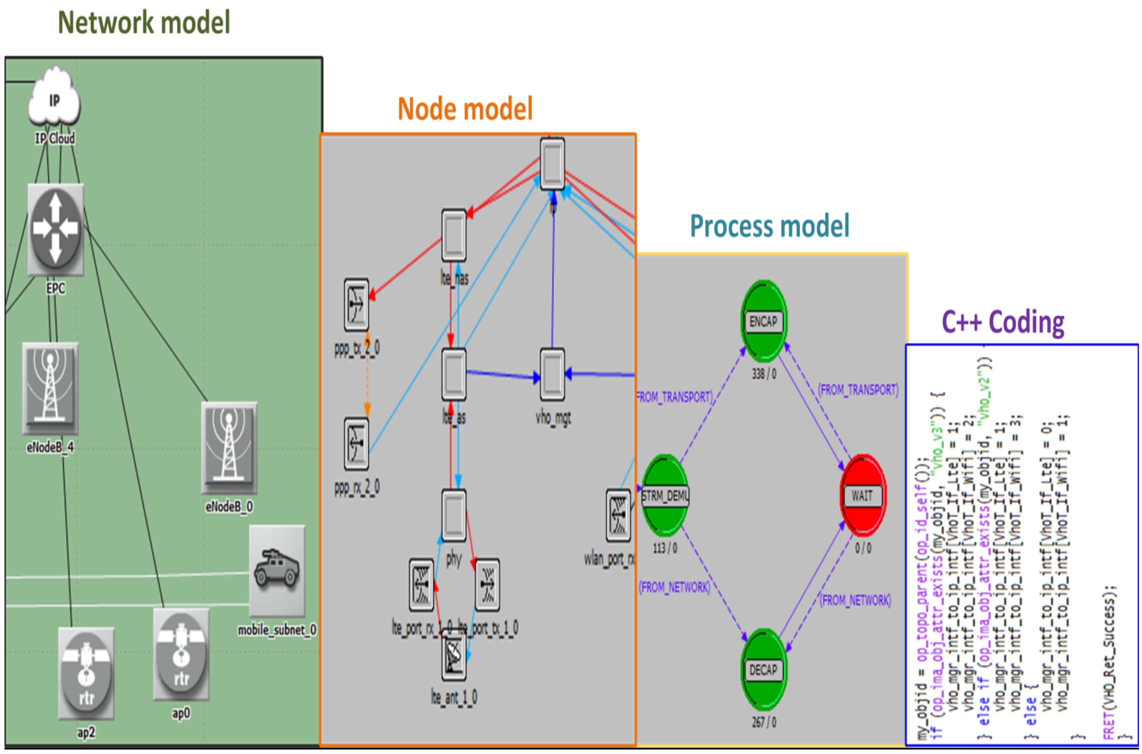

Figure 4.4: OPNET modeler hierarchical models.

4.6.4 Node model design

The multi-mode OBU is designed based on LTE-A router. The main modifications were made at lower layers of TCP/IP stack as is illustrated in the Figure 4.5 (a). The developed node has two PHY interfaces, WiFi, and LTE and, by default (before including the proposed algorithm), the IP (Network) layer does load balancing to them (traffic is balanced between these two interfaces). By default, the OBU is connected to LTE macro-cell eNB and as it moves, it performs handover activities to other wireless networks with higher RSS values.

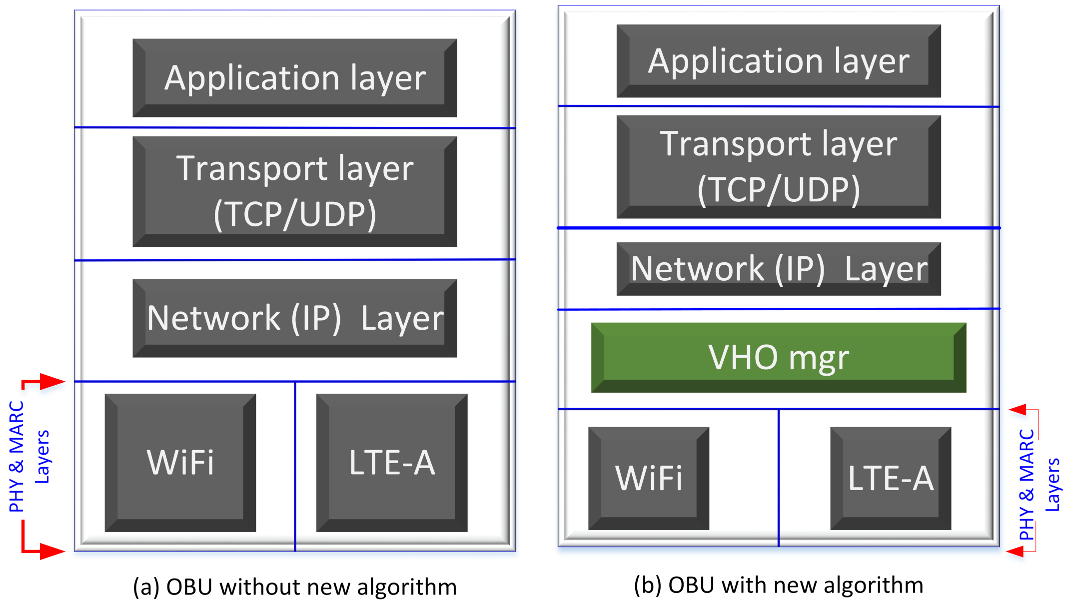

Figure 4.5: The OBU Node TCP/IP Protocol Stack.

Figure 4.5 (b) shows the implementation of the vehicle OBU that integrates the proposed handover algorithm in its TCP/IP stack protocol. Our handover algorithm is implemented in the MAC layer of both LTE and WiFi media access technologies (MAT) and the result of the algorithm will be sent to the Vertical Handover Management (VhoMGT) module that chooses the MAT interface to be activated. This was achieved by modifying the existing MAC layer protocol mainly for

$CELL\_SELECTION$ and $HANDOVER$ modules. The function $lte\_ue\_as\_vho\_get\_ho\_params()$ is introduced to include and compute new handover parameters and $lte\_ue\_as\_vho\_selec\_best\_nbr()$ method selects the best candidate SAP based on the computed handover parameters. Each interface will send the results of these functions to the VhoMGT module. Based on the events received, the VhoMGT executes $vho\_compute\_active\_interface()$ function to decide the MAT interface to be activated and a message is sent to the IP layer to inform it about the route that should be installed for data forwarding.

The IP layer will forward data to only one interface at a time. To keep seamless connectivity, every interface which is involved in the vertical handover process (in this case LTE and WiFi) is configured with a static route to destination 0.0.0.0 and netmask 255.255.255.255. In this way, the IP module will configure the route 0.0.0.0/32 for the LTE or WiFi interface based on the winner interface. It is worth noting that the VhoMGT could be used not only for LTE and Wifi MATs but also for any other type of Media Access Technologies (MAT). It takes event information from MATs and decides the one to be activated. Figure 4.6 displays the Vehicle OBU node model developed in OPNET Modeller.

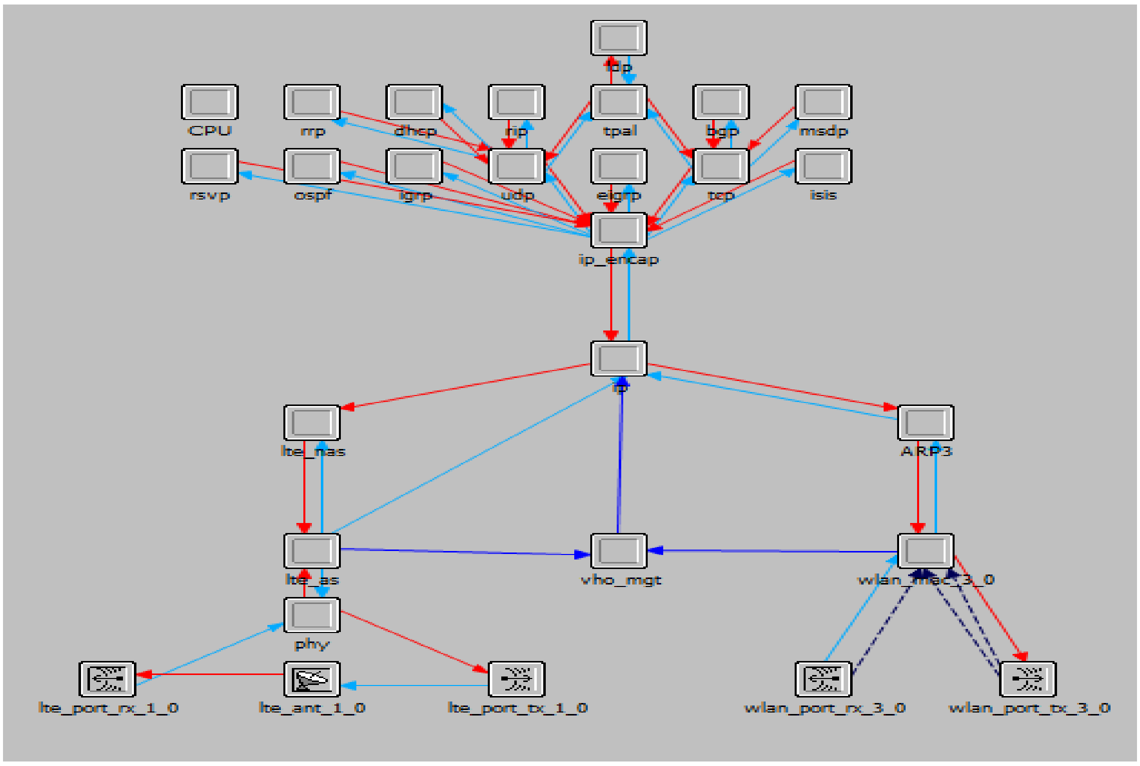

Figure 4.6: Vehicle OBU node model developed in OPNET Modeler.

4.6.5 VhoMGT process model design

The designed VhoMGT process model consists of two finite state machines (FSM) (see Fig. 4.7). The init state initializes all the necessary initializations. After initialization, the protocol will switch to the idle state and wait for any event from either LTE of Wifi MAC layers. The wait FSM executes code from the exit executive part of the state every time it receives events from LTE or WiFi interfaces. More details of VhoMGT codes are given in Appendix B.

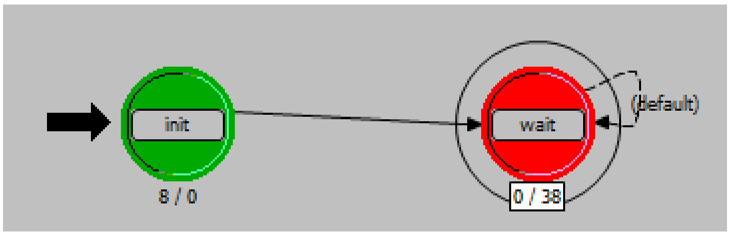

Figure 4.7: The process model of the designed VHO management module.

4.6.6 Enhancements to the standard LTE eNodeB

The proposed novel handover algorithm involves both node and base stations. Thus, the LTE eNB node was enhanced in order to efficiently process information received from the newly created node model, the vehicle OBU. The main modifications were done in *lte_as* processor of LTE eNodeB node model. The measurement information is received via function $lte\_enb\_as\_cand\_enb\_list\_generate()$. This information is then saved in sorted order by w_m/cell radius report. This sort operation is done by the function $lte\_enb\_as\_candidate\_enb\_compare()$. The handover start event is handled by the function $lte\_enb\_as\_handover\_start()$ that chooses the first entry from the sorted list maintained by the function $lte\_enb\_as\_candidate\_enb\_compare()$. More details (OPNET codes) of modifications of LTE eNB are included in Appendix A.3.

4.6.7 Enhancements to the standard Wi-Fi AP

In the same way, the WiFi AP also needs further enhancement in order to fit the proposed handover algorithm. The primary modifications are done at the *wireless_lan_mac* processor of every WiFi AP node. The state of interest in this process model is SCAN state where the algorithm will run for every available AP and will choose the best one. In SCAN state, the function that will run the algorithm called $wlan\_hcf\_vho\_find\_best\_ap()$. More details of OPNET modifications for WiFI nodes are included in Appendix A.3.

4.6.8 Simulation scenario

Figure 4.8 shows the scenario used for our studies where the multi-mode vehicle OBU is moving across a multi-tier HetNet environment that includes LTE-A (macro and pico) and Wi-Fi radio access technologies. The simulated scenario consists of one macro-cell eNB whose coverage radius covers the whole simulated area. Also, two pico-cells HeNBs are deployed at both edges of a macro-cell network for overcoming the weak connectivity. Also four Wi-Fi APs (IEEE 802.11p) RSUs are deployed at different locations (road intersections). All the WiFi Access Points (APs) are connected to the PDN gateway in E-EPC.

Based on the proposed handover algorithm, the vehicle OBU is initially connected to the macro-cell eNB and it performs a handover if any of the candidate networks offer a higher selection probability or if the network being used disappears. The mobile subnet representing the vehicle consists of two nodes: a multi-mode vehicle On-Board Unit (OBU); equipped with the new node model, discussed in Section 4.6.4, and the application client (Vehicle_App_Client). The vehicle speed varies from 20km/h for the low-speed scenario, 30 km/h to 60 km/h for medium speed and 120 km/h for high speed of movement. The vehicle moves within the coverage area. both delay-tolerant (such as HTTP and FTP) and delay-sensitive applications (e.g., voice and video conference) are considered.

As our main objective is to evaluate handover performance, we have strategically placed all SAPs in a way that portrays our desired topology by setting the coordinates of eNB and SAPs (see Figure 4.10). Figure 4.9 shows the simulated network architecture in OPNET simulator environment.

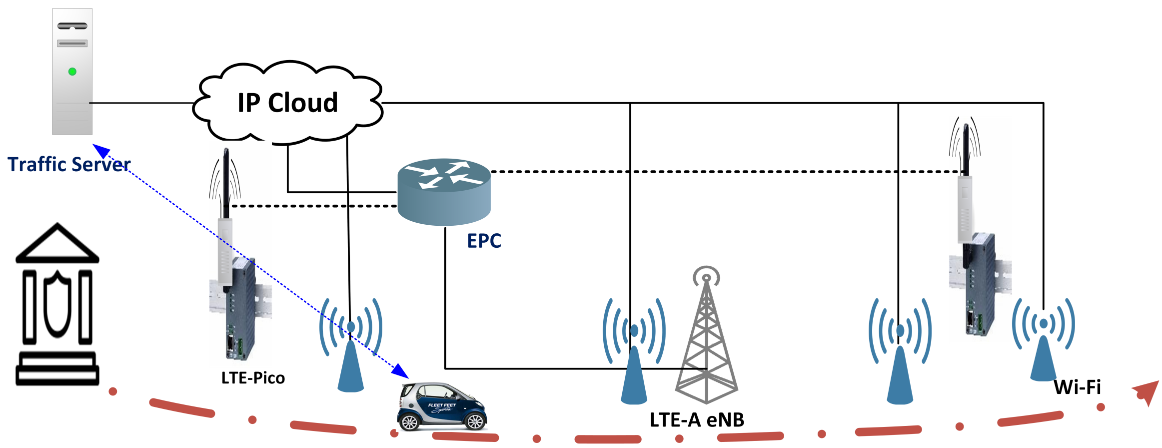

Figure 4.8: Simulation environment for V2I-DHA.

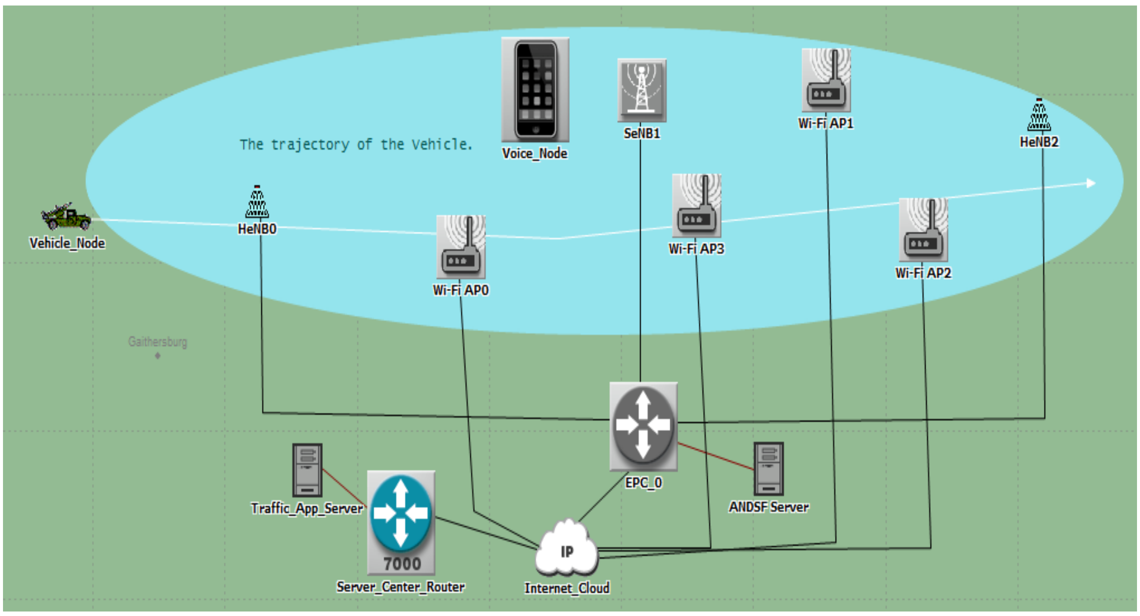

Figure 4.9: Simulated platform in OPNET simulator.

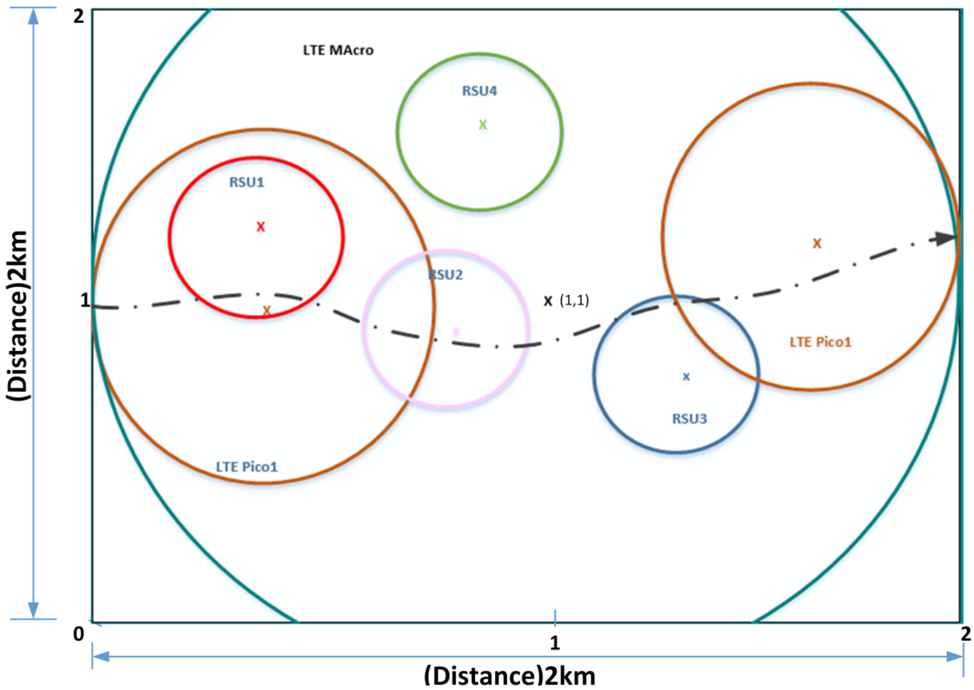

Figure 4.10: Wireless technologies coverage areas in the simulated scenario.

4.6.9 Performance assessment

To compare the performance of the proposed algorithm, we developed three network scenarios/models in OPNET simulator. In the first scenario, the conventional RSS-based approach is used to select the target SAP for handover. In the second scenario, the OBU selects the most suitable candidate SAP for handover using the proposed network selection method (algorithm). The third scenario implements the handover method called "Efficient ANDSF-assisted Wi-Fi Control for Mobile Data Offloading" proposed by D. Kim et al. [36] that automatically controls the handover decision in a heterogeneous network that includes WiFi and cellular network radio access technologies.

In this article, [36], a mobile user moves across a heterogeneous network that

Table 4.1: Simulation parameters.

Parameter	**Values**
Network area (m * m)	1000 * 1000
Transmit power of LTE Macro/SAP	0.5W/0.1W
LTE Macro/ SAP gain	14 dBi/5 dBi
WiFI SAP (IEEE 802.11p) transmit power	0.05W
Vehicle speed (km/h)	$20 - 120$
Path loss	$L = (40(1 - 4 * 10^{-3}\Delta h_b)\log_{10} R - 18\log_{10}\Delta h_b + 21\log_{10} f + 80)dB$
Radio propagation	Large-scale propagation
log-normal shadow fading	10 dB
LTE-A Channel bandwidth	1.4MHz
WLAN data rate	11Mbps
Mobility	Vector based trajectory
Simulating time	600 sec

includes WiFi and cellular network radio access technologies thus performing handovers. The primary goal of this method was to avoid unnecessary Wi-Fi scanning and unnecessary Wi-Fi connections while users are moving. The proposed method applies ANDSF features to advise the mobile UE about the neighbouring candidate wifi APs. To decide whether the WiFi AP should be selected or not, this method utilizes the variation in the measured RSSI values.

Similar to our proposed algorithm, this particular handover mechanism has applied an ANDSF entity for network selection and we have considered the same radio access technologies for computer simulation implementation. Thus, the performance of our proposed algorithm will be investigated against the conventional handover method and Efficient ANDSF-assisted Wi-Fi Control for Mobile Data Offloading (in the subsequent sections this article will be referred as "ANDSF-assisted handover").

Simulation parameters are as in Table 4.1. In all scenarios, all neighboring cells are considered to have enough bandwidth to accommodate new connections, thus we disabled all background traffic for all BS/AP.

As the main objectives of this algorithm consist of handover management improvement, several indicators have been defined including the number of handovers performed, handover latency, and the handover failure rate ($HOFR$). The Handover Failures (HOF) occur when a handover process is initiated but not carried out to completion. The $HOFR$ shows the number of HOF relative to the number of all handover attempts (successful + failure) [98]. The $HOFR$ is calculated as follows:

$$HOFR(\%) = \frac{N_{HOF}}{N_{SuccessfuHO} + N_{HOF}} \tag{4.10}$$

Moreover, the network performance of the proposed algorithm is evaluated based on common QoS parameters like user throughput, end-to-end delay and packet delay variations.

4.7 Results and Discussion

As discussed above in Section 4.6.9 the simulation results are based on handover performance. Various metrics are investigated to prove the efficiency of the proposed handover algorithm compared to the conventional mechanism.

4.7.1 Number of handovers performed

Every unsuccessful handover activity is associated with a certain number of dropped packets. Thus an increased number of handovers could easily affect the quality of service for involved communications.

Figure 4.11 presents the results of the number of handovers performed per the considered trajectory of movement when the vehicle moves at various speeds ranging from 20 km/h to 120 km/h. The number of handovers performed in our proposed handover algorithm is reduced in comparison to those performed in cases of the conventional and ANDSF-assisted handover methods. This is due to the fact that the vehicle OBU, in the proposed algorithm, scans only those SAPs located in its movement direction and which would provide the vehicle OBU with reasonable residence time with respect to the speed of the vehicle. V2I-DHA achieved up to 11% and 37% lower numbers of handovers, over the conventional and ANDSF-based handover methods, respectively. The higher number of handovers in the case of both conventional and ANDSF-assisted handover methods, is due to the fact that the vehicle OBU scans all advertised networks regardless of the direction of movement. Contrarily, in the proposed mechanism, the average number of handovers is between 2.5 and 3.5 during the considered trajectory of the vehicle movement. It is also worth noting that the number of handovers performed decreases with the increase in the speed of movement for all considered scenarios. This could be explained by the different factors including Doppler shift effects and high instability in the values of RSSP measured by the UE from the target cell.

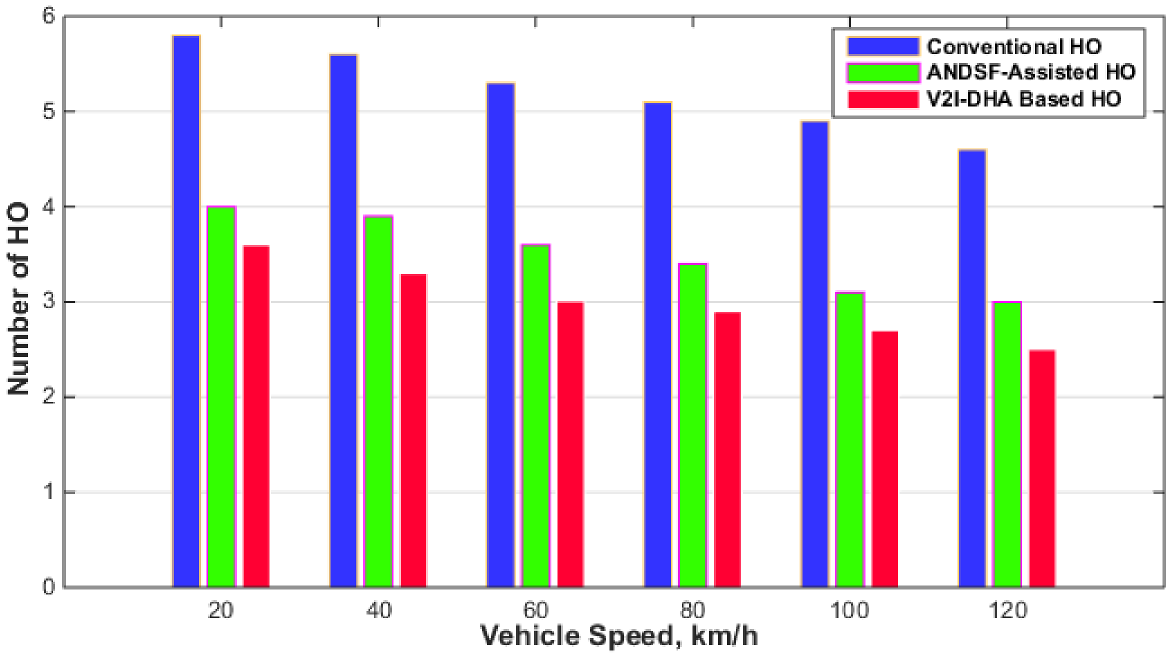

Figure 4.11: Mean number of handovers performed at various vehicle speeds.

4.7.2 Handover latency

This parameter denotes the time elapsed between the handover initiation and completion. Figure 4.12 presents the comparative handover latency between the considered three scenarios. The decrease in the proposed method could be explained by the minimised scanning time since the vehicle OBU scans only potential candidates (lying in its direction) and the handover request is only sent to those with the highest network selection probability. It can be noted from the Figure 4.12 that our proposed algorithm offers an approximately 29% reduction in handover latency compared to the conventional handover method and 15% compared to the ANDSF-Assisted handover method. However, it is noted that increase in the speed of movement implies increased handover latency. This is due to the rise in radio link failures(RLF). These RLFs may occur due to the fact that the vehicle OBU crosses the boundaries of the serving cell before initializing the handover activity to the target network.

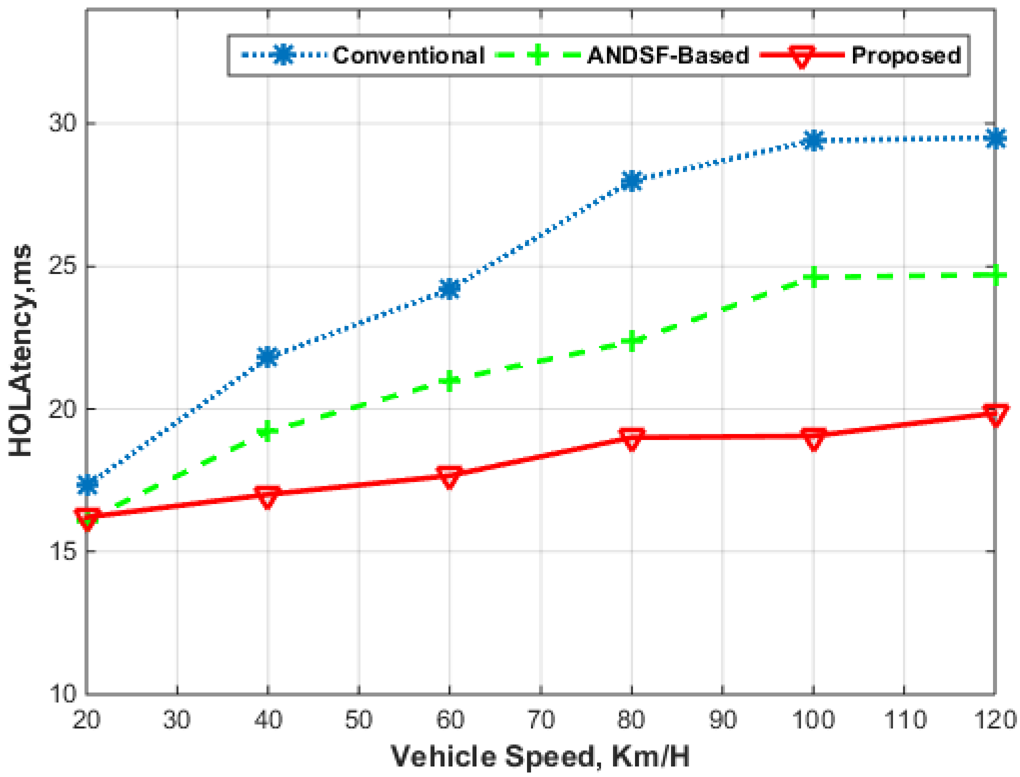

Figure 4.12: Comparison of handover latency for various vehicle speeds.

4.7.3 Handover failure rate(HOFR)

Figure 4.13 exhibits the handover failure rate against the speed of the vehicle. The high HOFR occurs in the conventional handover mechanism since it does not consider the direction of the vehicle and thus the vehicle OBU tends to connect to any available target network which shows RSSP/RSSI greater than default threshold value. The higher the HOFR, the more network resources (bandwidth) are wasted due to multiple messages exchanged between the vehicle OBU and both serving and target networks for handover activities. In our algorithm, the HOFR is handled much better by considering multiple criteria and thus the vehicle OBU can select the most appropriate target cell to proceed for a successful handover activity. The proposed V2I-DHA provides better HOFR performance by approximately 40% and 11% over conventional methods and ANDSF-Assisted handover, respectively.

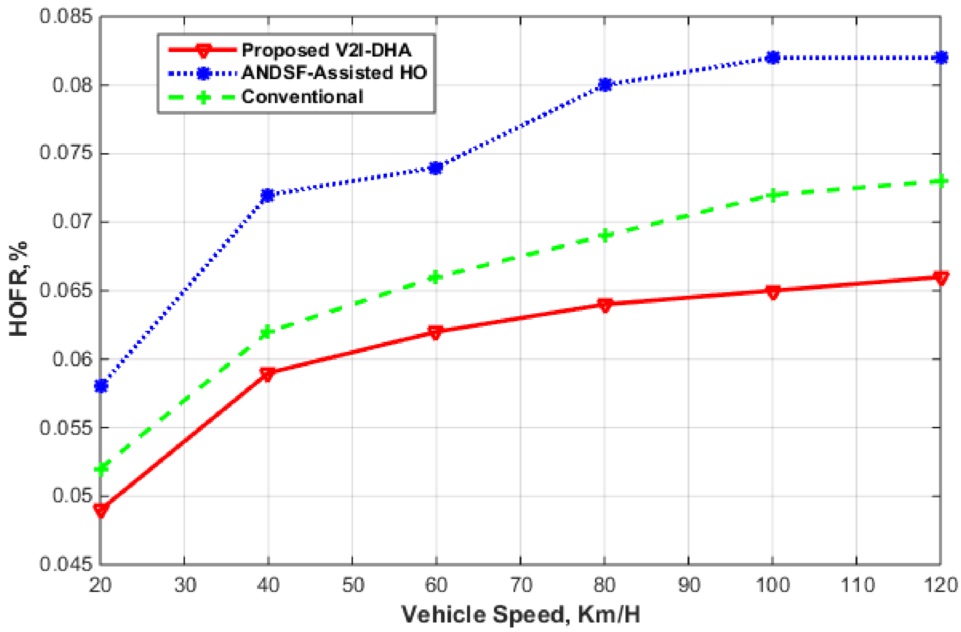

Figure 4.13: Handover failure performance for network selection at various vehicle speeds.

4.7.4 OBU throughput

Figure 4.14 shows the average OBU throughput for the voice application that requires bandwidth of 64 kbps. The moving vehicle OBU operating on a 1.4 MHz channel bandwidth with a voice call during a period of 500 seconds (which is the total simulation duration, 600 seconds, minus 100 seconds for simulation initialization). The graph compares the user throughput for simulated scenarios. The vehicular speed varies from 20 km/h to 120 km/h. The proposed handover algorithm offers up to 45% and 37% higher throughput over the conventional and ANDSF-assisted handover methods, respectively. The improvement was the result of less packets dropped due to the reduced number of handovers carried out by the vehicle in the proposed method. Also, the results reveal that both ANDSF-Assisted handover and the proposed V2I-DHA offer the same throughput for low speed ($< 20km/h$). Furthermore, we notice that the performance of throughput deteriorates with an increase in the vehicular speed. This degradation can be related to the increased number of unsuccessful handovers due to the incomplete handover signalling messages between the vehicle OBU and the selected target networks caused by the high speed of movement of the vehicle. It can thus be concluded that the network throughput is negatively affected by the increase in the speed of the vehicle when performing handovers to small cell networks.

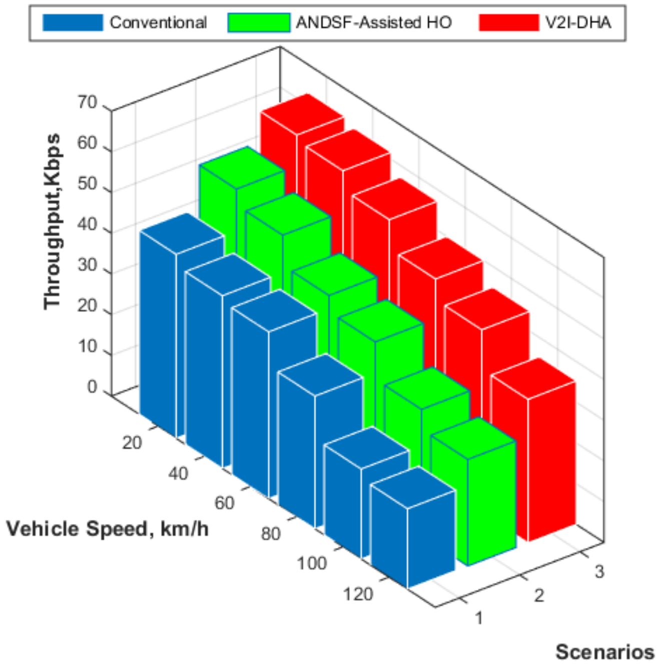

Figure 4.14: Comparison of user throughput of conventional, ANDSF-assisted, V2I-DHA, and V2I-DHA handover methods at for various vehicular speeds.

Furthermore, the impact of the proposed handover algorithm on the WLAN throughput is illustrated in Figure 4.15. In the case of the conventional and the ANDSF-Assisted handover methods, the WLAN cells are not effectively exploited due to the well-known unoptimized WiFi handover issues (a WiFi end device will persistently "cling on" to the current connection until the RSSI falls below a threshold). The proposed algorithm solves this problem by including more handover parameters that enable the vehicle OBU to determine the list of potential WLAN APs in a pro-active manner so that the handover process takes less time and less dropped packets. Consequently, our proposed algorithm outperforms both the conventional and the ANDSF-Assisted handover mechanism in terms of the average number of user received packets.

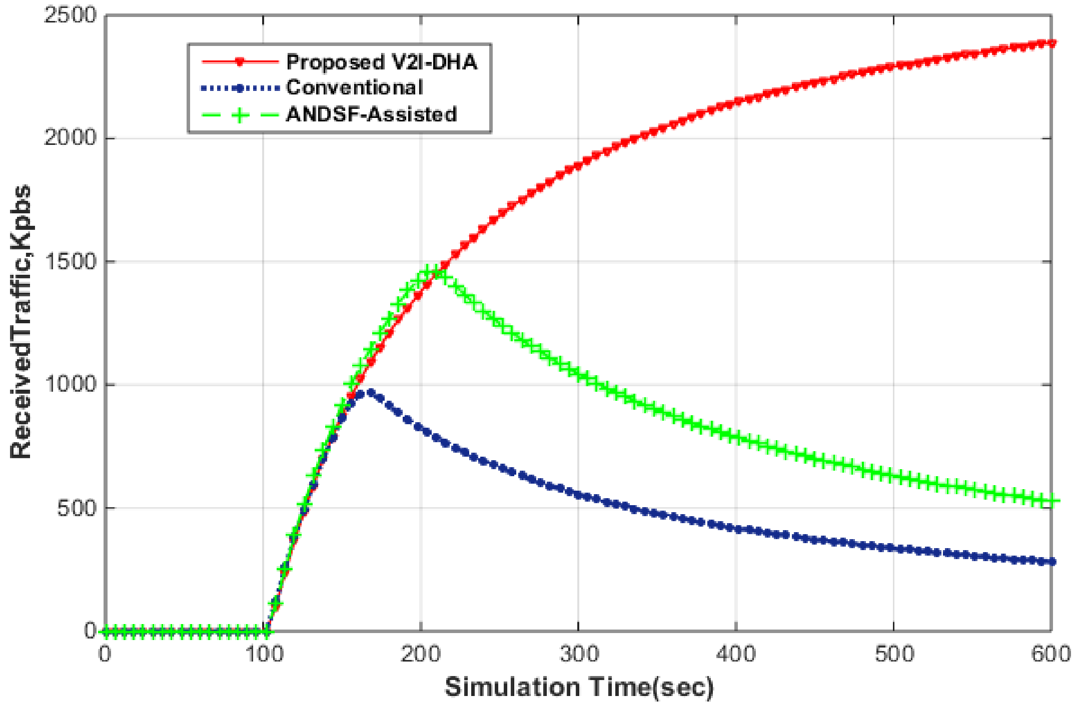

Figure 4.15: Comparison of WLAN throughput for conventional, ANDSF-assisted, and V2I-DHA handover methods at vehicle speed of 60 Km/h.

4.7.5 End-to-end delay

Figure 4.16 illustrates the packet end-to-end delay experienced by the vehicle OBU for the voice application. This parameter reports the total voice packet delay, called "mouth-to-ear" delay. The higher value of packet end-to-end delay affects the overall QoS of user applications, especially delay sensitive ones such as voice applications. Packet end-to-end delay is the summation of various delays, namely, network_delay, encoding_delay, decoding_delay, compression_delay, decompression_delay and dejitter_buffer_delay. The proposed V2I-DHA algorithm mainly reduces the network_delay. This is achieved by minimizing the number of candidate SAPs to be scanned and also making an accurate decision for the cell selection. The simulation results reveal that our algorithm decreases the packet end-to-end delay by approximately 20% and 12% compared to the conventional and ANDSF-Assisted handover methods, respectively.

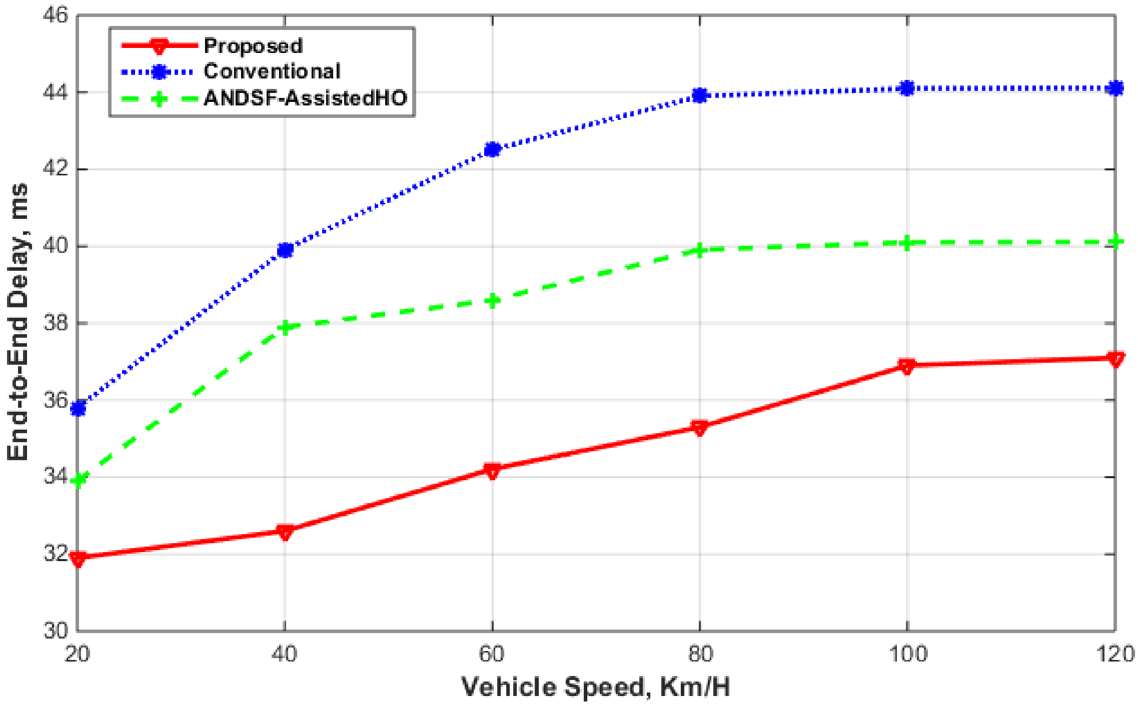

Figure 4.16: End-to-end delay comparison of different handover mechanisms at various UE speeds.

4.8 Summary

This chapter has discussed a novel handover algorithm for multi-tier heterogeneous networks that not only reduces handover latency and handover failure ratio but also significantly improves user throughput and decreases end-to-end delay.

In V2I-DHA, the best target network was selected among the short-listed potential candidate networks and thus the scanning time becomes insignificant. Unlike the conventional RSS-based network selection, V2I-DHA applies the knowledge of physical locations for both the node and the target network BS to calculate the selection probability, which is used to determine the most suitable network for a near future handover. The efficiency of the proposed algorithm was investigated by computer simulation using OPNET. V2I-DHA had significantly better handover latency and failure ratio than the conventional RSS-based method. Also, V2I-DHA offered a better QoS performance.

The performance of V2I-DHA was comparatively studied against the conventional handover method and one more related handover algorithm, named ANDSF-Assisted handover method. Simulation results showed that V2I-DHA reduced the number of frequent handovers up to 37%, the mean handover latency was up to 40% lower, HOFR was up to 29% lower, user throughput was up to 45% higher and mean end-to-end delay was up to 20% lower over the conventional handover method. V2I-DHA is technology independent and thus it can be used to improve the handover management in any multi-tier heterogeneous network environment. V2I-DHA can be easily implemented by placing a vertical management layer between MAC and IP layers of TCP/IP models. Table 4.2 summarizes the simulation results obtained from analysis of V2I-DHA. In all cases, V2I-DHA outperformed both conventional and ANDSF-based selection methods. With respect to handover performance, the handover failure ratio and handover latency are degraded with increase of speed of movement. Similarly, QoS performance is degraded with increase in vehicle speed. Next, in Chapter 5, another handover algorithm is proposed that selects the most suitable target network based on both node mobility and network load.

Table 4.2: Handover performance comparison.

V2I-DHA				
Vehicle speed		Low	Medium	High
Average handover events	Proposed	3.50	3.00	2.61
	ANDSF_based	4.00	3.40	2.71
	Conventional	5.07	5.00	4.60
Mean handover failure ratio	Proposed	4.90%	6.00%	6.5%
	PANDSF_based	5.01%	6.5%	7.20%
	Conventional	6.02%	7.3%	8.20%
Mean handover latency (ms)	Proposed	16.01	18.10	20.20
	ANDSF_based	18.04	21.20	24.70
	Conventional	21.60	24.15	29.81
Mean user throughput (Kbps)	Proposed	60.00	65.17	39.80
	ANDSF_based	49.90	30.01	23.09
	Conventional	38.70	30.21	20.81
Mean packed Delay	Proposed	30.10	34.15	37.00
	ANDSF_based	36.20	38.76	40.16
	Conventional	38.1	42.7	44.0

Chapter 5

Fast Handover Using Node Mobility and Network Load

5.1 Introduction

In Chapter 4, the improvement in handover in a multi-tier heterogeneous network was achieved by modifying the network discovery and selection processes. A primary objective of this thesis is to minimize the number of unnecessary frequent handovers that affect the overall network performance in terms of QoS. To achieve this objective, in this chapter, we report a novel network selection algorithm, called node Mobility and network Load based handover Algorithm for V2I communications (V2I-MoLoHA) that enables the vehicle OBU an efficient handover decision.

By self-selecting the most appropriate target network, the vehicle is able to not only reduce the number of unnecessary and unsuccessful handovers but also improve the resources consumed and overall performance of mobility. Moreover, by performing a fast handover, it also improves the overall handover latency.

The chapter starts by introducing the concept of the V2I-MoLoHA algorithm and the key contributions compared to its predecessor V2I-DHA. Section 5.2 discusses similarities and dissimilarities of V2I-MoLoHA and V2I-DHA and highlights the assumptions made for developing V2I-MoLoHA. Section 5.3 gives the description of the

V2I-MoLoHA algorithm. Performance evaluation is presented in Section 5.4. Simulation results are discussed in Section 5.5 and the chapter is summarised in Section 5.6

5.2 Discussion and Assumptions

Successfully maintaining the quality of on-going communications for users in high-speed vehicles moving through urban 5G multi-tier, multi-RAT dense network environments is a significant challenge [7]. Due to the presence of dense small network cells overlaid by macro-cells, the mobile node will need an efficient network selection mechanism for selecting the most ideal candidate network both while moving from a macro to a small cell network (i.e., downward network selection) and from a small cell to a macro cell network (i.e, upward network selection).

Generally, in a multi-tier heterogeneous network, the key challenge with downward handover is associated with handover to a non-ideal cell (see Figure 5.1). In this case, a fast-moving node may perform multiple handovers to a number of small cells within a very short time and the dwelling period of the node within the coverage areas of the small cells (e.g., NKWB in Figure 5.1 (b)) may be so small that it may have to move out of the cell even before completing all the handover signalling procedures. On the other hand, the problem with an upward handover is linked with delayed handover. In this case, a node moving even at a moderate to high speed may cross the coverage area of a serving small cell eNB (it is a base station for LTE-A) before a handover is completed. Thus, it may result in the radio link failure (RLF) with the current serving cell and the node tries to establish its radio link to another base station. Thus, not only handover failures but unnecessary handovers also occur. However, it is possible to deal with these issues if the node could appropriately select an ideal network (e.g., the candidate BS/AP) amongst all the neighbouring networks (e.g., neighbouring BSs/APs) for the future handover activity.

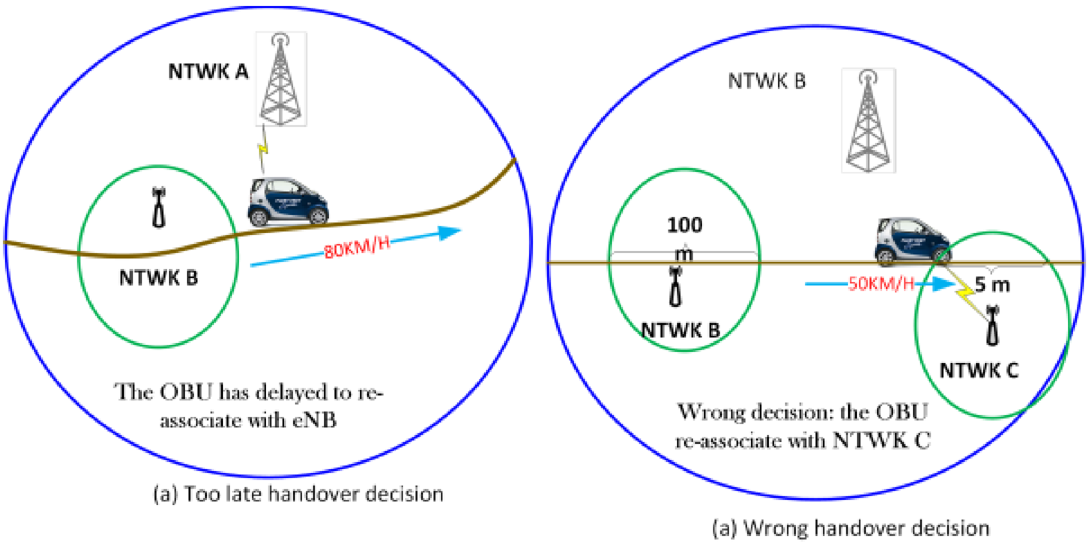

Figure 5.1: High speed UE handover issues.

In this chapter, we present the network selection method that we called V2I-MoLoHA (Mobility and network Load aware Handover Algorithm for V2I communications). This algorithm addresses both handover challenges discussed above, specifically for a high-speed mobile node such as a vehicle. For downward handover, the network selection operates in three stages: first, the vehicle OBU creates a set of potential candidate networks based on its direction. The second stage consists of ranking potential candidates based on the calculated dwelling time. The final stage involves selecting the most appropriate candidate network based on the calculated load index and the measured RSS values. As the main objective is to minimize both latency and packet loss for handover activity, stages one and two are performed before the vehicle arrives in the service area of the candidate networks. This minimizes the scanning time since the vehicle OBU will evaluate the RSS value and available bandwidth only for the most potential candidate network. The upward handover discussed in Subsection 5.3.2 applies the knowledge of dwelling time for deciding the appropriate time to initiate a handover request to macro-cell BS. In this chapter, we have used the following terminologies: an OBU implies an in-vehicle communication device that can connect to the infrastructure networks; SAP or small cell access point represents any type of small cell base station(BS) or access point (AP).

Before describing the working principle of V2I-MoLoHA, it is important to highlight the similarities and dissimilarities of this algorithm and its predecessor V2I-DHA. Additionally, this section reports the assumptions that we made during the design of V2I-MoLoHA.

5.2.1 V2I-MoLoHA vs V2I-DHA

1. Unlike the network selection algorithm (V2I-DHA) presented in the previous chapter, which employs only two distance-based parameters, the V2I-MoLoHA uses three parameters (relative direction, dwelling time and load index) for the overall process of selecting the most appropriate candidate SAP. Among these parameters, there is relative direction index which enables the vehicle to only scan those neighbouring networks that lie on the movement direction trajectory of the vehicle and not scan other candidate networks. This reduced scanning implies less handover time or faster handover. Secondly, because of the multiple parameters considered, the vehicle can successfully choose the most appropriate target network for handover and therefore reduce the number of unnecessary and unwanted handovers including ping-pong effects.

2. Unlike V2I-DHA that estimates the dwelling time based on the distance between the target network SAP and the trajectory of movement, the V2I-MoLOHA employs its movement information to accurately determine the dwelling time used to rank all neighbouring cells SAPs.

3. The criterion of the current load of each potential SAP introduced in V2I-MoLoHA was not considered for V2I-DNSA. A SAP may provide a consider-

able dwelling time for a moving node, but if it does not have free channels to accommodate the new session the handover is automatically blocked. The V2I- MoLoHA utilizes information received from the target BS/AP to calculate load index, which determines the less loaded candidate network. Thus, V2I-MoLoHA reduces the handover-blocking probability by considering the current load parameter.

4. While V2I-DHA relies on the ANDSF server for filtering SAPs available in its direction, V2I-MoLoHA enables the vehicle OBU to self-determine its direction of movement based on geographical coordinates taken at two different consecutive locations.

5. In V2I-DHA, the process of selecting the best SAPs from the PSAPs was based solely on calculated selection probability followed by the estimation of the distance between the current physical location of the vehicle and the PSAPs. In contrast, for V2I-MoLoHA, the best SAP selection is done by first ranking all PSAPs and then computing the load index of the topmost on the list of PSAPs.

5.2.2 Assumptions

After discussing the similarities and dissimilarities of current and the previous handover algorithms, we next state the assumptions that we have made to develop the V2I-MoLoHA handover algorithm.

Assumption 5.1: As is illustrated in the Figure 5.2, we consider a multi-tier multi-RAT network with a large number of small cells and assume that the vehicle starts its journey (with varying speed) from a certain point A in the macro-cell network and its destination, point B, is also located in a distant destination in the same macro-cell network. Generally, the typical LTE cell size is around 10 sq-km (700/800 MHz) [99], thus a vehicle can spend a reasonable time in the service area of the serving macro-cell BS.

Assumption 5.2: We assume that the vehicle OBU is able to determine its geographical location (latitude and longitude). This information could be collected by using different geo-technologies such as GPS.

Assumption 5.3: We assume that each small cell AP (SAP) has the knowledge of its geo-location coordinate and shares this information with the ANDSF server located in the core network via the gateway router (see Figure 5.2). How the vehicle acquires and utilizes this information (coordinates of SAPs) is explained in Section 4.5.

Assumption 5.4: During its entire journey, the vehicle OBU dynamically maintains a small database of all SAPs in its direction of movement that we have called the set of potential candidates SAPs (PSAPs). The PSAPs are ranked and the next handover will be initiated with the first SAP on the list of PSAPs. Every time the vehicle OBU is handed over to a new SAP, the vehicle OBU sets a timer that is used to determine the correct time to initiate the handover request back to the macro-cell BS (explained in Section 5.3.2).

5.3 Description of V2I-MoLoHA

This chapter reports a novel network selection algorithm for effective V2I communications in a multi-tier heterogeneous urban network environment. As was stated above in Section 5.1, the V2I-MoLoHA considers both upward and downward handover types. We now proceed by describing the proposed network selection method for downward handover activity.

5.3.1 Downward handover mechanism

In the proposed network selection method for a downward handover, the SAP of the most suitable small cell network is selected based on three parameters: the relative

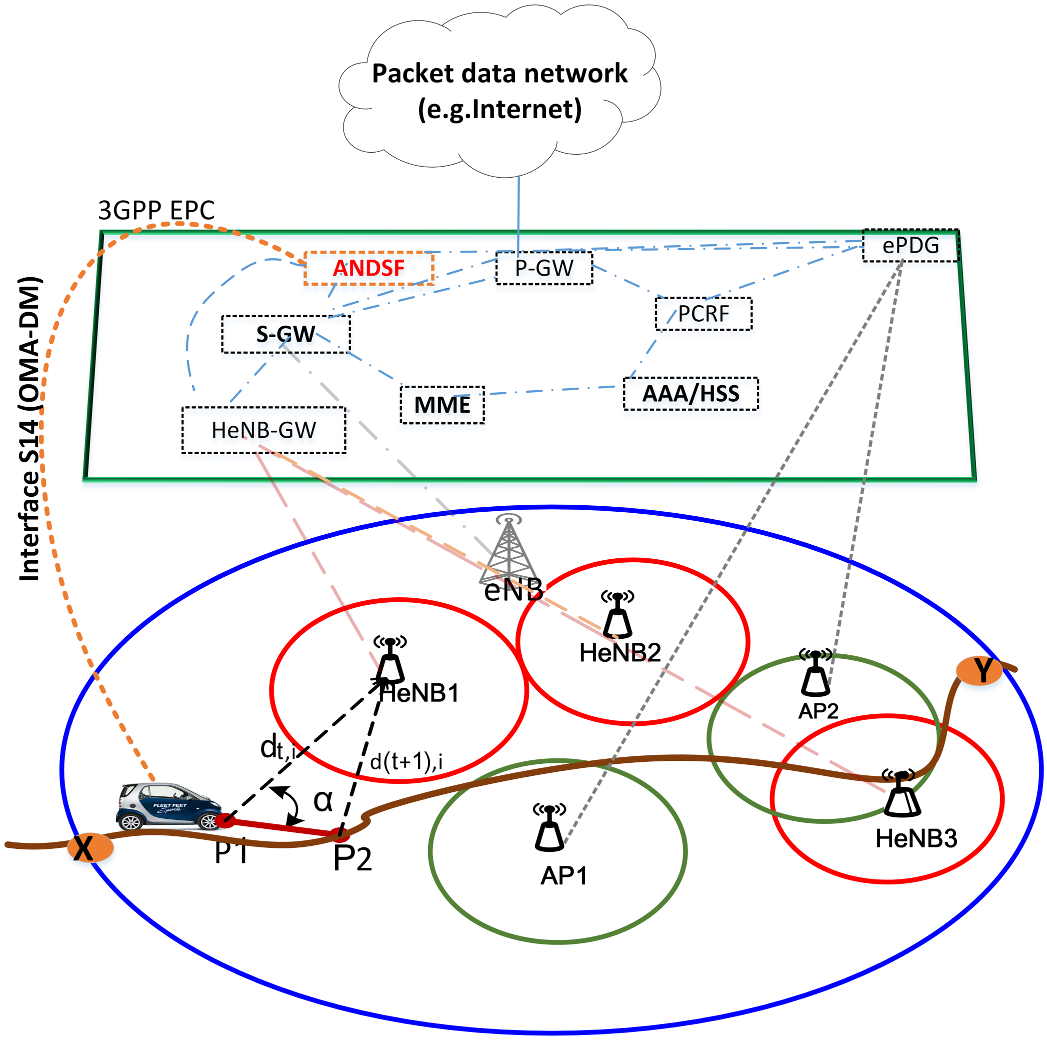

Figure 5.2: Assumed scenario (LTE-A eNB overlays multiple LTE-A small cells and WiFi access points).

movement direction index, the dwelling time of a UE and the network load of the neighboring SAPs. The main purpose of the relative movement direction index is to eliminate the useless candidate networks (those lying in the opposite direction of the movement of the vehicle). These candidate networks are eliminated from the set of the candidates to be evaluated. The proximity index calculates the closeness of the candidate network to the trajectory of the movement and is eventually used to calculate the residence time index. Load index computes the available network capacity while the RSS indicates the quality of the received signal from the candidate network base station/access point.

The relative movement direction is determined based on the calculated distance variation, which indicates how much the UE has moved towards or away with respect to a candidate SAPs physical location. 5.3 shows how the distance variation is calculated in our proposal. Two successive positions of the UE, P1, and P2, are considered and the distance variation is calculated as the difference between distances d_{t-1} (UEs distance from a neighbouring HeNB calculated at P1) and d_t (UEs distance from neighbouring HeNB calculated at P2). As the movement of the UE on the earths surface is two-dimensional (i.e., height is omitted) the distance can be calculated using the Haversine function [100] that considers the spherical form of the earth (refer to Equation 5.1).

$$d = 2R \sin\sqrt{\sin^2(\frac{\Delta_{lat}}{2}) + \cos(lat_v) * \cos(lat_{SAP_i}) * \sin^2(\frac{\Delta_{lon}}{2})} \tag{5.1}$$

Where (Lat_v, Lon_v) and $(Lat_{SAP_i}, Lon_{SAP_i})$ denote the coordinates of the UE and candidate SAP respectively. Δ_{lat} and Δ_{lon}, respectively, denote latitude separation and longitude separation, and $R = 6371km$ denotes the radius of the earth.

Moreover, as discussed before, an OBU calculates the relative direction of its movement with respect to each neighbouring SAP, to short-list those SAPs with respect to which the OBUs movement is progressive and to eliminate the SAPs that lie in the opposite direction of its movement trajectory. Equation (5.2) calculates the distance variation for the relative movement direction parameter.

The *distance variation* (γ_i) is calculated as follows:

$$\gamma_i = d_{t-1,i} - d_{t,i} \tag{5.2}$$

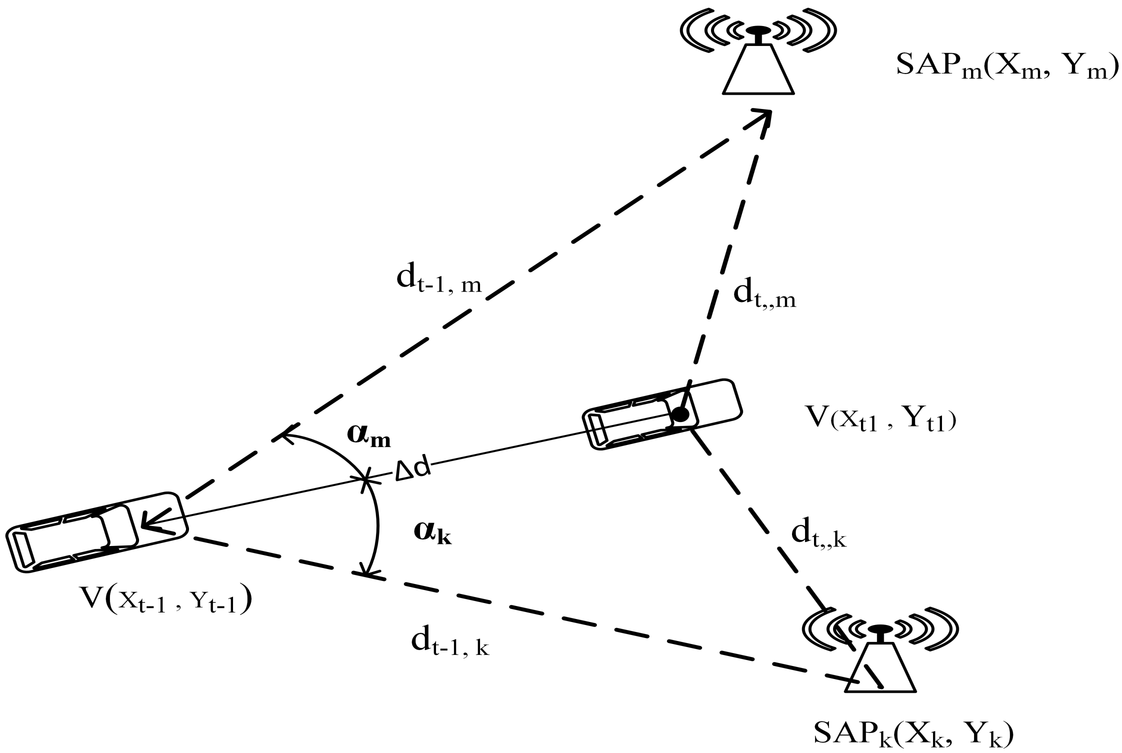

Figure 5.3: Determining relative movement direction of the UE.

where $d_{t-1,i}$ and $d_{t,i}$ denote the calculated distances of the OBU from the candidate SAP_i measured at positions, P_1 and P_2, respectively (see Fig.3). If $\gamma_i > 0$, the vehicle OBU is moving towards the cell coverage of SAP_i, or else it is moving away from it. Therefore, any SAP with $\gamma_i < 0$ is not shortlisted as candidate.

Next, the OBU ranks the short-listed candidate SAPs based on the dwelling time. This is defined as the time that the vehicle spends within the service area of a candidate SAP and is dependent on the vehicular speed, the maximum coverage area of a candidate SAP, the cosine factor and the speed of the vehicle. The cosine factor is used to rationalize the portion of the movement trajectory that is covered in the service area of the candidate SAP. In Figure 5.4 the angle α is the angle formed by the line joining both previous and current positions of the vehicle OBU and the

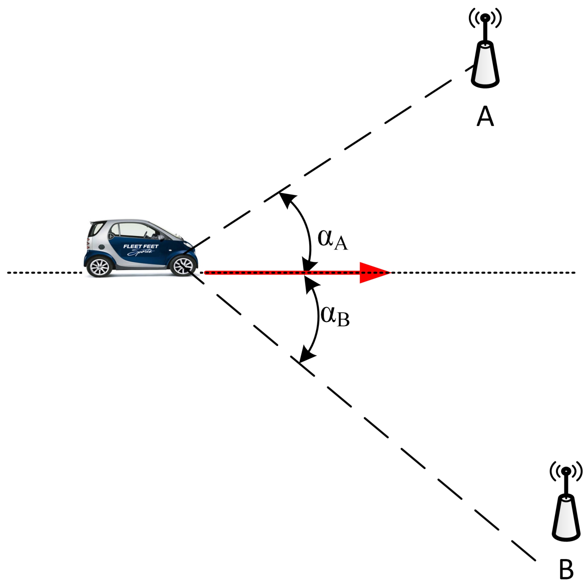

Figure 5.4: Determining proximity index.

distances from both positions to the candidate SAP. The smaller the value of α, the more dwelling time (duration) of the OBU within the coverage area of a candidate SAP. Thus, referring to Figure 5.3, from the calculated cosine factor it is obvious that SAP_m ranked the highest compared to SAP_k.

$$\cos\alpha_i = \frac{d_{t-1,i}^2 + \Delta d^2 - d_{t,i}^2}{2 * d_{t-1,i} * \Delta d} \tag{5.3}$$

Here, please note that the maximum value of $cos\alpha$ is obtained for $\alpha = 0$, which indicates that the candidate SAP_i is exactly located on the vehicle's future path of movement. On the other hand, the minimum value is obtained for $\alpha = \frac{\pi}{2}$ or $\frac{3\pi}{2}$, implying that the candidate SAP is perpendicular to the current location of the vehicle. It is important to note here that any measurement error in the value of angle α will remain the same for all candidate SAPs and thus will not affect the performance of the proposed mechanism [101]. Finally, the dwelling time t_r is calculated as:

$$t_r = \frac{C_r * \cos\alpha_i}{V_{speed}} \tag{5.4}$$

where C_r and V_{speed} denote the radius of the maximum coverage area of the target small cell SAP and the speed of the OBU (i.e., the vehicle), respectively.

Finally, to maintain load balancing, in this thesis, a candidate network is evaluated based on its load ratio (available capacity/total capacity) instead of its leftover bandwidth [7] as is commonly done. Equation 5.5 calculates the available bandwidth of the candidate SAP_i, while the load index (li) is represented in equation 5.6.

$$B_r = B_{APi} - \sum_{uj \subset V_{AP_i}} b_{ij} \tag{5.5}$$

$$l_i = \frac{B_r}{B_{Api}} \tag{5.6}$$

Eventually, the OBU scans the RSS of the top-ranked candidate SAP and if found suitable in terms of network load, execute a handover with it. Algorithm 1 details the proposed downward network selection procedure.

5.3.2 Upward handover mechanism

An upward handover is mandatory to prevent the OBU from losing its ongoing connection as it moves out of the coverage area of the serving small cell SAP. In a way, it is a forced handover and should be initiated and completed quickly to avoid any connection disruption. Therefore, the network selection for upward handover should be initiated early enough, preferably much before the OBU reaches the edge of the serving small cell, to provide it with adequate time for successfully completing the

Algorithm 1 Downward Candidate Network Selection

Input: SAP_i *coordinates* $(lat_{SAP_i}, lon_{SAP_i})$,

$Vehicle\ coordinates(LAt_v, Lon_v)$ and $R = 6371km$

Output: *Dwelling time* (t_r)

while *UE is connected to Macro Cell BS* , **do**

Get current vehicle position, p_1

Get $lat_{SAP_i}, lon_{SAP_i}, lat_v, lon_v$ and R

$\Delta_{lat_1} = lat_{SAP_i} - lat_{v_{p_1}}$

$\Delta_{lon_1} = lon_{SAP_i} - lon_{v_{p_1}}$

$d_{i1} = 2R\sin(\sqrt{\sin^2(\frac{\Delta_{lat_1}}{2}) + \cos(lat_{v_1}) * \cos(lat_{SAP_i}) * \sin^2(\frac{\Delta_{lon_1}}{2})})$

Set New Position = $P_2 = \frac{d_{i1}}{2}$

$\Delta_{lat_2} = lat_{SAP_i} - lat_{v_{p_2}}$

$\Delta_{lon_2} = lon_{SAP_i} - lon_{v_{p_2}}$

$d_{i2} = 2R\sin(\sqrt{\sin^2(\frac{\Delta_{lat_1}}{2}) + \cos(lat_{v_2}) * \cos(lat_{SAP_i} * \sin^2(\frac{\Delta_{lon_2}}{2})})$

$\gamma_i = d_{i1} - d_{i2}$ * *Distance variation**

if $\gamma_i \leq 0$ **then**

delete SAP_i

else

foreach $\gamma_i > 0$ **do**

$\delta d = P_2 - P_1$

$cos\alpha_i = \frac{d_{i1}^2 + \Delta d^2 - d_{i2}^2}{2 * d_{i1} * \Delta d}$ * *Cosine factor**

$t_{r_i} = \frac{C_r * cos\alpha_i}{V_{speed}}$ * *dwelling time**

return t_{r_i}

int[ ] SAPs = new int[ ] $t_{r_0}, t_{r_1}, \ldots, t_{r_n}$ * *list of potential candidate SAPs**

Array.Sort (SAPs). * *descending order sorting**

if $(SAPs[0].li >= li_{th} \&\& SAPs[0].RSS >= RSS_{th})$ **then**

HandoverEvent =true /*Send handover command to macro-cell BS*/

else

HandoverEvent =false /*Keep connection with macro cell BS*/ ;

entire handover procedure before it moves out of the small cells coverage area. To facilitate the timely decision for network selection and complete the upward handover, our proposed method divides the small cell network coverage area into two virtual circular coverage areas (assuming that the network coverage is shaped as a circle) [13]. As shown in Figure 5.5, the inner circle, called the useful coverage, does not involve any handover activities. Here, it is assumed that an OBUs RSS is always higher than a threshold value and is enough to provide a better quality of communication. On the other hand, most of the handover occurs when the OBU lies within the outer coverage area, called the handover area. Referring to our proposed network (cell) selection

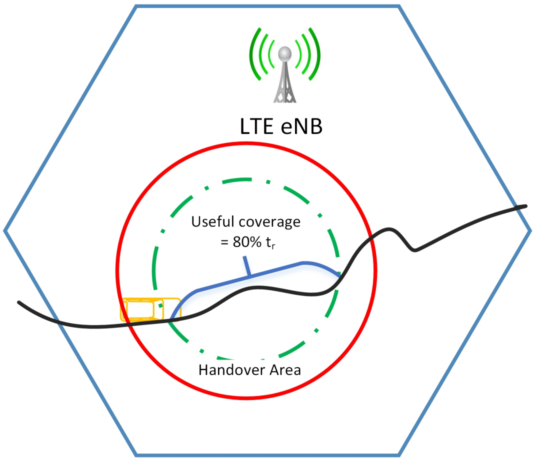

Figure 5.5: Upward network selection.

procedure as explained in Subsection 5.3.1, it is possible for the OBU to estimate its dwelling time (approximately) in the current cell before going for a handover. Based on experimental simulation results (refer to Figure 5.15 in Section 5.5.6), we observed that the packet delivery ratio of the OBU decreases when the useful coverage area (refer to Fig. 4) becomes greater than 80% of the calculated dwelling time (the time an OBU spends within the coverage area of the selected SAP). Thus, we propose that to get a satisfactory handover performance, the handover activity should initiate immediately after the OBU has traveled 80% of the dwelling time, which is the distance traveled inside useful coverage. In other words, the useful coverage is proposed to be 80% of the total duration that an OBU spends in the service area of the selected SAP.

Algorithm 2 Network Selection for Upward Handover.

1. While connected to the selected $HeNB_i$;
2. Set traveled distance in micro-cell to d_t
3. If dt =80%t_r
4. Send a handover request to the eNB
5. End.

5.4 Performance Evaluation

As was previously mentioned in 4.6.2, OPNET modeler is the main network simulation software used throughout this thesis. Thus, this section reports different results analyses obtained based on various simulation scenarios. Moreover, in this section, we not only present the network performance of the V2I-MoLoHA but also the related experimentation to support the proposed algorithms. In Section 5.4.1, we analyze the effectiveness of the proposed downward network selection method that ranks all available small cell eNBs based on Algorithm 1. This was achieved by combining Google map data and the proposed algorithm through MATLAB simulator. The key parameters for Algorithm 1 are geographical coordinates (latitude and longitude) for both vehicle positions and candidate SAPs. These coordinates are obtained from Google map (Queen Street, Auckland City Centre, New Zealand). The positions of the vehicle and SAPs are chosen randomly. It is worth noting that this approach is only used to evaluate the effectiveness of the proposed Algorithm 1 in terms of short-listing and ranking the potential SAPs.

The proposed the performance of the network selection method as a whole, (i.e., both downward and upward selection methods.) is investigated in Subsection 5.4.2.

5.4.1 Downward network selection method: ranking ability

To evaluate the algorithm 1-based downward selection method, we created the scenario presented in Figure 5.6. Using Google Map data (latitude and longitude), six equal sized small cell SAPs, SAP_1 to SAP_6, are strategically placed on both sides of the considered route (Queen Street, Auckland City Centre, New Zealand). While the route passes through the entire coverage area of SAP_4, the coverage area of SAP_3 tangentially touches the considered trajectory of the movement. Figure 5.6 shows the initial and next movement positions, P_1 and P_2, respectively of the vehicle carrying the OBU. Table 5.4.1 lists the considered Google Map coordinates for this particular scenario. The Figure 5.7 shows the ranking of SAPs based on algorithm 1. In Figure 5.7 all the six SAPs are ranked based on the calculated dwelling time of the UE in each of the cells while the UE is moving at varying speeds ranging from $10km/h$ to $100km/h$. The plotted results show that SAP_4 and SAP_3, respectively, provide the highest and lowest dwelling time. Thus, this clearly shows that SAP_4 and SAP_3, respectively, provide the maximum and minimum coverage areas through which the vehicle OBU has to pass when moving from the start to the destination point on its route. As mentioned in Subsection 5.3.1 , the vehicle OBU will only scan the top-ranked SAP, which is SAP_4 to select it for the handover activity. This implies that the proposed network selection method can avoid unnecessary scanning activities and handover attempts to the SAPs leading to an improvement in the overall network performance.

5.4.2 Performance of the whole network selection method

While the previous subsection evaluated the effectiveness of the proposed downward network selection method, this section evaluates the performance of the entire network selection method (i.e., both downward and upward selection methods). As previously

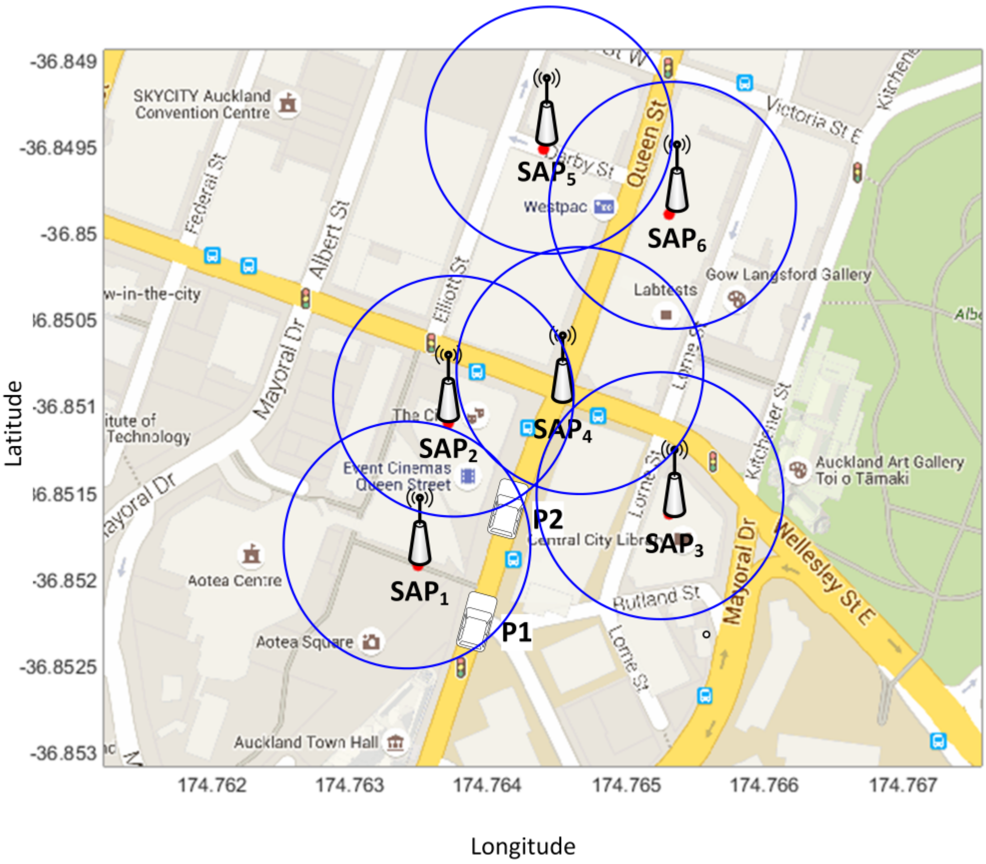

Figure 5.6: Map and route layout considered for evaluation of downward handover algorithm.

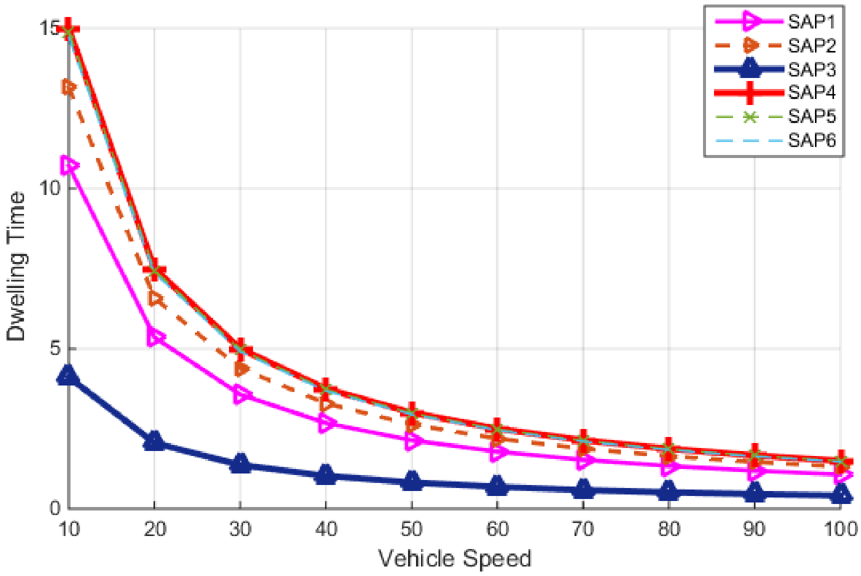

Figure 5.7: Ranking the available candidate SAPs.

discussed in Section 4.6.2, OPNET simulator is utilized through this thesis for investigating the network performance of the proposed algorithms. Thus, we proceed by explaining the further enhancements made to the vehicle OBU and both LTE eNodeB and WiFi AP, particularly for implementing the V2I-MoLoHA algorithm.

5.4.3 Enhancements to the vehicle OBU node model

The implementation of the V2I-MoLoHA algorithm is built on the top of its predecessor V2I-DHA presented in Chapter 4. In this algorithm, a code has been added to the vehicle OBU node model for computing and transmitting the dwelling time parameter to the right entity in the network in order to let it choose the target eNodeB/AP and also to compute the load index for a particular eNodeB/AP. The dwelling parameter is computed by modifying the function *lte_ue_as_vho_get_ho_params*(), discussed in Section 4.6.4. The dwelling is calculated based on the cell radius, angular movement and the vehicle speed; thus the functions *Lte_ue_as_vho_cell_radius_get*() and

Table 5.1: Considered coordinates (decimal degrees).

Location	Latitude	Longitude
Veh. Position 1	-36.852162	174.763936
Veh. Position 2	-36.851474	174.764235
$HeNB_1$	-36.851089	174.763712
$HeNB_2$	-36.851615	174.765314
$HeNB_3$	-36.849881	174.765314
$HeNB_4$	-36.849506	174.764405
$HeNB_5$	-36.850900	174.764517
$HeNB_6$	-36.851913	174.763493

lte_ue_as_vho_alpha_angle_get() are introduced to the computer cell radius and angular displacement parameters, respectively.

In order to have information about the data rates at the UE, a couple of new functions were added to the OBU node model. The main functions are:

- *lte_ue_as_vho_data_rate_compute*(): This function is used to re-compute the data rate every time a new packet is received at the LTE UE MAC.
- *lte_ue_as_vho_data_rate_access*(): This function is used to get the data rate that will be sent to the associated eNodeB in the measurement process
- *lte_ue_as_vho_data_rate_destroy*(): This function deletes the data rate computation instance.

5.4.4 Enhancements to the standard LTE eNodeB node

In the LTE eNodeB, these changes were done at the LTE eNodeB MAC protocol. A few lines of code have been added to store the dwelling time parameter and data rate parameter received from the vehicle OBU in the measurement process.

The computation of the load index of a particular eNodeB is computed based the current data rate which depends on the number of connected devices. However, the computation of this parameter would increase the handover delay at eNodeB. In order to avoid this delay, this parameter is computed at Evolved Packet Core (EPC) network level, in the GPRS Tunnelling Protocol (GTP). This was achieved by modifying the packet passed from the serving eNodeB that will go through EPC, these changes were coded in the function $lte\_s1\_handover\_required\_generate()$. This packet includes the list of potential target networks that have passed other filtering parameters (e.g., RSS and dwelling time). The data rate computation is done by the function $data\_date\_compute()$ and is called per received/transmitted packet, on the fly. In the GTP protocol, the packet will be processed by the function $umts\_gtp\_choose\_target\_enb()$ that chooses the target network and sends this information to the serving eNodeB for handover execution.

5.4.5 Enhancements to the standard Wi-Fi AP node

Similarly, the implementation for Wi-Fi AP involves the computation of both the dwelling time and the load index. The codes for these parameters are added to the WiFI AP MAC layer functions. For dwelling time the code is present in the $wlan\_mac\_hcf.pr.c$ file and it adds new fields and data structure to store the dwelling time associated with a specific AP.

The load index is computed based on the number of stations that are currently associated with the target AP. This information is obtained by analyzing the BSS load element of 802.11 beacon frame [102]. This element provides information on the cell load, from the AP point of view and is only enabled and used when QoS is supported. It includes station count, channel utilization, and available admission capacity.

5.4.6 Simulated scenarios

In order to evaluate the network performance of the V2I-MoLoHA algorithm, more small cells (SAPs) are introduced into the network topology simulated in the network topology simulated in Chapter 4. As illustrated in Figure 5.8, the simulated network includes one macro-cell eNodeB, eight LTE-A small cells (Pico-cells) and six Wi-Fi APs. Other parameters are as mentioned in Table 4.6.8, for the sake of comparison.

In order to investigate the effect of the network load algorithm on the proposed handover algorithm, each SAP served a varying number of active users throughout the simulation. As was mentioned in Table 4.6.8, the simulated scenarios deploy the channel bandwidth 1.4 MHz for each LTE-A SAP. According to [103], the channel bandwidth 1.4 MHz provides 6 RBs or 936 kbps transport block. As will be explained later in this section, various numbers of OBUs running video applications at 50kbps are deployed in the service area of selected SAPs and the algorithm would select the less loaded SAP.

5.4.7 Performance study

To evaluate the performance of the proposed handover algorithm under different conditions we define two sets of experiments:

(i) In the first set, we analyzed the effect of the proposed algorithm under the various vehicular speeds from 20 to 120 km/h with a granularity of 20. We suppose that the speed of movement remains constant during simulation duration.

(ii) In the second set, we evaluate the impact of the proposed handover algorithm on the delay sensitive applications such as VoIP. Here we investigate the impact of our handover algorithm on network QoS performance including throughput, end-to-end delay, the packet delivery ratio (PDR). Finally, we analyze the effect of the proposed V2I-MoLoHA on macro-cell offloading.

Similar to its predecessor V2I-DHA presented in Chapter 4, the performance of

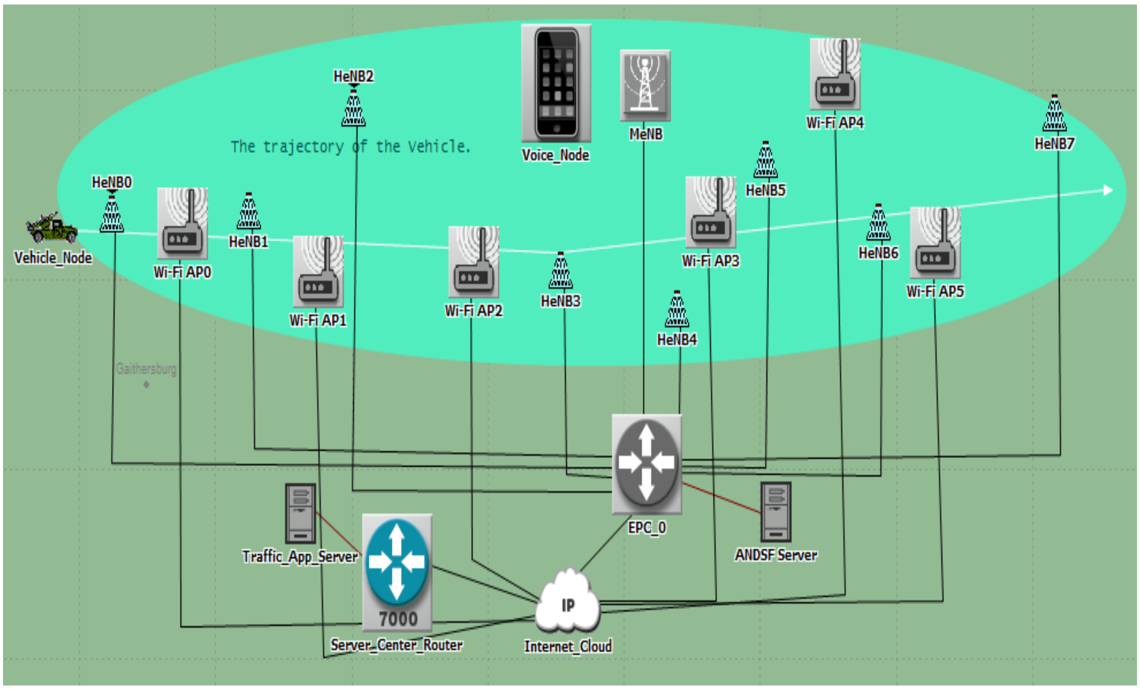

Figure 5.8: Simulated network topology.

the V21-MoLoHA is investigated against two existing handover mechanisms: the conventional RSS-based approach and the handover method called " Efficient ANDSF-assisted Wi-Fi Control for Mobile Data Offloading proposed in [36].

5.5 Simulation Results and Discussion

5.5.1 Number of handovers performed

The increased number of handovers is primarily related to the network overloading due to the handover-related messages that are exchanged between the node and the serving BS as well as between the serving and the target BS. Thus in a multi-tier heterogeneous network, an efficient handover mechanism should minimise the number of unnecessary handovers performed by the mobile node.

The results of simulation depicted in Figure 5.11 show the comparison of our proposed V2I-MoLoHA and three more handover methods discussed in the previous chapter, these are the conventional RSS-based handover method, ANDSF-Assisted handover proposed in [36] and V2I-DHA presented in Chapter 4. Under the proposed method the number of handovers is reduced due to its ability to apply both mobility and network load information for selecting the best target network. The simulation results revealed that the V2I-MoLoHA achieved up to 48.7% and 24.06% less handovers over the conventional and ANDSF-based handover methods, respectively.

The direct impact of the increased numbers of handovers in the conventional and ANDSF-Assisted scenarios is explained by the data traffic received by the vehicle OBU shown in Figure 5.10. The fluctuation in the amount of traffic received under the conventional scenario ANDSF-Assisted scenarios is associated with the number of unwanted/unnecessary handovers. Unlike the unstable traffic received attributed to the conventional and ANDSF-Assisted systems, the proposed algorithm improves and stabilizes the download traffic received by the vehicle OBU from the traffic server. As per Figure 5.10, the proposed method outperforms the other considered scenarios in terms of the reduced amount of traffic exchanged between the vehicle and the traffic server.

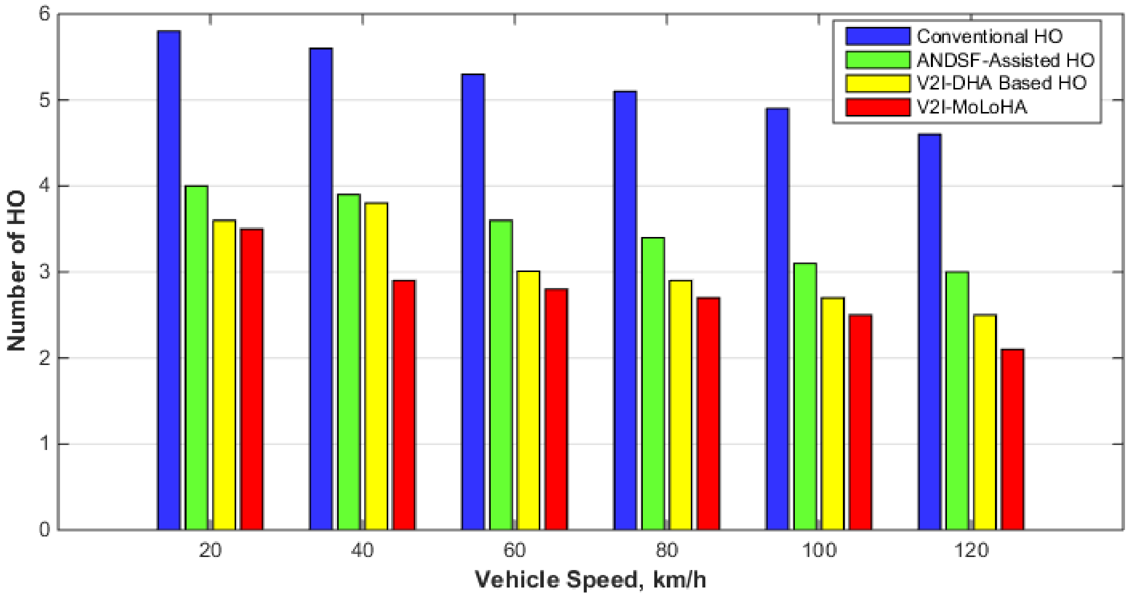

Figure 5.9: Number of handovers performed versus vehicle speed. Comparison of conventional HO, ANDSF-assisted HO, V2I-DHA, and V2I-MoLoHA.

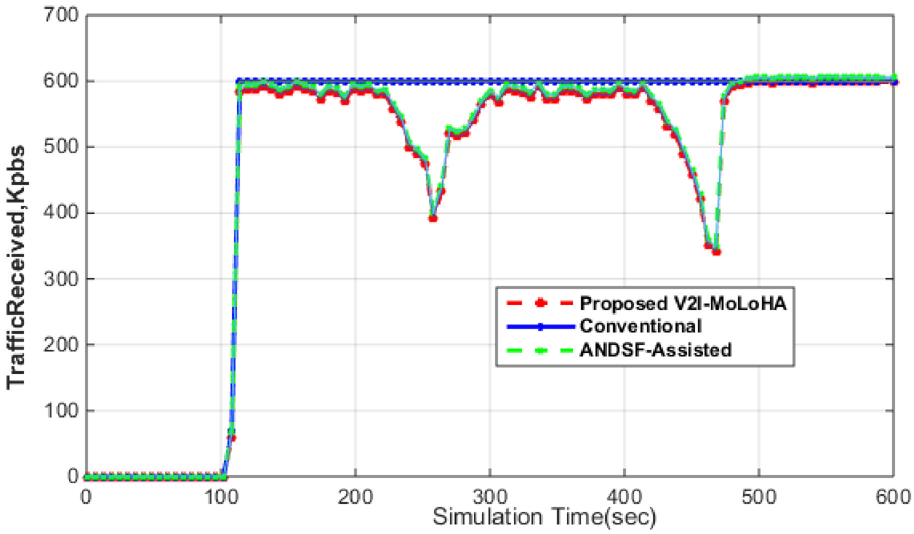

Figure 5.10: Comparison of downlink traffic received by vehicle OBU from the traffic application server, at the vehicular speed of 60km/h.

5.5.2 Handover failure ratio(HOFR)

Handover failure (HOF) involves network resources wasted for handover negotiations. Moreover, HOF deteriorates the expected QoS of ongoing communications, particularly for real-time applications sensitive to any type of disruption. The simulation results presented in Figure 5.11 exhibit how much the proposed V2I-MoLoHA reduces the percentage of HoF ratio. V2I-MoLoHA achieved up to 43.52% and 54.4% lower handover failure over the conventional and ANDSF-assisted handover methods,respectively. This is due to the proposed network selection method that starts handover activities well in advance of approaching the service areas of target networks. This feature is well confirmed by the results depicted in the downlink traffic received by the vehicle OBU from the traffic application server(See Figure 5.10).

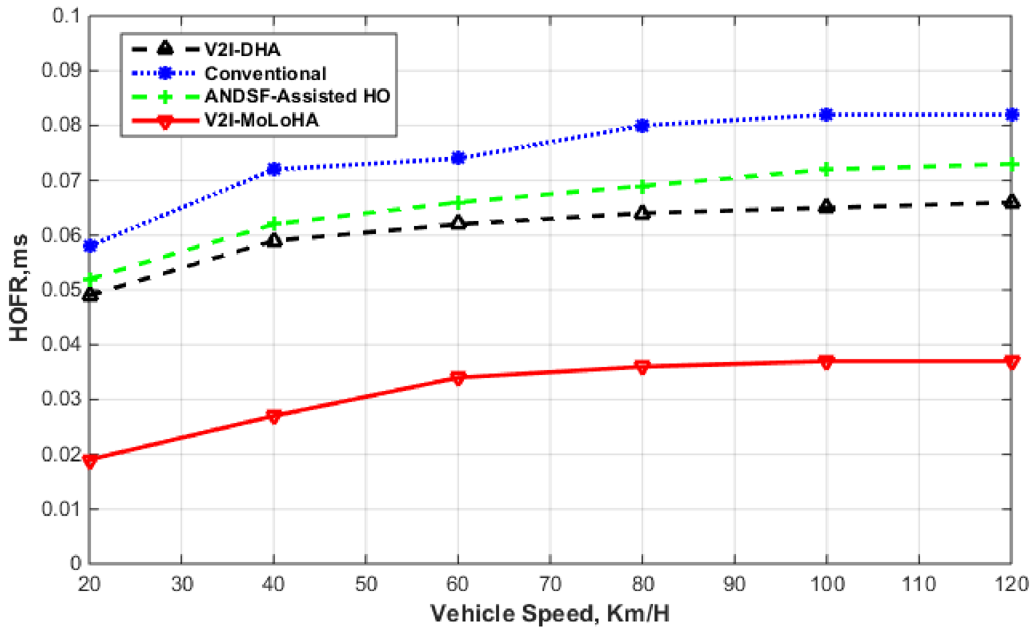

Figure 5.11: Handover failure ratio versus vehicle speed. Comparison of conventional, ANDSF-assisted, V2I-DHA, and V2I-MoLoHA handover methods.

5.5.3 Handover latency

Figure 5.12 shows the mean HO delay with vehicle speed varying from 20 km/h to 120 km/h. At low speed, all considered handover mechanisms offer almost the same handover delay. The proposed V2I-MoLoHA is dominated by its predecessor V2I-DHA due to the complexity of the network decision algorithm. Unlike V2I-DHA, the V2I-MoLoHA evaluates both mobility direction and network load for deciding the most suitable target network. In addition, the V2I-MoLoHA performs both downward and upward algorithms. The performance of the V2I-MoLoHA is clearly observed at the high speed where the average handover delay is reduced up to 34% and 29% compared to the conventional handover mechanism. Thus, based on the simulation results, we can confirm that the proposed V2I-MoLoHA performs much better than other considered handover methods.

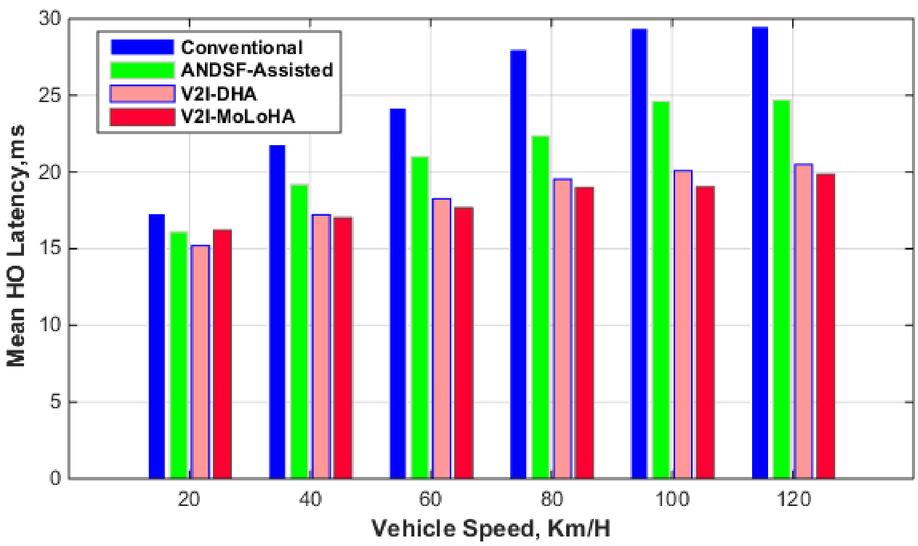

Figure 5.12: Mean handover latency versus vehicle speed. Comparison of conventional, ANDSF-assisted, V2I-DHA, and V2I-MoLoHA handover methods.

5.5.4 User throughput

Figure 5.13 exhibits the comparative average of the user throughput for a variable speed of the vehicle. These results we obtained by enabling a voice application that requires a bandwidth of 64 kbps for 600 seconds, which is the simulation duration. In addition to voice traffic, we have enabled background data traffic that requires a bandwidth of 36 kbps to simulate different live updates required to keep seamless connectivity. The graphs shown in Figure 5.13 show that the proposed V2I-MoLoHA offers an improved user throughput up to 92 Kbps while the lowest value is attributed to the conventional handover method that provides up to 41 Kbps for low speed and about 20 Kbps for high speed of movement. Generally, the V2I-MoLoHA achieved up to 52.55% and 32.34% higher throughput over the conventional and ANDSF-based handover methods, respectively. Although the speed is increased from 20km/h to 120 km/h, the graphs have also revealed that the user throughput provided by the V2I-MoLoHA is not much affected due to the consideration of network load while deciding the target network for a near future handover. The average throughput remains stable even when the speed of the vehicle increases.

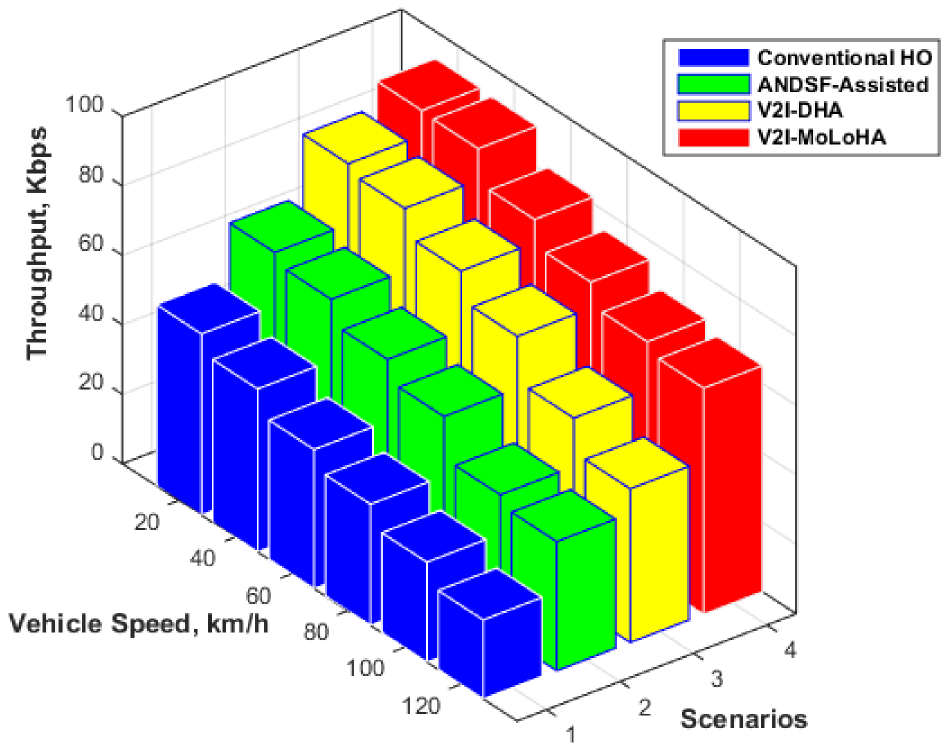

Figure 5.13: Comparison of user throughput of conventional, ANDSF-assisted, V2I-DHA, and V2I-MoLoHA handover methods at various vehicular speed.

5.5.5 End-to-end delay

As previously discussed in Subsection 4.7.5, end-to-end delay is also known as mouth to ear delay and it is the summation of various delays produced at different stages of communication. Figure 5.14 depicts the simulation results end-to-end delay performance for considered handover methods at various vehicular speeds. The proposed V2I-MoLoHA achieved up to 36.32% and 22.89% lower packet delay over the conventional and ANDSF-based handover methods, respectively. Generally, end-to-end delay rises with increase in the speed of movement. At high speed, the vehicle may move out of a cell before finalizing handover activities resulting in uncompleted handover which is associated with more dropped packets. Consequently, the sender should retransmit the same packets and thus could increase the end-to-end delay.

For different speeds, the proposed V2I-MoLoHA offers the lowest delay while the highest delay is attributed to the conventional handover method. According to the simulation results, the highest end-to-end delay recorded is 47ms which is still good compared to ITU QoS requirements [45]. This is because of the simplified ideal simulated scenarios that considered few network switching nodes compared to the real network systems where the communication could pass through an increased number of switching devices and various propagation media which add significant delays. However, the fact that the proposed handover algorithm reduces the end-to-end delay for the simulated scenarios, we can confirm that our handover algorithms could also perform efficiently in real communication networks.

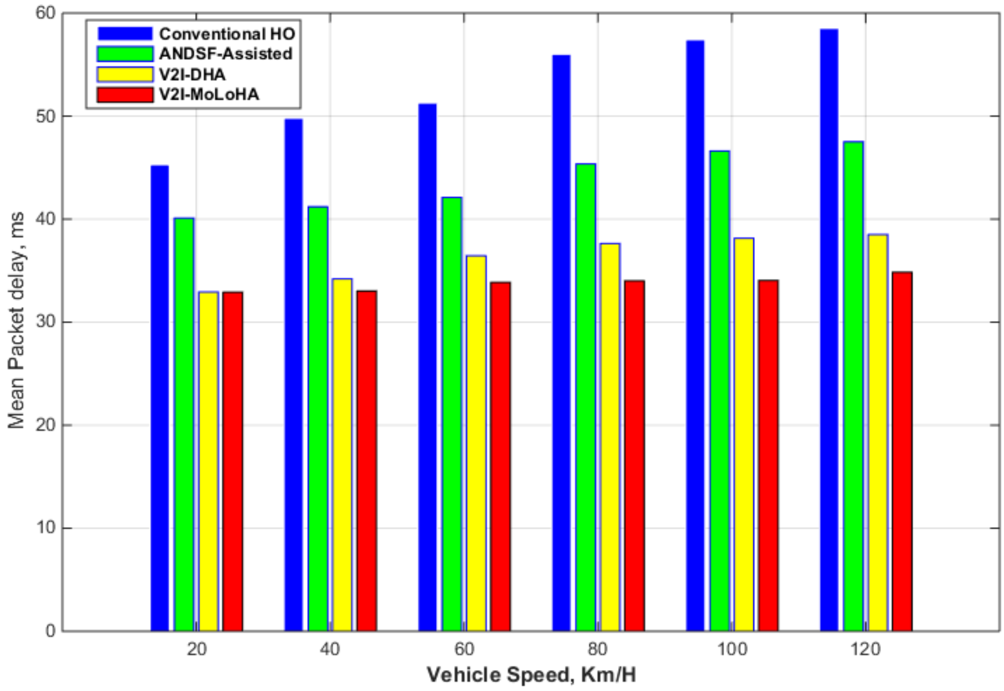

Figure 5.14: End-to-end delay versus vehicle speed. Comparison of conventional HO, ANDSF-assisted HO, V2I-DHA, and V2I-MoLoHA.

5.5.6 Effect of upward handover algorithm on packet delivery

The results presented in Figure 5.15 show that our proposed V2I-MoLoHA introduces fewer handover processes, decreasing up to 20% the PDR while maintaining the QoS demanded by the voice traffic session. Figure 5.15 shows the effects of the size of useful coverage (UC) area proposed in upward selection on the simulation results. While, the highest PDR, in this case, is obtained for $UC = 80\%$ of t_r, the lowest PDR is recorded when $UC = 90\%$ of t_r. We have also noted that PDR degrades with an increase in the vehicle's speed of movement due to the delayed handover as explained in Section 5.1. We can thus conclude that PDR is negatively affected by the increase in the speed of the vehicle.

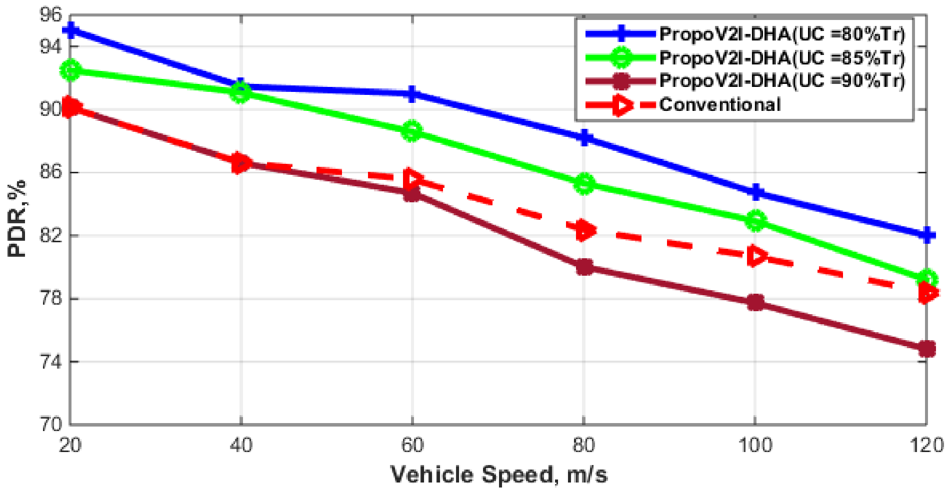

Figure 5.15: Improvement in packet delivery ratio.

5.5.7 Effect of V2I-MoLoHA on macro-cell offloading

The key idea of deployment of small cell networks is to address the exponential increase in mobile data traffic. This is achieved when the large macro base stations offload traffic to the low power small cell base stations. The simulation results shown in Figure 5.16 present the amount of traffic carried through WLAN APs with the speed of movement of $60km/h$. During the first 240 seconds all considered scenarios offer the same traffic amount; however, from 250 ms the proposed V2I-MoLoHA provides up to 75% and 50% higher than the conventional and ANDSF-Assisted handover methods, respectively. This reveals the efficiency of the proposed V2I-MoLoHA in terms of macro-cell offloading to small cells. Furthermore, Figure 5.17 presents a comparison of average user throughput for LTE-A and Wi-Fi technologies. The results for LTE-A were achieved by disabling all Wi-Fi APs. The simulation results exhibited in this figure reveal that the integration of both LTE-A and Wi-Fi systems offer higher user throughput compared to LTE-A only. On the other hand, these results confirm the viability of LTE-A to support V2I applications since it provides more than 85% of the required throughput at the low speed.

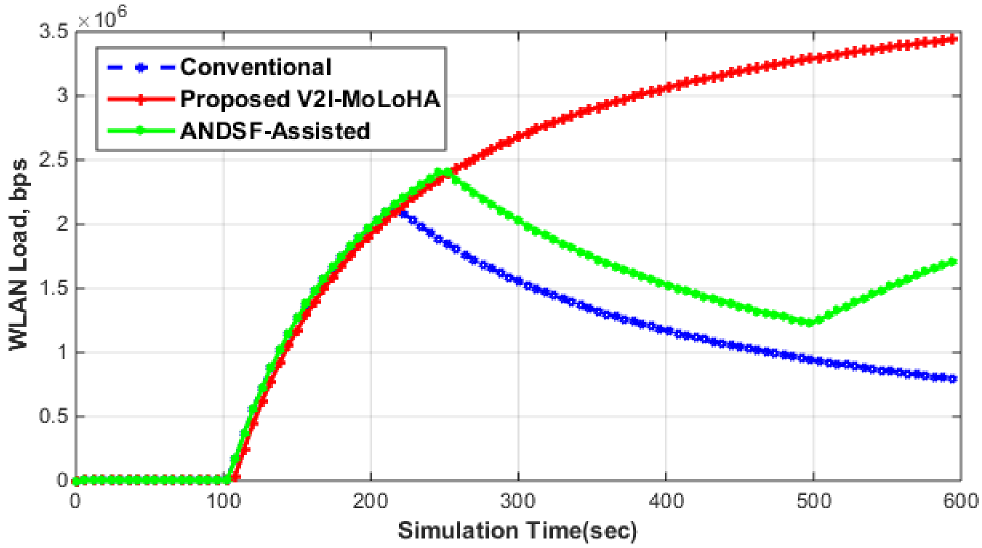

Figure 5.16: Comparison of WLAN load for conventional HO, ANDSF-assisted HO, and V2I-MoLoHA at vehicle speed of 60 Km/h.

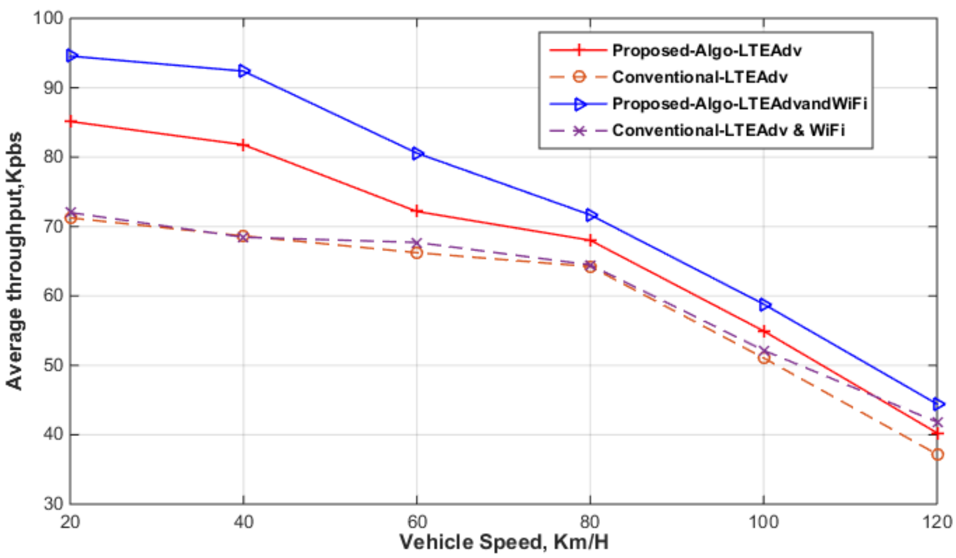

Figure 5.17: Wireless technologies usage comparison.

5.6 Summary

In this chapter, we have presented a mechanism, V2I-MoLoHA, which combines the knowledge of node mobility information and network load of the target network for selecting the most suitable network for improving handover performance in a multi-tier heterogeneous network. Both downward and upward handover methods are considered for V2I-MoLoHA. For downward handover, the mobile node is enabled for self-calculating dwelling time and load index parameters, which are mainly utilized for the handover decision. On the other hand, the upward handover is a simple but effective method that applies the dwelling time (already calculated in downward handover) for timely triggering the upward handover.

The effectiveness of the proposed analytical model for the downward network selection method was first analysed by combining Google map data and the proposed algorithm through MATLAB simulator. It was observed that V2I-MoLoHA can accurately select the best target network based on the geo-location data and the speed of movement. In addition to the MATLAB experiments, OPNET simulation experiments were carried out to study the performance of the network selection method as a whole (i.e., both downward and upward selection methods). In terms of handover performance, the impact of various vehicular speed on the handover frequency, handover latency, failure ratio was investigated. Moreover, the performance on QoS improvement was studied by evaluating well-known QoS parameters, including user throughput, end-to-end delay and packet delay ratio (PDR). In terms of handover management, the V2I-MoLoHA performs better than the conventional and ANDSF Assisted handover methods by reducing the number of unnecessary handovers and failure ratio as well as handover latency. With respect to the quality of service, the V2I-MoLoHA offers up to 15 Kbps higher user throughput and up to 10% higher PDR while the end-to-end packet delay is reduced up to 12ms lower compared to the conventional handover method.

The proposed model can be applied for multi-tier multi-RAT 5G networks, which deploys network densification in the form of heterogeneous small cells of different coverage areas overlaying the macro-cells. On the other hand, in a multi-tier heterogeneous network, the target network for handover can be selected based on the user applications. Table 5.2 summarizes the simulation results obtained from analysis of V2I-DHA. In all cases, V2I-MoLoHA outperformed both conventional and ANDSF-based selection methods. With respect to handover performance, the handover failure ratio and handover latency are degraded with increase of speed of movement. Similarly, QoS performance is degraded with increase in vehicle speed. Next, in Chapter 6, a multi-criteria cell selection mechanism is proposed for user application based handover for a multi-tier network environment.

Table 5.2: Handover performance comparison.

V2I-MoLoHA				
Vehicle speed		Low	Medium	High
Average handover events	Proposed	3.50	3.00	2.61
	ANDSF_based	4.00	3.40	2.71
	Conventional	5.07	5.00	4.60
Mean handover failure ratio	Proposed	4.90%	6.00%	6.5%
	PANDSF_based	5.01%	6.5%	7.20%
	Conventional	6.02%	7.3%	8.20%
Mean handover latency (ms)	Proposed	16.01	18.10	20.20
	ANDSF_based	18.04	21.20	24.70
	Conventional	21.60	24.15	29.81
Mean user throughput (Kbps)	Proposed HO	92.09	74.70	65.31
	ANDSF_based	57.70	49.18	25.58
	Conventional	39.01	27.81	20.02
Mean packed Delay (ms)	Proposed	32.50	34.80	35
	ANDSF_based	40.75	45.18	47.01
	Conventional	45.00	51.79	57.81

Chapter 6

Multi-Criteria Cell Selection Method for V2I Communication

6.1 Introduction

Chapters 4 and 5 reported two novel network selection algorithms for improving handover management in multi-tier heterogeneous networks from node mobility and network load perspectives. The objective of this thesis is to design efficient handover techniques proving an acceptable service quality for different applications with respect to their various QoS requirements. In this chapter we present a multi-criteria cell selection method for V2I communication, that selects the target network based on the QoS requirements of the ongoing applications. The handover that applies this network selection method is named multi-criteria based handover algorithm for V2I communication (V2I-MHA). We consider five dissimilar application profiles and the key difference is how much weight an application profile allocates to the requirements of the application.

6.2 Related Work

Since in V2I communication, a vehicle on the move must select the most suitable underlying network in real-time (either to disseminate data to urban regions having a dense capacity of users, or to exchange low latency emergency messages with the RSUs or for running safety applications). It is very important to consider multiple parameters to make the network selection. This can be implemented using multi-criteria decision making (MCDM) algorithms.

A significant number of MCDM-based handover decision methods can be found in the recent literature [104–107]. The common research problem for these studies is to overcome the issue of selecting a wrong candidate network for an anticipated handover, due to insufficient information mostly at the terminal side. The authors in [105] applied the MCDM algorithm to develop a QoS-aware handover method that selects the suitable candidate network in a heterogeneous network environment that includes LTE and WLAN RATs. The most appropriate target network is selected based on estimated user dwelling time. Similarly, The study in [106] applied a technique for order preference by similarity to ideal solution (TOPSIS) to select the most appropriate candidate network based on a single application or multiple applications. This method considered different criteria, including, maximum data rate, security, delay, battery power consumption, and cost. Although these proposals provide effective handover decision methods (compared to the conventional RSS-based handover), they are inaccurate in terms of selecting parameters (criteria) involved in handover decisions. A typical example is the dwelling time utilized in [105], where it is assumed to be received from the candidate network AP/BS, but it is not clearly explained how this parameter should be calculated. The authors of [107] developed a MCDM-based handover decision method that relies on a media independent handover (MIH) protocol. This method considers the information from application layers, user context and network context to select the most suitable candidate network in a heterogeneous network environment. In our proposal, we agree with the authors in [105] that the dwelling time is the key handover decision parameter for avoiding unwanted frequent handovers, that is why this parameter was considered in chapter 5.

6.3 Multi-Criteria based Handover Algorithm for V2I Communications (V2I-MHA)

The proposed V2I-MHA can be presented by assuming that the vehicle OBU is initially connected to macrocell BS and there are m small cell candidates, with m SAPs (Small cell Access Points): $SAP_1, SAP_2, .., SAP_m$ Where all candidate SAPs for the user(vehicle OBU) can be indexed by 1 to m in a set C: $C = [SAP_1, SAP_2, , SAP_m]$ For each handover event, the suitable SAP from the candidate set C will be determined by the proposed V2I-MHA algorithm with a combination of the following criteria: Guaranteed bandwidth, packet latency (PL), packet loss ratio (PLR) and the network usage cost associated with each candidate network operator. The proposed V2I-MHA is based on the Simple Additive Weighting (SAW) method [108] and the weighting vector of the decision element is determined by the Eigenvalue method of Analytical Hierarchical Process (AHP). While there are numerous methods used for multi-criteria decision making, SAW was selected due to its simplicity resulting in less processing time, which is a key requirement for a good decision mechanism, particularly in vehicular networks that perform frequent handover decisions. Contrary to its predecessor Mobility and network Load aware Handover Algorithm (V2I-MoLoHA)) algorithm, this algorithm focuses on the quality of service (QoS) requirement for the ongoing applications. Moreover, the V2I-MHA also considers the user budget that specifies how much money the user is willing to pay for the service.

To maintain the accepted QoS requirements, we define application profiles that classify user preferences into different sets. For instance, a voice application which requires uninterrupted communication may prefer to connect to a network that provides less packet latency and less packet loss ratio. On the other hand, the guaranteed bandwidth is not of importance compared to video streaming applications. Subsequently, for each application profile, a weight vector is developed based on the importance weight of attributes. Also, the consistency ratio (CR) is calculated to verify the consistency of the considered weighting matrices. A weight vector is acceptable when the calculated CR is less than $0.1(CR0.1)$ [109]. User profiles are discussed next:

6.3.1 Application profiles

We define application profiles to classify the user preferences into dissimilar sets. These profiles are defined based on application requirements and user budget. With respect to V2I communications, we consider the following five application profiles:

- **Maximum Quality:** Under this profile, the algorithm always selects the best performing network among all the possible choices, irrespective of the associated cost. With respect to V2I communications, this profile may be reserved for safety-related applications such as accident warnings.

- **Guaranteed VoIP**: The most important parameters are packet delay and packet loss ratio. The delay is a key issue as a conversation must be processed in real time. We also consider a reduced number of handovers to avoid an increased packet loss ratio. Moreover, the usage cost should be reasonable since the call may take time. In the context of V2I communications, this profile can include traffic management applications where traffic authorities may directly communicate to vehicle drivers through OBU via VoIP.

- **Guaranteed streaming:** This is a typical profile for streaming applications. The algorithm selects the network that offers not only a high throughput but also a low packet loss ratio. In V2I communications, vehicles may send/receive video data (on-road traffic calculation) to/from a traffic server.

- **General:** This is the most general possible profile, where the user does not specify any constraint for the QoS parameters. In V2I communications, this profile may represent entertainment and personalized applications. Examples of such applications include searching for the nearest gas station or looking for the nearest McDonalds restaurant. These applications do not usually suffer from stringent communication constraints, like restricted latency or packet loss, although high data throughput may be occasionally required.

- **Minimum cost**: This profile depends much on the budget of the user, and the key component for making the network selection decision depends on the network usage fee that is charged per unit of data (MB). The higher the weight of cost attribute, the algorithm will select the cheapest candidate access network. In the context of V2I communications, this profile involves users on board who may decide to connect to different radio access networks via the vehicle OBU.

6.3.2 Application requirements

- **Guaranteed bandwidth (GB)**: This parameter is given higher weight for bandwidth-hungry applications, such as Video streaming. Moreover, this parameter will help manage the use of available bandwidth as the user will select the candidate based on the ongoing bandwidth requirements.

- **Packet End-to-End latency (PL)** : This parameter specifies the latency that the application can tolerate before decreasing its performance.

- **Packet loss ratio (PLR)**: The losses on the channel that the application tolerates in order to guarantee effective performance.

- **Cost**: This parameter defines user preferences in terms of service fee. For maximum quality profile (P1), this parameter is given the lowest value, while it is given highest value for the minimum cost profile.

6.3.3 Proposed MCDM-based network assessment function

As mentioned in introducing this section, the proposed V2I-MHA applies the simple additive weight (SAW) decision method to select the suitable target network. SAW is a classical multi-attribute decision method and is widely used for network selection due to its simplicity [108,110]. To determine the overall score of a candidate network, the normalized contributions from each metric r_{ij} is multiplied by the weight W_i assigned to the j^{th} metric. The candidate network with the highest score is selected and is given by Equation (1).

$$CandidateNetRatio_i = \begin{cases} \frac{RequirementAttributeValue_{ij}}{CandidateAttributeValue_{ij}}, & j = GB \\ \\ \frac{CandidateAttributeValue_{ij}}{RequirementAttributeValue_{ij}}, & j = Cost, PL, PLR \end{cases} \tag{6.1}$$

$$CandidateNetValue_i = \sum_{i=1}^{n} \omega_i * CandidateNetRatio_i \tag{6.2}$$

$$\sum_{j=1}^{n} \omega_i = 1 \tag{6.3}$$

where W_i denotes the weight of a criterion j and the value assigned to W_i shows the relative importance of that criterion in a decision matrix. Besides, there are two types of the considered criteria, including benefit type criteria (high value is better) and cost type criteria (low value is the better). In the proposed V2I-MCCS, we have three *cost criteria*: $Cost, packetE2Edelay, Packetlossratio$ and one $Benefit$ *criterion*: $GuaranteedBandwidth$. Here, each network metric is assigned a weight depending on its influence on the handover decision of the vehicle OBU. The decision matrix is given below:

$$M = \begin{array}{c} \\ RAT_1 \\ RAT_2 \\ . \\ . \\ . \\ RAT_n \end{array} \begin{array}{c} \begin{array}{cccc} \text{GB} & \text{PL} & \text{PLR} & \text{Cost} \end{array} \\ \begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} \\ X_{21} & X_{22} & X_{23} & X_{24} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ X_{n1} & X_{n2} & X_{n3} & X_{n4} \end{bmatrix} \end{array}$$

6.3.4 Computing the weight vector

The weight value shows the relative importance of criteria in a decision matrix. In this research work, the appropriate weight vector for each application profile is calculated based on the Analytical Hierarchy Process (AHP) method, a famous decision-making framework developed by Saaty [111]. Table 6.1 presents weight values optimized for all application profiles, considered in this research work. Moreover, the consistency of the calculated weight vectors is justified by the consistency ratio. As presented in the last row of Table 6.1, for each application profile, the consistency ratio is less than 0.1, indicating sufficient consistency.

We proceed with explaining the three steps that lead to the weighting vector.

- The first step involves developing the pairwise matrix that establishes the relative priority of each attribute against every other attribute. The pair-wise

Table 6.1: Weight values optimized for application profiles.

Requirement Parameter	Maxim Quality	Guaranteed VoIP	Guaranteed Video	General	Minimum Cost
Guaranteed Bandwidth	0.321429	0.237245	0.375141	0.250000	0.161797
Packet Latency	0.321429	0.386297	0.271775	0.250000	0.142400
Packet Loss Ratio	0.321429	0.211662	0.271775	0.250000	0.212937
Cost	0.035714	0.164796	0.081309	0.250000	0.419058
CR	**0.0000**	**0.038227**	**0.029161**	**0.0000**	**0.096453**

comparison utilizes index values from 1 to 9. At a time two criteria are evaluated based on their relative importance. If a criterion A is equally preferred as criterion B, the pair receives an index value of 1. If A is extremely preferred to B, the index value of 9 is used. Moreover, the reciprocal relationships are also applied. For instance, if A is extremely non-preferred to B, this pair receives an index value of 1/9. The values are entered row by row into a cross-matrix. The diagonal of the matrix contains only values of 1. Table 6.2 presents index values and their delimitations according to Saatys AHP [109].

- The second step computes the weights of the individual criteria. This step starts with multiplying the values in each row together and calculating the n^{th} root of the product. Then the calculated root of the product is normalized to get the appropriate weight. The normalization is done by dividing each row product by the sum of the product column.

- Finally, the consistency of the pair-wise matrix is assessed by calculating and checking the value of the consistency ratio (CR). The developed pair-wise matrix is consistent when the CR value is less than 0.1. CR is calculated as follows:

$$CR = \frac{CI.}{RI} \tag{6.4}$$

$$CI = \frac{Lamda_{max} - n}{n - 1} \tag{6.5}$$

where $Lamda_{max}$ is the sum of the product of each criterion normalized weight and the sum of each criteria column, and n is the number of criteria. The amount of the random index (RI) depends on the number of criteria being compared and its value can be obtained from Table 6.3.

Table 6.2: Saaty's 1-9 scales of pairwise comparison.

Definition	**Index value**	**Explanation**
Equally preferred	1	Two activities contribute equally to the objective
Weak or Slight	2	
Moderately preferred	3	Experience and judgement slightly favour one activity over another
Moderate Plus	4	
strongly preferred	5	Experience and judgement strongly favour one activity over another
Strong Plus	6	
Very Strongly preferred	7	An activity is favoured very strongly over another
Very, very Strong	8	
Extremely preferred	9	The evidence favouring one activity over another is of the highest possible order of affirmation

Table 6.3: The average stochastic uniformity index target value of judgement matrix.

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

6.4 V2I-MHA Decision Process

The development of different network selection algorithms in this research work is done in a progressive and incremental method. Thus, the V2I-MHA is built on top of its predecessor V2I-MoLoHA (Mobility and Load aware Handover Algorithm for V2I communications). Once the filters in the previous algorithm (V2I-MoLoHA) have filtered out inappropriate candidate networks, this algorithm applies the multi-criteria decision-making method to make sure that the candidate network is selected based on application requirements. The V2I-MHA is expected to provide an improved network resource management due to different application profiles defined based on various sets of criteria. Similarly to V2I-MoLoHA, this algorithm considers both handover directions: downward and upward network selection.

6.4.1 V2I-MHA for downward selection

The V2I-MHAA for downward selection method is presented in Figure 6.1. Initially, it is assumed that a UE is connected to the macro-cell base station (BS). During its stay in the macro-cell service area, the UE sends an ANDSF request to the ANDSF server and the ANDSF response includes a list of all small cell networks available in the service area of the serving macro-cell BS. As presented in Figure 6.1, the proposed V2I-MHA for downward network selection is composed of two main asynchronous stages: data collection and decision process. The first stage provides the list of potential candidate networks. The second stage consists of the decision process phase that involves the execution of the MCDM mechanism. The selection decision includes all parameters defined above, including guaranteed bandwidth, packet latency, packet loss ration and network usage cost. If none of the candidate small cells meets the on-going application and user budget requirements, the UE keeps its connection with the macro-cell BS, otherwise, the network selection will be performed, and then the downward handover is executed to the selected SAP.

6.4.2 V2I-MHA for upward selection

As the UE approaches the boundary of the service area of the small cell networks, the UE should select the suitable network for handover. For this type of network selection, the candidate set C includes the macro-cell base stations or eNBs and a number of small cells excluding the current serving BS. Thus, the new set C_N becomes, $C = [BS_M, SAP_1, SAP_2, , SAP_{m-1}]$ (excluding the serving SAP)

As it is presented in Figure 6.2, the proposed upward handover can be triggered by either of two events: (a) a SAP availability event and (b) a call event. A SAP availability event occurs when the C_N is not empty. On the other hand, a call event occurs when a new call is initiated from the vehicle OBU and the appropriate network will be selected based on the requirements of the call. For instance, let us say that an OBU initiates a delay sensitive call while connected to a small cell SAP. As the new call requires uninterrupted connectivity, this call event will instantly trigger the selection method for selecting a suitable network. In this situation, the best choice could be switching from a small cell network to a macrocell network and all calls are moved to the newly selected network.

Per our proposal, if an OBU is running multiple applications mapped on different profiles, the proposed method selects the most suitable candidate network based on the application with the highest priority. The accurate time for initiating a handover

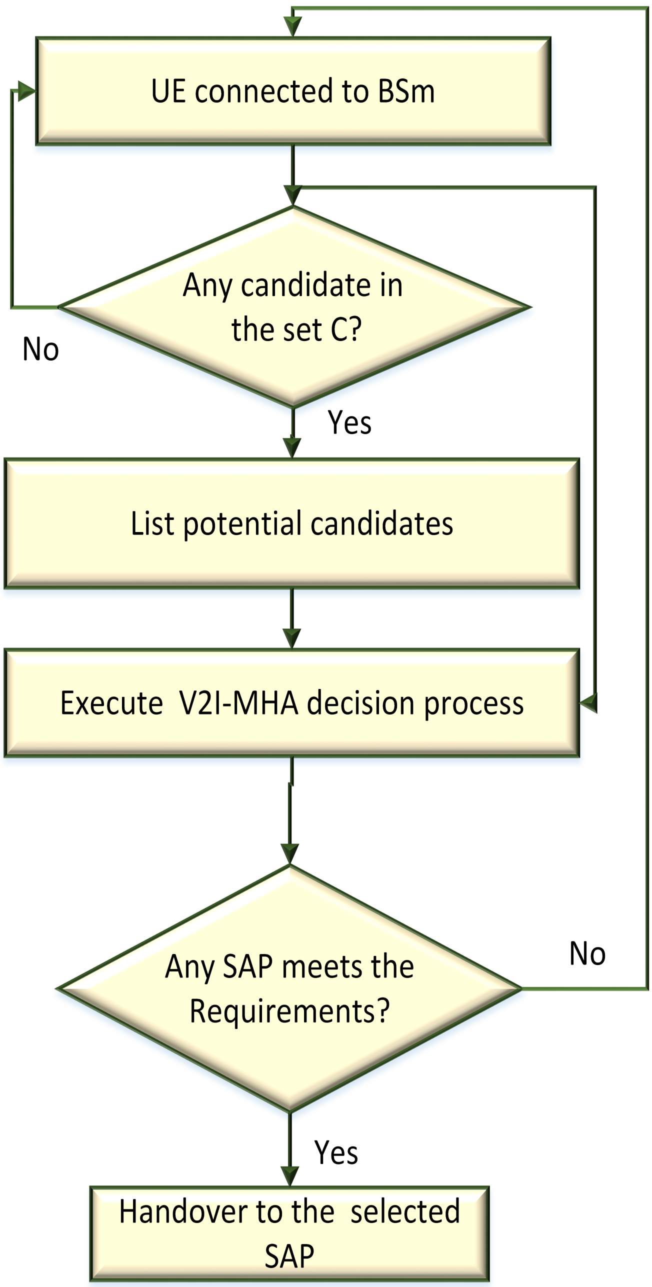

Figure 6.1: V2I-MHA for downward network selection model.

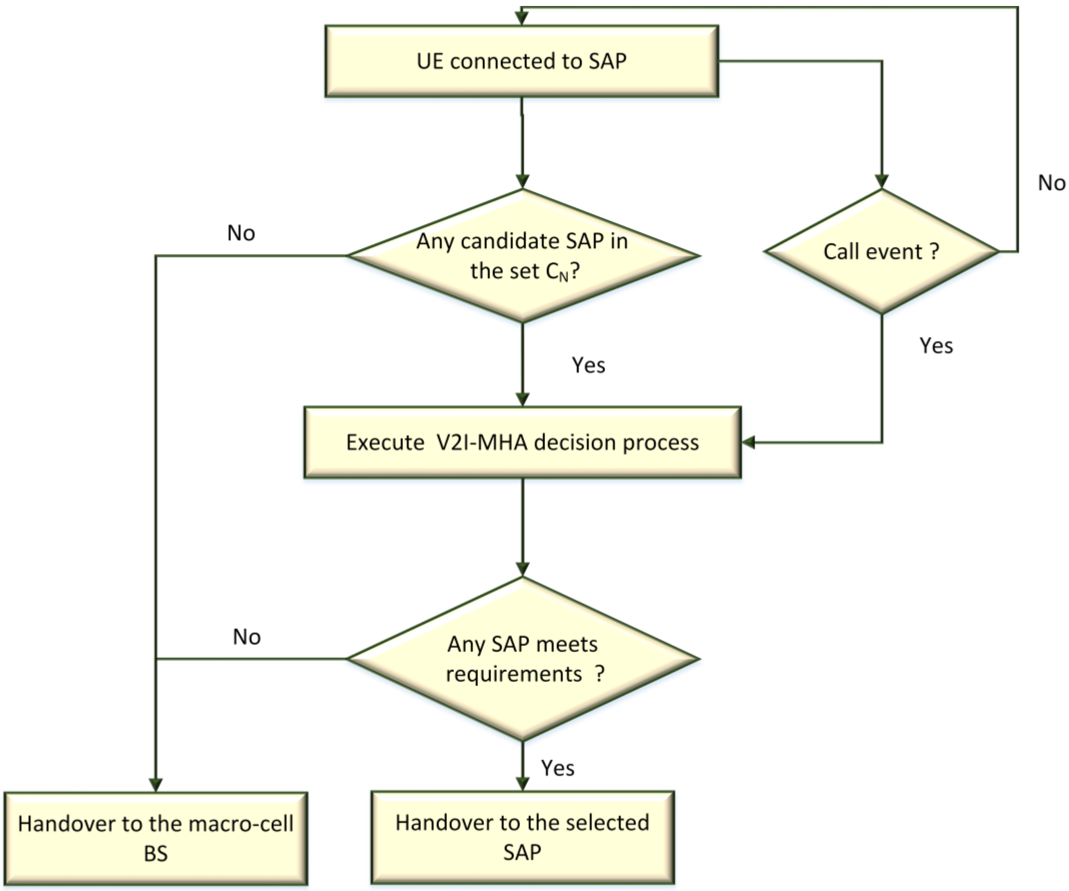

Figure 6.2: V2I-MHA for upward network selection model.

request is estimated based on Algorithm 2 presented in the previous chapter (Subsection 5.3.2). Finally, there are two options: switching back to the macrocell network (upward network selection) or handover to another small cell. While the small cell networks may not be available in the vicinity of the mobile node, it is assumed that the macro-cell network is always available. There are two cases where the mobile node decides to connect back to the macro-cell BS: either there is no SAP found in the neighbouring set or all SAPs in the set do not meet the V2I-MHA requirements based on the on-going application.

6.5 Performance Study

Similar to previous algorithms presented in the previous chapters, the performance of the V2I-MHA is evaluated through OPNET simulator.

6.5.1 Enhancements to the UE node model

The implementation ofthe V2I-MHA algorithm involves some modifications in the existing UE node in order to keep track of the currently active applications per UE. Also, further modifications are done at EPC for taking the handover decision based also on application to profile mapping. In order to keep track of this information, every UE will initiate an application profile. The application profile is a structure with the information presented in Figure 6.3:

```c
typedef struct AppProfileT_Node {
    PrgT_Mutex *mutex;
    char *node_name;
    int node_imsi;

#define MAX_PROFILES            (5)
    unsigned int profiles_msk[MAX_PROFILES];
#define PROFILE_MSK_WEB                 (1 << 0)
#define PROFILE_MSK_VIDEO_STRM          (1 << 1)
#define PROFILE_MSK_VOICE               (1 << 2)
#define PROFILE_MSK_FTP                 (1 << 3)
#define PROFILE_MSK_DB                  (1 << 4)
#define PROFILE_MSK_VIDEO_CONF          (1 << 5)
#define PROFILE_MSK_REMOTE_LOGIN        (1 << 6)

#define PROFILE_ID_VIDEO_CONF   (0)
#define PROFILE_ID_REMOTE_LOGIN (0)
#define PROFILE_ID_VOICE        (1)
#define PROFILE_ID_VIDEO_STRM   (2)
#define PROFILE_ID_WEB          (3)
#define PROFILE_ID_FTP          (3)
#define PROFILE_ID_DB           (3)
#define PROFILE_ID_COST         (4)
```

Figure 6.3: Mapping the proposed application profiles to the traditional standard applications.

The *mutex* field is used to avoid concurrent access to an object with type $AppProfileT\_Node$, the $node\_name$ is the node name that an object of this type is associated with. The $node\_imsi$ is the International Mobile Subscriber Identity (IMSI) of the node that an object of this type is associated with. The $profiles\_msk()$ is an array of the proposed application profiles so, there are five $MAX\_PROFILES$ per this object. When an application is mapped to a profile, the application specific flag ($PROFILE\_MSK*$) is set on the $profiles\_msk[PROFILE\_ID*]$ correspondent entry in the array. For instance, the voice application is mapped to profile 1, guaranteed voice. The profile flag for voice application is $PROFILE\_MSK\_VOICE$

and voice application is mapped to profile 1, $PROFILE\_ID\_VOICE$. So, at the UE level, when a voice packet is received an operation like the next one will be executed: $(AppProfileT\_Node*)p- > profiles\_msk[PROFILE\_ID\_VOICE] = PROFILE\_MSK\_VOICE$ The UE creates an object of type $AppProfileT\_Node$ at the initialization time. More exactly, this is done in the $lte\_ue\_nas.pr$ process. All transmitted and received packets pass through this protocol. When this protocol receives application packets, it scans for the $L4$ port and will do the application to profile mapping. This mapping is done by calling $lte\_support\_ip\_dgram\_to\_\varepsilon\_bearer\_map()$.

6.5.2 Simulated scenario

As the V2I-MHA runs on top of its predecessor the V2I-MoLoHA (presented in Chapter 5), we maintain the same simulation scenario presented in Subsection 5.4.6 shown in the Figure 5.8. However, for the performance evaluation of the V2I-MHA, each candidate network is configured with different performance parameters as presented in Table 6.4. The values in Tables 6.4 and 6.4 are selected based on various literature [112–115]. This helped us to generate diverse alternatives to evaluate the efficiency of our proposed mechanism regarding target network selection. In the simulation, the vehicle moves within the designed trajectory, crossing different coverage areas while performing a video streaming session. The chosen network should fulfil the minimum QoS requirements of the ongoing applications.

6.5.3 Performance assessment

The performance of the V2I-MHA is evaluated by performing different simulations for all considered application profiles. Depending on the application profile applied, the

Table 6.4: Simulated network parameters.

Technology	**GB (Mb)**	**Packet E2E Latency (ms)**	**Packet Loss Ratio**	**Price/Mb**
LTE-A Macrocell (eNB)	0.9360	48.8200	3.1510	0.9000
WiFi AP	3.5000	30.0800	0.9800	0.0800
LTE-A Small Cell (HeNB)	1.5000	41.8000	0.8600	0.0950

Table 6.5: QoS requirements per application.

Use Case Application	**Nominal Throughput (Kbps)**	**Latency Requirements (ms)**	**Acceptable PLR (%)**
VoIP	32 - 64	100 - 150	3
Video	512 - 5000	100 - 150	2
Best Effort	>10	<20000	$\leq$ 10

V2I-MHA behaves in a different manner. These behaviours are analyzed based on the type of traffic considered against the proposed application profiles. For delay-sensitive applications, we consider both voice and video applications and the performance is evaluated based on a comparative study of the throughput, packet delay and packet loss offered for each application profile. Moreover, we analyze the number of handovers performed per application profile.

6.5.4 Throughput analysis

The vehicle OBU is running both voice and video sessions which require a minimum guaranteed bandwidth of 64kbps and 900kbps respectively. Thus, the selected target network should provide a minimum of 964 kbps to maintain the acceptable QoS for these two concurrent sessions.

Figure 6.4 shows the throughput attributed to each application profile. It clearly observed that Maximum quality (MaxQ), and video profiles almost achieved 0.964 Mbps which is the total required throughput. The throughput obtained with the voice profile is slightly lower than that of MaxQ and video because the voice profile doesn't put more weight on bandwidth attribute. We also observed that general profile obtains half of the required throughput as there is no service prioritization. The lowest throughput is obtained to the minimum cost (MinCost) profile as its priority is not better performance but rather the network usage fees.

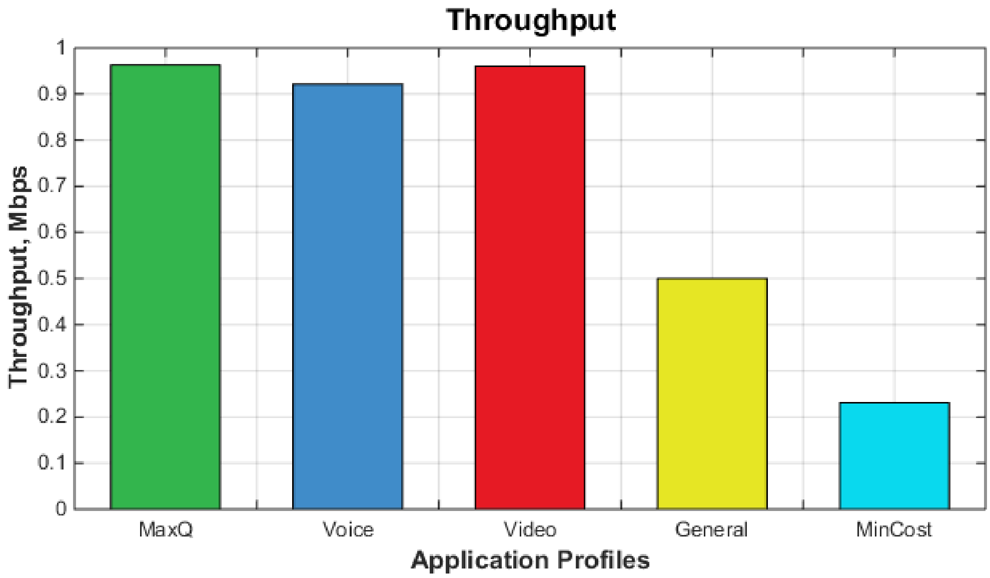

Figure 6.4: User throughput comparison.

6.5.5 Performance study of packet delays and packet losses

As was mentioned in Subsection 6.5.4, the vehicle OBU has two active applications, voice and video sessions, throughout the simulation duration. From Figure 6.5, we observe that the lowest packet latency is achieved for the maximum quality profile, while the highest latency is attributed to the minimum cost profile. The voice profile performs a little bit better than video due to the higher weight the voice puts on the packet delay parameter.

Concerning packet loss, Figure 6.6 reveals that maximum quality, voice, and video profiles minimize packet loss up to 3%, while the general and minimum cost present a higher packet loss of up to 29.5% and 33%, respectively.

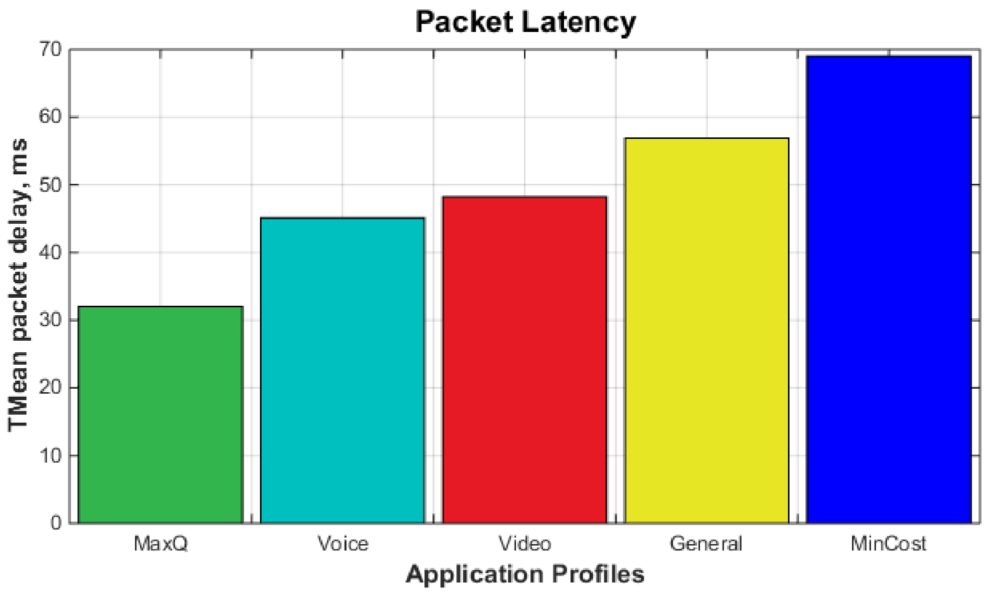

Figure 6.5: Packet end-to-end delay comparison.

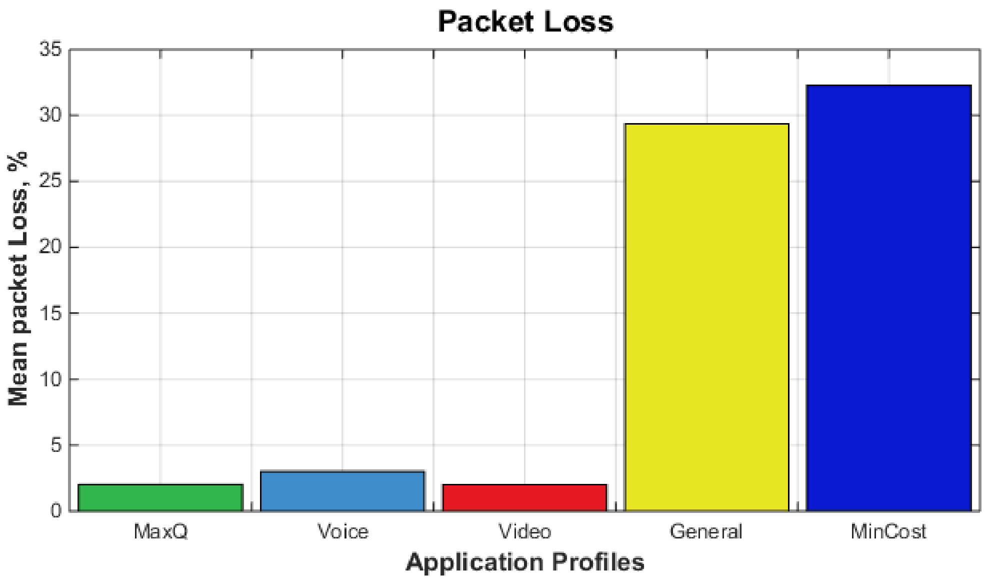

Figure 6.6: Packet loss comparison.

6.5.6 Performance study of handover events and data traffic

Table 6.6 compares the handover events for all considered application profiles. The minimum number of handover events is three performed by the maximum quality profile, while the highest number of events is attributed to the minimum cost profile since the vehicle OBU keeps switching to the cheapest network technology. This is well explained by the data traffic analysis presented in Figure 6.7 which exhibits the total data traffic exchanged between the vehicle OBU and the server per technology. This gives us a clear picture of the total traffic transmitted/received via each interface during the simulation time. We observe that maximum quality, voice, and video profiles have utilized the macro-cell eNB more than small cells, while general and minimum cost profiles preferred small cells, mostly Wi-Fi technology.

Table 6.6: Handover events.

Profile	**Maximum Quality**	**Voice**	**Video**	**General**	**Minimum Cost**
Handover events	3	4	4	6	8

Although voice and video profiles have the same performance in terms of handover events, the data traffic received/transmitted per each technology are different. For instance, the video profile amount of data traffic transmitted and received via Wi-Fi SAPs is higher than those of voice profile, this is due to the fact that Wi-Fi offers better bandwidth according to the simulated scenario while the video traffic puts higher weight on bandwidth requirements and the voice profile. This reinforces the profile dependency where the total data traffic is associated with weights of preference

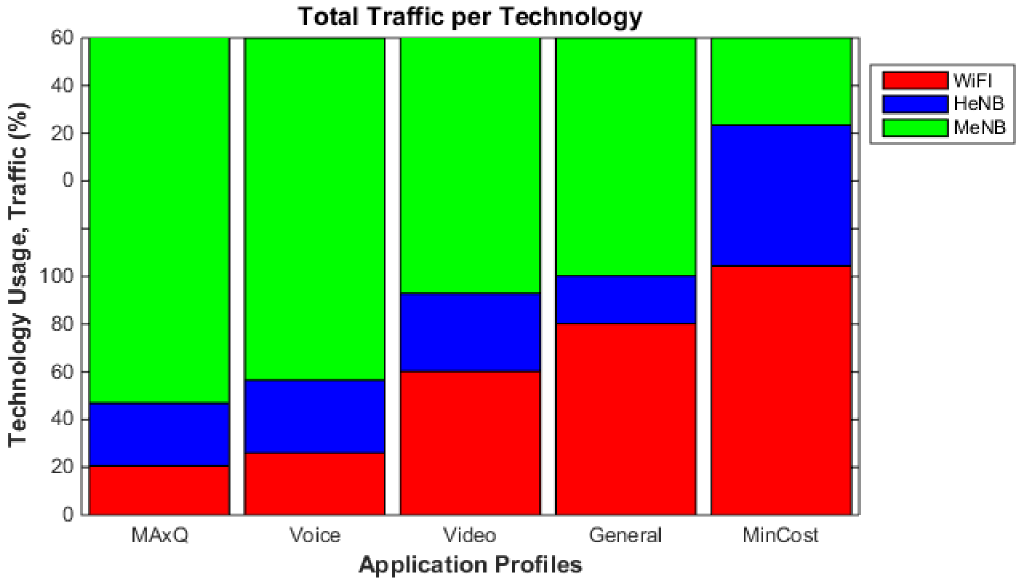

Figure 6.7: Comparison of data traffic per technology.

attributed to each decision parameter, utilized for our handover method.

Concerning the network usage fee, it is observed that the total data traffic for minimum cost is mostly received/transmitted via Wi-Fi SAPs since Wi-Fi is considered as the cheapest technology (see Table 6.4). The implications for system planning and deployment are discussed in Chapter 7.

6.5.7 Summary

In this chapter, we have presented a handover algorithm which uses a combination of multiple parameters for improving network selection for a high speed mobile node over a multi-tier heterogeneous network. The proposed method selects the most suitable target network for a near future handover based on the QoS requirements of the ongoing applications. This was achieved by applying the SAW, one of multi-criteria decision making algorithms that utilize multiple parameters for optimizing

Table 6.7: QoS performance comparison for application profiles (V2I-MHA).

V2I-MHA					
Application Profile	Max. Quality	Voice	Video	General	Min. Cost
Mean Throughput	97%	92%	96%	50%	23%
Mean Packet Delay (ms)	31.21	45.01	49.00	58.26	69.81
Mean Packet Loss	1.00%	2.50%	1.00%	28.90%	34.07%
Average Handover Events	3	4	4	6	8

the handover decision process.

We have defined five different application profiles that apply the knowledge of candidate network metrics such as bandwidth, packet latency, packet loss and network usage monetary cost to decide the most suitable target network for an anticipated handover. To preserve the QoS of each considered profile, we have applied AHP for accurately deciding the appropriate weights attributed to each decision parameter for different application profiles.

The performance of our proposed algorithm was investigated under voice and video applications. The simulation results revealed that maximum quality voice and video profiles have better performance in terms of user throughput and packet latency, as well as packet loss comparison. On the other hand, the minimum cost profile does not optimize these parameters, as their priority is not the quality of service, rather the cost. Finally, the investigation of the handover events and amount of data traffic per profile showed that the handover events could be minimized in trade-off network usage fee. Tables 6.7 exhibits the impact of proposed application profiles on QoS performance.

The lowest performance is attributed to minimum cost profile since its main goal is not providing QoS; rather providing the lowest network usage cost. Thus, when planning V2I communications, active road safety-related applications should be marked as maximum quality profile traffic. Next, in Chapter 7, the implications for system planning and deployment are discussed.

Chapter 7

Conclusions and Future Works

This chapter includes implications for system planning, conclusion and future work. Section 7.1 presents the considerable findings from Chapters 4 to 6 from the perspective of system planning and deployment. The thesis is summarized in Section 7.2. Finally,a number of conceivable future advancements of this research are presented in Section 7.3 for possible future developments.

7.1 Implications for System Planning and Deployment

The handover algorithms for improving handover management over multi-tier heterogeneous networks were presented in Chapters 4 to 6. The primary objective of this thesis was to develop handover techniques to achieve improved system performance and deployment. To achieve this, system planners could apply the results presented in the previous chapters to design and deploy V2I communication over a multi-tier multi-RAT environment. This section presents a set of the guidelines and recommendations drawn from the analysis of the results outlined in Chapters 4 to 6 from a system planning perspective.

In Section 7.1.1, an evolution path of the deployment of V2I applications over heterogeneous networks is presented and the issues associated with deployment of V2I applications in different areas are discussed in Section 7.1.2.

7.1.1 An evolutionary path for adopting V2I application

Figure 7.1 shows an evolutionary path for adopting and deploying V2I applications over various radio access technologies. At the bottom left region of the path, the 802.11p technology was the first standard exclusively developed for supporting vehicular communications. DSRC provides vehicular connectivity over a relatively small coverage area at relatively low deployment costs. Currently, most vehicles use DSRC technologies based on Wi-Fi standards for both V2V and V2I communications. However, the key challenge of DSRC technology is linked to the limited service area. To overcome the issue, auto industries designed OBU equipment that works on cellular connections (3G and 4G standards). For instance, the recent LTE-A release 14 [116] supports a range of V2X services. At the top right of the evolution path, the 5G network is expected to bring significant value to advanced driver assistance systems, improved active safety applications (real-time data), better traffic efficiency, increased situation awareness and remote diagnostics to mention a few [117].

While DSRC 802.11p technology is mainly utilized in specific places such as traffic lights and bus stops, 3G and 4G are good candidates for wider areas such as the highways and rural environment. On the other hand, 5G builds upon LTER direct DD communication to bring new ways of connecting, e.g. multi-hop to extend coverage. Furthermore, 5G promises ultra-high reliable data transmissions and reduced packet latency through a faster, flexible frame structure that will provide the vehicular network with new capabilities for improved safety use cases, especially at high-speeds, e.g. highway.

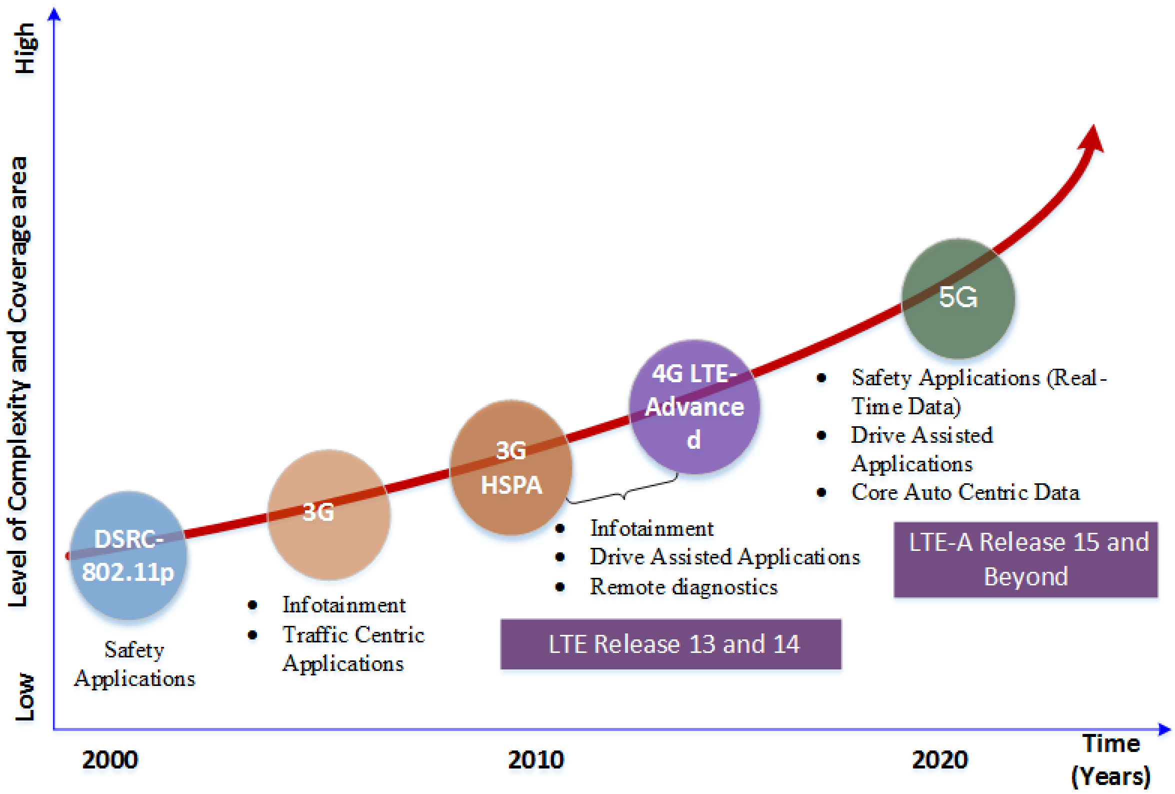

Figure 7.1: An evolutionary path of V2I applications with different underlying network technologies.

7.1.2 Deployment of V2I Communications

Deployment of V2I communications relies on a variety of technologies to support the safety and environmental goals. In addition to DSRC which is a proven technology to support V2X, ITS planning should consider that emerging technologies, like 5G, will play an important role in shaping the vehicle of the future. However, the key challenge is associated with handover management for high-speed users such as vehicles. While there is no formal 5G specification today, research has shown that effective 5G handover techniques should be based on multiple parameters, not just on RSS value [24, 25, 118, 119]. These parameters include mobility information, UE capability, and network capacity as well as user preferences. This thesis has investigated the impact of these parameters on handover performance. A notable contribution of this thesis is the design of novel handover algorithms suitable for V2I communications over multi-tier multi-RAT network environments. When deploying a V2I communications system, planners are often given flexibility in choosing various networking technologies within the available RSU technologies to satisfy various application requirements. This section provides some practical guidelines for deploying V2I networks in a typical urban, highways, and rural environment.

- **V2I Communications in an urban environment**

  When planning for V2I communications in a typical urban environment, system planners need to consider complex road situations and smart vehicles which are connected to the Internet and to each other. To achieve the primary goal of connected vehicles, safety - information must reach its destination reliably within an exceedingly short time frame. These trends pose substantial challenges to the underlying communication system due to the increased number of vehicles and the scarce wireless resources such as limited network capacity as well as cell coverage areas. Thus, connected vehicles will have to rely not only on DSRC technology, but also on various radio access technologies including cellular, WiMAX, and Wi-Fi communication systems in order to provide more capacity and wider coverage beyond what current DSRC technology can provide. This thesis has examined the feasibility of deploying existing multi-tier multi-RAT communication systems for supporting V2I communications in an urban environment with dense small cells. Analytical results from Subsection 5.4.7 showed that vehicle speed has a significant effect on communication quality in terms of user throughput and packet delivery drop probability. It is important to note that when the speed of movement becomes higher than 50 km/hr, the user throughput decreases by about 50% while the PDR degrades about 40%. In addition to throughput and PDR, mean packet delay also increased, as depicted in Figure 5.14 (Chapter 5). The results presented in Chapter 6 confirm that speed of movement has a dramatic effect on the overall system performance.

- **V2I Communications on highway environment**

  When planning V2I communication on highway environment, system planners cannot rely on DSRC only, due to its limited cell coverage area. The alternative method is a combination of different RATs also known as heterogeneous networks. However, guaranteeing QoS (latency, bandwidth, reliability) in such an environment is the key challenge for system planners. This thesis analyzes this issue and proposed application profiles in Chapter 6 that could address QoS issues by implementing a fair network resource management. This mechanism allows cell association based application requirements and mobility conditions. For instance, digital maps could be downloaded through Wi-Fi APs (located at the point of interest) while road warning messages could be broadcast via cellular technology (wider coverage). It has been shown that in a heterogeneous network, the normal QoS mechanism (considered as general in this thesis, Chapter 6) is unsuitable for providing QoS guarantee to delay sensitive and bandwidth-hungry applications. For V2I communication over heterogeneous networks, a good performance would require a new QoS mechanism that could define new traffic differentiation based on V2I applications.

- **V2I Communications in a rural environment**

  The main object of V2I communications in rural areas involves informing/warning drivers about traffic and driving conditions ahead, while deploying DSRC-based RSU in rural areas is almost impossible due to the deployment cost. In this thesis, we have investigated the feasibility of utilizing a combination of different RATs including cellular and Wi-Fi radio access technologies. The simulation results presented in Chapter 5, particularly in Subsection 5.4.2, exhibit the viability of LTE-A RAT in terms of providing acceptable user throughput and packet delay. The result presented in the Figure 5.17 (Chapter 5) confirm the viability of a LTE-A network for supporting V2I communications. Thus, LTE-A could be a good candidate underlying network, while planning for V2I communication in typical rural areas.

7.2 Conclusions

This thesis has focused on developing efficient handover algorithms for V2I communications over heterogeneous wireless networks. The growing V2I applications (e.g., road safety, traffic management and infotainment applications) and the lack of adequate underlying networks for these V2I applications were the main motivation of this research. In heterogeneous networks, supporting V2I communication is quite challenging due to multiple issues such as connectivity loss, handover latency, and QoS fluctuations caused by the high mobility of vehicles driving through the coverage areas of various sizes and different technologies. While there are several factors affecting the performance of V2I communication in a heterogeneous network environment, selecting a wrong target network for a near future handover and the increased number of handovers are the most significant. Other factors such as available network resources at the target network and the type of V2I application also severely influence the performance of V2I communications. To achieve QoS for V2I communications over heterogeneous wireless networks, a movement direction based network selection method for handover was developed in this thesis and investigated by simulation to evaluate the performance improvement achieved over the existing network selection algorithms. However, selecting a target network for a handover process without considering network load does not guarantee a successful handover. Thus, a novel selection algorithm that considers both vehicular mobility and network load was developed through the use of both analytical and simulation models. The effects of types of traffic on QoS performance were also investigated in this thesis. This thesis has made a number of original contributions, which are reported in Chapters 4 to 6. A summary of the contributions is outlined below.

Handover protocols are a major factor in determining QoS performance in multi-tier multi-RAT network environments. The conventional/traditional handover approach (RSS-based network selection method) has problems that can heavily limit the performance of V2I communications over heterogeneous networks. To overcome these problems, this thesis has developed a distance-based handover algorithm, V2I-DHA, by modifying the network selection method of the existing handover mechanism (Chapter 4). The performance of the V2I-DHA protocol was evaluated using the Riverbed (OPNET) simulator. Simulations were conducted to measure the handover performance metrics such as the number of successful handovers, mean handover delay and handover failure rate. Moreover, the achieved improvement in QoS performance is also evaluated based on well-known QoS metrics, such as throughput and mean packet delay. System performance analysis showed that the V2I-DHA could offer a significant performance gain over the conventional handover mechanism and the ANDSF-Assisted handover method. The V2I-DHA achieved a decrease of 50% for frequent handovers, 40% lower handover failure rate, 40% lower handover latency, 50% higher throughput, and 43% lower packet delay. The V2I-DHA performs better due to the reduced scanning activities that improve the overall handover process. The V2I-DHA can be easily implemented by placing a vertical management layer between the MAC and IP layers of TCP/IP models.

V2I applications require a seamless communication; hence, it is necessary to consider network resource availability in the target network to minimize the handover drop probability. In Chapter 5, a novel mobility and network load-based network selection for the handover algorithm (V2I-MoLoHA), was developed based on dwelling time and network load index. The V2I-MoLoHA includes network selection methods for both downward and upward handovers. The downward selection operates in two stages. First, the direction of movement calculated in the V2I-DHA is combined with the proximity index to estimate the dwelling time that is used to enhance the mobility based selection method. The calculated dwelling time advances the cell-specific knowledge that minimizes the chances of selecting the wrong target network. Secondly, the network load at the target network is evaluated before initiating the handover request. If the candidate with the highest dwelling time is overloaded, the algorithm proceeds with the second candidate on the list. The network selection method for upward handover is designed to prevent the vehicle OBU from losing its ongoing connection as it moves out of the coverage area of the serving small cell SAPs.

The performance of the V2I-MoLoHA was evaluated in two stages. First, the effectiveness of the downward network selection method was studied using Google map data and MATLAB and the results obtained showed that the V2I-MoLoHA can accurately select the best target network based on vehicular geo-location data and speed of movement. Secondly, the performance of the network selection method as a whole (i.e., both downward and upward selection methods) was evaluated using the Riverbed (OPNET) simulator. In addition to the performance metrics evaluated for the V2I-DHA in Chapter 4, the V2I-MoLoHA includes PDR which is mainly used to investigate the impact of the proposed upward selection method. The simulation results revealed that the V2I-MoLoHA achieved up to 49% and 24% lower numbers of handovers, 54% and 44% lower handover failure, 17.58% and 27.34% lower handover delay, 53% and 32% higher throughput, 36% and 23% lower packet delay, over the conventional and ANDSF-based handover methods, respectively. To further improve QoS for V2I communications, a multi-criteria based algorithm (V2I-MHA) was developed and presented in this thesis (Chapter 6). The V2I-MHA takes into account not only QoS requirements but also user budget preference. The V2I-MHA represents a step forward for applying multi-criteria selection algorithms in optimized decision making. The V2I-MHA includes network selection methods for both downward and upward handover processes. With the V2I-MHA, various V2I applications, ranging from safety to infotainment, could be treated according to their QoS requirements. Furthermore, a multi-mode OBU node was developed for evaluating the performance of proposed network selection algorithms for handover. This multi-interface node integrates both LTE-A and Wi-Fi radio access network interfaces and it was developed by modifying an LTE-A mobile router node. While the QoS for V2I communications over multi-tier multi-RAT dense networks has been investigated from a handover events perspective in this thesis, further QoS issues associated with the backhaul network support for V2I communications in dense network environments still need to be investigated. As the commercial deployment of V2I applications is gradually becoming a reality, the development of flexible and reliable vehicular network simulating tools will become increasingly important. To accomplish these requirements, further research is needed, especially the deployment of cognitive connectivity to extend the network selection algorithms presented in this thesis.

7.3 Future research directions

This thesis provides different contributions for efficient V2I communications over the multi-tier multi-radio access technologies environment. The aim was to answer the research question, What can be done to optimize handover performance for efficient V2I communications over multi-tier, multi-RAT networks? This section summarizes some research issues that could be investigated for future extension to this research.

- **A simulation/emulation tool**

The performance of the handover algorithms proposed in this thesis have considered two radio access technologies, LTE-A and W-Fi. This assumption basically simplifies simulation models for performance analysis. However, future mobile terminals are expected to embed a complex adaptive multimode interface requiring new levels of connectivity over the heterogeneous wireless environment. Thus, a dedicated simulation tool that embeds multiple RATS and different mobility modules must be developed to facilitate different handover study cases. Furthermore, the tool could be utilized to compare the performance of various handover proposals.

- **Applying Game Theory methods**

  This thesis has focused on improving handover performance for high speed mobile nodes by assuming that the node knows the physical locations of neighbouring networks. We applied node mobility information and spherical trigonometry for designing handover decision algorithms (Chapters 4 and 5). However, wireless nodes in the real environments may have different motives of handing off to a neighbour network. Thus, to improve strategical decision making, game theory methods may also be helpful for selecting the most effective target network in a fair manner.

- **Applying cognitive connectivity**

  This thesis investigated different handover decision parameters for efficient V2I communications over different RATs. In addition to the decision parameters considered in this thesis, cognitive ratio mechanisms could be applied at a physical layer enabling vehicle OBUs to sense their environment and dynamically select the appropriate radio interface for future transmission.

- **Extension of proposed algorithms to embrace V2X communications**

In this thesis, a particular emphasis was to improve handover performance by modifying the conventional RSS-based network selection approach for handover. Two RATs (WLAN and LTE-A) were used for evaluating the performance of the proposed handover methods. However, the next generation of vehicle-to-everything (V2X) connectivity enables a broad and growing set of use cases much more than traditional V2I applications. The development of enhanced handover algorithms that include more transmission technologies such as Bluetooth to accommodate always-on telematics would be useful contribution.

The development of a robust

- **Extension of ANDSF**

  In this thesis, mobility based handover methods were developed and presented in Chapters 4 and 5. The ANDSF entity was used to provide geographical locations of AP and eNBs of the candidate networks by modifying its network location information function. However, the proposed methods could be affected by the high dynamic changes in vehicular network topologies. Therefore, In addition to suggesting a list of neighbouring candidate networks along with their physical locations, a network context-aware entity should be developed for dynamically identifying the traffic and updating the mobile nodes according to real-time changes in the network. An analytical model for predicting the less congested network in near future would be a useful contribution.

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Appendix A

Miscellaneous Useful Information on OPNET modelling Domains

A.1 Introduction

OPNET simulator software, commonly know as Optimum Network performance, is developed by Riverbed Technology Inc. It is software networking simulation. OPNET is a simulating tool suitable for all types of network, it is capable to simulate various real life network configurations and it has a big number of commercial models available in network elements. Thus simulating real life network environment using OPNET gives results closer to the reality.OPNET includes popular network communication technologies such as WLAN, cellular network (3G/LTE) and WiMAX.

OPNET includes two main versions of OPNET simulator: academic version (OPNET IT Guru) and commercial version(OPNET Modeler). academic version only supports the standard model of each communication technology, and users do not have no access to edit module. On the other hand, OPNET Modeler or commercial version allows users to modify all node and process models of communication technologies. The typical example is the vehicle OBU (4.6.4) that was designed in this thesis based on the standard *lterouter*. by modifying node models network researchers manage to evaluate the performance of the newly created network protocols as well as various communication algorithms. OPNET simulator is available for download at www.riverbed.com. OPNET beginners can refer to [120] and [121].

A.2 Steps adopted to design a multi-interface node

To implement vertical handover between different Media Access Technologies (MAT), media access technologies must communicate with each other. This was achieved by developing a Vertical handover Management Module is an OPNET module which controls the Media Access Technology interfaces (LTE, Wifi) based on events receives from them. VhoMGT decides which MAT should be active, which one should Tx/Rx information, and inform the IP Module about the winning interface.

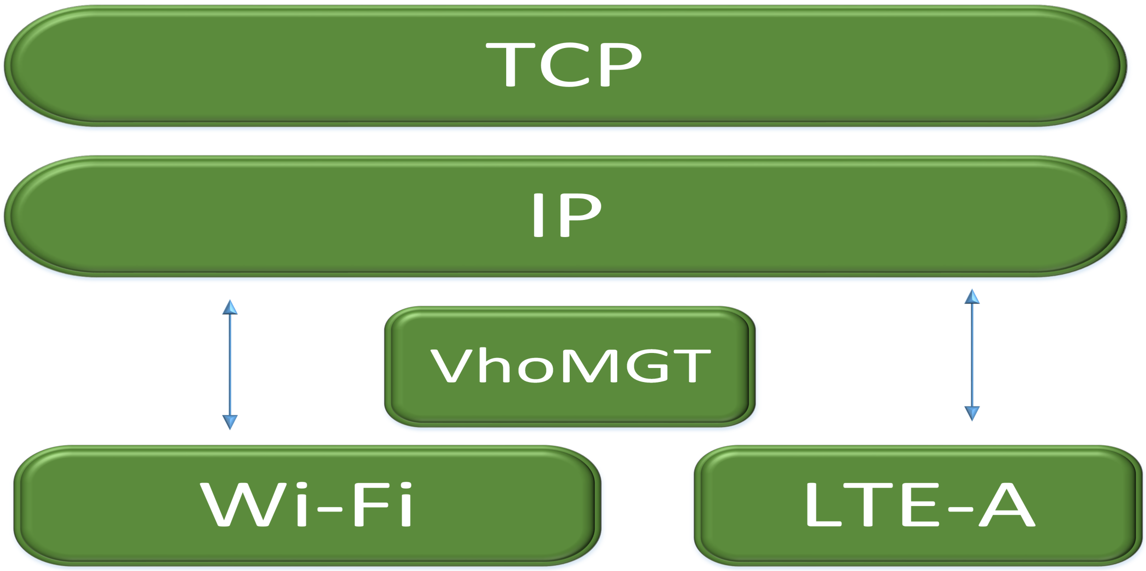
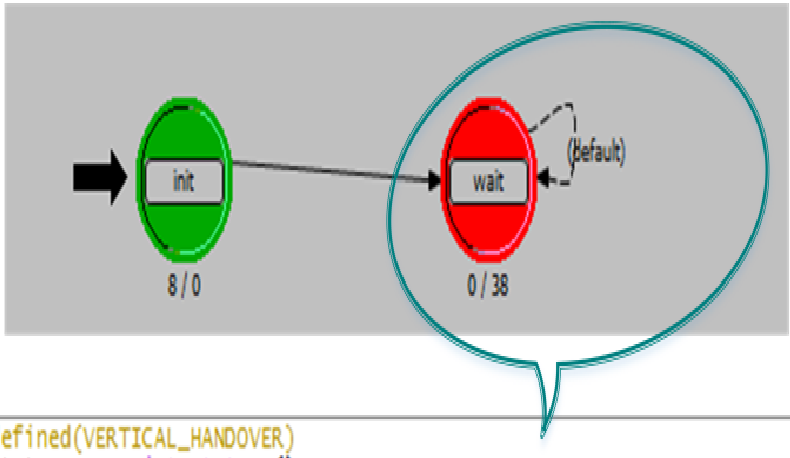


Figure A.1: The location of VhoMGT in TCP/IP stack

The VhoMGT module is placed as illustrated in the TPC/IP stack as it is illustrated in A.1. Moreover, Figure A.1 presents the OPNET implementation of VhoMGT min TCP/IP stack.




```
#if defined(VERTICAL_HANDOVER)
intrpt_type = op_intrpt_type();
intrpt_code = op_intrpt_code();
intrpt_strm = op_intrpt_strm();

if (intrpt_type == OPC_INTRPT_STRM) {
    pk = op_pk_get(intrpt_strm);
    op_pk_nfd_get_int32(pk, "interface_number", &intf);
    op_pk_nfd_get_int32(pk, "interface_status", &cmd);
    VHO_PRINT_DEBUG("VHO_MGT", "Rcv HO cmd(%s) for interface(index: %d, name: %s)",
        ho_status_str[cmd], intf, ho_intf_name[intf]);
    vho_mgt_update_if_state(intf, cmd);

    intf = vho_compute_active_interface();
    if (intf <= VhoT_If_Not_Used || intf >= VhoT_If_Unsupported) {
        VHO_PRINT_DEBUG("VHO_MGT", "Invalid interface computed!!!");
    } else {
        if (intf != active_interface) {
            active_interface = intf;
            vho_activate_interface(active_interface);
        }
    }
}

#if 0
// tests
if (intrpt_code = 7777 && intrpt_type == OPC_INTRPT_SELF) {
        if (active_interface == VhoT_If_Wifi) {
            vho_activate_interface(VhoT_If_Lte);
            active_interface = VhoT_If_Lte;
        } else {
            vho_activate_interface(VhoT_If_Wifi);
            active_interface = VhoT_If_Wifi;
        }
    op_intrpt_schedule_self(op_sim_time() + 30, 7777);
}
#endif

#endif /* defined(VERTICAL_HANDOVER) */
```

Figure A.2: OPNET implementation of VhoMGT in TCP/IP stack

A.3 Enhancement of Wi-Fi and LTE-A nodes

The implementation of the proposed algorithms in OPNET modeller has involved the changes in existing Wi-Fi and LTE-A nodes, mainly at MAC layer. These changes are represented in Figures A.3 and A.4 show the modified OPNET FSM for Wi-Fi and LTE-A respectively.

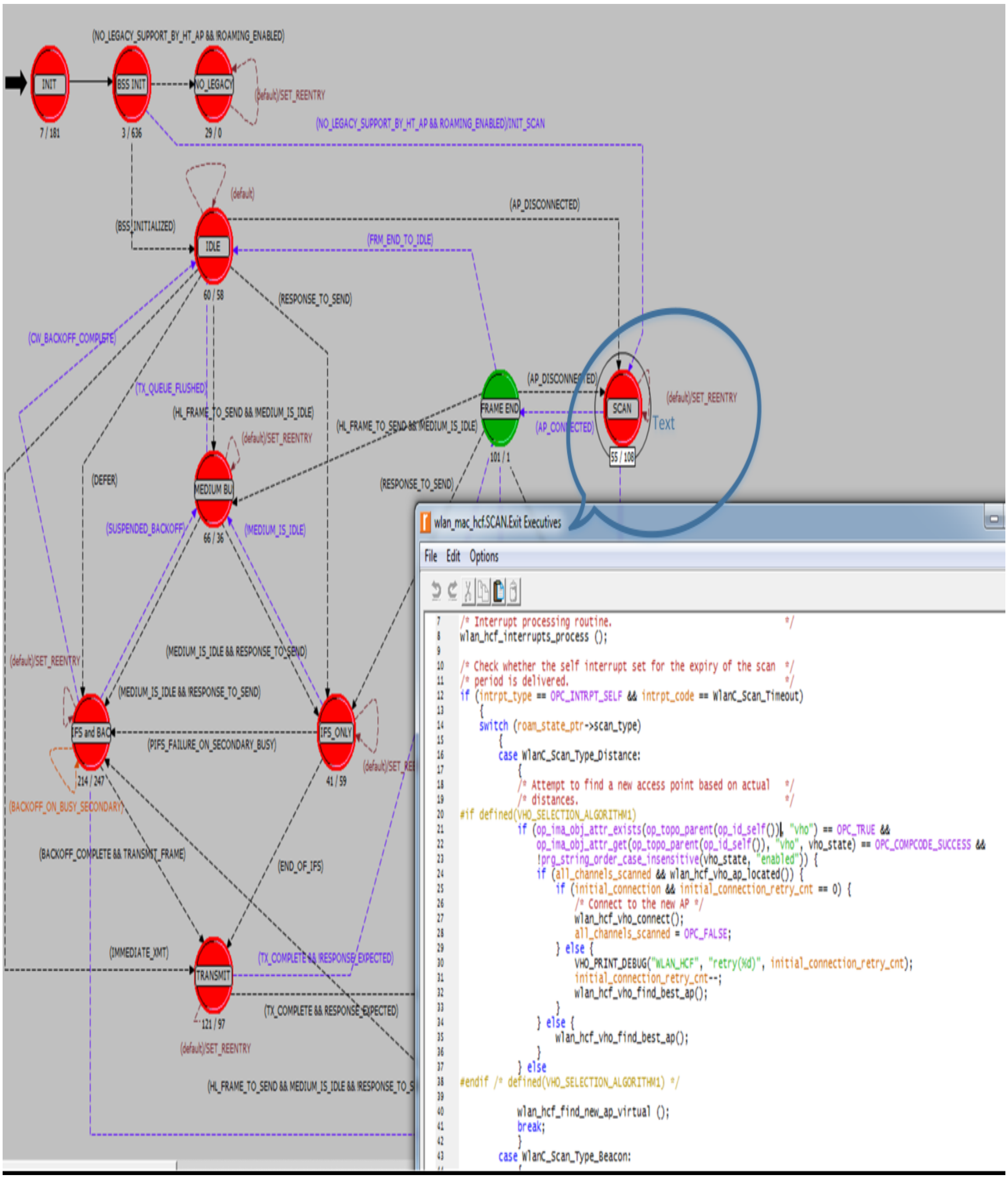


Figure A.3: Enhancement in Wi-Fi node

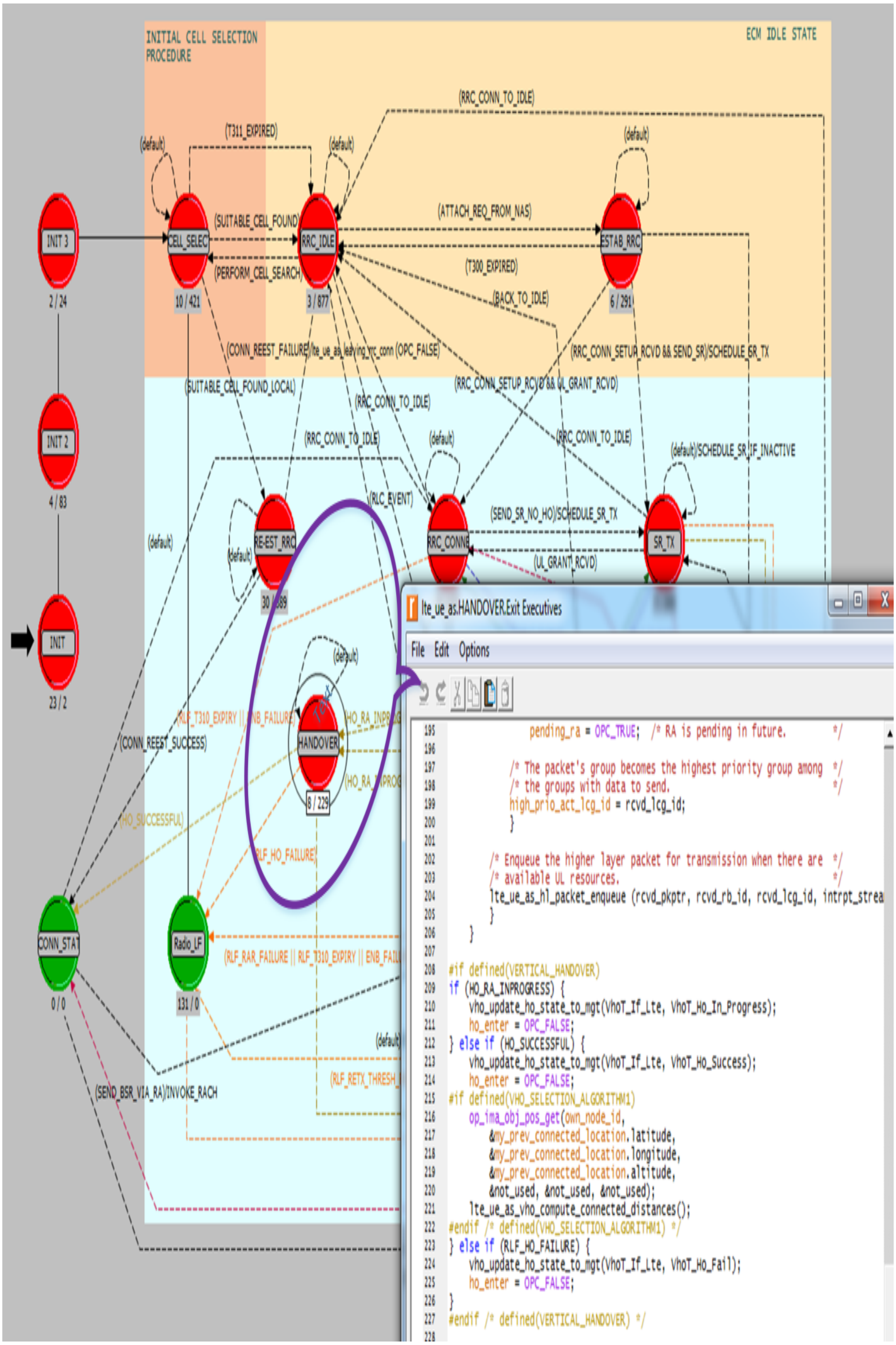


Figure A.4: Enhancement in LTE-A node