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Heterogeneous LTE/ Wi-Fi architecture for intelligent transportation systems

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HETEROGENEOUS LTE/ WI-FI ARCHITECTURE FOR INTELLIGENT TRANSPORTATION SYSTEMS

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by Noha Mohamed Sadek Taher

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Approval Sheet Goes Here

DEDICATION

First and foremost, I thank Allah the Almighty for providing me with strength, persistence and patience that enabled me to complete this thesis, and overcome numerous hurdles and challenges.

I dedicate this thesis to my dear Mother and Father for their infinite and exceptional support. I also dedicate it to my beloved sister and to all my professors. I would like to seize this opportunity to thank a number of people for their roles in making my journey a success.

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LIST OF ABBREVIATIONS

2G	2^{nd} Generation
3G	3^{rd} Generation
3GPP	3^{rd} Generation Partnership Project
4G	4^{th} Generation
AP	Access Point
BER	Bit Error Rate
BS	Base Station
BSS	Basic Service Set
BSSID	Basic Service Set Identifier
CAM	Cooperative Awareness Message
CCRS	Coordinated and Cooperative Relay System
DCF	Distributed Coordination Function
DENM	Decentralized Environmental Notification Message
DL	Downlink
DSRC	Dedicated Short Range Communications
DSSS	Direct Sequence Spread Spectrum
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
EDCA	Enhanced Distributed Channel Access
eMBMS	evolved Multimedia Broadcast and Multicast Service
eNodeB	enhanced NodeB
EPC	Evolved Packet Core
ePDG	evolved Packet Data Gateway
EPS	Evolved Packet System
ETCS	European Train Control System
ETSI	European Telecommunications Standards Institute
FDD	Frequency Division Duplex
FHSS	Frequency Hopping Spread Spectrum
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GTP	GPRS Tunneling Protocol
GV	Gateway Vehicle
HCF	Hybrid Coordination Function
HSS	Home Subscriber Service
HTH	Hierarchical Two Hop
I2V	Infrastructure to Vehicle
IEEE	Institute of Electrical and Electronics Engineers
ISD	Inter Site Distance
ISO	International Standardization Organization

ITS	Intelligent Transportation Systems
LTE	Long Term Evolution
LTE-A	LTE Advanced
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MRN	Mobile Relay Node
OBU	On Board Unit
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OV	Ordinary Vehicle
P-GW	PDN Gateway
PCF	Point Coordination Function
PCRF	Policy and Charging Roles Function
PDN	Packet Data Network
QCI	QoS Class Identifier
QoS	Quality of Service
RN	Relay Node
RSU	Road Side Unit
S-GW	Serving Gateway
SAE	System Architecture Evolution
SC-FDMA	Single-Carrier Frequency Division Multiple Access
TDD	Time Division Duplex
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
VANET	Vehicular Ad-hoc NETworks
VoIP	Voice over IP
WiMax	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

ABSTRACT

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Heterogeneous LTE/Wi-Fi Architecture for Intelligent Transportation Systems

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Intelligent Transportation Systems (ITS) make use of advanced technologies to enhance road safety and improve traffic efficiency. It is anticipated that ITS will play a vital future role in improving traffic efficiency, safety, comfort and emissions. In order to assist the passengers to travel safely, efficiently and conveniently, several application requirements have to be met simultaneously. In addition to the delivery of regular traffic and safety information, vehicular networks have been recently required to support infotainment services. Previous vehicular network designs and architectures do not satisfy this increasing traffic demand as they are setup for either voice or data traffic, which is not suitable for the transfer of vehicular traffic. This new requirement is one of the key drivers behind the need for new mobile wireless broadband architectures and technologies.

For this purpose, this thesis proposes and investigates a heterogeneous IEEE 802.11 and LTE vehicular system that supports both infotainment and ITS traffic control data. IEEE 802.11g is used for V2V communications and as an on-board access network while, LTE is used for V2I communications. A performance simulation-based study is conducted to validate the feasibility of the proposed system in an urban vehicular environment. The system performance is evaluated in terms of data loss, data rate, delay and jitter.

Several simulation scenarios are performed and evaluated. In the V2I-only scenario, the delay, jitter and data drops for both ITS and video traffic are within the acceptable limits, as defined by vehicular application requirements. Although a tendency of increase in video packet drops during handover from one eNodeB to another is observed yet, the attainable data loss rate is still below the defined benchmarks. In the integrated V2V-V2I scenario, data loss in uplink ITS traffic was initially observed so, Burst communication technique is applied to prevent packet losses in the critical uplink ITS traffic. A quantitative analysis is performed to determine the number of packets per burst, the inter-packet and inter-burst intervals. It is found that a substantial improvement is achieved using a two-packet Burst, where no packets are lost in the uplink direction. The delay, jitter and data drops for both uplink and downlink ITS traffic, and video traffic are below the benchmarks of vehicular applications. Thus, the results indicate that the proposed heterogeneous system offers acceptable performance that meets the requirements of the different vehicular applications.

All simulations are conducted on OPNET Network Modeler and results are subjected to a 95% confidence analysis.

CHAPTER 1: INTRODUCTION

This chapter introduces the thesis and provides a roadmap of the work.

1.1 REPORT OUTLINE

The thesis report is divided into the following chapters:

Chapter 1: General overview, aim and purpose, motivation and contribution, research questions and related work.

Chapter 2: Background about ITS, vehicular networking applications, stigmergic approach, access network technologies, opportunities and challenges of vehicular wireless communication.

Chapter 3: Introduction and motivation to heterogeneous vehicular networks, system architecture and proposed model

Chapter 4: Explanation of simulation model and scenarios, design choices, network architecture and traffic characteristics.

Chapter 5: Performance metrics, simulation results, analysis and discussion.

Chapter 6: Conclusion

1.2 GENERAL OVERVIEW

Intelligent transportation systems (ITS) have recently attracted growing attention from car manufacturers, governmental entities, standardization organizations, and road operators. Driven by economic and social benefits, tremendous efforts are now directed at realizing greener, smarter and safer vehicular systems. The main goals of ITS are to increase road safety, minimize traffic congestion and deliver comfort services to passengers by means of vehicle to infrastructure (V2I) or vehicle to vehicle (V2V) communication [1]. To realize these goals, different applications (i.e. safety, traffic efficiency, and infotainment) should be effectively supported by the underlying vehicular network. Each of these applications has unique features in terms of generation patterns, delay and performance requirements, and spatial scope [2].

In addition to the delivery of regular traffic and safety information, vehicular networks have been recently required to support infotainment services [3]. Infotainment applications include video streaming, video conferencing, online gaming, and web browsing. Lately, there has been a tremendous increase in video traffic for both stationary and mobile users. Also considering its growing popularity, it is predicted that the demand for video traffic will continue to increase even more in the future [4]. Additionally, with the widespread use of smart-phones like iPhone and Android platforms, the emergence of tablets like iPad, and the continued use of laptops, there is a sudden increase in mobile devices' availability in the market that are capable of displaying high-quality video content.

Previous vehicular network designs and architectures do not satisfy this increasing traffic demand as they are setup for either voice or data traffic, which is not suitable for the transfer of video traffic [5]. This new requirement is one of the key drivers behind the need for new mobile wireless broadband architectures and technologies.

To cater to the diverse vehicular application requirements, this thesis proposes the integration of IEEE 802.11(Wi-Fi) and LTE cellular networks. The proposed heterogeneous vehicular network combines two technologies with long-range and short-range coverage, namely LTE and Wi-Fi (IEEE 802.11) respectively. Each technology has a different objective and their integrated deployment will improve the vehicular system performance.

Long Term Evolution (LTE) by 3rd Generation Partnership Project (3GPP) [6] and IEEE 802.11 (Wi-Fi) [7] are two of the most viable communication standards that could be jointly exploited in today's vehicular networks. On one hand, Wi-Fi offers a relatively high capacity at a very low cost (because of economies of scale) and it has a high market penetration. However, it has a lower coverage range compared to LTE. This makes it suitable for use as an access network inside the vehicle and for V2V communication between nearby vehicles. On the other hand, LTE offers a wide coverage and better Quality of Service (QoS) but, it requires costly licensed spectrum and is lagging behind Wi-Fi in terms of the economies of scale [8]. These characteristics fit with the long range communication requirements of the V2I network. By integrating Wi-Fi with LTE, high capacity is coupled with long-range communication to improve the overall performance of the vehicular system.

LTE represents state-of-the-art cellular technology due to the evolved architecture of both its radio access and core networks. LTE possesses extraordinary features such as high data rate, low end-to-end delay, extended coverage range and commercial availability that make it an ideal candidate for use in ITS networks [9]. LTE supports a downlink peak data rate of 100 Mb/s and an uplink peak data rate of 50 Mb/s for a 20 MHz spectrum. Its radio interface uses orthogonal frequency-division multiple access (OFDMA) for the downlink and Single-Carrier FDMA (SC-FDMA) for the uplink, and supports multi-antenna techniques such as Multiple Input Multiple Output (MIMO) and beam-forming to increase peak and cell edge bit rates respectively [9]. LTE also supports scalable carrier bandwidths, such as 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz, and supports both frequency-division duplex (FDD) and time-division duplex (TDD) multiple-access techniques.

IEEE 802.11 (Wi-Fi) is a popular wireless networking technology that provides high-speed communications. The standard includes physical and Medium Access Control (MAC) layers' specification. The popularity of Wi-Fi has grown steadily since its introduction. Cisco [10] states that 33% of the total mobile traffic is sent/received by the WLAN interface and they expect this percentage to grow by 2017 to approximately 67%. In addition to its use in mobile devices (like mobile phone and laptops), it is also used in vehicular networking where vehicle on-board units (OBU), and fixed road-side units (RSU) are equipped with Wi-Fi transceivers.

1.3 AIM AND PURPOSE

This thesis studies the limitations and capabilities of current network technologies and subsequently, proposes a heterogeneous vehicular network architecture that optimizes the performance of vehicular applications. The main goal is to determine the impact of delivering video data on top of traffic control data over the vehicular network. Another goal of this research is to analyze the internetworking between LTE, as a V2I network, and

Wi-Fi, as an onboard access network and inter-vehicular (V2V) network, in the context of urban ITS applications.

Other objectives of this research include providing methodologies, techniques and guidelines that can be followed in future research:

- Design an architecture for a heterogeneous LTE–Wi-Fi–Ethernet vehicular network.
- Develop, test and evaluate a scenario-driven LTE–Wi-Fi–Ethernet network simulation in OPNET.
- Create a new custom three-interface (LTE, Wi-Fi and Ethernet) router using OPNET.
- Investigate the different constraints that impact the system performance metrics: data rate, data loss ratio, end-to-end delay, and jitter.
- Analyze the simulation results of different network scenarios with different network loads.

1.4 MOTIVATION AND CONTRIBUTION

The research in the field of vehicular networking is facing many challenges which need to be addressed. The vast majority of research in the field of vehicular networks and communications focuses on the performance of a single type of application, rather than all types of applications in these networks. Studies are concerned with either traffic efficiency and safety applications, or comfort and infotainment applications. This does not represent the real situation where currently all types of applications (traffic efficiency, safety and infotainment) coexist in vehicular networks. Thus, it is important to study how the concurrent delivery of various applications affects the performance of the vehicular network.

Reliability, mobility support and low-latency are critical to satisfy the performance requirements of the different vehicular applications. On one side of the spectrum, infotainment applications have high bandwidth demands and QoS-sensitive requirements [11]. While on the other side of the spectrum, safety-critical applications are characterized by low latency and high message delivery rate. To support safety application demands, a large amount of data traffic needs to be exchanged between vehicles and Base Stations

(BSs). This will consequently add a heavy burden to the BSs, which is not likely to be accepted by network operators.

Additionally, these extra traffic connections increase the effect of interference and thus increase data error rate. Moreover, this also causes an increase in packet delays due to resource depletion. Furthermore, the scheduler at the BS may have difficulties scheduling transmissions within the tight delay bounds required for safety-critical applications [12].

Another challenge in vehicular networking is that traditional single radio wireless technologies do not meet the requirements of vehicular applications and do not satisfy the growing demand of vehicular users. Neither purely infrastructure-based nor purely ad-hoc networks address the current performance and capacity issues in vehicular networks [5]. Similarly, the sole use of cellular networks (like UMTS, LTE, GSM) or data networks (like Wi-Fi, WiMax) does not solve the above-mentioned issues either.

In addition, there was a lack of node models that support multi-radio access technologies in commercial networking simulation software environments. Since future wireless networks will be of multi-radio access type, there is a need for models that simulate such networks.

Accordingly, it is believed that a heterogeneous vehicular network that collaboratively employs multiple access technologies is the best candidate for a contemporary vehicular network. Hence, the need arises to explore the impact of deploying a heterogeneous wireless vehicular network.

The contribution in this research is three-fold. First, this thesis studies and analyzes the performance of a realistic ITS system which supports the simultaneous transmission of traffic control data, as well as, infotainment data. Second, the simulation-based research evaluates the proposed heterogeneous LTE–Wi-Fi network and its feasibility to the urban mobile vehicular environment. Third, this thesis contributes with an implementation of a simulation model with node models containing multiple radio access technologies in OPNET Modeler. To the best of the authors' knowledge, this is one of the early studies that systematically investigate the mentioned topic.

1.5 RESEARCH QUESTIONS

In order to clearly define the scope of this thesis, the research questions addressed in this thesis are stated as follows:

1) What is the network performance, in terms of data rate, data loss ratio, delay and jitter, in the LTE–Wi-Fi heterogeneous vehicular network using the 7-cell urban scenario?
2) For what settings of parameter values is the performance of LTE and Wi-Fi optimized?
3) How do different parameters affect the performance of the proposed wireless heterogeneous network?
4) What types of vehicular applications can be supported by the network?
5) Does the proposed network architecture satisfy the performance requirements of all or only some vehicular applications?
6) Does the network performance degrade trivially or significantly with the addition of video data on top of traffic control data?
7) What is the impact of inter-cell interference on the network performance with a complete spectrum overlap between the 7 cells?
8) What is the impact on end-to-end delay and packet loss for video streaming traffic under different network loads?
9) Can LTE/Wi-Fi bring real improvements for vehicular users in terms of capacity and supported applications while still fulfilling the requirements of traffic applications?
10) What are the typical vehicular scenarios of inter-networking between LTE and Wi-Fi?

1.6 RELATED WORK

This section summarizes the studies that investigate different wireless network technologies and architectures for use in vehicular applications.

An attempt [13] was made to solve the traffic control problem in light urban environment using a Wi-Fi communication scheme based on the stigmergic approach. The same problem was also studied using WiMAX for a harsher vehicular environment [14]. The work reported by Ali et al. [15] extends on previous efforts by using LTE technology.

Recently, the feasibility of LTE and IEEE 802.11 for vehicular networking applications was investigated [1, 3, 16-22]. An integrated LTE-IEEE 802.11p system was proposed for vehicular networking [16]. Group communication between the spatially-apart vehicular ad-hoc networks (VANETs) was achieved through the backhaul LTE network. Simulation results showed high data packet delivery ratios and limited delays. Altintas et al. [17] provided a demonstration of vehicles that can act as information hubs during disasters using a heterogeneous network gluing Wi-Fi, LTE and TV white space. Human or machine centric information is conveyed from an area where the telecommunications infrastructure is disrupted to an area where it is available. The demonstration was a combination of different means of communication technologies including Wi-Fi, TV white space, cellular networks, and the movement of the vehicles themselves. Use of the TV white space for inter-vehicle communications was the first trial carried out in any metropolitan area in the world. TV white space used four TV channels at 641 MHz, 647 MHz, 653 MHz and 659 MHz. Bandwidth of each channel used in the demonstration was set to 1 MHz with 2.5 MHz of guard left on each side of the band.

LTE was used to exchange Cooperative Awareness Messages (CAMs) between clusters, and Wi-Fi was used for delivering in-cluster information [18]. A clustering algorithm for intersection collision avoidance was proposed and a channel allocation algorithm was applied to reduce interference of Wi-Fi channels between different clusters. The authors [19] envisioned a heterogeneous LTE-IEEE 802.11p network that provides multimedia communication services over spatially apart vehicular groups. A cluster head election mechanism was proposed. The system showed acceptable performance in terms of LTE throughput and end-to-end delay.

A cooperative protocol based on coalition game theory was introduced to disseminate data in LTE-VANET network [20]. In the proposed heterogeneous network, some vehicles were selected as mobile gateways to connect to both networks. Then, a coalition game theory was used for vehicles to join coalitions which can maximize the data rate. The delivery of real-time streaming of scalable video coded (SVC) video over vehicle-to-infrastructure (V2I) links was investigated [3]. Three scenarios were studied: In the first scenario, IEEE 802.11p was used to communicate between vehicles and roadside units

(RSUs), while in the second, LTE was used for communication between vehicles and BSs. The third scenario used both LTE and IEEE 802.11p collaboratively for V2I communications. It was shown that the third scenario gave the best results.

Similarly, the inter-vehicles to infrastructure (V2V2I) model [21] used IEEE 802.11p for V2V communications and LTE for V2I communications. It was assumed that some vehicles will be equipped by IEEE 802.11p technology only, whereas others will have both LTE and IEEE 802.11p interfaces. The focus was on enabling reliable end-to-end IPv6 communications to in-vehicle networks, using services offered by neighboring LTE-enabled vehicles. A performance evaluation of LTE and IEEE 802.11p for vehicular networking was provided [1]. The performance of both standards was compared in terms of end-to-end delay, packet delivery ratio and throughput. The effect of different parameters, such as beacon transmission frequency, vehicle speed and density, was studied. It was concluded that LTE offered superior network capacity and mobility support as compared with IEEE 802.11p; however there was an increase in the delay in the presence of high cellular network load. Remy et al. [22] used the LTE network as a cluster management infrastructure for the IEEE 802.11p VANET. The performance was compared with the decentralized VANET architecture for an urban sensing application.

The area of broadband communications using heterogeneous networks in high-speed trains has attracted the interest of many researchers [23-26]. The authors [23] studied a relay-based heterogeneous LTE-IEEE 802.11a network in high-speed trains. In the proposed architecture, relays were placed on the top of each wagon. The relays communicate with the LTE base station (BS) over long range LTE links and with the user equipment (UEs) inside the train via IEEE802.11a short range links. Both Multicasting and unicasting scenarios were studied. The two cases that simulate the presence and absence of the relay nodes were compared. Enhancements in data rates and energy consumption were noted in the relay-based scenario.

A recent study [24] addressed the challenges of cellular communication on high-speed trains, mainly handover problems and drop-off performance. The hierarchical two-hop network and the seamless dual-link handover scheme were the methods recommended to address the above challenges. The study proposed using multiple radio access technologies (UMTS and LTE) to resolve the handover issue by connecting the train to two mobile networks simultaneously. Keeping multiple network links allows the train to maintain the connection through one link during the handover process of the other link. Additionally, the dual-link scheme was used where two external antennas are deployed at the front and rear of the train, and the BS with the better signal quality was selected. The proposed approach showed improved results in handover performance.

In addition, Zhou et al. [25] provided an overview on broadband wireless communications for high-speed trains. This study presented challenges associated with direct cellular communication between train users and BSs, namely signal degradation due to fast fading and drops during handover. Also, two-hop network structure and radio-over-fiber technology were introduced. The researchers [26] attempted to design a dual-link and dual-layer system for LTE communication on high-speed trains. Users communicate directly with access points (APs) located inside each carriage then, APs forwards the data to a ground base station (BS). A handover scheme based on dual-link was proposed where two antennas were mounted one at the front and another at the rear of a train. One of them performs the handover to the target BS while, the other maintains the communication with the serving BS so that the communication is not interrupted during the handover process. The performance of the proposed system enhanced the system performance in terms of handover probability, handover probability failure and communication interruption probability.

On the other hand, the use of LTE relay systems was also studied [27-29]. The authors [27] analyzed the QoS performance of a hybrid router equipped with LTE and Wi-Fi radio interfaces, and investigated different approaches to preserve the QoS for VoIP and video applications. An overview of LTE mobile relay nodes (MRN) was presented [28]. Various solutions that employ mobile relay nodes (MRN) for vehicular users were discussed along with the benefits and challenges of each. Then, the downlink performance of a MRN system was assessed with a finding that the use of MRNs improves the performance of vehicular UEs especially at the cell edge. The authors [29] introduced a coordinated and cooperative relay system (CCRS) that provided enhanced cellular coverage in public means of transportation such as trains, buses and ships. They addressed architectures, challenges and enhancements for incorporating CCRS into LTE-A.

Recently, the feasibility of LTE for vehicular applications has been extensively studied in the literature [2, 30-37]. The performance of LTE in high speed train was studied [30]. The delay and data integrity (data loss, duplication, out-of-sequence and corruption) of European Train Control System (ETCS) messages were analyzed. The simulation-based study concluded that the ETCS requirements were satisfied by the LTE network. The recorded transfer delays were one order of magnitude lower than the limits set by ETCS requirements which suggests that LTE has resources to serve more users or offer additional services to existing users.

The survey [2] evaluated LTE's capability to support ITS and vehicular applications. The qualitative analysis presented the features, strengths and weakness of LTE, as well as, open issues and design choices. The authors advocated the use of LTE in rural areas where the car density is low and no IEEE 802.11p-equipped vehicle exist within the transmission range. Additionally, LTE can be particularly useful for intersection warning applications when IEEE 802.11p is hindered by non-line of sight communications due to obstacles such as buildings. On the other hand, they stated that there are several challenges associated with the wide deployment of LTE in vehicular environments. So, they suggested that the capacity of LTE should be analyzed for video, VoIP and file sharing applications, in addition to the basic ITS applications.

Kim et al. [31] recommended the use of LTE (4G) over HSUPA (3G) for vehicular ad-hoc networks (VANET). Both standards were tested on real-time test-bed for different vehicle speeds. It was found that LTE satisfies the delay requirements of VANET. Moreover, the previous work [32] is an evaluation of LTE's suitability for ITS applications. It includes a performance evaluation of various LTE scheduling schemes and a comparison with IEEE 802.11p standard.

Phan et al. [33] performed a capacity analysis for an LTE-based vehicular network focusing on road safety applications. Two types of ITS safety traffic were studied namely, Cooperative Awareness Messages (CAM) and Decentralized Environmental Notification Messages (DENM). Network simulations showed that LTE provided a satisfactory performance for transmission of DENMs and congestion happened temporarily only with increased network load. On the other hand, the delivery of CAMs was limited by the downlink channel capacity. This is due to the nature of CAM traffic pattern where vehicles continuously send data to be distributed to neighboring vehicles. Consequently, the downlink traffic increases with the increase of number of vehicles.

Khil et al. [34] evaluated the performance of different LTE downlink scheduling strategies in various V2I urban and rural environments, in which safety, voice and video traffic coexist. The system performance was assessed in terms of delay and packet loss ratio. Low delay values but, high packet loss ratios were noted. The use of smartphones in vehicular applications has been lately studied, as it offers the advantages of real-time testing and low cost deployment.

Gel et al. [35] introduced a software platform called VAiPho for developing vehicular applications on smartphones. The application makes use of various wireless communication technologies such as Wi-Fi, cellular 3G/4G technologies and Bluetooth. Similarly, Abid et al. [36] leveraged the use of LTE smartphones-based vehicle-to-infrastructure (V2I) communication. The focus was on safety-critical ITS services and infotainment applications (i.e. video and VoIP). The simulation results covering latency, throughput, and packet loss ratio showed that LTE can successfully support the above-mentioned applications. Along similar lines, Ambrosin et al. [37] proposed two frameworks for the experimentation of vehicular networks. The first framework is based on Android smartphones and the second is based on laptop computers. Both frameworks emulated a vehicular ad-hoc network.

However, for all surveyed studies, the simultaneous support of ITS control traffic and infotainment traffic using both V2I and V2V communication over a heterogeneous LTE/Wi-Fi vehicular network has not been addressed in the literature. Consequently, this perspective will be investigated in this thesis.

CHAPTER 2: BACKGROUND

2.1 INTELLIGENT TRANSPORTATION SYSTEMS (ITS)

The Intelligent Transportation System (ITS) concept refers to the application of communications, control and information technologies to the transportation domain. It aims at enhancing the efficiency, safety and convenience of the transportation system. The need for developing ITS emerged from the growing mobility of people and goods that resulted in traffic congestion, pollution, injuries and fatalities.

Today, approximately 900 million vehicles worldwide are on the roads and there are estimates for the year 2020 that this number will increase to 1.1 billion [38], which will inevitably have negative economic and social effects. Vehicles are the third place, after home and office, where citizens spend more time daily. The U.S. Department of Transportation and Safety Administration revealed that commuters spend 500 million hours per week in their cars [2]. According to Traffic Safety Facts published by the United States National Traffic Safety Administration (NHSTA), there were 5,505,000 vehicular crashes in 2009, which resulted in a direct economic loss of $230.06 billion. The numbers of fatalities, injuries and property damage were 30,797, 1,517,000 and 3,957,000 respectively [39].

Transportation issues cause a decrease in safety for both passengers and pedestrians, huge loss of time, high pollution levels, degradation of quality of life, and enormous waste of non-renewable energy. These issues make it necessary to develop safe and efficient mobility systems. Thus, the main purpose of ITS is improving the transportation system operations by increasing productivity and efficiency, saving lives, cost, time and energy. In the past decade, numerous solutions were proposed and implemented; for example: message signs are displayed at strategic locations (tunnels, bridges, merging highways) along the highway to warn drivers about changing road conditions, warning messages about hazardous situations are broadcasted to vehicles, and automatic tolling. The ITS concept has only recently become a reality through the developments in various technological fields such as micro-electronics, telecommunication technologies, mobile computing and sensor networks. A major leap forward is also expected in the near-term.

2.2 Vehicular Networking Applications and Requirements

Vehicular networking is the enabling technology of many vehicular applications and systems. A large number of options for V2V and V2I communication systems are being investigated. Vehicular networking offers a wide array of applications and use cases, each with a different set of requirements. A use case refers to the utilization of an application in a particular situation with a specific purpose. These applications can be divided into three main categories defined by gathering applications with the same requirements:

1) Active road safety applications:

The primary objective of applications in this category is to decrease the probability of accidents, and reduce the number of injuries or loss of life to a minimum. This can be accomplished through providing assistance to vehicle drivers to avoid collisions with other vehicles. Information like vehicle position, speed and distance heading is exchanged between vehicles and road side units (RSUs) which is then used to predict and avoid collisions. This category has the most demanding system performance requirements as the minimum transmission frequency is 10Hz and the maximum is as high as 20Hz, and the maximum latency is 100ms.

In European Telecommunications Standards Institute (ETSI) documents [12], two types of safety messages are standardized: periodic and event-triggered messages. Periodic messages are referred to as Cooperative Awareness messages (CAMs) while, Decentralized Environmental Notification Messages (DENMs) refer to event-triggered messages. CAMs are short periodic messages broadcasted to provide information about position, speed, kinematics, and basic status of the vehicle. DENMs are event-triggered short messages broadcasted from the vehicle to its neighbors to alert them of a hazardous event. Some examples of road safety use cases for each of the two message types are given as follows [2, 11].

a. **Cooperative Awareness messages (CAMs):**

- **Intersection collision warning:** When vehicles approach road intersections, the risk of lateral collisions increases. To reduce that risk, information about vehicles approaching intersections is transmitted to the neighboring vehicles.
- **Emergency vehicle warning:** Emergency vehicles such as ambulance and police cars need to respond promptly to emergency situations. So, they communicate to other vehicles in their vicinity to free an emergency passageway. This information can be disseminated by close vehicles and RSUs for other vehicles further away.
- **Collision risk warning:** In this use case, a RSU detects a collision risk between two or more vehicles that are not able to communicate directly. So, to eliminate or reduce the risk of collision, the RSU broadcasts this information to all vehicles in the neighborhood.

b. **Decentralized Environmental Notification Messages (DENMs):**

- **Wrong way driving warning:** a vehicle driving in wrong way transmits this information to other vehicles and RSUs.
- **Stationary vehicle warning:** An accident, mechanical problem or breakdown can cause a vehicle to discontinue functioning and stop at one location on the road. In this case, this vehicle needs to inform other vehicles and RSUs about this situation.
- **Hazardous location notification:** Vehicles are notified about hazardous situations, such as road obstacles, slippery road conditions or construction work.

2) Traffic efficiency and management applications:

This category of applications aims at improving traffic flow, as well as, enhancing traffic coordination and management. Speed management and co-operative navigation are two types of functions under this category. Speed management applications help the driver to control the speed of his vehicle for smooth driving and avoiding unnecessary stopping. Co-operative navigation optimizes traffic efficiency by managing the vehicles' navigation through cooperation among vehicles, as well as, between vehicles and RSUs. Traffic information and recommended itinerary, and co-operative adaptive cruise control are examples of this type. System performance requirements of this category are not as strict as the previous category with a medium latency less than 200ms and transmission frequency between 1 and 10Hz.

3) Infotainment applications

This class of applications provides the user with information to enhance the passenger comfort, convenience and entertainment or enable global Internet services. System performance requirements are relatively relaxed where the maximum acceptable delay is 500ms and the minimum transmission frequency is 1Hz. Co-operative local services and global internet services are 2 groups of applications under this class. Co-operative local services are concerned with infotainment that can be acquired from locally based services like local electronic commerce, point of interest notification, and media downloading. On the other hand, global Internet services focus on data that can be obtained from the global Internet like insurance and financial services, fleet management, interactive games, video conferencing, multimedia streaming, web browsing, and software and data updates.

Vehicular applications can be supported through vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications. In the V2I communication model, vehicles wirelessly exchange safety and operational data with the roadside infrastructure. The V2I communication model is used in various applications such as infotainment, electronic toll collection, electronic road signs and work zone warning. It is achieved using vehicular onboard units and road-side units (RSUs). Dedicated Short Range Communications (DSRC - IEEE 802.11p), WiMAX (IEEE 802.16), Wi-Fi (802.11) and Long Term Evolution (LTE) are some of the technologies that can be used in V2I communications. In this case, Onboard Units (OBUs) are placed at each vehicle to transmit/ receive data to/from roadside units (RSUs). OBUs are typically equipped with a global positioning system (GPS) to provide real-time information on vehicle's position. Additionally, the OBU includes an event data recorder, which stores vehicle data that can be retrieved in case of an accident to be used in forensic analysis [5]. RSUs are base stations or access points that are connected to application servers.

The V2V communication model enables vehicles to communicate with each other without the need for an infrastructure network. V2V communications consist of vehicular nodes driving on a road and forming a vehicular adhoc network (VANET). This communication model has several applications like collision avoidance, intersection collision warning, road obstacle warning, and lane change assistance. V2V safety applications require low latency as these applications are needed in dynamic and unpredictable road environment [5].

2.3 STIGMERGIC APPROACH

The term stigmergy was introduced by the French entomologist Grassé [13] to describe the mechanism used by termites to coordinate their mound-building activities. Stigmergy is a form of indirect communication used by social insects to coordinate their activities. Researchers made use of the stigmergic approach to coordinate activities by designing successful algorithms in many application fields such as routing in communication networks, combinatorial optimization, and task allocation in multi-robot systems [40].

Nest building in ants is the typical example of stigmergy, which is used to find the shortest path between the ant's nest and a food source. Pheromone is a chemical substance excreted by ants and used for communication. Ants deposit pheromone trails along their paths as a means of indirect communication. At first, ants start wandering around their nest searching for food in a random manner. Those who find food carry it back to the nest while leaving a pheromone trail along the path. Other ants detect these pheromones and follow the trail back to the nest. Since pheromones evaporate over time, the more attractive trails accumulate more pheromones thus, offer an advantage over the other trails [13]. Ants using the shortest path tend to deposit more pheromones, which consequently attracts other ants in the colony. The amplification process continues with more ants joining the shortest path until the whole colony converges to the optimal path [41].

The stigmergic approach is one of the proposed approaches to solve urban traffic problems. Data exchanged between vehicles and the infrastructure is based on the bio-inspired routing approach. The idea is based on the behavior of biological systems such as ant colonies, where an urban traffic area is seen as a network of nodes interconnected by paths through which vehicles navigate [13]. Vehicles would move from one node to another until they reach their final destination. During the trip, vehicles continuously send the travel time data to a central node, which compiles information from all vehicles in the area.

In analogy with the biological ants' system, the travel information corresponds to the pheromones left on different trails. At the beginning of a trip, the driver sends a message to the central control node indicating the start and destination nodes of the trip. The central node then calculates the best path from the start node to the destination node, which is in turn communicated to the vehicle.

2.4 ACCESS NETWORK TECHNOLOGIES

2.4.1 OVERVIEW

Vehicles are already equipped with advanced computing and sensor systems onboard, each dedicated to one function of the car operation. These systems enable vehicles to collect information about themselves and the surrounding environment. The new component is the addition of wireless communication systems onboard to exchange this information in real time with other vehicles and with the remote infrastructure.

Vehicular networking serves as one of the most important technologies that enables the implementation of various vehicular applications. In addition to safety and traffic efficiency applications, vehicular end-users can benefit from a rich set of connectivity alternatives to access the Internet for a wide range of applications such as email, gaming, browsing, file download, IP telephony, and multimedia streaming. Several wireless access technologies have been proposed as candidates to support the above-mentioned vehicular applications. As summarized in Table 1, the main communication technologies have different characteristics and can satisfy the different vehicular application requirements.

The section gives a background of those radio access technologies with a special focus on LTE and Wi-Fi networks.

Table 1: Summary of Wireless Communication Technologies

Feature	Technology					
	Wi-Fi	**WiMax**	**802.11p**	**UMTS**	**LTE**	**LTE-A**
Bit Rate (Mbps)	6-54	72	3-27	2	Up to 300	Up to 1000
Channel Bandwidth (MHz)	20	1.25, 2.5, 5, 10, 20	10	5	1.4, 3,5, 10,15, 20	Up to 100
Frequency Band	2.4, 5.2 GHz	2-11 GHz	5.86-5.92 GHz	700-2600 MHz	700-2690 MHz	450 MHz-4.99 GHz
Range	100 m	20 km	1 km	10 km	30 km	30 km
Coverage	Intermittent	Ubiquitous	Intermittent	Ubiquitous	Ubiquitous	Ubiquitous
Capacity	Medium	Medium	Medium	Low	High	Very High
QoS Support	EDCA	QoS classes	EDCA	QoS classes and bearer selection	QCI and bearer selection	QCI and bearer selection
Mobility Support	Low	High (up to 120 km/h)	Medium	High	Very high (up to 350 km/h)	Very high (up to 350 km/h)
Broadcast/ Multicast	Native broadcast	MBS	Native broadcast	MBMS	eMBMS	eMBMS
Standards	IEEE	IEEE	IEEE, ISO, ETSI	ETSI, 3GPP	ETSI, 3GPP	ETSI, 3GPP
Market Penetration	High	Medium	Low	High	Potentially high	Potentially high

2.4.2 LONG TERM EVOLUTION (LTE)

The advanced LTE features are ideal for ITS applications, which are characterized by rapidly changing environment, stringent delay requirements and transmission of small periodic packets. In this section, the features and capabilities of LTE will be presented so that its role in ITS networks can be studied and evaluated. The Third Generation Partnership Project (3GPP) standardized Long Term Evolution (LTE) which was first initiated in 2004. LTE currently accounts for 14% of the total mobile traffic and it is predicted that it will be responsible for 10% of connections and 45% of total traffic by 2017 [42]. Unlike the circuit-switched 2G/3G networks, LTE is purely a packet-switched IP-based network that is backwards compatible with previous generations of cellular networks.

2.4.2.1 Network Architecture

The LTE network is basically separated into a radio network part and a core network part. The number of logical network nodes was reduced to streamline the overall architecture, and reduce cost and latency in the network. Figure 1 provides an overview of the overall architecture of LTE network and its components [43].

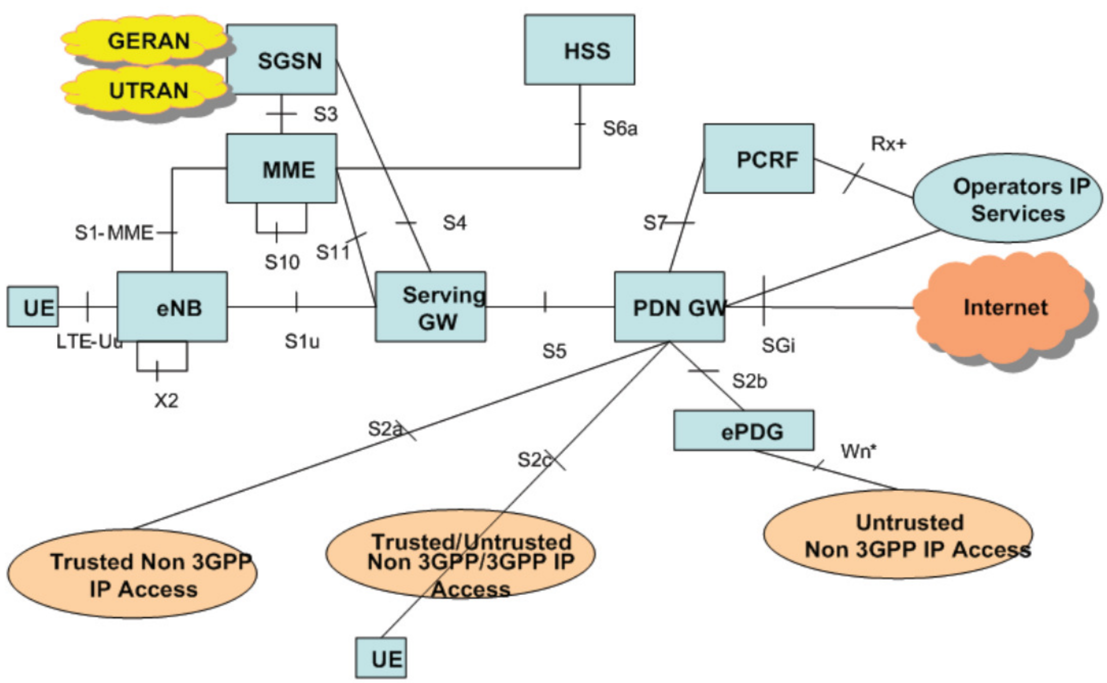


Figure 1: High-level Architecture for 3GPP LTE [43]

Long Term Evolution (LTE) introduced a new radio access network called Evolved-UTRAN (E-UTRAN) which, in contrast with the earlier UTRAN radio access network of 3G/UMTS, has integrated all of the radio-related functions into a single node called an evolved NodeB (eNodeB or eNB) [44]. LTE refers to the evolution of the radio network. The non-radio aspects are grouped under the term "System Architecture

Evolution" (SAE), which includes the Evolved Packet Core (EPC) network. Together LTE and SAE comprise the Evolved Packet System (EPS). The eNodeB connects the user equipment (UE) to the core network. eNodeBs are logically connected to each other via the X2 interface and EPC uses the S1 interface to communicate with eNodeBs. The protocols that run between the eNodeBs and the UE are known as the Access Stratum (AS) protocols. The E-UTRAN is responsible for all radio-related functions, mainly:

- Radio resource management (RRM): covers all functions related to the radio bearers, such as radio bearer control, radio admission control, radio mobility control, scheduling and dynamic allocation of resources to UEs in both uplink (UL) and downlink (DL).
- Header Compression: helps to ensure efficient use of the radio interface by compressing the IP packet headers that could otherwise represent a significant overhead, especially for small packets such as VoIP.
- Security: all data sent over the radio interface is encrypted.
- Connectivity to the EPC: consists of the signaling toward MME and the bearer path towards the S-GW.

The core network (EPC) is responsible for the overall control of the UE and establishment of the bearers. The main nodes of the Evolved Packet Core (EPC) are:

• **Serving Gateway (S-GW)**: Responsible for managing user data tunnels between the eNodeBs in the radio network and the Packet Data Network Gateway (PDN-GW). It also manages handovers when the UE moves from one eNodeB to another within the same network, and handovers between LTE and other 3GPP networks (such as UMTS and GPRS).

• **PDN Gateway (P-GW)**: It is the gateway to the Internet and some network operators also use it to interconnect to intranets of large companies over an encrypted tunnel to offer employees of those companies direct access to their private internal networks. It is responsible for IP address allocation for the UE, as well as, QoS enforcement and flow-based charging according to rules from the PCRF (Policy and Charging Roles Function). Additionally, it is responsible for the filtering of downlink user IP packets into the different QoS-based bearers based on Traffic Flow Templates (TFTs). The P-GW performs QoS enforcement for guaranteed bit rate (GBR) bearers.

• **Mobility Management Entity (MME)**: This is the main control node of the core network (CN). The MME manages the signaling between the E-UTRAN and EPC, provides user authentication by communicating with the HSS, and is responsible for handover operations between eNodeBs. The MME also handles all functions related to the establishment of traffic bearers and provides all the security key management functions. The protocols running between the UE and the CN are known as the Non Access Stratum (NAS) protocols, as the MMEs are not involved in air interface matters.

• **Evolved Packet Data Gateway (ePDG)**: The gateway responsible for providing interworking between LTE and non-3GPP untrusted networks.

• **Home Subscriber Service (HSS):** Database that contains the subscription data of all subscribers in the mobile network. It also contains information about the visited network when a subscriber roams to another network. The HSS generates the security data needed for authentication and encryption functions implemented by the MME. It also holds information about the PDNs to which the user can connect. In addition, the HSS holds dynamic information such as the identity of the MME to which the user is currently attached or registered.

• **Policy and Charging Roles Function (PCRF):** Manages the collection of data for billing and limits the UE's possible service level according to each subscriber's subscription.

2.4.2.2 QUALITY OF SERVICE (QOS)

Multiple applications may be running in a UE at any time, each one having different QoS requirements. For example, a UE can be engaged in a VoIP call while at the same time browsing a web page. Voice over IP (VoIP) has more stringent requirements for QoS in terms of delay and delay jitter than web browsing. In order to support multiple QoS requirements, different bearers are set up, each associated with a QoS. Bearers can be categorized into two broad classes based on the nature of the QoS they provide:

1) Minimum guaranteed bit rate (GBR) bearers: can be used for applications such as VoIP. These have an associated GBR value for which dedicated transmission resources are permanently allocated at bearer establishment or modification. Bit rates higher than the

GBR may be allowed for a GBR bearer if resources are available. In such cases, a maximum bit rate (MBR) parameter, which can also be associated with a GBR bearer, sets an upper limit on the bit rate that can be expected from a GBR bearer.

2) Non-GBR bearers: do not guarantee any particular bit rate. These can be used for applications such as web browsing or FTP transfer. For these bearers, no bandwidth resources are allocated permanently to the bearer.

Each bearer has an associated QoS Class Identifier (QCI), and an Allocation and Retention Priority (ARP). Each QCI is characterized by priority, packet delay budget and acceptable packet loss rate. Only a dozen of such QCIs have been standardized so that vendors can all have the same understanding of the underlying service characteristics. The set of standardized QCIs and their characteristics is provided in Table 2 [45].

Table 2: Standardized LTE QCIs [45]

QCI	Resource Type	Priority	Packet Delay (ms)	Packet Error Loss Rate	Services
1	GBR	2	100	10^{-2}	Conversational voice
2	GBR	4	150	10^{-3}	Conversational video (live streaming)
3	GBR	3	50	10^{-3}	Real-time gaming
4	GBR	5	300	10^{-6}	Non-conversational video (buffered streaming)
5	Non-GBR	1	100	10^{-6}	IMS signaling
6	Non-GBR	6	300	10^{-6}	Video (buffered streaming) TCP-based (www, e-mail, ftp,...etc)
7	Non-GBR	7	100	10^{-3}	Voice, video (live streaming), interactive gaming
8	Non-GBR	8	300	10^{-6}	Video (buffered streaming) TCP-based (for example, WWW, e-mail), chat, FTP, P2P file sharing.
9	Non-GBR	9			

2.4.2.3 LTE PERFORMANCE REQUIREMENTS

Some performance requirements of LTE networks [43] are listed in Table 3. As stated before, LTE has to meet the latency requirements of the delay sensitive Intelligent Transportation System (ITS) applications. Otherwise, if a packet delivery is delayed then, the information in that packet is no longer useful, which can lead to a fatal accident. The latency encountered by LTE packets can be classified into two major categories: Control plane latency and User plane latency. Control plane latency is the time required to perform the transition from one LTE state to another. A User Equipment (UE) has one of three states: Connected (active), Idle or Dormant (battery saving mode). 3GPP defines that the transition time from the Idle state to the Connected state should be less than 100ms, excluding downlink paging and Non-Access Stratum (NAS) signaling delay. The user plane latency is defined as the one way transit time between the availability of a packet at the IP layer in the UE and its availability at the Internet Protocol (IP) layer in the eNodeB. A user plane latency of around 5ms one way is expected from the E-UTRA. Low user plane latency is essential for delivering interactive services like VoIP, gaming and most importantly ITS traffic.

Table 3: LTE Performance Requirements [43]

Metric	Performance Requirement
Peak Data Rate	Downlink: 100Mbps Uplink: 50Mbps (for 20MHz spectrum)
Mobility Support	Up to 500 km/hr but, optimized for low speeds from 0 to 15 km/hr
Control Plane Latency	< 100ms (transition time from idle to active state)
User Plane Latency	< 5ms
Control Plane Capacity	> 200 users per cell (for 5 MHz spectrum)
Coverage (cell size)	5 – 100 km with degradation after 30 km
Spectrum Flexibility	1.25, 2.5, 5, 10, 15 and 20 MHz

The LTE radio interface is based on Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink and on Single Carrier Frequency Division Multiple Access (SC-FDMA) in the uplink. OFDMA technology divides the available bandwidth into multiple narrowband sub-carriers and allocates a group of closely spaced orthogonal sub-carriers to a user based on the requirements, system configuration and current system load. LTE supports multi-antenna techniques such as Multiple Input Multiple Output (MIMO) and beam-forming to increase peak and cell edge bit rates respectively. In the LTE access network, there is no centralized intelligent controller which helps to speed up the connection set-up and reduce the time required for a handover. In an effort to support as many regulatory requirements as possible and improving spectrum flexibility, the LTE frequency bands range from 800MHz up to 3.5GHz, and the supported bandwidth is very flexible ranging from 1.25 to 20MHz. Besides, LTE supports both the time division duplex (TDD) and the frequency division duplex (FDD) technologies.

2.4.3 IEEE 802.11 (Wi-Fi)

Wi-Fi networks include any wireless local area network (WLAN) product that is based on the Institute of Electrical and Electronics Engineers' (IEEE) 802.11 standards, as defined by the Wi-Fi Alliance [7]. Wi-Fi and WLAN are used interchangeably in this document to refer to the IEEE 802.11 standard. Any device that supports Wi-Fi can use a wireless network access point (AP) to gain access to a network resource such as Internet. Such devices can be laptops, smart-phones, tablets,…etc. The IEEE specifications focus on the lowest two layers of the OSI 7-layers model, which incorporate the data link/ Medium Access Control (MAC) and physical components.

Table 4 summarizes the IEEE 802.11 standard family. Following are the most important IEEE 802.11 standards [46]:

- 802.11a (1999): operates in the 5GHz frequency band with a maximum data rate of 54Mb/s. It uses an OFDM based interface.
- 802.11b (1999): operates in the 2.4GHz frequency band with a maximum raw data of 11Mb/s.

- 802.11g (2003): operates in the 2.4GHz with a maximum data rate of 54Mb/s, as it also uses OFDM coding.
- 802.11n (2009): it can transmit a maximum of 140Mb/s and operates in both frequency bands (2.5 and 5GHz). Multiple-input multiple-output (MIMO) antennas technology was added to this standard which provided a significant improvement compared to the previous standards.

For a typical deployment using 802.11b and 802.11g, the ranges could be about 20 meters indoors and 70 meters outdoors. On the other hand, the 802.11n protocol can extend those numbers to the double.

Table 4: IEEE 802.11 Family

Protocol	Release	Frequency (GHz)	Typical Throughput (Mbps)	Maximum Data Rate (Mbps)	Modulation
802.11	1997	2.4	0.9	2	FHSS/ DSSS
802.11a	1999	5	23	54	OFDM
802.11b	1999	2.4	4.3	11	DSSS
802.11g	2003	2.4	19	54	OFDM
802.11n	2009	2.4 / 5	74	600	OFDM
802.11y	2008	3.7	23	54	OFDM

2.4.3.1 TYPES OF IEEE 802.11

The Basic Service Set (BSS) is the basic building block of a wireless local area network (WLAN). The BSS is a group of stations that communicate wirelessly with each other. The “basic service area” refers to the area served by the WLAN communication, which defines the propagation characteristics in the medium at a given data rate. When a station is within the basic service area, it can communicate with other members of the same BSS. There are three types/ modes of BSS: independent basic service set, infrastructure basic service set and extended service set [47]. The 802.11 interface of a mobile node is configured to operate in one mode or the other. Some new interfaces provide automatic switching of mode after detecting the type of network.

An independent BSS where stations communicate directly with each other is shown in Figure 2. Independent BSS is also referred to as ad-hoc network. Typically, independent BSSs are composed of a small number of stations set up for a specific purpose and for a short period of time. One common example is to create a network to support a single meeting in a conference room. When the meeting begins, the participants create an independent BSS to share data and when the meeting ends, the network nodes disengage.

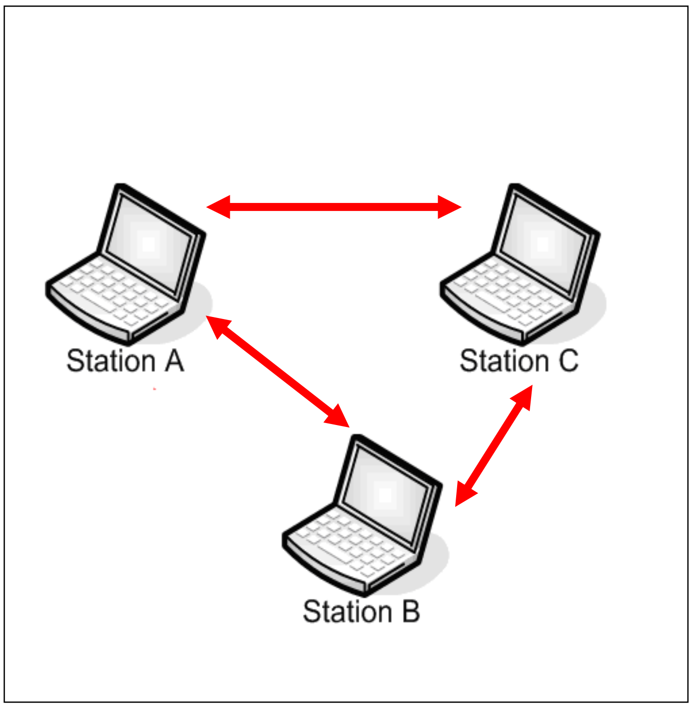


Figure 2: Wi-Fi Independent Basic Service Set

An Infrastructure BSS is illustrated in Figure 3. All nodes within the BSS communicate through the access point (AP). APs are used for all communications in infrastructure networks, including communication between mobile nodes in the same basic service area. Each BSS has an AP, which defines its coverage area. A station/ mobile node needs to associate with an AP to gain network connectivity. For example, if station A needs to communicate with station B, the communication will happen in two hops. First, station A sends the packet to the AP; then, the AP relays the packet to station B.

Although multi-hop communication consumes more transmission power and time than a direct transmission path from the sender to the receiver, it has two major advantages. First, an extended communication range is possible for infrastructure BSS as all mobile stations should be within reach of the AP, but no restriction is placed on the distance between mobile stations themselves. Second, APs can assist the stations to save power by noting when a station enters a power-saving mode and buffer packets for it. So, battery-operated stations can turn their wireless transceivers off and power them up only to send and retrieve buffered packets from the AP, which provides battery-operated stations a longer service time.

In infrastructure BSS, the AP periodically broadcasts beacons within a BSS. The beacon contains BSS identifier (BSSID), which uniquely identifies a BSS. The BSSID field in the infrastructure mode is the MAC address of the AP, which forms the BSS. The nodes in the infrastructure mode only use the information in beacon frames if the BSSID is equal to the MAC address of the AP in the BSS.

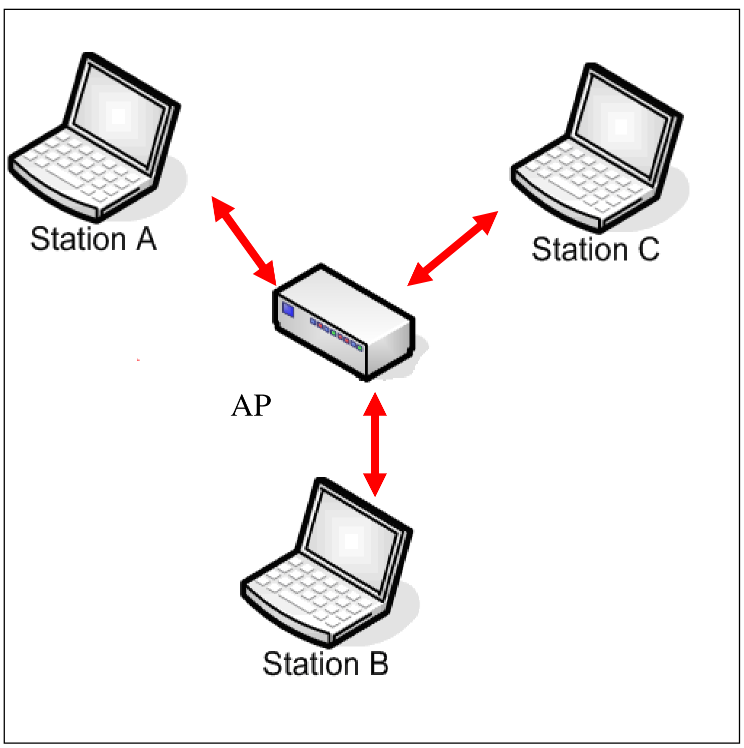


Figure 3: Wi-Fi Infrastructure Basic Service Set

Independent BSS and Infrastructure BSS can offer coverage to small offices and homes, but they cannot provide network coverage to larger areas. To provide an extended coverage, BSSs can be linked together to form an Extended Service Set (ESS). An ESS is created by connecting BSSs together with a backbone network. The mobile stations can move from one BSS to another and re-associate with the new AP. Figure 4 is an example of two BSSs (BSS 1 and BSS 2) linked to form an ESS. In each BSS, AP connects to each station wirelessly. AP1 and AP2 are connected by a backbone network, which can be either wired or wireless. If station A wants to send a packet to station D, the communication must take three hops: first, station A transfers the packet to AP1; second, AP1 relays the packet to AP2 via the backbone network; third, AP2 forwards the packet to station D. Although the backbone network will consume some power, it significantly increases the service area of the WLAN network.

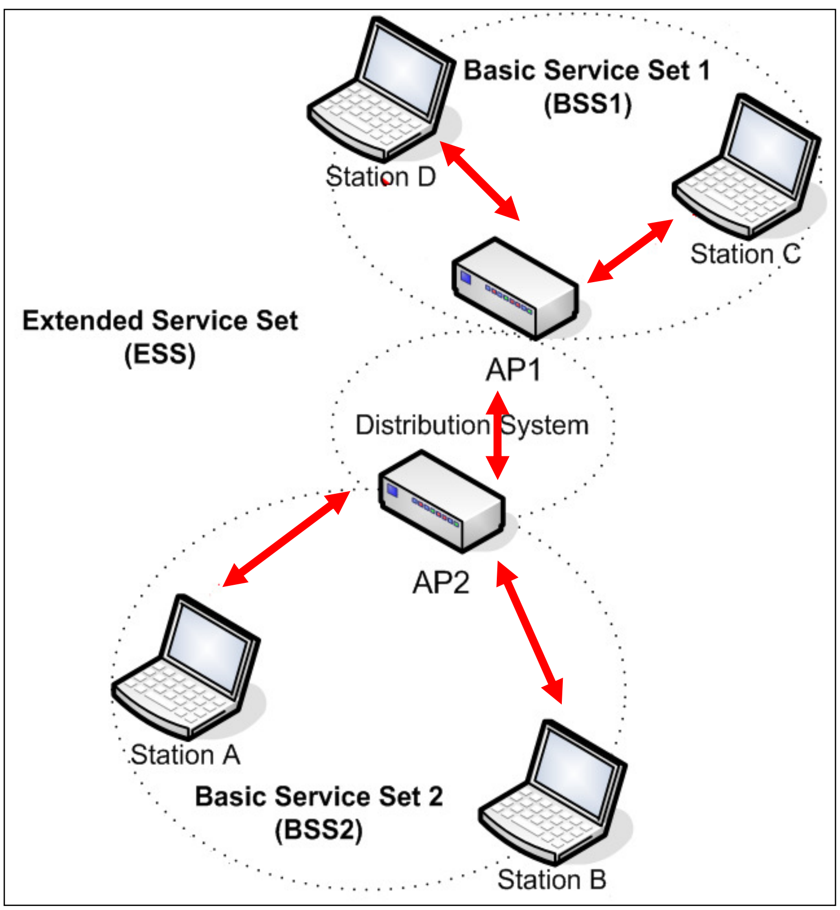


Figure 4: Wi-Fi Extended Service Set

2.4.3.2 Quality of Service (QoS) Support

The IEEE 802.11 MAC sub-layer defines two medium access coordination functions, the mandatory Distributed Coordination Function (DCF) and the optional Point Coordination Function (PCF) [48]. DCF is a distributed medium access scheme using asynchronous transmission mode based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. DCF does not provide any QoS guarantees. PCF is a synchronous service that implements a polling-based contention-free access scheme. It can be used with the infrastructure mode only and unlike DCF, its implementation is not mandatory.

IEEE 802.11e proposed a new MAC layer coordination function called Hybrid Coordination Function (HCF) with the aim of providing queue-based QoS support. HCF uses a contention-based channel access method, also called the enhanced distributed channel access (EDCA), which operates concurrently with an HCF controlled channel access (HCCA) method. One main feature of HCF is the concept of transmission opportunity (TXOP), which refers to a time during which a given QSTA (QoS-enhanced station) has the right to send data frames.

EDCA provides prioritized QoS by enhancing DCF. Before entering the MAC layer, each data packet received from higher layers is assigned a specific user priority value. At the MAC layer, EDCA defines 4 different FIFO queues, i.e. access categories (ACs). Each data packet from higher layers along with a specific user priority value is mapped to a corresponding AC using a mapping table. As shown in Table 5, different types of applications such as background, best-effort, video and voice traffic [48] can be mapped to different AC queues (i.e. AC_BK, AC_BE, AC_VI, AC_VO respectively). High-priority traffic has a higher chance of being sent than low-priority traffic. A station with high priority traffic waits less before it sends its packet, on average, than a station with low priority traffic.

Table 5: 802.11e Mapping between User Priority and Access Category [48]

User Priority	802.11e Access Category (AC)	Service Type
1	AC_BK	Background
2	AC_BK	Background
0	AC_BE	Best Effort
3	AC_VI	Video
4	AC_VI	Video
5	AC_VI	Video
6	AC_VO	Voice
7	AC_VO	Voice

2.5 OPPORTUNITIES OF VEHICULAR WIRELESS COMMUNICATION

There has been an increasing market demand for Internet connectivity in vehicles. In a study conducted by Alcatel-Lucent [2], 50% of the participants found the idea of a connected vehicle highly appealing and 22% would be willing to pay $30-65 per month for value-added connectivity services while onboard. Passengers in cars, trains, trams or buses can enjoy the convenience of having internet access while travelling anywhere. This can be realized through the existing cellular infrastructure by installing an antenna onboard of the vehicle.

On the other hand, communication capabilities of mobile devices are constantly improving, where most devices now have multiband cellular, as well as, Wi-Fi capabilities. In addition, Wi-Fi is currently integrated in all laptops, mobile phones, personal digital assistants (PDAs) and tablets. In this case, no special software or terminal is required which further facilitates connectivity. Moreover, the breakthrough in wireless communication technologies over the last two decades has created many opportunities for supporting vehicular communication. Wireless technologies that offer acceptable data rates and delay with minimum service interruptions satisfy the requirements of several vehicular applications. All these factors allow consumers to remain connected anywhere and anytime which in turn increases Internet usage. So, there are considerable opportunities available for vehicular Internet access if the access can be made ubiquitous, simple, and useable.

2.6 CHALLENGES OF VEHICULAR WIRELESS COMMUNICATION

As previously mentioned, vehicular applications are generally characterized by high Quality of Service (QoS) requirements and low latencies, which is currently a challenge at high mobility.

For multimedia applications (such as video streaming, video conferencing and online gaming) specifically, a high data rate is particularly important. However, the current radio access techniques could not offer high data rates and low latency in high mobility environments. In addition, complex roadway environments and high-density roadways pose significant challenges at the physical layer. Following are few issues that limit the performance of wireless technologies at high speed [8, 49].

1) Doppler Frequency Shift

In the wireless mobile environment, Doppler frequency shift (f_d) emerges due to the relative motion of the receiver with respect to the transmitter. The relative movement shifts the frequency of the signal, making it different at the receiver than at the transmitter. So, when a vehicle transmits a signal while moving, the frequency of the transmitted signal is shifted by an offset. As the vehicle speed increases, the frequency distortion also increases. As a result, frequency shifting increases and leads to a loss in orthogonality between sub-carriers causing inter-carrier interference. Doppler frequency shift (f_d) can be calculated as,

$$f_d = \frac{v}{c} \times f \times \cos\theta \qquad (1)$$

Where v is the velocity of the receiver in m/s, c is the velocity of light (3×10^8 m/s for electromagnetic waves travelling in vacuum), f is the emitted frequency of transmitter, and θ is the angle between the receiver's forward direction and the line of sight from the transmitter to the receiver.

Equation (1) shows that when the base station is placed far away from the vehicle, f_d is relatively low as θ will be close to 90°. For a 1.8GHz carrier frequency, the Doppler frequency shift of a 120 km/hr vehicle will reach 200Hz from equation (1). In orthogonal frequency division multiplexing (OFDM) systems, the carriers can never be perfectly synchronized, which causes inter-carrier interference. The increase in Doppler frequency shift causes a rapid increase in the bit error rate (BER), which is a restriction for OFDM systems applied in vehicular networks. To reduce Doppler frequency shift, base stations (BSs) should be placed far away from the vehicles. However, there are other contradicting requirements that call for a smaller distance between the BS and the vehicle namely, handover rate and penetration loss discussed below.

2) High Handover Rate and Group Handover

Fast handover is another issue faced by mobile users travelling at medium and high speeds. Whenever a user's device approaches and crosses the cell boundaries of the BS to which it is connected, the received signal fades and communication is interrupted. To maintain the communication link, the device should connect to another BS, which means that a handover from an old BS to a new BS has to take place.

The handover rate mainly depends on two factors: vehicle speed and cell size. Rapidly passing through overlap areas of cells leads to high handover failure rate. The handover rate increases as vehicle speeds increase. i.e. the handover occurs more frequently with higher vehicle speeds. Similarly, small cell sizes causes handover to happen more frequently. For example, a high-speed train with 350 km/hr speed and a cell size of 3 km (typical in LTE systems) will have a handover every 30 seconds. Assuming an average overlap area between two consecutive cells of 300 meters, the handover process must be completed and connection switched from the old cell to the new cell within around 3 seconds. These fast handovers result in packet losses, reordering and delays.

In addition to the high handover frequency problem, group handover is another issue that affects the performance of the wireless system. In trains, buses and large vehicles, multiple mobile terminals need to execute the handover process when they enter the coverage of a new cell. With a large number of passengers, all the handover requests should be handled simultaneously, which heavily loads the system. Therefore, it is very important to minimize handover durations and optimize the handover process.

3) Penetration Loss

The penetration loss of wireless signals affects the performance of broadband vehicular networks. High speed buses, trains and some vehicles have a metallic body with one-layer or multi-layer glass windows. To improve thermal insulation, multi-layer glass windows include a thin metallic layer to reflect sun's rays. This leads to high penetration losses for the signals which in turn negatively affects the system's performance. The position of the wireless antenna and many other system parameters need to be carefully designed to avoid such issues.

4) Bandwidth and QoS Requirements

As indicated earlier, vehicular users are interested in broadband multimedia applications such as video streaming, video conferencing, online gaming and Voice over Internet Protocol (VoIP). With a large number of passengers in vehicles, trains, trams and buses, it is necessary to estimate the total bandwidth needed and design the system accordingly. For example, in a cellular network, a high bandwidth can be achieved by reducing the cell size to reuse the limited frequency spectrum. Small cells are particularly useful for densely populated areas. In addition to bandwidth requirements, QoS constraints of real-time services need to be satisfied. This includes passenger entertainment services, traffic control and critical safety services.

CHAPTER 3: HETEROGENEOUS VEHICULAR NETWORKS

In recent years, various wireless access technologies have been deployed to provide users with a wide range of services. This provides more flexibility and various connectivity options for users. Until recently, both research and industrial communities were focusing on just one network technology to support vehicular systems. The majority of research papers focus on studying either cellular networks, Wi-Fi or VANETs for vehicular access. Nevertheless, an upcoming trend of vehicular communication networks is moving towards heterogeneous networks that employ multiple network technologies instead of focusing on just a single technology.

In the context of communications networks, "heterogeneous networks" is used as a comprehensive term to refer to multiple concepts. For example, 3GPP LTE standard defines heterogeneous networks as the integrated coverage of macro, micro and pico cells. However, this definition is not applicable in the case of vehicular networking. It has been agreed that a heterogeneous vehicular network refers to a system characterized by the integration of different communication technologies such as cellular networks, Wi-Fi and IEEE 802.11P DSRC [50].

Two opposing categories have been identified in heterogeneous vehicular networking [50]:

Class A follows a generalized network stack which abstracts applications from the lower layers applied technology, providing an "always best connected" experience to upper layers. This approach effectively avoids issues caused by shadowing and fading effects. Moreover, the use of multiple technologies in parallel can help in cross-validating fraudulent messages and protecting against physical layer attacks. The use of IEEE 802.11 for cellular offloading is one use case of this class.

Class B employs a "best of both worlds" approach which exposes information of lower layers to applications at higher layers. This strategy enables applications to select the best fitting technology for a particular task/ use case. The use of multiple technologies utilizes each system to its full capacity by exploiting its benefits and mitigating its drawbacks. The architecture proposed in this thesis is based on this class.

3.1 MOTIVATION

There are several incentives that drive the use of heterogeneous networks in the vehicular domain. One of the main reasons is that multiple technologies are widely available on mobile terminals nowadays. This includes portable devices like smart phones, tablets, personal digital assistants (PDAs) and laptops, as well as, modern vehicular OBUs. The decreasing cost of wireless transceivers encourages the use of more than one radio in the on-board unit (OBU) of a vehicle. Vehicles which have such dual access capabilities can serve as mobile gateways for other vehicles to access the Internet. Heterogeneous vehicular networking is further motivated by the idea that in the short and medium term, cellular networks will not be able to offer sufficient network capacity without a drastic increase in deployment density and price [51, 52]. It is even projected that in the long term cellular networks might not be capable of providing sufficient network capacity.

One other key motivation behind the use of heterogeneous vehicular networks is making the best use out of each technology. Each technology has a number of associated benefits and drawbacks. On one side of the spectrum, Dedicated Short Range Communication (DSRC), also known as IEEE 802.11p, offers low latency and is thus suitable for safety critical applications. However, DSRC's drawback is that it has a limited coverage. On the other side of the spectrum are the cellular technologies which offer high coverage ranges and the capacity to deliver large amounts of data. On the down side, LTE faces a reduced performance in case of multi-casting and broadcasting. The use of heterogeneous networks improves the overall system performance by exploiting each technology to its full ability. This is achieved by utilizing each technology's advantages and avoiding its drawbacks.

Heterogeneous networks offer reliability, mobility support and low-latency to satisfy the performance requirements of the different vehicular applications (safety, traffic efficiency and infotainment). On one hand, infotainment applications have high-bandwidth demands and QoS-sensitive requirements [2]. While on the other hand, safety-critical applications are characterized by low latency and high message delivery rate. To support safety application demands, a large amount of data traffic needs to be exchanged between vehicles and base stations (BSs). This will consequently add a heavy burden to the BSs, which is not likely to be accepted by network operators. Additionally, this extra traffic connections increase the effect of interference and thus increases data error rate. Moreover, this also causes an increase in packet delays due to resource depletion. Furthermore, the scheduler at the BS may also have difficulties scheduling transmissions within the tight delay bounds required for safety-critical applications. Thus, it is difficult for a single technology to accommodate all of the application requirements simultaneously specially, when most of these requirements are conflicting in nature.

The integration of vehicular ad-hoc networks (VANETs) and cellular networks using mobile vehicular gateways will improve the vehicular system performance. Wireless communication becomes available for vehicles at all times and places along with the flexibility of choosing the available wireless interface (cellular or VANET). By integrating VANET with LTE, high data rate can be coupled with wide-range of communication.

In the heterogeneous network, there are mainly two types of vehicles: Gateway Vehicles (GVs) and Ordinary Vehicles (OVs). GVs are equipped with both LTE and Wi-Fi interfaces while, OVs are only Wi-Fi enabled. A GV can be connected to 2 networks simultaneously; the LTE network using its E-UTRAN interface and to other OVs through its Wi-Fi interface. The GV can thus serve as a mobile gateway (i.e. relay node) for other OVs in its vicinity to access the LTE network. This can be accomplished by receiving data from OVs (using its Wi-Fi interface) and relaying it to the LTE network (via its LTE interface).

This integration significantly reduces dead zones in the vehicular network, as the probability of coverage is maximized due to the simultaneous presence of both LTE and Wi-Fi networks. Moreover, with such integration mobile operators' services can be leveraged by providing vehicular passengers with seamless data access at affordable price rates and with minimum or no investment in the LTE core network technology. Furthermore, the overall cost, network load, and frequency of handover occurrence at eNodeB can be considerably reduced.

3.2 MULTI-HOP HETEROGENEOUS VEHICULAR NETWORKS

There are various architectures for heterogeneous vehicular networks. We will be focusing on the Hierarchical Two Hop (HTH) network architecture, which is also referred to as dual-layer network.

The HTH network architecture emerged when conventional one-hop architectures could not deliver the required performance, especially in high speed vehicles. In traditional one-hop vehicular architectures (shown in Figure 5), the vehicle passengers communicate directly with the cellular infrastructure base station (BS). To improve the degrading signal quality because of Doppler shift and multipath fading, advanced access technologies should be employed at UEs, which increases the complexity and cost of the mobile devices. Additionally, it has been reported that conventional cellular systems fail to work properly for passengers on high speed trains at a speed higher than 300km/h, even if the network is optimized with current technologies [25].

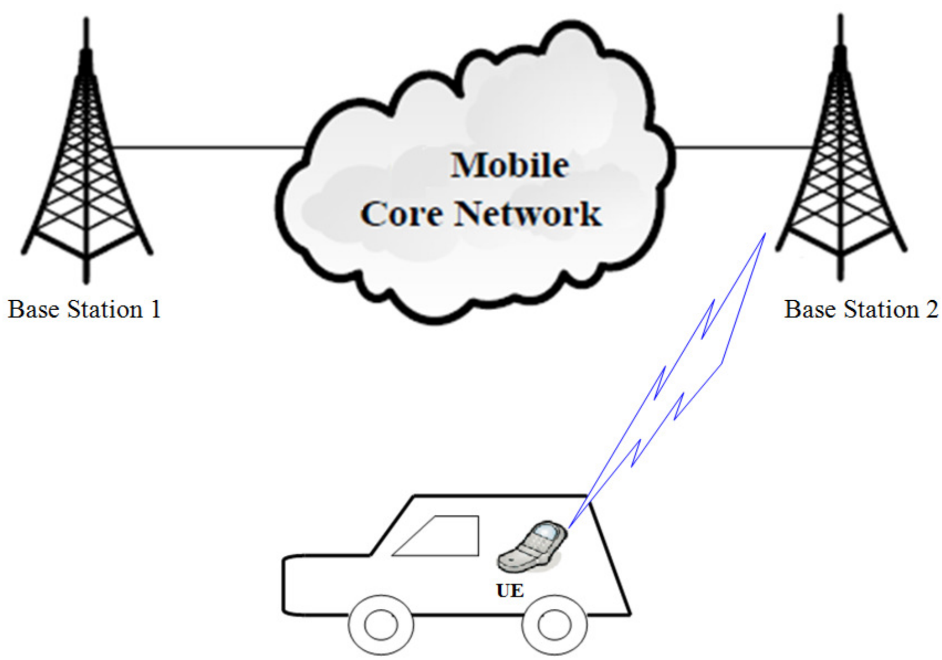


Figure 5: Network for Vehicular Wireless Communications: One-hop Architecture

As shown in Figure 6, in HTH network architecture all the UEs inside the vehicle communicate with a relay node (RN) placed onboard of the vehicle, and the RN relays the UE connections to a BS on the road side. The RN communicates with the BSs by an external antenna outside the vehicle. The HTH approach has been widely adopted in high speed trains [24, 25, 49].

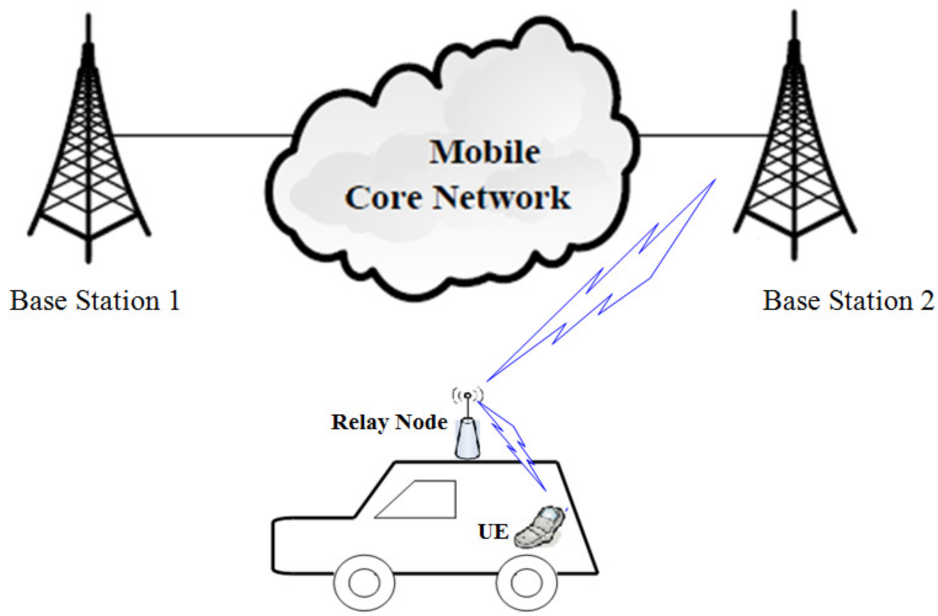


Figure 6: Network for Vehicular Wireless Communications: Two-hop Architecture

There are several advantages of using HTH vehicular networks. The benefits of the HTH structure becomes more evident as the number of passengers in a vehicle increases, meaning that trains, buses and cars' gains are highest, high, and medium respectively. For example, with dozens of train passengers, the savings are higher as the infrastructure BS will communicate with only one train terminal. The control signaling and radio resource management will be significantly reduced where a single handover will be performed as opposed to group handover (dozens of devices) in the one-hop architecture. Moreover, since RNs (OBUs) are not as limited by size and power constraints as the regular UE, they can better exploit different smart antenna techniques and advanced signal processing schemes [28].

Furthermore, by proper placement of indoor and outdoor antennas on the vehicle, a RN can thwart the vehicle penetration loss (VPL) caused by a well isolated vehicle. Field tests show that the VPL in a minivan can be as high as 11 dB at a frequency of 1.8 GHz and 25 dB at the frequency of 2.4 GHz [53], and higher values are expected in modern vehicles. Lastly, backhaul connections between RNs and eNodeBs offer better propagation conditions (less shadowing and pathloss, and higher line-of-sight connection probabilities) compared to direct connections between eNodeB and in-vehicle UE. RNs can significantly improve the performance of the in-vehicle UE, especially at the cell edge [28].

3.3 SYSTEM ARCHITECTURE

Designing and implementing a heterogeneous network should preferably be based on the intelligent integration of already available technologies so as to minimize the deployment cost and speed up the deployment process. The proposed HTH vehicular network combines two technologies with long-range and short-range coverage, namely LTE and Wi-Fi respectively. Each technology has a different objective and their integrated deployment will improve the vehicular system performance. On one hand, Wi-Fi offers a relatively high capacity at a very low cost and it has a high market penetration. However, it has a lower coverage range compared to LTE. This makes it suitable for use as an access network inside the vehicle and for V2V communication between nearby vehicles. On the other hand, LTE offers a wide coverage and better quality of service (QoS) reliability but, it requires costly licensed spectrum, and is very much lagging behind Wi-Fi in terms of the economies of scale [27]. These characteristics fit with the long range communication requirements of the V2I network. By integrating Wi-Fi with LTE, high capacity is coupled with long-range communication to improve the overall performance of the vehicular system.

The envisioned IEEE 802.11-based VANET-LTE heterogeneous network architecture is shown in Figure 7. Vehicles that are equipped with both LTE and Wi-Fi interfaces are referred to as Gateway Vehicles (GVs) whereas, only Wi-Fi is supported on-board Ordinary Vehicles (OVs). A GV is under the coverage region of at least one LTE eNodeB, and its LTE and Wi-Fi interfaces are both activated. On the other hand, an OV either lacks an LTE interface or is not present in an LTE coverage area. In other words, it is assumed that the LTE interface is either absent or disabled on OVs.

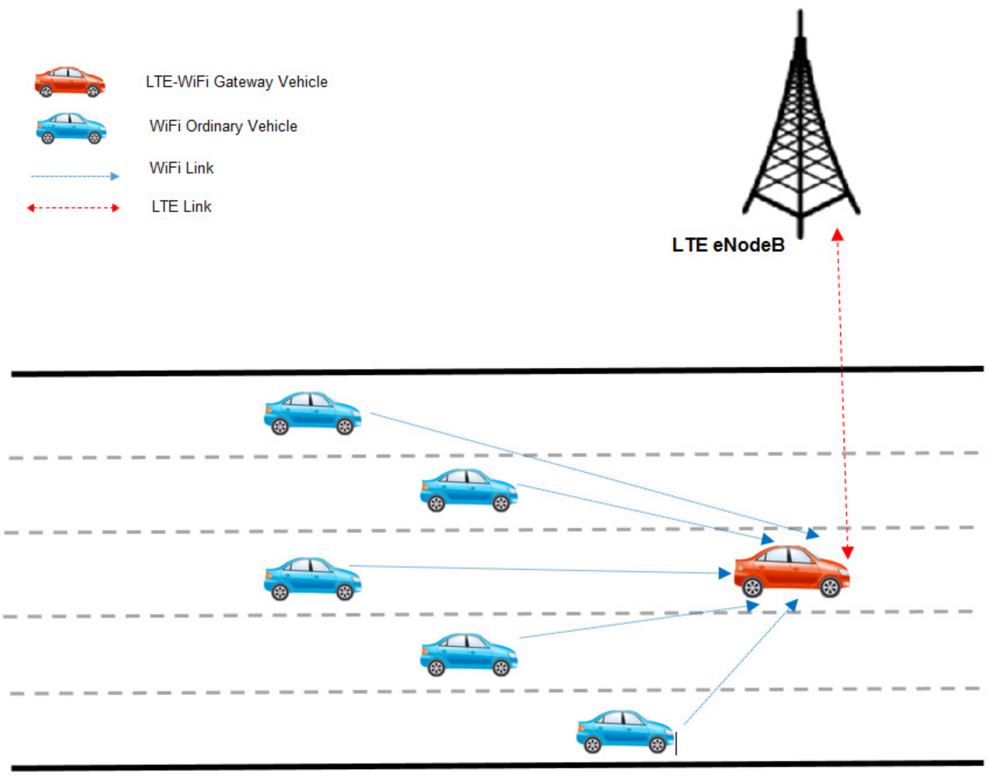


Figure 7: VANET-LTE Network Architecture

The proposed architecture divides the vehicular network into Vehicle-to-Vehicle (V2V), Vehicle-to- Infrastructure (V2I), On-board Vehicle Communication (OVC), and backhaul network. The V2V network allows communication between GVs and OVs through Wi-Fi. The V2I network between the vehicle and LTE eNodeB provides access to the core components of the LTE network. The OVC network consists of a Wi-Fi Access Point (AP), passengers' devices and a vehicular OnBoard Unit (OBU) for ITS data. In this scenario, LTE is the access network that is used to access the Internet and the connectivity is shared to vehicular users using Wi-Fi as the on-board access network. At the same time, LTE is used to carry ITS traffic which is communicated to the vehicle's OBU through an

Ethernet link. The LTE links are full duplex. Typically, an LTE eNodeB is deployed alongside the road and the vehicles are under the coverage regions of the different eNodeBs.

From the data flow perspective, GV samples and gathers the information from OVs (through Wi-Fi) then, in turn periodically sends the relevant data to the infrastructure (via LTE). Data is exchanged between the GV and LTE eNodeB in both the downlink and uplink directions. In the downlink direction, LTE eNodeB unicasts the data to GVs where both ITS and infotainment traffic are sent over the LTE link yet, they are routed differently inside the vehicle based on the intended destination. ITS data is sent to the vehicle's OBU via Ethernet for further processing and decision making. On the other hand, infotainment traffic is sent to the passengers' devices through Wi-Fi. In the uplink direction, GV forwards the traffic data (collected from OVs) to the LTE infrastructure at a pre-determined transmission rate.

In order to reduce the amount of traffic exchanged between vehicles and eNodeBs, a clustering strategy is employed. The GV is the cluster head which maintains the status of the cluster. Only the LTE-enabled cluster head is allowed to receive/ transmit data from/ to eNodeBs through LTE interfaces. Every OV transmits small data packets called Cooperative Awareness Messages (CAMs) to their corresponding cluster head/ GV, providing state information such as speed or location. Such CAMs are transmitted every 100ms [18]. We consider that vehicle clusters are already formed and that in each cluster, vehicles are moving together. Thus, cluster members can be assumed not to vary throughout the journey. A single cluster of vehicles consists of 1 GV and 5 OVs.

The proposed I2V architecture is depicted in Figure 8. A wireless LTE node is placed on the vehicle's roof with antennas mounted outside to communicate with the LTE cellular network and in turn, a Wi-Fi access point (AP) is used to provide access to users inside the vehicle.

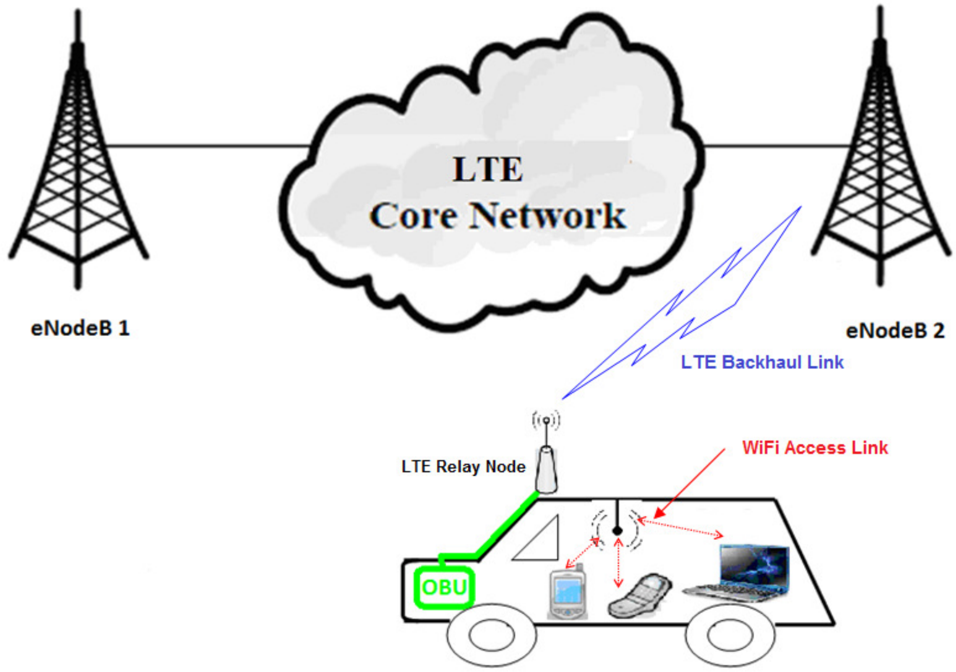


Figure 8: Vehicular Two-hop LTE–Wi-Fi Network

Since most devices (smart phones, laptops and tablets) have a Wi-Fi interface, Wi-Fi is used to provide Internet access to users on board. One advantage of this is that devices with Wi-Fi-only interface can also use the cellular network (through the GV), which may bring extra income to service providers. Another added value is that the vehicle which is connected to the LTE network (GV) can serve as a RN (i.e. mobile gateway) for other vehicles in its vicinity. It can provide access to the LTE network by receiving data from nearby vehicles (using its Wi-Fi interface) and forwarding the received data to the LTE network. With such integration, dead spots in the network can be minimized by a significant extent [16].

3.4 PROPOSED MODEL

The model proposed in this thesis represents an urban traffic model where vehicles move at a speed of 60km/hr, which is the maximum speed for a moving vehicle in an urban area. Urban areas are characterized by a limited maximum speed and the presence of different routes. It is assumed that BSs are distributed over the city for full coverage and mobile vehicles roam between these BSs. Also, traffic information is sent from the traffic server through the network to the moving vehicles. This is known as Infrastructure to Vehicle (I2V) transmission.

Two types of traffic are sent over the network namely, ITS traffic and infotainment data. ITS traffic refers to information about traffic conditions of the surrounding environment. This information is sent to all vehicles within the concerned area and vehicles in turn collect this information then, the best route to the desired destination is determined. Three types of ITS traffic are considered in this thesis namely V2V, uplink and downlink ITS traffic. V2V ITS traffic represents cooperative awareness messages (CAMs) sent from OVs to GV through Wi-Fi. Uplink ITS traffic consists of consolidated data collected from OVs and sent to the infrastructure via LTE. Downlink ITS traffic represents traffic control information sent to GV and is required by vehicular networking applications in the domain of traffic efficiency.

Besides ITS data, infotainment traffic is also sent to the moving vehicles. Infotainment refers to a variety of content such as video on-demand, video conferencing, video streaming, Voice over IP (VoIP), and Internet access.

Both ITS and infotainment traffic are sent over the LTE backbone network yet, they are routed differently inside the vehicle based on the intended destination. ITS data is sent to the vehicle's OBU via Ethernet for further processing and decision making whereas, infotainment traffic is sent to the passengers' devices through Wi-Fi. This routing is performed using a multi-interface router which has 3 network interfaces namely, LTE, Wi-Fi and Ethernet. Ethernet was selected for OBU communication as part of ongoing research on all IP vehicular networks [54]. IEEE 802.11g has been selected as it is widely supported by consumer devices. It offers users a uniform and mass-standard connectivity as the same standard is widely used in various parts of cities like hot-spots, tourist centers and information points [55].

CHAPTER 4: MODELING AND SIMULATION

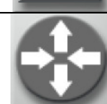
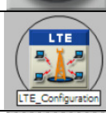
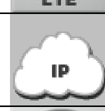
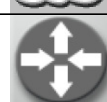
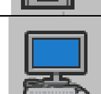
4.1 OPNET

OPNET (**Op**timized **N**etwork **E**ngineering **T**ool) [56] is used to evaluate the network performance. OPNET is an object-oriented general purpose network simulator. It is a proprietary simulation software based on Discrete Event System (DES). In this thesis, OPNET Modeler 17.5 is used for the design, implementation and evaluation of the proposed network models.

4.2 NETWORK COMPONENTS

Table 6 demonstrates the OPNET objects used in the network model.

Table 6: Used OPNET objects

Object Name	OPNET Icon	Node Description
lte_enodeb_atm4_ethernet4_slip4_adv		LTE eNodeB
lte_epc_atm8_ethernet8_slip8_adv		LTE EPC (Evolved Packet Core)
lte_attr_definer_adv		LTE Attributes Configuration
lte_wkstn_adv		LTE workstation
ip32_cloud		IP Cloud
ethernet4_slip8_gtwy		Gateway
Ethernet_server		Server
ethernet_wkstn_adv		Ethernet workstation
wlan_wkstn_adv		WLAN workstation

In OPNET, a single EPC device models the Mobility Management Entity (MME), serving gateway (S-GW), and packet data network gateway (P-GW). The LTE–Wi-Fi–Ethernet router was created as a custom component in OPNET. It has three physical interfaces, namely LTE, Wi-Fi, and Ethernet and its node model is shown in Figure 9.

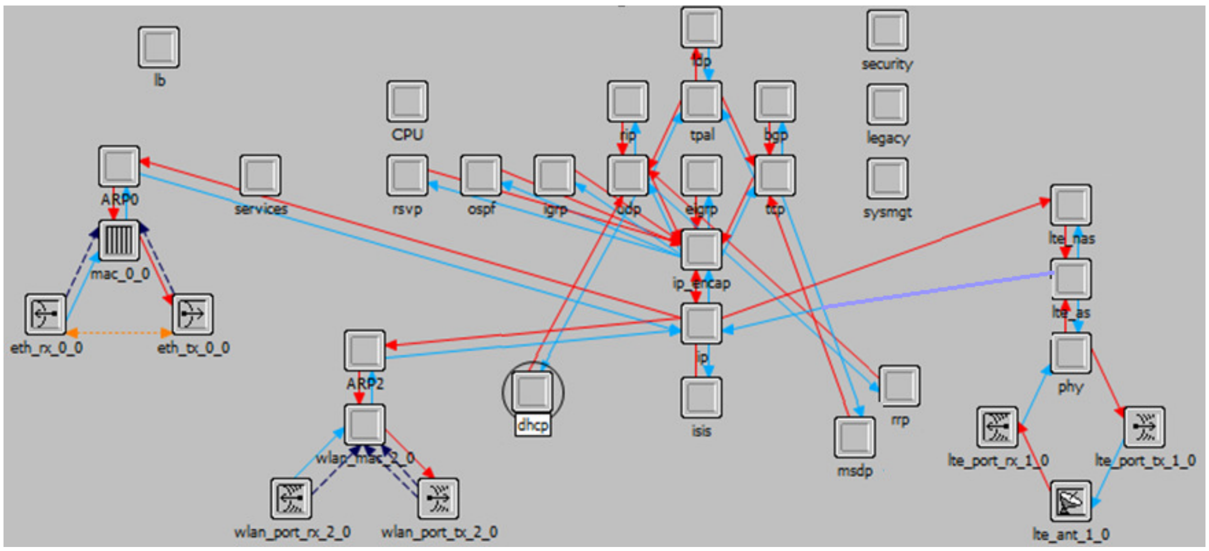


Figure 9: Node Model of LTE–Wi-Fi–Ethernet Router

4.3 Network Parameters

"LTE Attribute Configuration" node is used to store LTE physical configurations and Evolved Packet System (EPS) Bearer definitions, which are referenced by all LTE nodes in the network. Using the LTE configuration object, 10MHz FDD LTE physical profile was configured. The LTE configuration parameters are listed in Table 7.

Table 7: LTE Configuration Profile

Profile Name	Parameters	UL SC-FDMA Channel Configuration	DL OFDMA Channel Configuration
LTE 10 MHz FDD	Base Frequency	1.71 GHz	1.805 GHz
	Bandwidth	10 MHz	10 MHz
	Cyclic Prefix Type	Normal (7 symbols per slot)	Normal (7 symbols per slot)

The various network configuration parameters are shown in Table 8.

Table 8: Network Simulation Parameters

Parameter	Value
eNodeB	
Transmit Power	10Watts
Antenna gain	18dBi
MIMO	2×2
Bandwidth	10MHz
Frequency band	1.8GHz
Rx sensitivity	-123dBi
Duplexing technique	FDD
Antenna Height (Δh_b)	4m
Cell Radius	1.5Km
Inter-site Distance (ISD)	2.6Km
GV	
Transmit Power	0.2Watts
Antenna gain	0dBi
MIMO	1×2
Rx sensitivity	-106dBi
Shadow fading standard deviation	4dB
Downlink ITS IPT (Inter-Packet Transmission Time)	120s
Downlink ITS Size	1024Bytes
Uplink ITS IPT	30s
Uplink ITS Size	12000Bytes
OV	
CAM Transmission Interval	100ms
CAM Size	40Bytes

4.4 DESIGN CHOICES

The deployment of the proposed vehicular system requires accurate parameterization of the various wireless modules (e.g., location and density of eNodeBs, spectrum allocation, power levels,…etc.). This is necessary in order to meet the system requirements while at the same time minimize the operational and rollout costs. Consequently, estimating the system requirements in terms of coverage, capacity and spectrum allocation is a critical step in its deployment. In this section, theoretical values are calculated. Then, in the next chapter OPNET simulations are performed to find the LTE cell coverage and the optimum inter-site distance between adjacent cells. Finally, values obtained from the simulations are compared with those calculated analytically.

4.4.1 COVERAGE OF LTE ENODEB

Coverage refers to the communication range of the LTE eNodeB. One of the fundamental aspects that should be studied when deploying any vehicular communications wireless system is the provision of adequate coverage. The various wireless communication systems are different in terms of transmission power, cell size, center frequency, modulation technique, network architecture,…etc. However, they all must be properly parameterized to offer adequate coverage over the entire road network. Thus, this section investigates the coverage requirements of the proposed vehicular network, as well as, the parameters necessary to achieve those requirements.

In LTE, coverage is provided to the UE by the eNodeBs deployed in the system where each eNodeB creates a cell with a particular coverage range. To estimate the maximum cell range, a propagation path loss model is used. As mentioned in the previous section, this thesis considers an urban vehicular network system, which is characterized by larger cells and higher transmit power. So, the urban path loss model for vehicular environment explained by ITU is used [57]. The transmission path loss (in dB) is given by the following equation:

$$L = [40(1 - 4 \times 10^{-3} \Delta h_b)] log_{10} R - 18 log_{10} \Delta h_b + 21 log_{10} f + 80 \qquad (2)$$

Where f is the carrier frequency in MHz, R is the distance in km from the base station to the mobile station and Δh_b is the height difference in meters between the base-station antenna and the mean building rooftop height. Δh_b = 4m is typically used in urban and suburban environments with average buildings of four storey height.

The path loss between the eNodeB and the LTE mobile station is calculated as follows.

$$PL\ (dB) = P_t - P_r \tag{3}$$

Where PL is the path loss in dB, P_t is the eNodeB's transmitted power and P_r is the received power at the mobile station.

From equations (2), (3) and the network parameters in Table 7, the calculated theoretical cell radius (R) is equal to 1.6Km. In the next chapter, this theoretical value will be verified using OPNET simulations.

4.4.2 Inter-site Distance

The inter-site distance (ISD) is defined as the distance between two adjacent eNodeBs in the LTE network. In the LTE network design, the ISD is chosen in a way that maximizes network coverage, provides the desired capacity, and at the same time offers the desired performance (in terms of packet loss rate and data rate). Also, from the mobile operator's point of view, the minimum number of sites needs to be deployed to reduce the associated cost. The ISD is a tradeoff between coverage and performance. On one side, a large ISD offers a large cell range/ coverage. On the other side, as ISD increases, the cell capacity/ throughput (bits/sec) decreases [58]. Additionally, the handover failure probability decreases as the ISD decreases. This is because the received signal from the target eNodeB becomes stronger with the cell overlap increasing [49]. In light of that, the ISD has to be chosen in a way that optimizes the system performance.

For an omni-directional eNodeB, the inter-site distance (ISD) is calculated [55, 59] as follows:

$$ISD = \sqrt{3} \times R \tag{4}$$

Where R is the cell radius.

For a 1.6Km cell radius, the calculated theoretical ISD from equation (4) is approximately equal to 2.77Km. In the next chapter, this theoretical value will be verified using OPNET simulations.

4.4.3 Spectrum Allocation

The different LTE frequency bands are shown in Table 9 [6]. Band 3 has been selected for our proposed LTE network with a 10 MHz channel bandwidth. Band 3 uses 1800MHz frequency band and employs Frequency Division Duplexing (FDD) technique. Its uplink frequency range is 1710-1785MHz while, the downlink range is 1805-1880MHz, and the bandwidth is 75MHz.

Table 9: LTE Frequency Bands [6]

LTE Band	Uplink (MHz)	Downlink (MHz)	Duplex Spacing (MHz)	Duplex Mode
Band 1	1920 – 1980	2110 – 2170	190	FDD
Band 2	1850 – 1910	1930 – 1990	80	FDD
Band 3	1710 – 1785	1805 – 1880	95	FDD
Band 4	1710 – 1755	2110 – 2155	400	FDD
Band 5	824 – 849	869 – 894	45	FDD
Band 6	830 – 840	875 – 885	45	FDD
Band 7	2500 – 2570	2620 – 2690	120	FDD
Band 8	880 – 915	925 – 960	45	FDD
Band 9	1749.9 – 1784.9	1844.9 – 1879.9	95	FDD
Band 10	1710 – 1770	2110 – 2170	400	FDD
Band 11	1427.9 – 1447.9	1475.9 – 1495.9	48	FDD
Band 12	699 – 716	729 – 746	30	FDD
Band 13	777 – 787	746 – 756	31	FDD
Band 14	788 – 798	758 – 768	30	FDD

Band 17	704 – 716	734 – 746	30	FDD
Band 18	815 – 830	860 – 875	45	FDD
Band 19	830 – 845	875 – 890	45	FDD
Band 20	832 – 862	791 – 821	41	FDD
Band 21	1447.9 – 1462.9	1495.9 – 1510.9	48	FDD
Band 22	3410 – 3490	3510 – 3590	100	FDD
Band 24	1626.5 – 1660.5	1525 – 1559	101.5	FDD
Band 33	1900 – 1920		N/A	TDD
Band 34	2010 – 2025		N/A	TDD
Band 35	1850 – 1910		N/A	TDD
Band 36	1930 – 1990		N/A	TDD
Band 37	1910 – 1930		N/A	TDD
Band 38	2570 – 2620		N/A	TDD
Band 39	1880 – 1920		N/A	TDD
Band 40	2300 – 2400		N/A	TDD
Band 41	2496 – 2690		N/A	TDD
Band 42	3400 – 3600		N/A	TDD
Band 43	3600 – 3800		N/A	TDD

This design choice is based on the following factors. As shown in Figure 10, Band 3 provides a distinctive combination of capacity and coverage as it is well positioned between the low and high bandwidth parts of the frequency spectrum. On one hand, it offers a wide coverage area which is around double of that offered by the 2600 MHz band [60]. On the other hand, the high capacity of the wide spectrum (2 x 75 MHz for FDD) allocated to band 3 is particularly useful in dense urban areas. Additionally, band 3 provides a cost-effective solution as the 1800 MHz band is already widely used by operators for 2G GSM services. This allows the mobile operators to reuse the spectrum that they already own for LTE deployment, instead of licensing new spectrum.

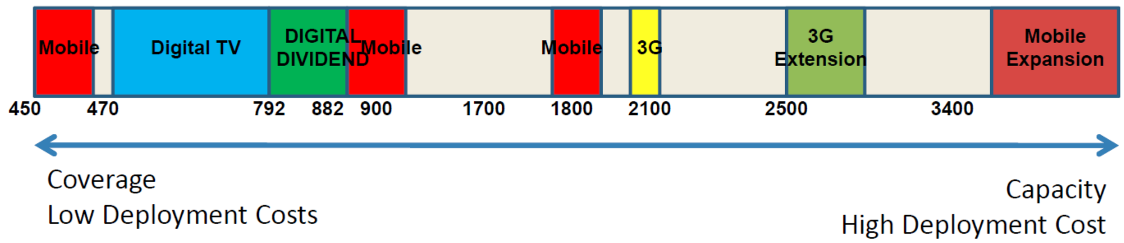


Figure 10: Band 3 Balance of Coverage and Capacity [60]

Moreover, there are fewer challenges attached with the FDD LTE technology. There are more FDD devices available in band 3 and Voice over LTE (VoLTE) is comparatively more viable in FDD than TDD version. Furthermore, band 3 continues to be the most widely used spectrum for LTE deployments [61] and is available in many parts of the world especially in Europe, Asia, Australia and Africa. Last but not least, LTE band 3 was selected in order to avoid interference with Wi-Fi, which uses the 2.4 GHz industrial, scientific, and medical (ISM) band. Wi-Fi has 14 allocated channels in the ISM band with 5 MHz channel separation with an exception of channel number 14 where the separation is 12 MHz. Channel 1 starts with 2401 MHz and channel 14 ends at 2495 MHz.

With multiple radio transceivers in close proximity, coexistence interference becomes a serious problem. 3GPP studies showed that concurrent operations of LTE and ISM radios working in adjacent or sub-harmonic frequency bands will cause significant coexistence interference that cannot be completely eliminated by filter technology [62]. As shown in Figure 11, the lower segment of the ISM band is adjacent to LTE time-division duplex (TDD) band 40 without guard band in between. This causes mutual interference where LTE transmission affects Wi-Fi reception, and Wi-Fi transmission affects LTE reception. Similarly, the upper segment of the ISM band interferes with LTE Band 41. Additionally, LTE FDD band 7, uplink (UL) LTE transmission causes interference to Wi-Fi, but the impact on the LTE receiver from Wi-Fi transmitter might be less significant because the corresponding LTE FDD Band 7 downlink (DL) is further away from the ISM band [63].

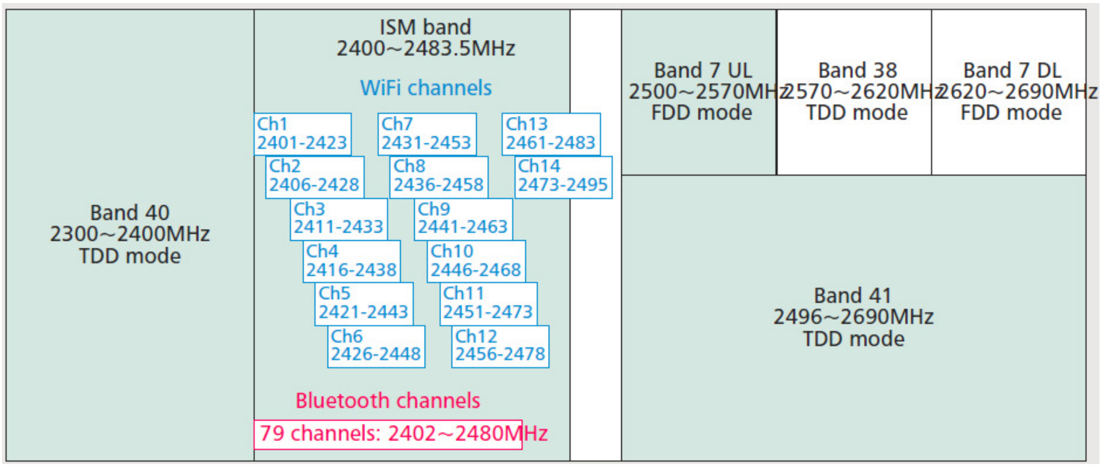


Figure 11: 3GPP Frequency Bands around ISM Band [62]

4.4.4 Network Model

The proposed model consists of seven cells arranged in a hexagonal honey-cell layout where each cell is covered by one eNodeB. The cell layout, radius, ISD, overlap area, and vehicle trajectory are all shown in Figure 12. The seven cell layout is the most commonly used model in cellular wireless networks. It consists of seven eNodeB's arranged in a hexagonal layout and separated by an ISD of 2.6 Km.

To evaluate the system's performance under worst case conditions, the inter-cell interference is maximized where all eNodeBs utilize the same operative frequency band (i.e. 1.8GHz). The vehicle is modeled moving in a radial path between the 7 cells under "ITU Vehicular Environment" model for path loss and "Vehicular B" model for multipath [57]. A shadow fading of standard deviation σ = 4 dB is modeled [64].

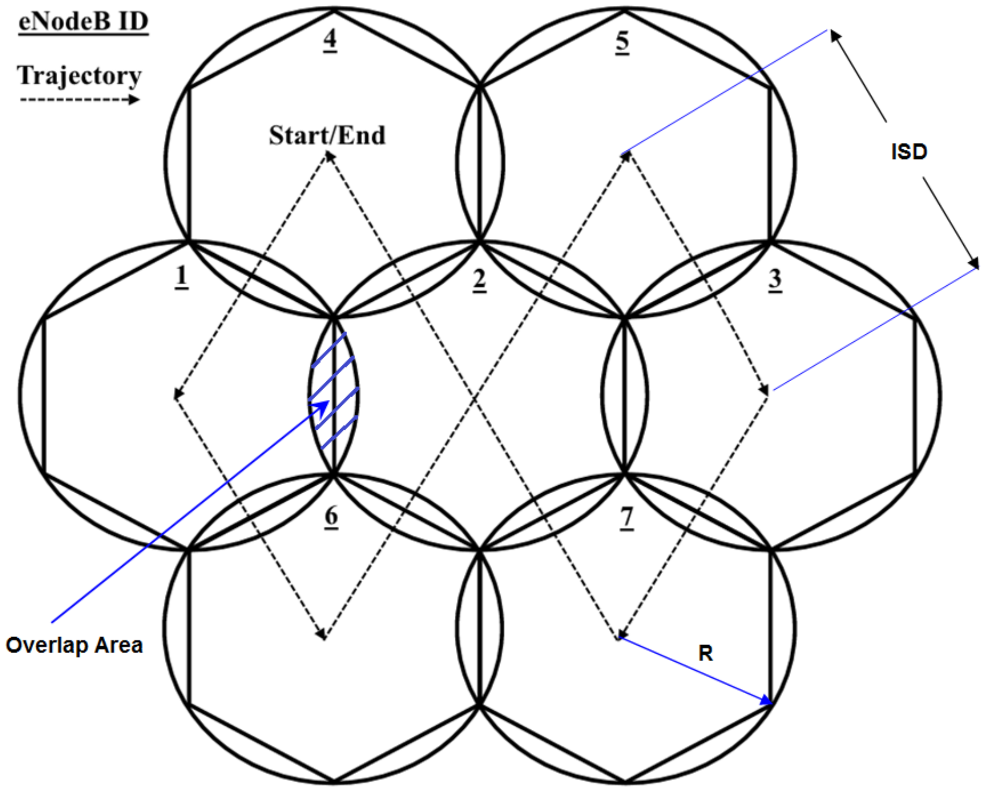


Figure 12: Honey-cell Coverage Layout and Mobile Vehicle Trajectory

4.5 NETWORK ARCHITECTURE

The network model is depicted in Figure 13. The proposed model consists of seven cells; each cell is covered by one eNodeB. The seven eNodeBs are connected to one EPC.

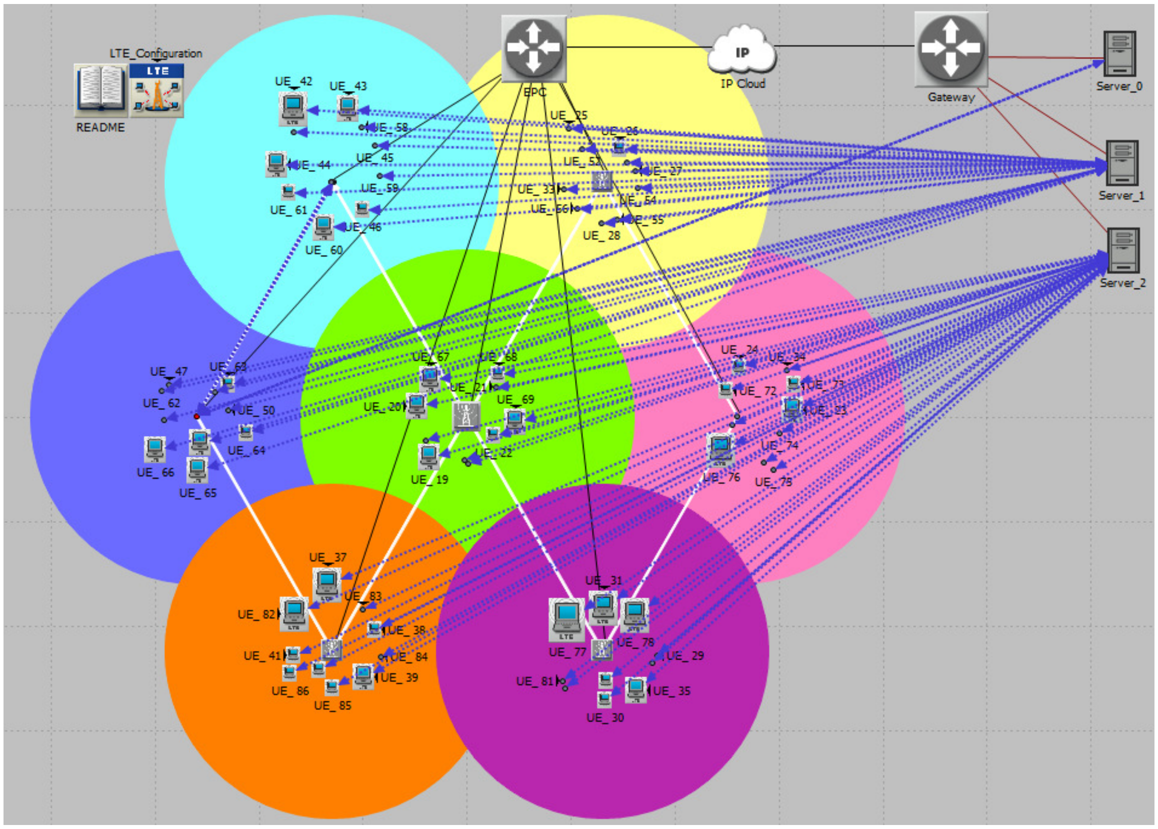


Figure 13: Proposed Network Architecture

The LTE backbone network consists of seven eNodeBs, one EPC (Evolved Packet Core), one IP Cloud, one gateway, and three servers. The servers support video, ITS, and Web HTTP browsing traffic. The vehicle is represented by a mobile subnet which consists of 1 hybrid router (LTE, Wi-Fi and Ethernet), 1 Ethernet node and 1 Wi-Fi workstation. The ip32_cloud node model represents an IP cloud supporting up to 32 serial line interfaces at a selectable data rate. The gateway represents an IP-based gateway connecting the IP cloud with the different servers.

4.6 SIMULATION ENVIRONMENT

The mobile subnet, representing the vehicle, is modeled moving in a radial path between the 7 cells under "ITU Vehicular Environment" model for path loss and "Vehicular B" model for multipath [57]. A shadow fading of standard deviation $\sigma = 4$ dB is modeled [64]. “Application Demand” is used to simulate all traffic between the different network nodes. Application demand is a mechanism to specify traffic exchanged between two nodes. It represents the traffic data rate and packet size but, does not model any specific protocol behavior. Application demands are implemented as a flow of request and response messages exchanged between the application layers of two nodes [65].

All the simulations are run for 1500 seconds, and all applications that generate traffic (such as video streaming) start simultaneously at 60 seconds. The mobile subnet starts to move at 120 seconds as a warm up time. A number of simulation runs were performed, with different random seeds in order to ensure statistical accuracy. Each simulation is run with 33 seeds for statistical analysis. It is important to note that all results presented in this thesis are subjected to a 95% confidence analysis (see Appendix A) [66].

4.7 TRAFFIC CHARACTERISTICS

There are mainly 5 types of simulated network traffic: downlink ITS, uplink ITS, V2V ITS, infotainment and background traffic (Table 10). The downlink ITS control traffic is sent as required by the vehicular networking applications in the domain of traffic efficiency and is simulated by sending 1024Bytes with 120s Inter-Packet Transmission Time (IPT), based on the system requirements for updating traffic information [13].

The uplink ITS traffic is simulated by 12000Bytes with 30s IPT. V2V ITS traffic represents cooperative awareness messages (CAMs) transmitted from OVs to GV where CAM size is 40Bytes with 100ms transmission interval. Infotainment traffic is simulated using a H.264 video flow with 1 Mbit/sec bit rate which corresponds to YouTube 480p video [67-70].

Table 10: Traffic Characteristics

Traffic Type	Transmission Interval (IPT)	Size (Bytes)
Downlink ITS	120s	1024
Uplink ITS	30s	12000
V2V ITS	100ms	40
Infotainment	11.79ms	1472
Background	60s	6000

Both ITS data and infotainment traffic are sent to the mobile vehicle (subnet). ITS data is sent to the vehicle's OBU (simulated by an Ethernet workstation) via Ethernet for further processing and decision making. On the other hand, infotainment traffic is sent to the passengers' devices (simulated by a Wi-Fi workstation) through Wi-Fi.

In order to make the scenario realistic, the LTE network caters for mobile phone users (referred to as background traffic) along with the vehicular networking traffic. Each cell supports 10 LTE stationary UEs where each UE user is assumed to be engaged in a web browsing session with a 100 bytes/sec data rate. A heavy web-browsing scenario is assumed where page inter-arrival time is 60 seconds and each page has 1000 bytes of text and 5 "medium images" each with size 1000 bytes [56]. All data is sent as generic UDP application in OPNET modeler.

4.8 SIMULATION SCENARIOS

This section explains the different simulation scenarios that are performed and evaluated.

4.8.1 BASELINE SCENARIO

The baseline scenario is the basic scenario from which all other scenarios are generated. In other words, it is the simplest form of the heterogeneous LTE–Wi-Fi vehicular model. It represents the congestion free network where only one vehicle is roaming between different eNodeBs. As shown in Figure 14, the baseline scenario consists of LTE network and a mobile subnet representing a mobile vehicle. The LTE network consists of 7 eNodeBs arranged in a hexagonal honey-cell layout, 1 EPC, 1 IP cloud, 1 gateway and 1 server.

The trajectory of the mobile subnet is shown in Red in Figure 14, where it is assumed that the vehicle moves in a radial path between the 7 eNodeBs. The start point and end point of the trajectory are the same: “eNodeB_4” at the top-left corner.

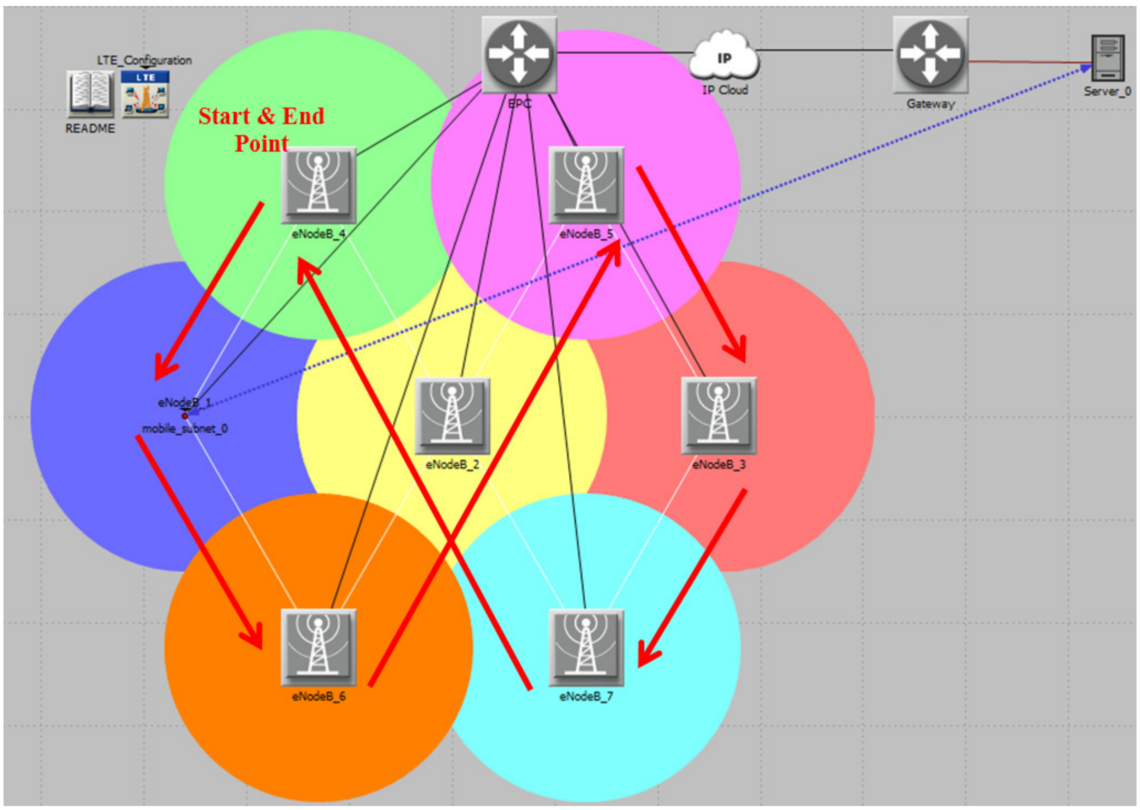


Figure 14: Network Model of Baseline Scenario

The mobile subnet is depicted in Figure 15 and consists of 1 LTE–Wi-Fi–Ethernet router, 1 Wi-Fi workstation and 1 Ethernet workstation. Only 2 types of traffic are used in this scenario: video and downlink ITS control traffic. There is no background traffic in the baseline scenario. The downlink ITS control traffic is sent every 120 sec with packet size of 1024 Bytes. The video traffic has a 1 Mbit/sec bit rate and 1472 packet size.

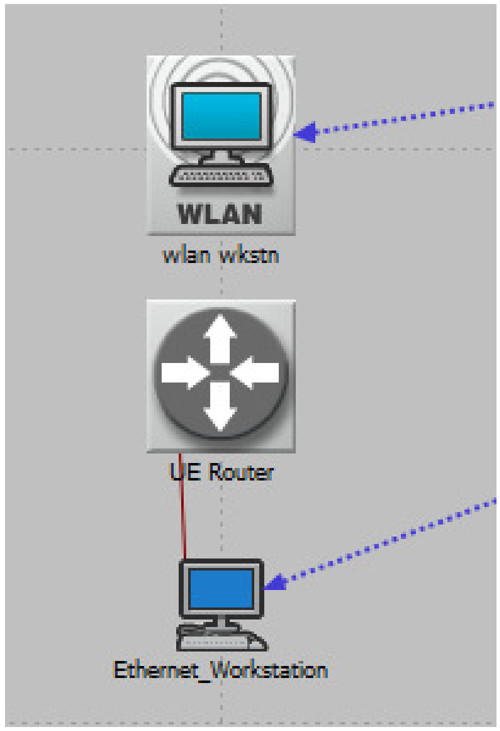


Figure 15: Mobile Subnet of Baseline Scenario

4.8.2 SCENARIO 1: CONGESTED CELLS 10 UES PER CELL

In order to make the scenario more realistic, the LTE network caters for mobile phone users (referred to as background traffic) along with the vehicular networking traffic. In the congested scenario, it is assumed that a large number of users are communicating in the system. As shown in Figure 16, each cell supports 10 LTE fixed UEs (total of 70 stationary UEs) where each UE user is assumed to be engaged in a web browsing session with a 100 Bytes/sec data rate. A heavy web-browsing scenario is assumed where page inter-arrival time is 60 seconds and each page has 1000 Bytes of text and 5 “medium images” each with size 1000 Bytes [56]. The mobile subnet representing a mobile vehicle roams between the 7 cells per the trajectory explained in the previous section.

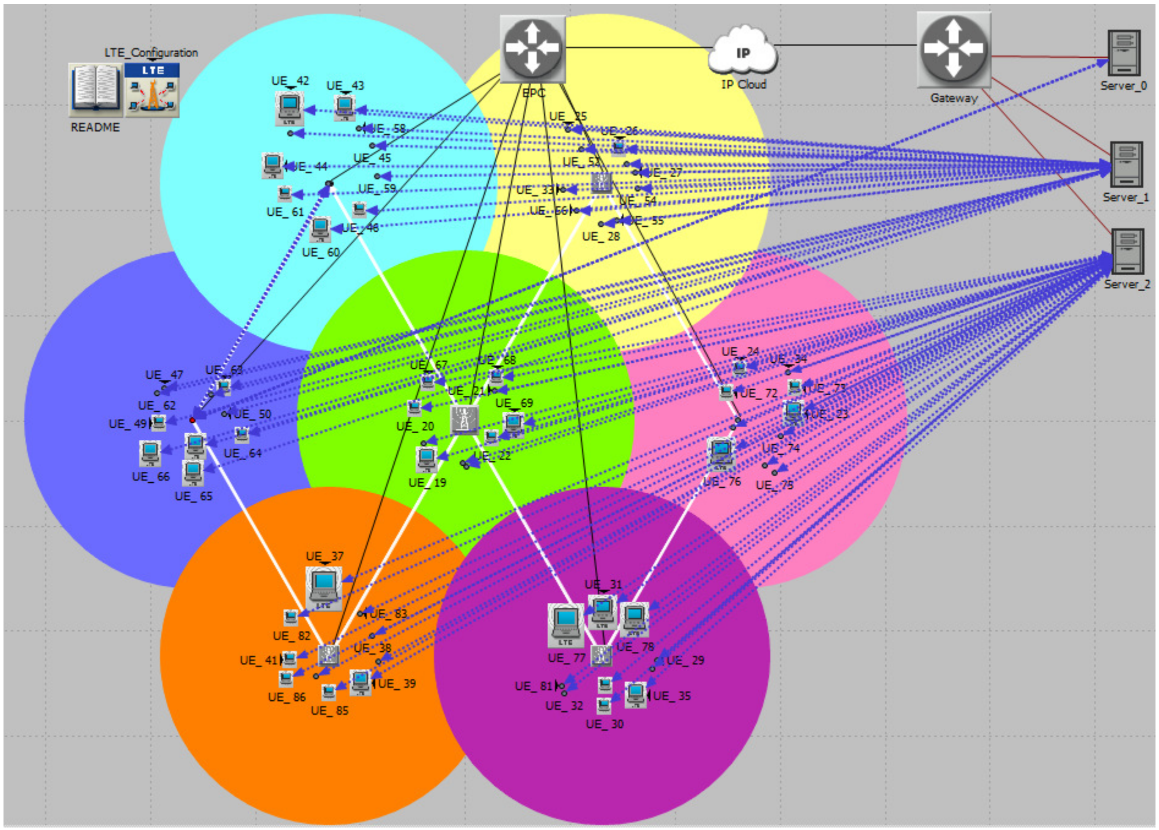


Figure 16: Network Model of Congested Scenario

4.8.3 SCENARIO 2: V2V – NO BURST MODEL

In this scenario, a V2V communication sub-system is added to the previous V2I system. V2V communication happens between the Gateway Vehicle (GV) and Ordinary Vehicles (OVs) through Wi-Fi. The V2V communication sub-system consists of 1 GV and 5 OVs. The GV has two wireless interfaces namely LTE and Wi-Fi, and is represented by the mobile subnet. OVs have only one wireless interface (Wi-Fi) and are represented by Wi-Fi nodes. OVs move in close proximity with the GV in a radial path between the 7 eNodeBs in the hexagonal cells layout.

In addition to the previous traffic types, two new traffic types are added to this scenario namely, V2V ITS traffic and uplink ITS traffic. V2V traffic represents Cooperative Awareness Messages (CAMs) that are transmitted from OVs (Wi-Fi nodes) to the GV (mobile subnet) and is sent via the Wi-Fi interface. The CAM packet size is 40Bytes and CAM transmission interval is 100ms.

The GV samples and gathers the information from OVs (through Wi-Fi) then, in turn periodically sends the relevant data to the infrastructure (via LTE). In the LTE uplink direction, GV forwards the traffic data (collected from OVs) to the LTE infrastructure at a pre-determined transmission rate. The uplink ITS traffic is simulated by sending 12000Bytes every 30s from the GV to the LTE network.

4.8.4 Scenario 3: V2V – Burst Recovery Mechanism

Burst is a communication technique used to reduce or prevent data losses in wireless communication systems. This is accomplished by sending successive identical packets within a certain time frame and separated by a pre-defined period of time. In essence, if one of the original packets is lost, the other redundant packets will still carry the same information to the desired destination.

There are basically 3 parameters that characterize burst communication, namely T_{packet}, T_{F2L} and T_{burst} [50]. T_{packet} is the time between two successive packets within the same burst. T_{F2L} is the time between the first and the last packet in the same burst. Finally, T_{burst} is the time between the first packets of two successive bursts.

T_{packet} depends on the Inter-Packet Transmission Time (IPT) of the uplink traffic and on number of packets used in one burst, as follows:

$$T_{packet} \leq \frac{IPT}{N_{burst}} \tag{5}$$

Where IPT is the Inter-Packet Transmission Time of the uplink traffic, and N_{burst} is the number of packets per burst. T_{F2L} depends on the number of packets used in one burst and must satisfy the following constraint:

$$T_{F2L} = T_{packet} \times (N_{burst} - 1) \tag{6}$$

T_{burst} must be less than or equal the IPT, which corresponds to the time needed for traffic and routing updates.

$$T_{burst} \leq IPT \tag{7}$$

The minimum number of packets that can be used in one burst is two. A two-packet burst is studied to optimize the LTE channel utilization and minimize the network load. From equation (5) and for a 30-sec uplink IPT, T_{packet} must be smaller than or equal to 15sec. In our scenario, T_{packet} = 14.9sec was chosen. In case of 2 packets per burst, T_{F2L} = T_{packet} from Equation (6). Equation (7) shows that T_{burst} must be less than 30 seconds.

CHAPTER 5: SIMULATION RESULTS, ANALYSIS & DISCUSSION

5.1 PERFORMANCE METRICS

This section describes the performance evaluation metrics of the proposed model. The performance of the network is evaluated in terms of data rate, Data Loss Ratio (DLR), delay and jitter parameters, defined as follows:

- Data Rate (in Bytes/sec) is defined as the sum of the data bytes received at the destination averaged over time.
- Data Loss Ratio (DLR) is defined as the ratio between dropped packets that do not reach the destination and the total number of packets sent from the source to the destination.
- Delay (in seconds) specifies the time elapsed between sending the request from the source and the reception of the response at the source. This metric serves as a measure of the average overall delay of the packets for a particular node.
- Jitter (in seconds) is defined as the packet delay variation. This metric is calculated as the standard deviation of packet delay for all packets sent over the network for a particular node.

Worst case values are considered where the DLR, delay and jitter values represent the upper bound of the resulting confidence interval whereas, the data rate values represent the lower bound of the confidence interval. It is important to note that the delay provided by OPNET is calculated as the time elapsed between sending the request from the source node (vehicle) and the reception of the response back at the source node. This means that the obtained delay and jitter values are round-trip values rather than end-to-end ones.

In a video streaming service environment, it is important to maintain the DLR threshold below 1% [71-72] such that the QoS requirement of video streaming service users is satisfied. Other references [70, 73] specify a higher DLR threshold of 2% however the worst case constraint of 1% will be employed for the evaluation of the proposed model. Additionally, the performance of video streaming depends greatly on delay and jitter.

According to ITU [74], the maximum acceptable video packet delay is set to 150ms and maximum allowable jitter is 50ms. For traffic control data, since most of the applications are time-critical, the end-to-end delay must be between 100 and 500ms [1].

In addition to the main performance evaluation metrics listed above, handover delay is another important metric that will be monitored in the results. The maximum limit for handover delay is defined by:

$$T_{Handover} = T_{search} + T_{IU} + 20ms + T_{processing} \quad (8)$$

Where T_{search} is the time required to identify the cell if it is unknown. The cell is unknown only in the case that the handover is not based on the UE measurements, and otherwise it is 0. T_{IU} represents the uncertainty of acquiring the first available random access occasion, and can be up to 30 ms. $T_{processing}$ is the time in which the UE must be able to process the received message and produce a response. The 20ms represents the implementation margin. According to 3GPP requirements, the maximum handover delay must not be more than 65 ms [15, 75, 76].

5.2 SIMULATION RESULTS AND ANALYSIS

The overall system performance, as specified by the communication requirements imposed by different types of vehicular networking applications, is investigated. For this purpose, the foremost emphasis is on evaluating the data loss, data rate, delay and jitter of video and ITS traffic applications in a realistic urban simulation environment. For all presented scenarios, the aforementioned performance evaluation metrics (data rate, DLR, delay and jitter) are analyzed. A 95% confidence analysis is performed for all presented results [66].

5.2.1 COVERAGE

Using OPNET simulations, the LTE cell radius was found to be 1.5Km. The theoretical cell radius calculated from equation (2) and equation (3) is 1.6Km. Thus, the cell radius obtained from OPNET simulations is close to that obtained analytically, which validates the simulated model. As such, for a cell radius of 1.5Km, the ISD between two cells should be equal to 2.59Km from equation (4). Using OPNET simulations, the ISD was confirmed to be 2.6Km (i.e. 400m overlap distance), as shown in Figure 17. The ISD that best satisfies the following two criteria is selected:

1) Handover should be performed successfully from one eNodeB to the other without any drops. For example, if a handover is to occur between eNodeB 1 and eNodeB 2, the UE should remain connected to either eNodeB 1 or eNodeB 2 without any disconnection during the handover period.
2) Minimum packet drops during the handover period.

The two aforementioned selection criteria were met at this ISD where the UE remains connected to an eNodeB during handover and maximum traffic is received. It was also observed that minimum delay and jitter were obtained at this ISD.

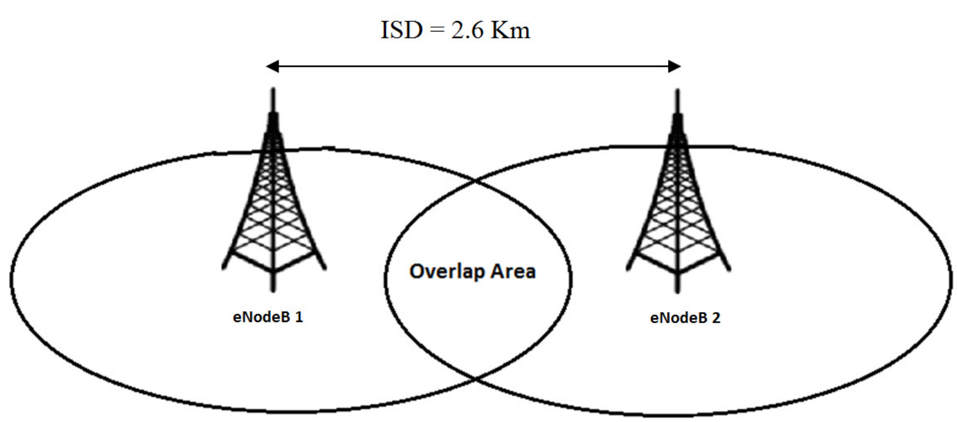


Figure 17: Overlap Area and Inter-site Distance of LTE Cells

To find the optimum ISD, the vehicle was moved between two eNodeB's where values of BS drops and traffic received were collected and compared. The simulation was run using different ISDs, and the first ISD that gave the best results was selected. As shown in Table 11, for an ISD of 2.6 KM, maximum traffic is received and no handover drops were obtained.

Table 11: ISD Results

ISD (Km)	Traffic Received (bytes/sec)	eNodeB Handover Drops
2	989.7331811	0
2.1	989.5637006	0
2.2	988.2271886	0
2.3	989.6339087	1
2.4	993.4733042	1
2.5	988.1879444	2
2.6	995.9214426	0
2.7	988.6794522	1
2.8	993.6711859	2
2.9	992.3762456	1
3	993.6228887	3

5.2.2 Baseline Scenario

Confidence analysis was performed for all presented results of the baseline scenario as shown in Table 12. The results obtained for vehicular video and ITS traffic of the baseline scenario are shown in Table 13. It can be seen that the data loss ratio (DLR) of video streaming traffic is 0.48% which is below the 1% threshold. The values of video's average delay and jitter are 12.48ms and 4.85ms respectively, which is far below the thresholds mentioned previously. For ITS traffic, the DLR is 1.3%. A delay of 22.9ms and jitter of 7.99ms have been observed, which is again within the acceptable limits of ITS applications.

Table 12: Baseline Scenario - Confidence Analysis for traffic, delay and jitter of Video and ITS traffic

Parameter	Video			ITS		
	Data (Bps)	Delay (ms)	Jitter (ms)	Data (Bps)	Delay (ms)	Jitter (ms)
μ	124416	12.46	4.8	8.49	22.15	6.6
σ	41.19	0.03	0.16	1.5	2.21	4.05
Range	[124402; 124430.1]	[12.45; 12.48]	[4.74; 4.85]	[8.42; 8.5]	[21.39; 22.9]	[5.22; 7.99]

Table 13: Baseline Scenario - Summary of Video and ITS Traffic Results

Metric	Video	ITS
Data Rate (Bytes/sec)	124402	8.42
DLR	0.48%	1.3%
Delay (ms)	12.48	22.9
Jitter (ms)	4.85	7.99

Figures 18-22 show OPNET results that validate the proposed system. In all figures, the x-axis represents the simulation time in minutes. Figure 18 shows the eNodeB to which the node is currently connected. Figure 19 shows the video traffic received by the Wi-Fi node while Figure 20 presents the observed response time for video traffic.

It is important to verify that handover from one eNodeB to the other happens successfully and in the correct order. Figure 18 shows the eNodeB to which the node is currently connected. It can be noted that the handover between the different eNodeBs happens correctly and in the right order, i.e. eNodeB 4 followed by eNodeB 1 then, 6, 2, 5, 3, 7, 2, 4.

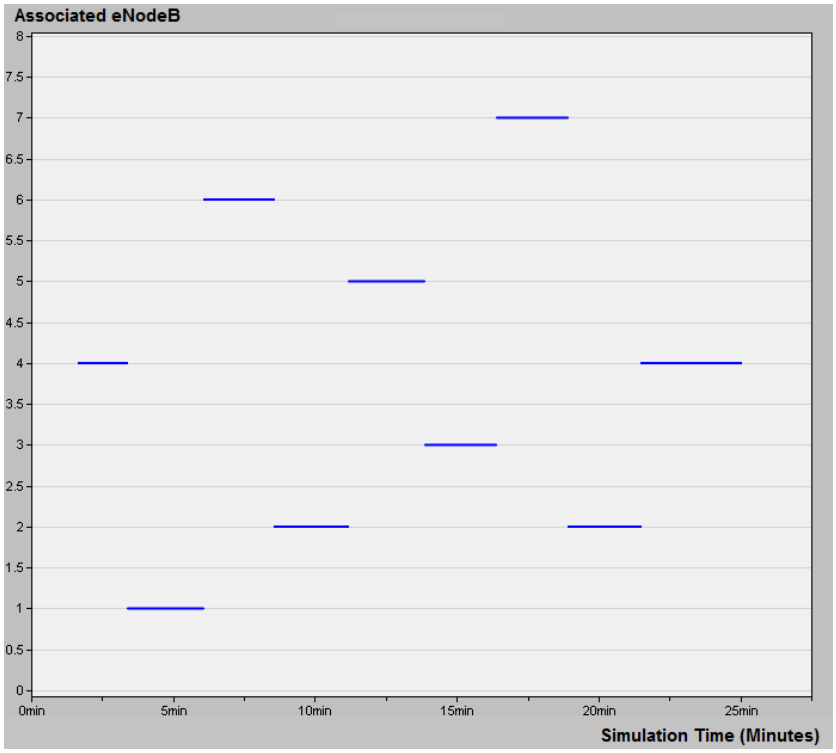


Figure 18: LTE Associated eNodeB – Baseline Scenario

Figure 19 shows that video traffic is successfully received by the Wi-Fi node throughout the simulation period. It was expected that there will be data drops during handover from one eNodeB to another, which has been confirmed by the OPNET simulations. It can be observed that video data drops occur during handover from one eNodeB to another. This can be explained as follows:

There are 2 types of handover mechanisms, namely Connect-Before-Break and Break-Before-Connect. Connect-Before-Break is a soft handover mechanism in which the UE can simultaneously connect to two or more BSs during an ongoing session whereas, Break-Before-Connect is a hard handover mechanism that requires disconnecting from source eNodeB before establishing a connection to the target eNodeB. In LTE, only the Break-Before-Connect hard handover mechanism is supported. The use of this mechanism reduces the complexity of the LTE network architecture however, it may result in data losses during handover [77].

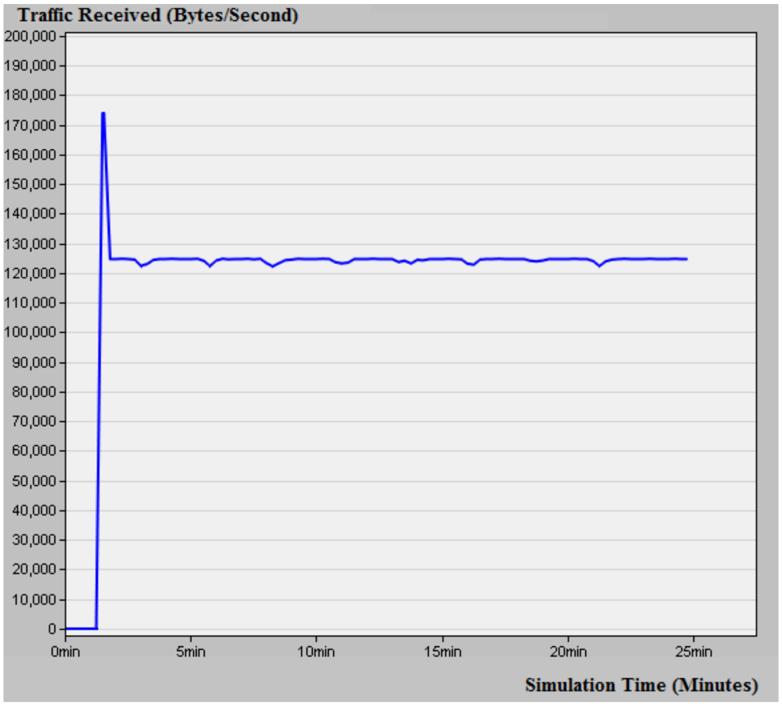


Figure 19: Video Traffic Received by Vehicular Wi-Fi node – Baseline Scenario

Figure 20 illustrates the response time of video traffic received by the Wi-Fi node. It is clear that the response time tends to increase during the handover periods.

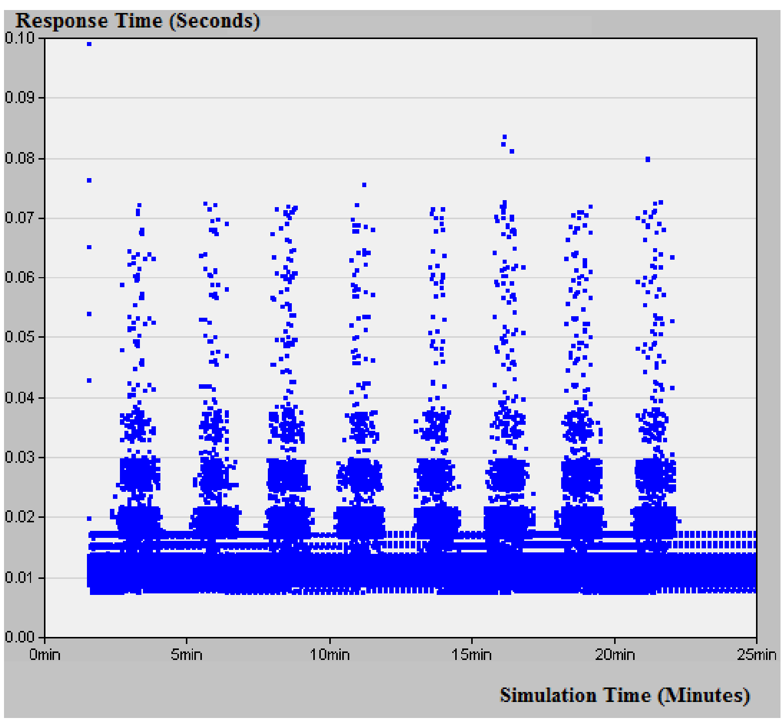


Figure 20: Response Time of Vehicular Wi-Fi node – Baseline Scenario

Figure 21 shows sample ITS traffic received by the vehicular Ethernet workstation in one seed. In this particular seed, all downlink ITS traffic was successfully received by the vehicular Ethernet node. ITS packets of size 1024 Bytes are sent every 120 seconds.

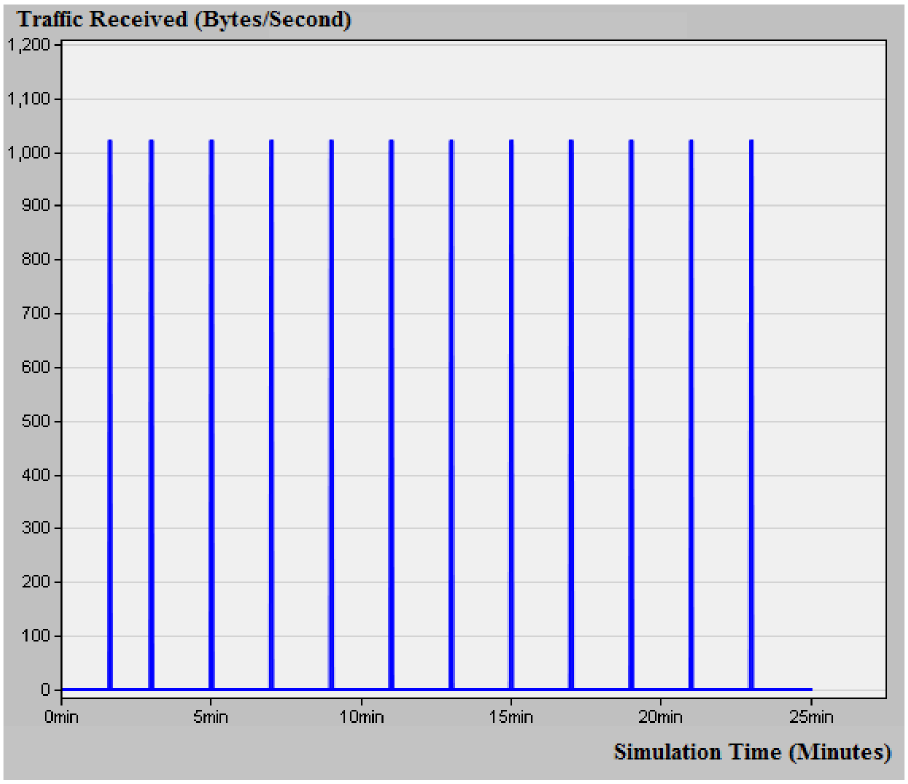


Figure 21: ITS Traffic Received by Vehicular Ethernet Node – Baseline Scenario

It is important to examine handover performance in mobile communication systems. As mentioned in the previous section, the maximum handover delay is 65 ms according to 3GPP requirements. In the baseline scenario, the handover delay was found to be equal to 14.8 ms which is far below the 65 ms limit. Figure 22 shows the handover delay of the LTE mobile node for one seed.

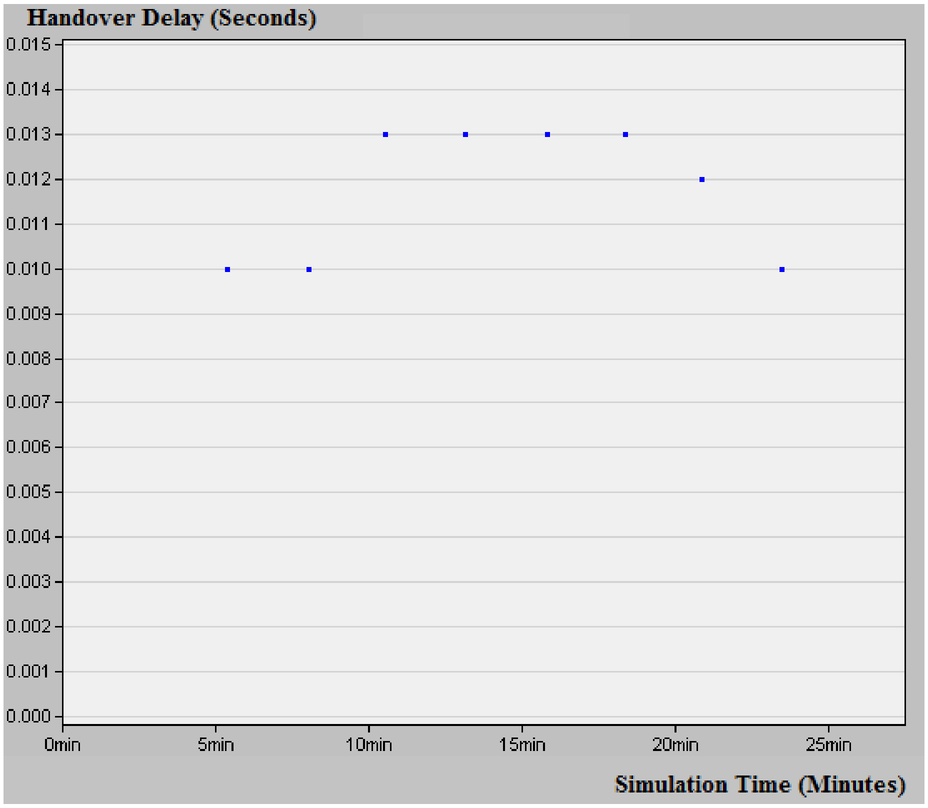


Figure 22: LTE Handover Delay – Baseline Scenario

5.2.3 SCENARIO 1: CONGESTED CELLS 10 UES PER CELL

Confidence analysis was performed for all presented results of Scenario 1 as shown in Table 14. The results obtained for vehicular video and ITS traffic of Scenario 1 are shown in Table 15. It can be seen that the data loss ratio (DLR) of video streaming traffic is 0.5% which is below the 1% threshold. The values of video's average delay and jitter are 13.08ms and 5.5ms respectively, which is far below the thresholds mentioned above. For ITS traffic, the DLR is 1.3%. A delay of 24.57ms and jitter of 6.05ms have been observed, which is again within the acceptable limits of ITS applications.

Table 14: Scenario 1 - Confidence Analysis for traffic, delay and jitter of Video and ITS traffic

Parameter	Video			ITS		
	Data (Bps)	Delay (ms)	Jitter (ms)	Data (Bps)	Delay (ms)	Jitter (ms)
μ	124364.7	13.06	5.44	8.49	23.97	4.82
σ	30.85	0.042	0.19	1.5	1.76	3.64
Range	[124354.2; 124375.3]	[13.05; 13.08]	[5.37; 5.5]	[8.42; 8.5]	[23.37; 24.57]	[3.57; 6.05]

Table 15: Scenario 1 - Summary of Video and ITS Traffic Results

Metric	Video	ITS
Data Rate (Bytes/sec)	124354.2	8.42
DLR	0.5%	1.3%
Delay (ms)	13.08	24.57
Jitter (ms)	5.5	6.05

Figures 23-26 show OPNET results that verify the system performance. In all figures, the x-axis represents the simulation time in minutes. Figure 23 presents the observed response time for video traffic during multiple simulation seeds. Figure 24 shows the video traffic received by the Wi-Fi node while Figure 25 demonstrates the eNodeB to which the node is currently connected. Similar to the Baseline scenario, it is again observed in Scenario 1 that there is an increase in data drops during handover from one eNodeB to another. As explained in the previous section, this is attributed to the Break-Before-Connect hard handover mechanism that is supported in LTE. Figure 26 shows the handover delay of the LTE mobile node for one seed. In scenario 1, the handover delay was found to be equal to 15.1 ms which is far below the 65 ms limit mandated by 3GPP requirements.

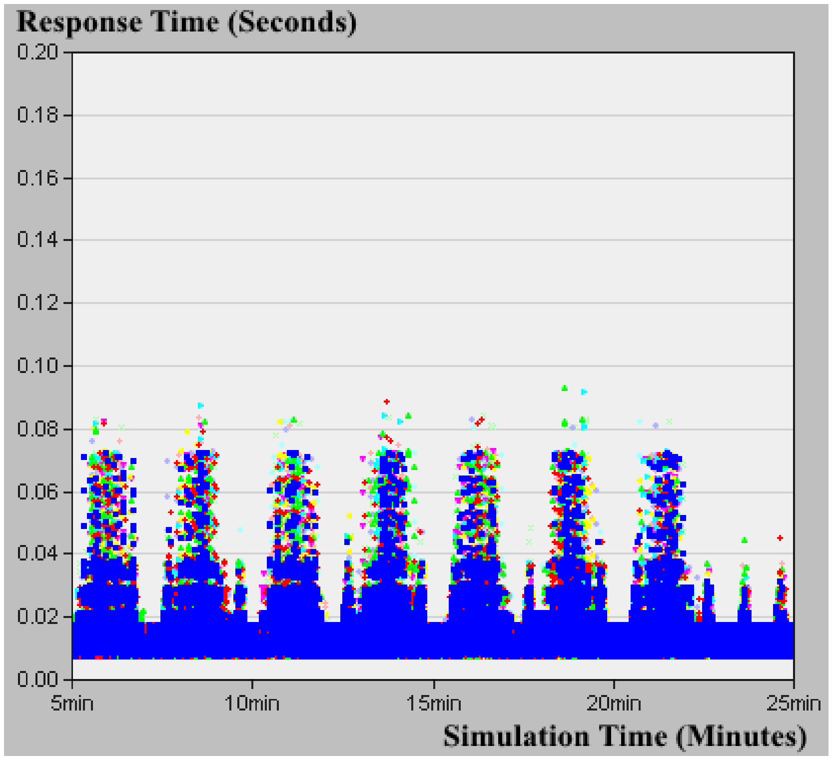


Figure 23: Response Time of Vehicular Wi-Fi Node – Scenario 1

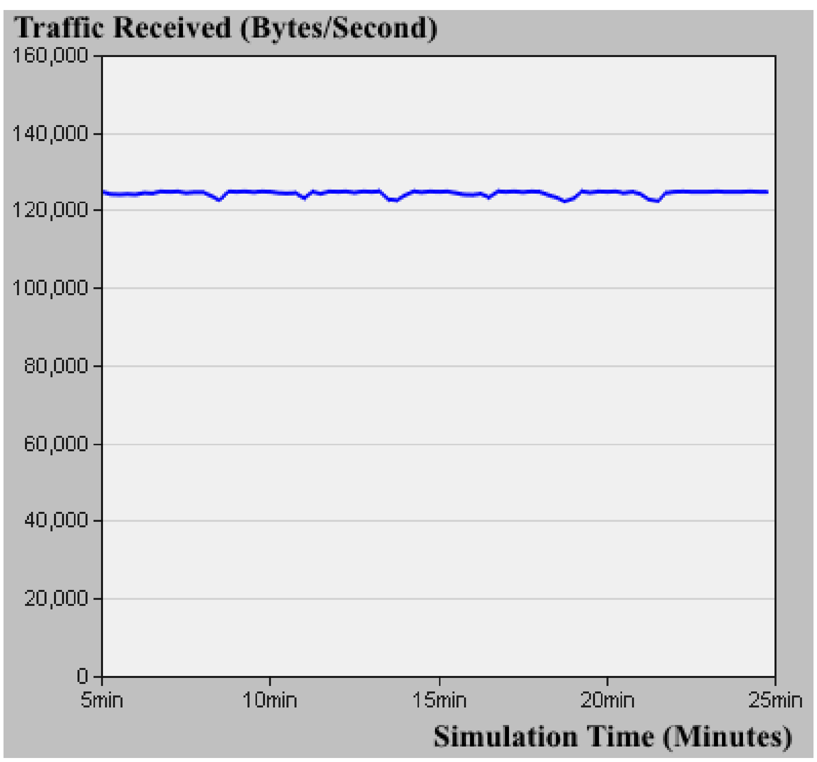


Figure 24: Video Traffic Received by Vehicular Wi-Fi Node – Scenario 1

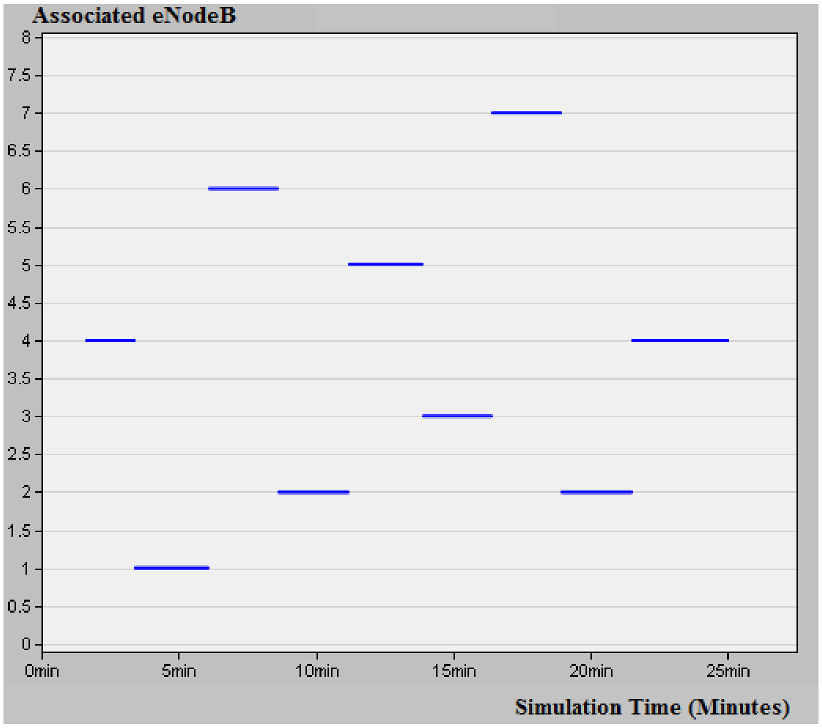


Figure 25: LTE Associated eNodeB – Scenario 1

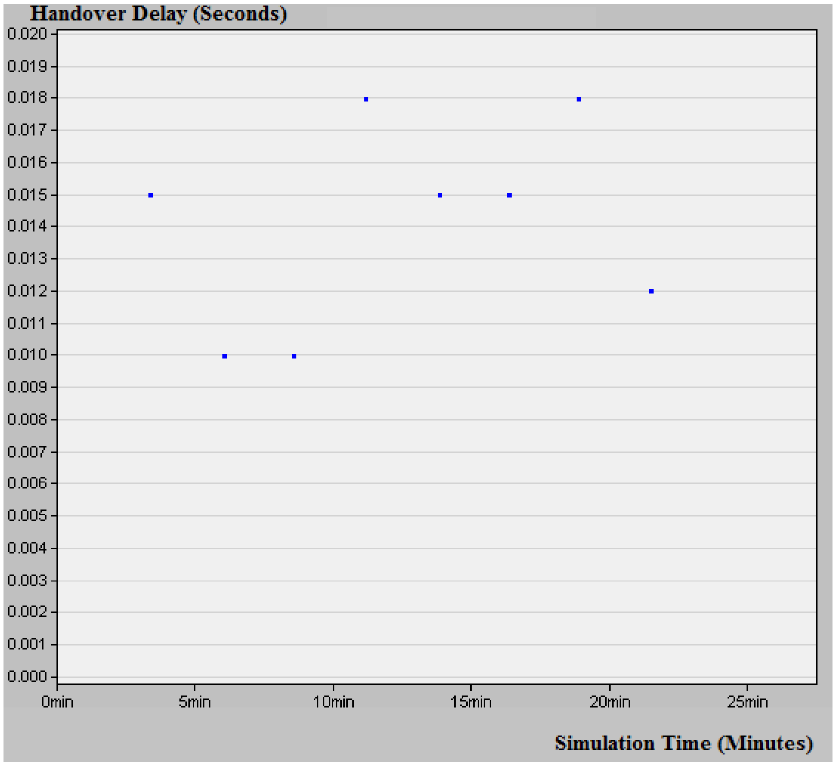


Figure 26: LTE Handover Delay – Scenario 1

It can be concluded that the delay, jitter and data drops for both ITS and video traffic are within the acceptable limits. Although video data drops have been observed during handover from one eNodeB to another yet, the overall data drop is still below the defined benchmarks. The obtained simulation results thus indicate that the proposed system simultaneously satisfies vehicular and infotainment application requirements.

5.2.4 Scenario 2: V2V – No Burst Model

The results obtained for vehicular video, downlink and uplink ITS traffic for Scenario 2 are summarized in Table 16. It can be seen that the maximum video streaming traffic delay is 12.94ms, while the maximum jitter is 5.84ms. For downlink ITS traffic, a maximum delay of 22.27ms and jitter of 6.7ms is observed. As for uplink ITS traffic, the maximum delay is 23.82ms and the maximum jitter is 9.69ms. The obtained values are all below the above-mentioned benchmarks for ITS applications. It can be also noted that the DLR for uplink traffic is 1.73%.

Table 16: Scenario 2 - Confidence Results of Video, Downlink, and Uplink ITS Traffic – No Burst Model

Metric	Video	Downlink ITS	Uplink ITS
Data Rate (Bytes/sec)	[124311.1; 124338.5]	[8.46; 8.56]	[393.07; 397.69]
DLR (%)	0.55%	0.8%	1.73%
Delay (ms)	[12.91; 12.94]	[20.97; 22.27]	[22.79; 23.82]
Jitter (ms)	[5.59; 5.84]	[4.48; 6.7]	[7.47; 9.69]

Figure 27 shows that there are 2 packet lost in the uplink data traffic; one of them happens while the GV is in LTE cell 1 while the other one is in LTE cell 2. Due to the criticality of the safety-related information communicated in the uplink direction, a zero DLR is desired. So in the next section, a burst recovery technique will be proposed to mitigate data losses in uplink ITS traffic.

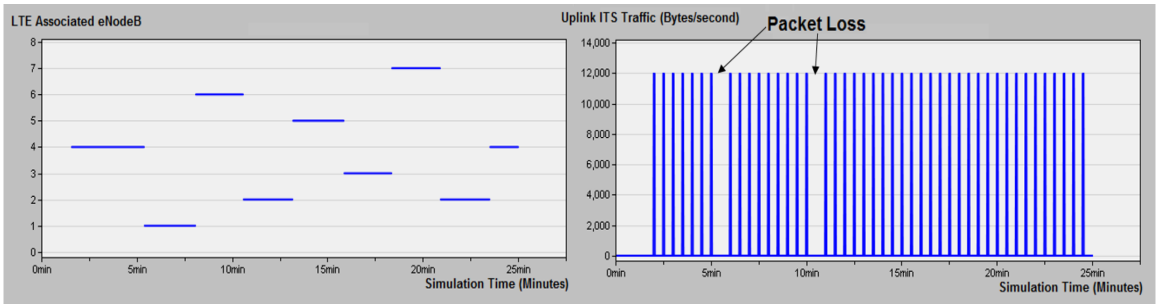


Figure 27: Uplink ITS Traffic and LTE Associated eNodeB – Scenario 2

Figure 28 illustrates the downlink ITS traffic received by the vehicular workstation in one seed. In this particular seed, all downlink ITS traffic was successfully received by the vehicular Ethernet node. It is clear that ITS packets of size 1024 Bytes are sent every 120 seconds.

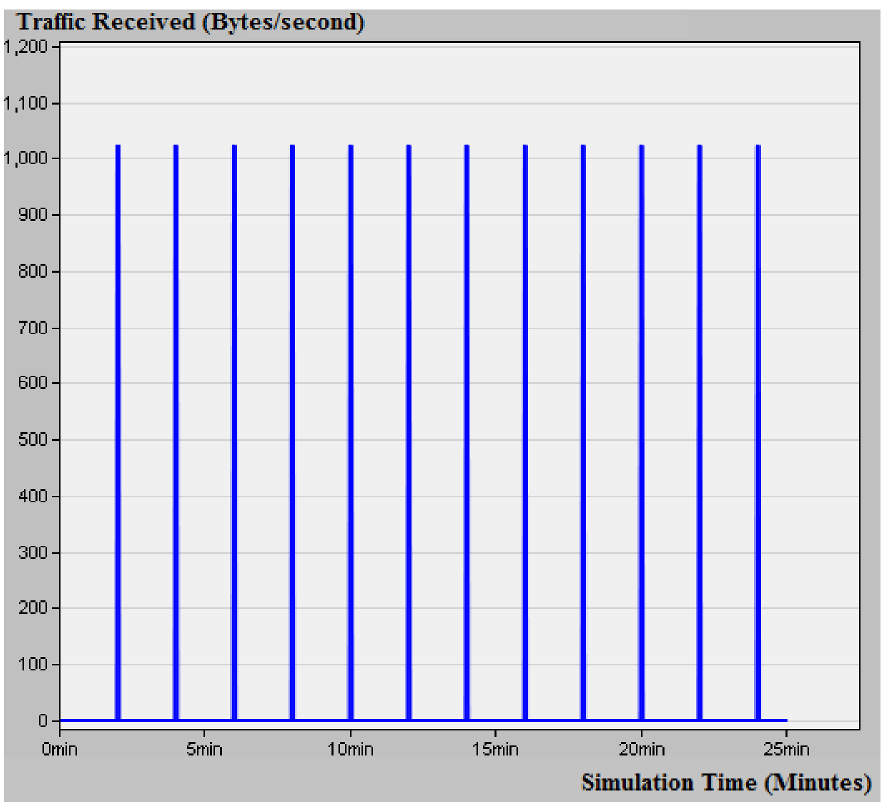


Figure 28: Downlink ITS Traffic Received by Vehicular Ethernet Node – Scenario 2

Figure 29 shows the handover delay of the LTE mobile node for one seed. In scenario 2, the handover delay was found to be equal to 14.9 ms which is still far below the 65 ms limit mandated by 3GPP requirements.

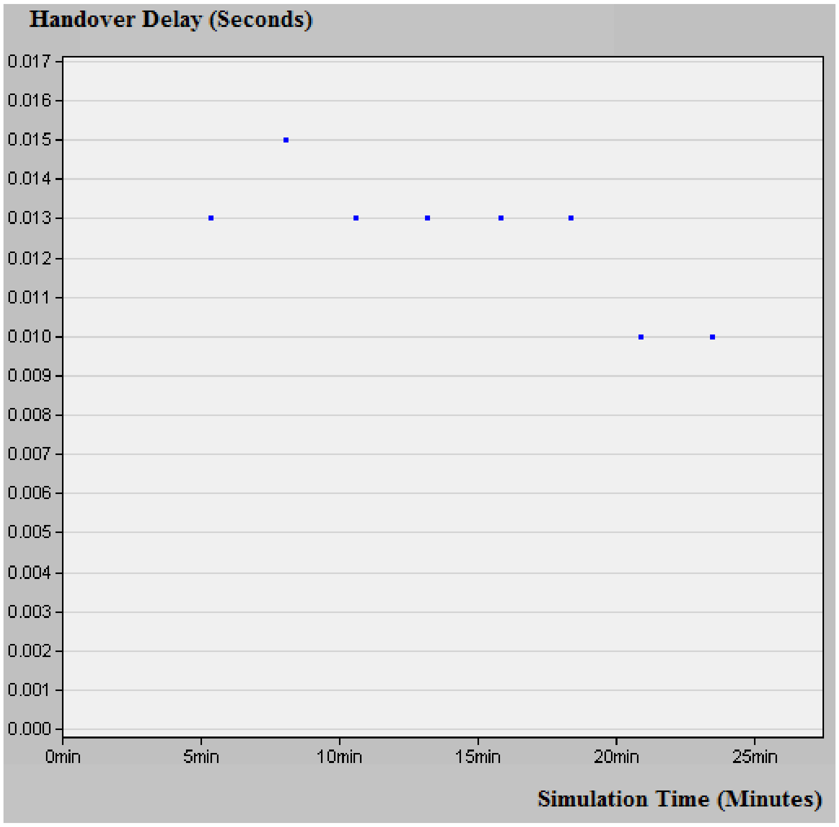


Figure 29: LTE Handover Delay – Scenario 2

The Wi-Fi V2V traffic results are presented in Table 17. Worst case values are considered where the DLR, delay and jitter values represent the upper bound of the resulting confidence interval. No data drops were reported for any of the OVs. In other words, all V2V data was successfully received by the GV via Wi-Fi. Figure 30 shows the traffic received by the GV. Additionally, the obtained delay values are far below the 100ms constraint of the CAM V2V transmission.

Table 17: Scenario 2 - Results of V2V Traffic – No Burst Model

Metric	V2V OV1	V2V OV2	V2V OV3	V2V OV4	V2V OV5
Data Rate (Bytes/sec)	400	400	400	400	400
DLR (%)	0%	0%	0%	0%	0%
Delay (ms)	0.790889	1.11316	1.407288	1.63815	0.4702
Jitter (ms)	0.443402	0.41698	0.387431	0.35542	0.41207

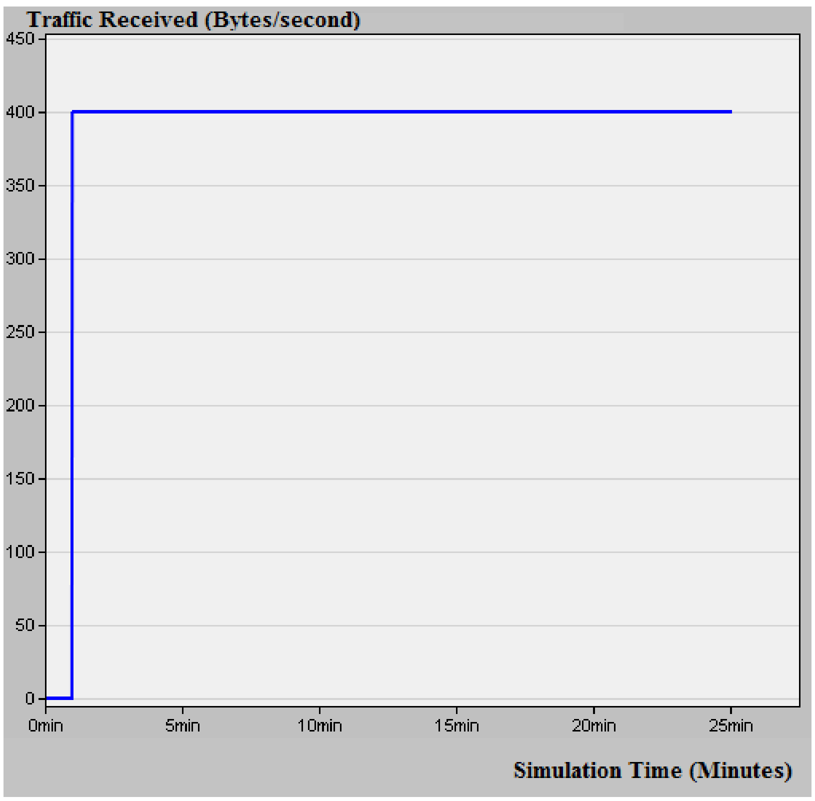


Figure 30: V2V GV Traffic Received – Scenario 2

5.2.5 SCENARIO 3: V2V – BURST RECOVERY MECHANISM

Figure 31 demonstrates a typical burst communication for ITS uplink traffic. It is clear that two packets were lost from the original uplink traffic, however their burst replicas arrive successfully which indicates that no actual uplink ITS data was lost.

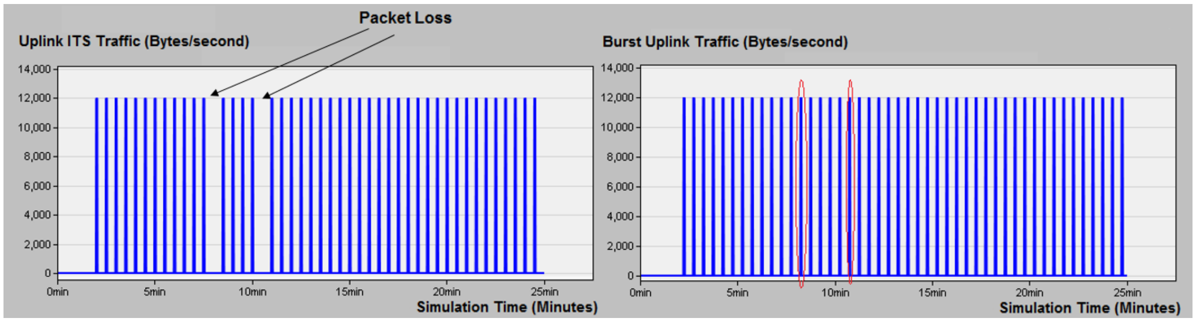


Figure 31: Uplink ITS Traffic with Burst – Scenario 3

Figure 32 demonstrates downlink ITS traffic received by the vehicular workstation in one seed. ITS packets of size 1024 Bytes are sent every 120 seconds. In this particular seed, one downlink ITS packet (at t= 10 minutes) was lost and not received by the vehicular node.

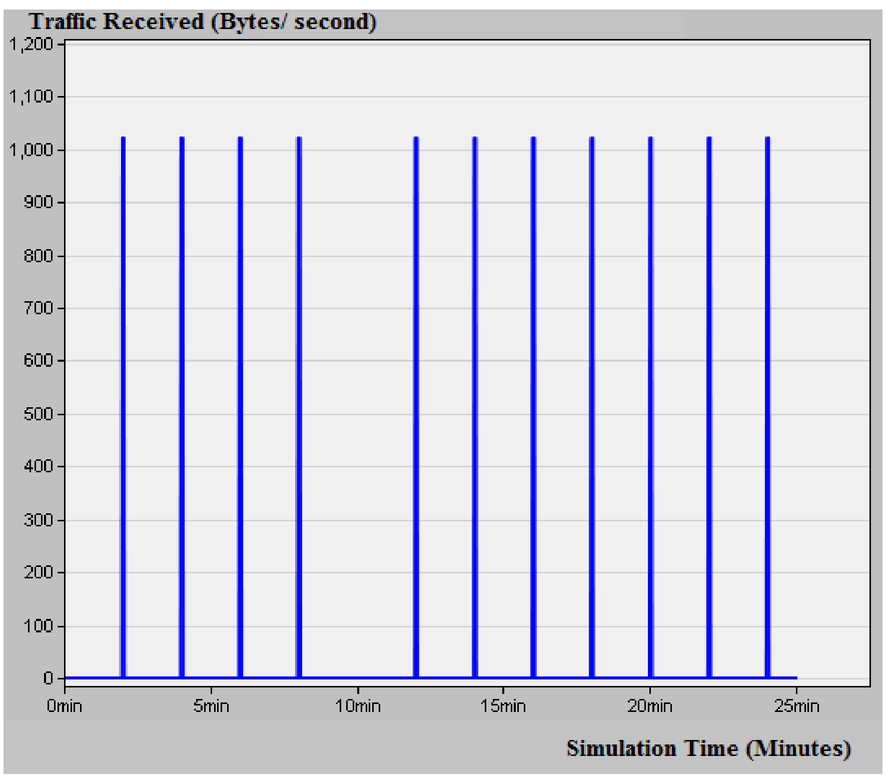


Figure 32: Downlink ITS Traffic Received by Vehicular Ethernet Node – Scenario 3

The handover delay of the LTE mobile node for one seed is shown in Figure 33. In scenario 3, the handover delay was found to be equal to 15 ms which is still far below the 65 ms limit mandated by 3GPP requirements, even after the addition of Burst packets.

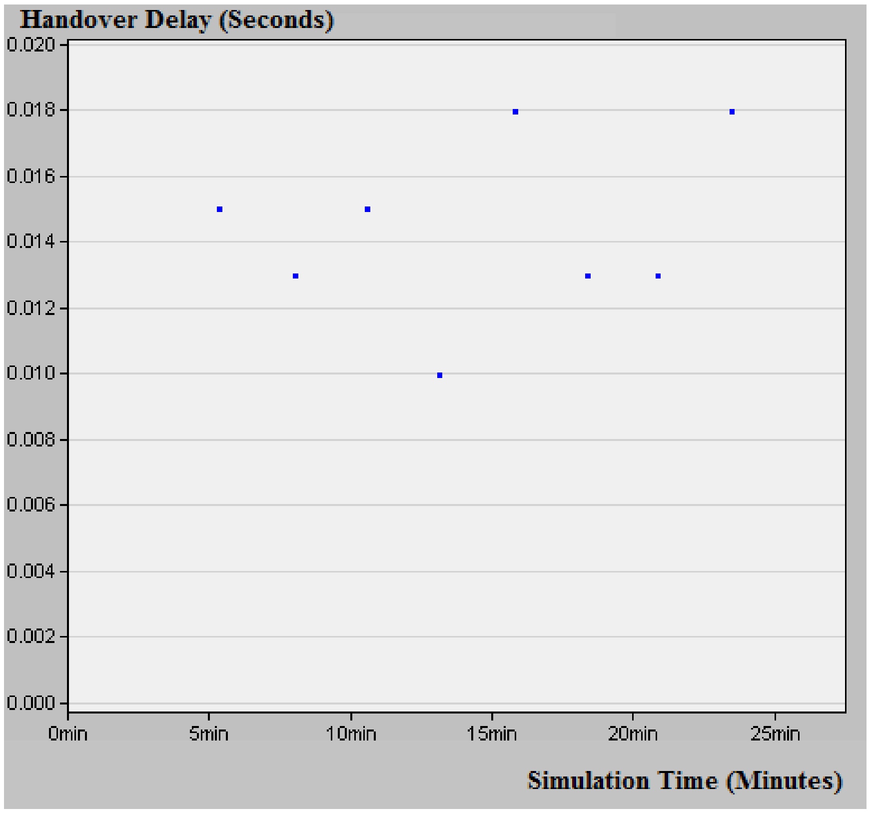


Figure 33: LTE Handover Delay – Scenario 3

Table 18 summarizes the results obtained for vehicular video, downlink and uplink ITS traffic for the Burst model. All received data, delay and jitter are within acceptable limits of ITS applications.

Table 18: Scenario 3 - Confidence Results of Video, Downlink, and Uplink ITS Traffic – Burst Model

Metric	Video	Downlink ITS	Uplink ITS
Data Rate (Bytes/sec)	[124321.4; 124347.2]	[8.39; 8.54]	[393.08; 397.1]
DLR (%)	0.5%	1.8%	0%
Delay (ms)	[12.9; 12.93]	[21.52; 22.53]	[23.4; 24.36]
Jitter (ms)	[5.56; 5.66]	[5.32; 7.58]	[8.69; 11.13]

Wi-Fi V2V traffic results for the Burst model are summarized in Table 19. The obtained delay values are far below the 100ms constraint of the CAM V2V transmission. Additionally, no data drops were reported for any of the OVs. In other words, all V2V data was successfully received by the GV via Wi-Fi. Figure 34 shows the traffic received by the GV where all data was successfully received by the GV with zero losses.

Table 19: Scenario 3 - Results of V2V Traffic – Burst Model

Metric	V2V OV1	V2V OV2	V2V OV3	V2V OV4	V2V OV5
Data Rate (Bytes/sec)	400	400	400	400	400
DLR (%)	0%	0%	0%	0%	0%
Delay (ms)	0.79	1.113	1.406	1.637	0.47
Jitter (ms)	0.4436	0.4178	0.3867	0.3547	0.4119

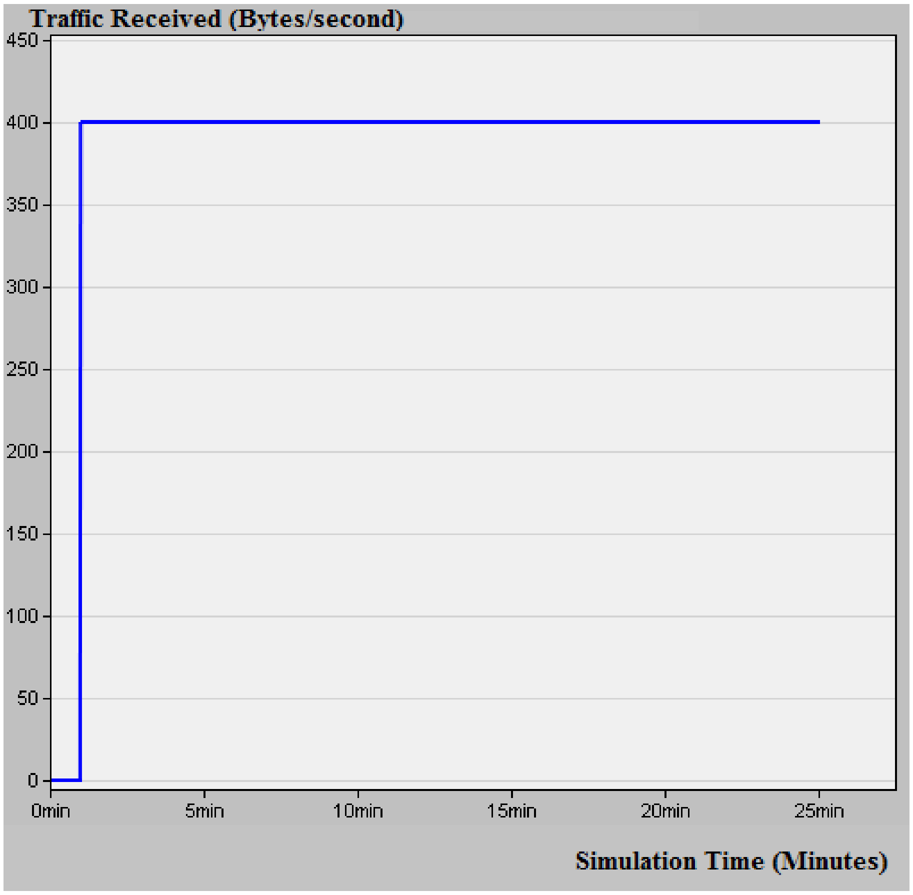


Figure 34: V2V GV Traffic Received – Scenario 3

In summary, the delay, jitter and data drops for both uplink and downlink ITS traffic, and video traffic are within the acceptable limits using the burst technique with only two packets per burst. The obtained simulation results thus prove that the proposed system simultaneously satisfies vehicular and infotainment application requirements.

5.2.6 ANSWERS TO RESEARCH QUESTIONS

The research and results presented in this thesis aim at assessing the performance of the heterogeneous LTE-Wi-Fi network in an urban vehicular environment, and concluding whether the proposed system can simultaneously support the requirements of different vehicular applications. This section summarizes the results presented above and answers the research questions that were listed at the beginning of the thesis.

Three typical vehicular inter-networking scenarios are proposed namely V2I, V2V and on-board vehicular communication. Different types of vehicular applications are supported by the proposed vehicular network namely, road safety, traffic efficiency and infotainment. The results show that the proposed heterogeneous network architecture meets the requirements of both infotainment and ITS traffic applications. The system performance is optimized for a 1.5Km LTE cell radius, 2.6Km inter-site distance, 1.8GHz LTE band 3, and IEEE 802.11g.

The network performance, evaluated in terms of data rate, data loss ratio, delay and jitter, is satisfactory where all the obtained results are within the acceptable limits of ITS applications. Although a tendency of increase in video packet drops during handover is observed yet, the attainable data loss rate satisfies the vehicular application requirements. Increasing the network load results in an increase in video data losses, delay and jitter yet, the obtained results are within the acceptable benchmarks. Thus, the network performance degradation is trivial when video data is delivered on top of traffic control data.

It can be concluded that the proposed architecture provides an added-value for vehicular users in terms of capacity and supported applications while still fulfilling the requirements of ITS applications.

CHAPTER 6: CONCLUSION

Intelligent Transportation Systems (ITS) promise major enhancements to the efficiency, safety, convenience and sustainability of transportation systems. ITS aim at improving road safety, alleviating urban traffic congestion and offering ubiquitous Internet access for passengers. In addition to the delivery of traffic efficiency and safety information, there has been a growing demand recently for vehicular networks to support infotainment services. So, there is a need for new vehicular network architectures as previous designs and architectures do not satisfy the increasing traffic demand since they are setup for either voice or data traffic, which is not suitable for the transfer of infotainment traffic.

In this thesis, an integrated IEEE802.11g and LTE heterogeneous vehicular network was proposed where infotainment traffic was sent in addition to ITS control traffic in an urban vehicular environment. Long Term Evolution (LTE) by the 3rd Generation Partnership Project (3GPP) and IEEE 802.11 are two of the most viable communication standards that could be jointly exploited in today's vehicular networks.

The proposed architecture divides the vehicular network into Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), On-board Vehicle Communication (OVC), and backhaul connection. The V2V network allows inter-vehicular communication through Wi-Fi. The V2I network between the vehicles and LTE eNodeB provides access to the LTE core network. The OVC network consists of a Wi-Fi Access Point (AP), passengers' devices and a vehicular OnBoard Unit (OBU) for ITS data. In this scenario, LTE is the access link used to access the Internet and the connectivity is shared to vehicular users using Wi-Fi as the last mile link. All scenarios are simulated using OPNET Network Modeler and results are subjected to a 95% confidence analysis.

The system architecture was first designed where the cell coverage, inter-site distance, spectrum allocation and network architecture were defined. Then, the system performance was evaluated in terms of data loss ratio, data rate, delay and jitter. In the V2I-only scenario, although a tendency of increase in video packet drops during handover was observed yet, the attainable data loss rate satisfies the vehicular application requirements.

In the combined V2I-V2V scenario, data losses in uplink ITS data traffic was initially observed so, Burst technique was proposed to prevent packet losses. A quantitative analysis was performed to determine the number of packets per burst, the inter-packet and inter-burst intervals. It was found that a substantial improvement was achieved using a two-packet Burst, where no packets were lost in the uplink direction. Additionally, for the given simulation scenario and network traffic load, it was shown that the proposed system meets both the video and ITS traffic application requirements. Thus, the feasibility of the proposed IEEE802.11g-LTE heterogeneous system in urban vehicular environments was demonstrated. Finally, this thesis addressed the research questions raised earlier at the beginning of the study.

APPENDIX A – CONFIDENCE ANALYSIS

All results subjected to a confidence analysis follow the following calculations. Let:

X: random variable

μ: Average of X

σ^2: Variance of X

X_i: sample of X obtained during i^th OPNET simulation (using different seed)

n: No. of OPNET simulations

x: Sample mean

s^2: Sample variance

$$x = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (1)$$

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(X_i - x)^2 \qquad (2)$$

In OPNET Network Modeler, a 'seed' value is required. This seed is used to initialize different random number generator equations. These equations are used to simulate the different behavior of non-deterministic aspects. Based on the Central Limit Theorem (CLT), if the distribution of a random variable is unknown, the distribution of its sample mean will approach a normal distribution, as the number of samples increases. The sample mean also approaches the ensemble mean and the variance of the sample mean is a scaled version of the ensemble mean (mean of $x = \mu$ = mean of X and variance of $x = \sigma_x^2 = \frac{\sigma^2}{n}$ where σ^2 = variance of X [56, 66]

Therefore, the confidence level is defined as the probability that x is below a certain distance from μ:

$$z = \frac{x - \mu}{\sigma_x} \qquad (3)$$

z: is a normal random variable (mean= 0 & variance = 1).

$$P(-z_\alpha < z < z_\alpha) = \alpha \qquad (4)$$

$$P\left[\frac{|x - \mu|}{\sigma_x} < z_\alpha\right] = \alpha \qquad (5)$$

By using 33 simulations, $n > 30$ and hence the sample standard deviation s can be used instead of σ as it is difficult to find $\sigma_x = \frac{\sigma}{\sqrt{n}}$. The Normal distribution will be used and z_α is calculated for a confidence level $\alpha = 95\%$.

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