A Channel Model and Coding for Vehicle to Vehicle Communication based on a Developed V-SCME.

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DEDICATION

TO MY FATHER

Dr.Baheej Al-Khalil

For his inspiration and sacrifices .Without his incredible support I could not have completed my studies.

TO MY MOTHER

Anan Ahmed

For her ceaseless prayers, encouragement and endless love.

TO MY WIFE

SURA

For her endless love and support.

TO MY DAUGHTER

TAMARA

May GOD bless her.

DECLARATION

I hereby declare that the work described in this thesis is original work undertaken by me for the degree of Doctor of Philosophy, at the Department of Computer Science and Immersive Technologies – University of Northampton, United Kingdom. No part of the material described in this thesis has been submitted for any award of any other degree or qualification in this or any other University or College of advanced education.

Ahmad Baheej Al-Khalil

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My special gratitude is due to my parents for their endless support. Their prayers and blessings were no doubt the true reason behind any success I have realised in my life.

Finally, I should always remember the support and endless wishes of my wife Sura. I owe sincere and earnest thankfulness to my dearest Brother Dr.Yaseen and Dr.Mustafa, and my sisters Huda and Zainab for their encouragement and support.

PUBLICATIONS

During the 4-years of the research study, the following papers were published within the department of Computer Science and Immersive Technologies at The University of Northampton.

1. October/2015, "A Predefined Channel Coefficients Library for Vehicle – to – Vehicle Communications" Published in 9th IEEE International Workshop on Communication Technologies for Vehicles. Munich – Germany.

2. May/2015, "Utilising SCM – MIMO Channel Model Based On V-BLAST Channel Coding in V2V Communication" Published in Springer for the 8th International Workshop on Communication Technologies for Vehicles. Sousse – Tunisia.

3. October/2014, "Feasibility Study of Utilising SCM – MIMO Channel Model in V2V Communication" Published in 7th IEEE International Workshop on Communication Technologies for Vehicles. St. Petersburg – Russia.

4. June/2013, "Enhancing the Physical Layer in V2V Communication Using OFDM – MIMO Techniques" The 14th Annual Postgraduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting. Liverpool – UK.

ABSTRACT

Over the recent years, VANET communication has attracted a lot of attention due to its potential in facilitating the implementation of 'Intelligent Transport System'. Vehicular applications need to be completely tested before deploying them in the real world. In this context, VANET simulations would be preferred in order to evaluate and validate the proposed model, these simulations are considered inexpensive compared to the real world (hardware) tests.

The development of a more realistic simulation environment for VANET is critical in ensuring high performance. Any environment required for simulating VANET, needs to be more realistic and include a precise representation of vehicle movements, as well as passing signals among different vehicles. In order to achieve efficient results that reflect the reality, a high computational power during the simulation is needed which consumes a lot of time. The existing simulation tools could not simulate the exact physical conditions of the real world, so results can be viewed as unsatisfactory when compared with real world experiments.

This thesis describes two approaches to improve such vehicle to vehicle communication. The first one is based on the development of an already existing approach, the Spatial Channel Model Extended (SCME) for cellular communication which is a verified, validated and well-established communication channel model. The new developed model, is called Vehicular – Spatial Channel Model Extended (V-SCME) and can be utilised for Vehicle to Vehicle communication. V-SCME is a statistical channel model which was specifically developed and configured to satisfy the requirements of the highly dynamic network topology such as vehicle to vehicle communication. V-SCME provides a precise channel coefficients library for vehicle to vehicle communication for use by the research community, so as to reduce the overall simulation time.

The second approach is to apply V-BLAST (MIMO) coding which can be implemented with vehicle to vehicle communication and improve its performance over the V-SCME. The V-SCME channel model with V-BLAST coding system was used to improve vehicle to vehicle physical layer performance, which is a novel contribution.

Based on analysis and simulations, it was found that the developed channel model V-SCME is a good solution to satisfy the requirements of vehicle to vehicle communication, where it has considered a lot of parameters in order to obtain more realistic results compared with the real world tests. In addition, V-BLAST (MIMO) coding with the V-SCME has shown an improvement in the bit error rate. The obtained results were intensively compared with other types of MIMO coding.

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LIST OF ABBREVIATIONS

3G	3rd Generation Mobile Networks
3GPP	Partnership Project Standards Body.
4G	4th Generation Mobile Networks
5G	5th Generation Mobile Networks
AoA	Angle of Arrival
AoD	Angle of Departure
AS	Authentication System
AWGN	Adaptive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
Car 2 Car	C2C
CCH	Control Channel
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
DAB	Digital Audio Broadcasting
D-BLAST	Diagonal Bell laboratories
DCF	Distributed Coordination Function
DSRC	Dedicated Short Range Communications
DVB	Digital Video Broadcasting
DVB-H	Digital Video Broadcasting – Handheld
FCC	United States Federal Communication Commission
FDM	Frequency Division Multiplexing
FM	Frequency Modulation
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
I2I	Infrastructure – to – Infrastructure
ICI	Inter-Carrier Interference
IEEE	Institute of Electrical and Electronic Engineer
IETF	Internet Engineering Task Force
IPv4	Internet Protocol Version 4.
IPv6	Internet Protocol Version 6.

ITS	Intelligent Transport Systems
IVC	Inter Vehicle Communication
LOS	Line of Sight
LTE-A	Long Term Evolution Advanced
MAC	Medium Access Control
MANETs	Mobile Ad-hoc Networks
MIMO	Multiple – Input – Multiple – Output
MS	Mobile Station
NLOS	Non-Line of Sight
OBUs	On Board Units
OCSP	Online Certificate Status Protocol
OFDM	Orthogonal Frequency Division Multiplexing
PDF	Probability Density Function
PER	Packet Error Rate
PHY	Physical Layer
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RSUs	Road Side Units
SCHs	Service Channels
SCM	Spatial Channel Model
SCME	Spatial Channel Model Extended
S-DMB	Satellite – Digital Multimedia Broadcasting
SISO	Single – Input – Single – Output
SM	Spatial Modulation
SNIR	Signal to Noise and Interference Ratio
SNR	Signal to Noise Ratio
SoS	Sum-of-Sinusoids
STBC	Space Time Block Code
V2B	Vehicle – to – Broadband Cloud Communications
V2I	Vehicle – to – Road Infrastructure Communications
V2V	Vehicle – to – Vehicle
VANETs	Vehicular Ad-hoc Networks
V-BLAST	Vertical – Bell Labs Layered Space Time

V-SCME	Vehicular – Spatial Channel Model Extended
WAVE	Wireless Access for Vehicular Environment
WHO	World Health Organisation
WiMAX	Worldwide Interoperability for Microwave Access
WINNER	European Wireless World Initiative New Radio
WLAN	Wireless Radio Networks

CHAPTER ONE
INTRODUCTION

In a United Nation's (UN) road safety report from around the world, it was documented that road safety deaths made up 2.2% of the leading causes of death in 2004 (WHO, 2009). It has been predicted that this will rise to 3.6% by 2030. Also, the report indicated that there were over 1.2 million deaths on the road per annum. In addition there were between 20 and 50 million non-fatal accidents per annum. There have been recommendations made by WHO in 2009 regarding the poor collaboration between the sectors made responsible for collecting and reporting data on road traffic incidents. These recommendations suggested that there must be better communication between the police, health and transport services to increase their ability to improve such operations.

The need for safety technology has developed at a rapid rate ever since major road safety regulatory authorities began advocating for stringent measure in the regulation of the auto industry. Harding *et al.* (2014) and Guenther & Salow (2015) firmly believed that vehicles are better suited at protecting their occupants in the case of a crash if advanced structural techniques are coupled with modern crash avoidance technologies. This explains the major reason why crash avoidance technologies have become an integral component and standard equipment in modern vehicles. Traffic-related mortalities have been a major concern, given the fact that thousands of lives are lost each year through traffic accidents (National Highway Traffic Safety Adminstriation, 2014). Yang *et al.* (2004) showed that about sixty percent of roadway collisions that could be avoided if the vehicle operator was given prior warning for at least half a second before the collision.

Azimi et al. (2011) expected that successful development and implementation of such systems will reduce the collision risks. The implementation of such systems is expected to help in reducing accident-related injuries that are about forty times more than deaths. Noland, (2013) showed that most of the traffic accidents occur due to the driver's inability to control situations that can be put under control through succinct utilisation of the available technological capabilities. For instance, Anand, (2006) have shown that many drivers suffer from Line-of-Sight (LoS) limitation of brake lights, given that under current circumstances, a driver can only see the brake lights from the vehicles that are directly in front of them. Secondly, the drivers suffer from large forwarding/processing delay in case of emergency events. In fact, the reaction time for most drivers range from 0.7 seconds to 1.5 seconds (Yang *et al.*, 2004) and this essentialy leads to delays in propagating the emergency warnings. There is therefore a need to provide the driver with information regarding traffic and road conditions to reduce these incidents, thus saving many people's lives.

Van Eenennaam *et al.* (2012) demonstrated that the use of wireless communication system over the road is more efficient to cover distances up to several kilometres contrary to what is the case in the sensors. For this reason, Vehicular Ad-hoc Network (VANET) have been proposed as one of the precise solutions to address these problems. The communication in VANET utilised in such models is largely unreliable due to the dynamic environment (Wang *et al.*, 2013; Da Cunha *et al.*, 2014).

VANET can be seen as a form of Mobile Ad -hoc Network (MANET) that offers a communication platform among nearby vehicles and roadside units or nearby fixed equipment (Garg, 2014). The aim of such a platform is to improve safety and efficiency of road transport (Naranjo *et al.*, 2012; Baldini *et al.*, 2013; Jia *et al.*, 2015).

Although the VANET has the characteristics of fast topology changes and high node mobility, Akhtar *et al.* (2015) stated that it still has the potential to offer a wide variety of services. These include safety-related warning messages that ensure improved navigation and other entertainment and information applications. In line with these capabilities, one of the greatest capabilities of VANET is the ability of the system to improve safety and streamline road transport in the 21st century (Frost and Sullivan, 2010).

Papadimitratos *et al.* (2009) stated that the high level of communication between vehicles and other supporting infrastructure located on the roadsides greatly enhances the ability of VANET to handle communication issues relating to delay, collision, and congestion.

Richardson *et al.* (2006) explained the implementation of the form of Vehicle-to-Vehicle (V2V) communication. V2V communication need some supporting mechanisms that will ensure the presence of maximum reduction of packets collisions, facilitate congestion control, and reduce latency in the delivery of emergency warning messages.

The current advanced Wireless ad hoc Network (WANET) that is coupled with location-based routing algorithms make it easy to maintain precise communication between vehicles (Mauve *et al.*, 2001; Leontiadis & Mascolo, 2007; Bilal *et al.*, 2013). Mou *et al.* (2014) mentioned that VANET also comes with other supporting applications that support inter-vehicle communication such as lane access systems, intelligence cruise control, and emergency warning systems.

Away from the accidents, it is plausible that urban traffic congestion is a major problem that is currently faced both by developed and developing countries (Arnott, 2001). INRIX Inc. (2014) showed that the congestion menace has been shown to result in the loss of billions of productive hours every year, with an immense negative impact on productivity and hence, world economy. According to Schrank *et al.* (2012) urban mobility reports from various countries, the cost of traffic congestion in terms of wasted fuel has risen sharply over the last few years. For example, in the United States, the cost of wasted fuel due to traffic congestion hit an all-time high of $121 billion in 2011 (Knaak & Roberts, 2014). Therefore, the implementation that the potential to produce smooth movement of vehicles aided by prompt V2V communication offers potential benefits in reducing the amount of fuel waste from traffic congestions. This in turn will result in massive savings on the billions of productive hours lost during traffic snarl ups. In this regard, the use of VANET seems to harbour immense benefits in reducing traffic-related deaths and injuries, as well as serving as a major boost on the world economy.

1.1. PROBLEM DESCRIPTION

Wireless communication in V2V is a very promising technology which will be widely deployed in the near future. Many channel models have been proposed for VANET communication e.g. (Abrate *et al.*, 2011; Gozalvez *et al.*, 2012; Urquiza *et al.*, 2014; Akhtar *et al.*, 2015), in an attempt to enhance the V2V communication efficiently. The process of how to find the most robust V2V channel model-coding is challenging due to the high dynamic environment. For this reasons, this work addressed and focused on three important challenges in V2V environment:

1- MIMO channel model in V2V.
2- Channel coding.
3- Design of a predefined offline channel coefficients library.

Finding a more realistic channel model which represents V2V communication is one of the main challenges due to multi-path propagation in such a dynamic environment (Wang *et al.*, 2012; Viriyasitavat *et al.*, 2015). Therefore, there is a need to design a V2V channel model based on established knowledge of physical phenomenon in V2V propagation environments. However, to evaluate how efficient the designed model is, a number of simulation tests are needed. Simulation tools have been preferred over out door experements because they are simple, easy and cheap. He *et al.*, (2009) and Hassan & Larsson, (2011) said that the simulation results are considered to be a proactive step in order to produce or develop an efficient physical link between vehicles in real world. Another challenge is to find a suitable channel coding by evaluating the existing coding methods with the proposed Multiple – Input – Multiple – Output (MIMO) channel model in V2V systems. However, to determine channel coding in MIMO systems requires furthers investigations. In addition, the available diversity of coding and the number of used antennas in MIMO systems such as 2x2, 4x4 and 8x8 need to be taken into consideration. Most of the obtained results that evaluate the channel performance in V2V e.g. (Cho *et al.*, 2009; Kihl *et al.*, 2010; Jiménez, 2015) are based on simulation, these results hardly reflect the reality of the V2V channel performance. However, to reflect reality, high computational power is needed to determine it during the simulation time (Boeglen *et al.*, 2011; Qiao *et al.*, 2012), therefore there is a need to a predefined library for V2V channel to be calculated offline.

1.2. RESEARCH PROGRESS

This research study is spilt into two parts. The various study tasks are shown in the bubble diagram of Figure (1.1) as follows:

- **Channel Model Part** (Clear bubbles): representing the research work on developing V-SCME as V2V channel modelling.
- **MIMO Coding Part** (Shaded bubbles): representing the research work for utilising different MIMO coding in V-SCME channel model.

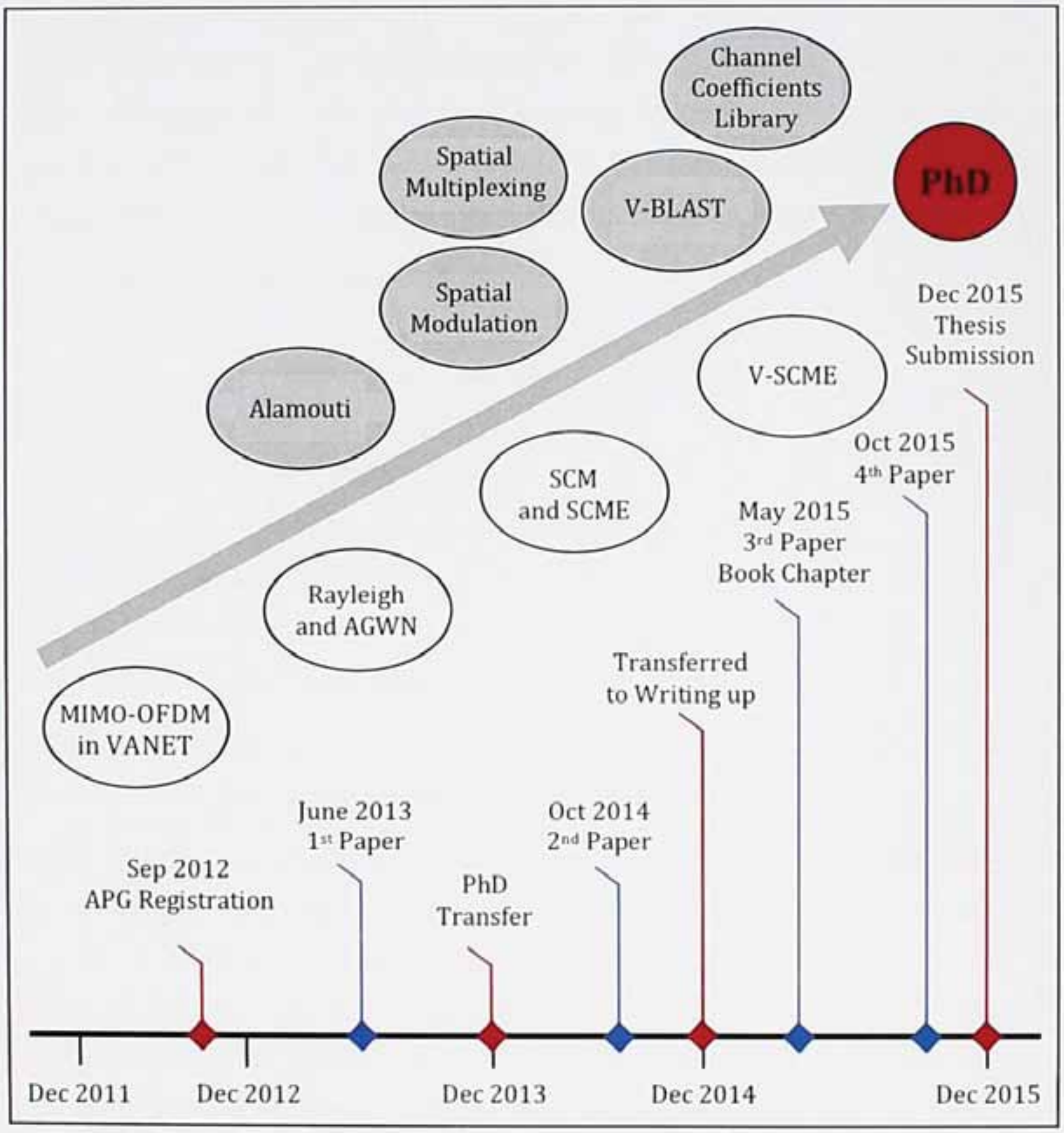


Figure 1.1: The PhD Research Progress and The Related Publications.

This research started by investigating the MIMO-OFDM technologies in VANET communication. It was concluded that consolidate OFDM and MIMO techniques have managed to reduce the Bit Error Rate (BER) in the multi fading channel problems. Later, the research investigated Rayleigh and Additive White Gaussian Noise (AWGN) channel models to be utilised as a V2V channel model. A high dynamic environment in V2V communication is a challenge. However, the simulation results showed that Rayleigh and AWGN are not representing V2V channel model due to the high dynamic environment. This has led to the finding of a more robust V2V channel model in order to overcome the high dynamic issue. The Spatial Channel Model Extended (SCME) has been utilised as a V2V channel model. However, SCME channel model is designed to satisfy the requirements of cellular communication. As a result, this research considered utilisition of a developed version of SCME called Vehicular – SCME (V-SCME). The developed channel model is designed to meet the requirements of V2V communication by considering the following :

1- Urban microcell as a V2V environment.
2- Polarisation.
3- The numbers of antennas 2x2, 4x4, etc.
4- Wavelength: 0.5 λ, 4 λ and 10 λ.
5- The frequency of IEEE 802.11p.
6- The number of multi-path and sub-paths for both LoS and NLoS.
7- The angles: AoD and AoA.
8- Vehicle speed.
9- The distance between vehicles.

V-SCME was developed to offer a good solutions for the VANET researchers, where it is more flexible and realistic as compared to other channel models.

For the MIMO coding research thread, a thorough study of the current MIMO technologies has been considered. The research focused to support BER vs. Signal to Noise Ratio (SNR) by utilising different coding techniques with different modulations Binary Phase Shift Keying (BPSK), 4 - Quadrature Amplitude Modulation (4-QAM), 16 - Quadrature Amplitude Modulation (16-QAM) and 64 - Quadrature Amplitude Modulation (64-QAM). The first technique is Alamouti Space Time code. Alamouti is used to increase the transmission reliability by transmitting the same stream from different antennas. However, the simulation results indicates that Alamouti is suitable for stationary communication rather than mobility communication. Similarly, spatial modulation and spatial multiplexing have been utilised in V2V communication. The simulation results indicated that V-BLAST is a good solution to deal with the dynamic environment when different distances and speeds are applied. Finally, In V2V communication a high computational power is needed to be determined during the simulation time, therefore this research provides an open access predefined library for V2V channel to reduce the overall simulation time with a more realistic channel model for V2V.

1.3. RESEARCH AIMS AND METHODOLOGY

I have chosen this research to help me understand the concepts of the VANET technology as deployed by using Wi-Fi, as well as how to design, plan , integrate with other networks, configure routing protocols, and choose suitable applications for such networks. I have thoroughly enjoyed this research experience.

In the process of this research, I reviewed the literature of the VANET technology (standards, protocols, topologies and applications) and developed a comparative criteria to identify the most suitable solution. Algorithm decisions were followed by statistical analysis leading to actual functional and behavioral simulation. This 4-year research activity focused on the following:

- Following the standards: Investigate the possibilities and capabilities to propose solutions without impacting the VANET technology standards. The techniques have been altered to accommodate the latest amendments.
- Keeping in touch with research committees: this is to ensure that the research is academically viable. This has been achieved by joining academic workshops, publishing the work in known conferences, and attending relevant events.

The aim of this research is to introduce a solution to the following problems:

- Understanding the main issues and problems for V2V channel model by identifying the strengths and the limitations of the available research.
- Development of a novel statistical model V-SCME for V2V communication channel based on MIMO systems, by developing the existing SCME to be suitable for vehicular communication.
- Evaluate the existing MIMO coding to choose the optimum coding technique in order to use it with V-SCME in V2V communication.

1.4. RESEARCH CONTRIBUTIONS

1. Development of a V2V statistical channel model V-SCME which is based on an already existing approach, the SCME for cellular communication.
2. Provision of a predefined channel coefficients online library to be accessed by the researcher for future simulation.
3. MIMO is a suitable choice for V2V communication and 2x2 MIMO is a good solution for V2V communication in terms of cost and complexity.
4. The V-BLAST is a robust coding technique to be utilised in MIMO systems with V-SCME in V2V communication. The use of V-BLAST coding is a good solution to deal with the dynamic environment when different distances and speeds are applied.

1.5. THESIS ORGANISATION

Figure (1.2) illustrates the structure of the thesis. Chapter (2) reviews the VANET technology in general, followed by detailed study of VANET architecture. It describes the concept of the VANET and it's main categories. The motivation of this chapter is to explain the VANET standardisation, spectrum policy and the VANET communication challenges due to the dynamic environment and finally give an overview about OFDM technique. Chapter (3) reviews the existing VANET channel models. Many research and implementation works regarding VANET simulation and channel modelling have been discussed with different approaches and methods. The chapter provided an overview about SCM and SCME in order to develop it for use as V2V channel model. Finally, the chapter reviews the three main components of VANET simulation tools: mobility generator, network simulator and VANET simulators.

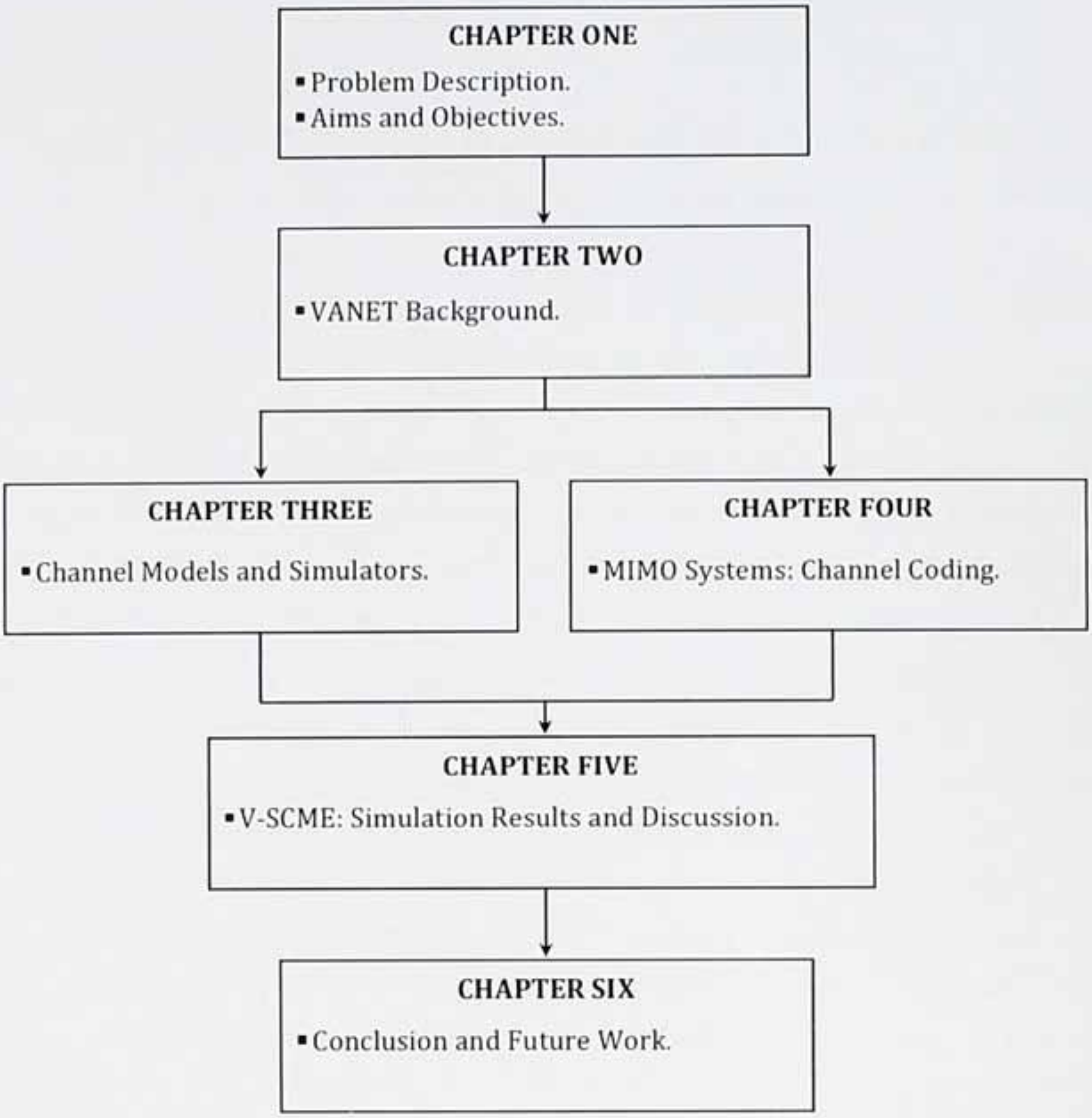


Figure 1.2: Thesis Organisation.

Chapter (4) has covered a lot of ground. It is mainly focused on providing informations regarding: principles of MIMO systems and the use of MIMO systems in VANET, fading channel models, diversity schemes and MIMO channel coding. Chapter (5) describes the developed V-SCME to be used as V2V channel model. The simulation results with different scenarios are discussed including: V-SCME/Alamouti, V-SCME/Spatial Modulation (SM), V-SCME/V-BLAST, V-SCME/Cumulative Distribution Function (CDF) and V-SCME/Channel Capacity. In the last part the chapter discussed the predefined channel coefficients library which is provided for further future work.

Finally, this thesis is concluded by Chapter (6) that discusses the main issues, point of views, achievements, and recommendation for future work.

CHAPTER TWO
VEHICULAR AD-HOC NETWORK BACKGROUND

2.1. INTRODUCTION

In recent years, research has been undertaken to improve vehicle inter-connection Intelligent Transport Systems (ITS). This research has focused on a newly emerged technology VANET, which is defined as an inter-connection between vehicles. VANET is becoming one of the most promising research fields in ITS because of it having the ability to provide different types of applications such as safety and non-safety applications (Zeadally *et al.*, 2010). Vehicle manufacturers integrate wireless inter-connection devices into their products to make the trip more comfortable and safe (Vermesan & Friess, 2013).

In VANET, the moving vehicle represents the dynamic nodes of the network, while the Road Side Units (RSUs) represent the static nodes (Caballero-Gil *et al.*, 2015), these vehicle nodes have a dynamic topology based on their pattern of movement and they are also self-organised nodes. During the journey sufficient battery power is generated by the vehicle which is an advantage unlike the Mobile ad hoc Network (MANET) where the power during the movement needs to be considered, as it is limited (Samara & Salem, 2013). The nodes move at different speeds and continuously change their positions which result in establishing a dynamic network topology. The idea of having VANET is to achieve a full wireless inter-connection system between the vehicles 'V2V' and Vehicle to Road side units 'V2R'. VANET system promises to help motorists satisfy driving requirements such as less congestion, accident warning, road exploration, etc. These requirements will not be achieved unless there are applications that benefit from this technology.

This chapter gives a background to VANET; section (2.2) is showing VANET potential architecture and deployment scenarios. The VANET standardisation and spectrum policy are presented in sections (2.3) and (2.4). Section (2.5) is allocated for signal propagation and multi-path challenges. A number of challenges in vehicular network are discussed in section (2.6). Finally, the OFDM technology and the modulation techniques in VANET is discussed in section (2.7).

2.2. VANET ARCHITECTURE

In VANET Chiu *et al.* (2013), vehicles interconnect with each other via short radio signals i.e. Dedicated Short Range Communication (DSRC) (United States Federal Communication Commission, 1992). This inter-connection can cover up to 1000 meters in an urban area (Lu & Poellabauer, 2010). During the journey the vehicles are considered to be supplied by On Board Unit (OBUs) devices. These devices allow the vehicles to interconnect with each other over the Wi-Fi within the distance of up to 1000 meters using single hop and multi-hops. The road will be supplied by a number of base-stations called RSUs. Nema *et al.* (2014) said that these RSUs will be systematically distributed on the road, to handle the data from the vehicles to pass it to another vehicle(s), another RSU(s) or to the infrastructure. US Department of Transportation, (2005) used RSUs-to-RSUs to increase the inter-connection distance between vehicles when the distance is between 300 and 1000 meters. RSUs acts as a router between the vehicles and also between other units in the network (Ramakrishnan *et al.*, 2010).

According to the above components OBUs and RSUs Faezipour *et al.* (2012) and Da Cunha *et al.* (2014) showed that VANET communication can be categorised into four main types:

1- **In-Vehicle Communication:** in-vehicle communication system is designed to sense the performance of the vehicle during the journey, such as the driver status if the driver is fatigued or suffers from sleepiness which is considered a high risk for the driver and public safety.
2- **Vehicle to Vehicle Communication V2V:** V2V considers the conventional method in VANET communication, where vehicles can share information regarding the road status such as a warning message related to an incidence of an accident. V2V is designed to expand driver assistance.
3- **Vehicle to Road Infrastructure Communication V2I:** is another type in VANET communication which is useful for ensuring the inter-connection between vehicles when the distance is between 300 and 1000 meters. Also, it could be used by the private sector or the government to provide the drivers with information about the traffic and weather status etc.
4- **Vehicle to Broadband Cloud Communication V2B:** This type of communication considers that vehicles communicate via wireless broadband such as 3G and 4G. The mechanism of this communication requires the vehicles to be provided with devices which are suitable for broadband communication. Vehicle tracking application could benefit from this category.

This thesis focuses on the channel modelling and coding of the V2V communication only. It develops a novel statistical model which considers the dynamic V2V network topology between the vehicles, dynamic obstacles, dynamic links and multi-path issues. Contemplating these issues to develop a V2V channel is challenging and it will be discussed intensively in Chapter (5).

2.3. STANDARDISATION

DSRC is the wireless communication protocol for VANET. It was approved by the United States Federal Communication Commission (FCC) in 1992. DSRC is allocated to support the ITS applications in the licensed band of 5.9 GHz spectrum Figure (2.1). In 2004, DSRC joined the Institute of Engineering Electrical and Electronics (IEEE) and was classified as IEEE 802.11p standard (IEEE Vehicular Technology Society, 2014). IEEE 802.11p standard shares some properties with IEEE 802.11a standard as they use the same Physical Layer (PHY). However, (IEEE, 2010) standardisation document showed that the only difference is the bandwidth channel which is 10MHz instead of the 20MHz. The purpose of the IEEE 802.11p standard (IEEE Vehicular Technology Society 2014) is to provide the minimum specification, ensuring that the devices are able to communicate in a rapidly changing environment. IEEE Vehicular Technology Society, (2014) produced Wireless Access for Vehicular Environment (WAVE), which is considered the core of the DSRC for fast moving vehicles Figure (2.2). IEEE Vehicular Technology Society, (2014) showed that the architecture of the WAVE contains both IEEE 802.11p and IEEE 1609 standards. In IEEE 802.11p, the standard is released to support PHY and the Medium Access Control layer (MAC) specifications, whereas IEEE 1609 standard cooperates with IEEE 802.11p standards (IEEE Vehicular Technology Society, 2014) to develop the specifications of additional layers in the protocol suite of the WAVE.

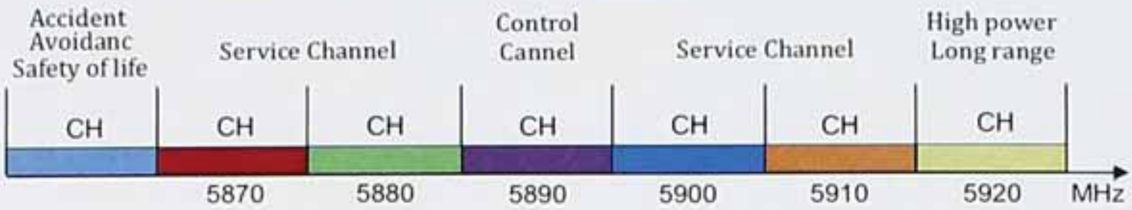


Figure 2.1: IEEE 802.11p Channels Frequency Domain.

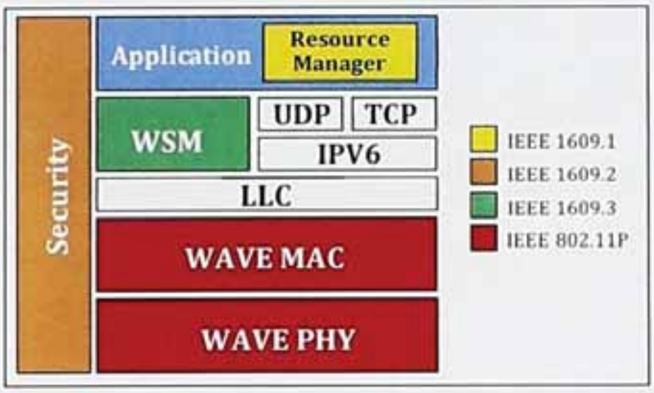


Figure 2.2: Wave Protocol Stack.

2.4. SPECTRUM POLICY

Although the vehicular networks standard IEEE 802.11p has been studied by many researchers e.g. Böhm & Jonsson, (2007), Jarupan & Ekici, (2011), Sharma & Singh, (2012), Abdelgader & Lenan, (2014); Moser *et al.* (2015) stated that there is still limited research which has been done to improve the performance of its PHY protocol. However, PHY protocol in VANET should present appropriate channel access and effectiveness to support and enhance the Quality of Service (QoS) of the vehicles mobility (Ndih & Cherkaoui, 2012). Providing the minimum specification of requirement is the purpose of the IEEE 802.11p standard to ensure that the devices are able to operate in conjunction when they are attempting to communicate in a rapidly changing environment. IEEE 802.11p frequency spectrum is allocated one Control Channel (CCH) and multi Service Channels (SCHs), as shown in Figure (2.3). CCH is specified for the network nodes to exchange network control messages whereas SCHs are used to exchange data packets and short wave messages. The channel bandwidth link is divided into transmission cycles, each cycle containing a control frame and a service frame. The duration of a frame is set to 50 milliseconds (IEEE Vehicular Technology Society, 2014).

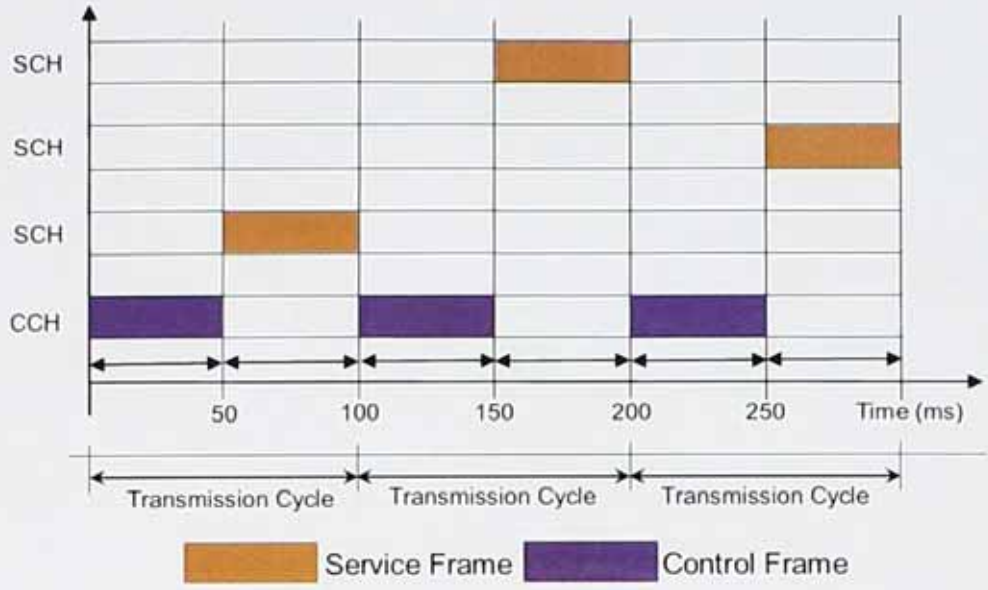


Figure 2.3: IEEE 802.11P Channels Time Domain.

2.5. SIGNAL PROPAGATION AND MULTI-PATH CHALLENGES

A wireless communication system in VANET typically consists of RSUs infrastructure (I), OBUs vehicles (V) and a wireless network protocols (Kim & Lee, 2014). The wireless signal is propagated as: V2V, V2I, I2I, and a special case as discussed in (2.2) V2B. However, the wireless communication system differs from the wired communication system in terms of signal propagation since the wireless signals are transmitting via an open environment. Sorrentino *et al.* (2012) said that LoS is the direct path between the V2V, V2I, I2I or V2B , which means that the wireless signal transmits and arrives at the receptionist without being affected by the factors surrounding the transmit and receive environment. These factors have different reflector components which are represented by scatters such as buildings, trees, vehicles etc. Thus, the wireless communication environment in VANET has a direct path between the sender and the recipients LoS, but also there are many scatters and reflectors objects which effect the wireless signal being received No-Line-of-Sight (NLoS). In the case of scatters, the receiver will receive a signal component and multi-path components which is caused by the objects presenting in the environment Figure (2.4).

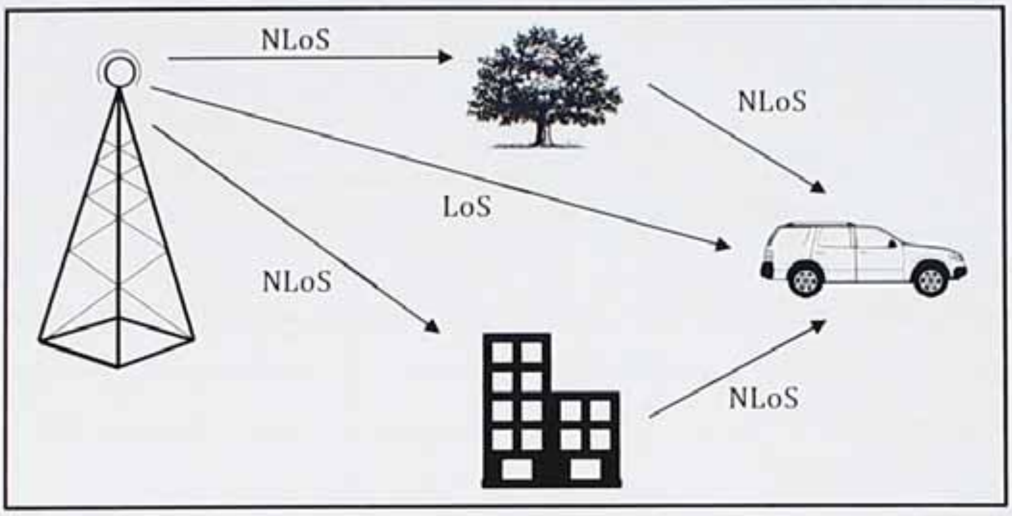


Figure 2.4: Wireless Signal Propagation LoS and NLoS.

Signals arriving from various distances are subject to an attenuation because of the free space (Carr, 2001). The delay is different which means that the fade which arrives to the recipients is different. In this context, the same signal that arrives to the recipients from different paths has different attenuations and different delays. So the signals which depend on different delays have a phase factor and they can either add constructively to produce constructive interference which increases the amplitude of the net signal, or they can also be destructive as they can cancel each other to produce destructive interference (Paulraj *et al.*, 2000). Multi-path components is a fact in the wireless communication, these components add with different phase factors due to the delays at different attenuations arising, because of free space losses and scattering (Carr, 2001). So the results are constructive or destructive interference. Paulraj *et al.* (2000) stated that constructive interference refers to the level of the signal where the level is going up which is absolutely good, while in the destructive interference the signal level goes down which is bad and in this case the receiver is unable to receive any signal. That is why wireless communication is an adverse environment because multi-path propagation adds other multi-path interference, which causes the destructive interference. In general, the wireless propagation environment can be represented as a system model. This model includes the main components: the transmitting signal $\boldsymbol{x(t)}$, the receiving signal $\boldsymbol{y(t)}$ through a wireless channel $\boldsymbol{H(t)}$ which is used by the transmitter and the receiver to transmit and receive the signal Figure (2.5).

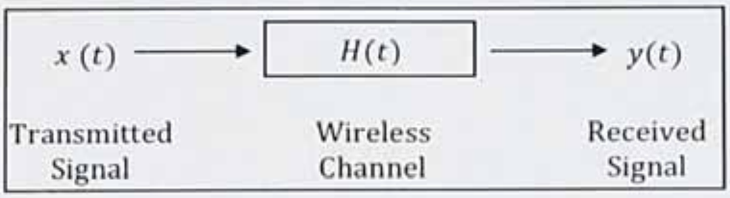


Figure 2.5: Wireless Communication System Components.

Halanay & Ionescu, (1994) said that the attenuation is simply a scaling of the signal which corresponds to multiplying the signal by a scaling factor (attenuation factor a_0), and a delay is simply corresponding to an impulse function $\delta\,(t - t_0)$ where t_0 is the delay.

$$a_0\,\delta\,(t - \tau_0) \qquad (2.1)$$

The transmitted signal $x(t)$ passes through two parts: for the first part it's attenuated by a_0 and in the second part delayed by t_0 that can be represented as a system with impulse response a_0 multiplying by $\delta\,(t - \tau_0)$ Table (2.1).

Each one is considered as multi-path component			
Multi-path Component	Multi-path Component	Multi-path Component	Multi-path Component
Attenuation Factor $a_0\,\delta\,(t - \tau_0)$ Corresponding Delay	Attenuation Factor $a_1\,\delta\,(t - \tau_1)$ Corresponding Delay	Attenuation Factor $a_2\,\delta\,(t - \tau_2)$ Corresponding Delay	Attenuation Factor $a_{n-1}\,\delta\,(t - \tau_{n-1})$ Corresponding Delay
LoS Main Path	NLoS 1st Path	NLoS 2nd Path	NLoS N-1 Path

TABLE 2.1: Multi-path Component in Wireless Model.

The wireless model in Table (2.1) is simply a combination between the paths as:

$$h(t) = a_0\,\delta\,(t - \tau_0) + a_1\,\delta\,(t - \tau_1) + \cdots + a_{n-1}\,\delta\,(t - \tau_{n-1}) \qquad (2.2)$$

Where,

$h(t)$ is the wireless channels impulse response.

The net impulse response of the system is the sum impulse of the responses corresponding to each path, which is the attenuation and the delay corresponding to that path. So the time domain impulse response of the wireless channels of this multi-path wireless channel is:

$$\sum_{i=0}^{n-1} a_i \, \delta\,(t - \tau_i) \quad (2.3)$$

The multi-path problem is a common problem in the wireless communication research area, and the research community has intensively proposed many mathematical and statistical models to represent different types of channels. The representation of signal propagation among vehicles needs the reproduction of the actual physical radio propagation process for any given environment. This process generates the impulse response of the channel through a determination of the possible paths from the transmitter to the receiver. The V2V research community has used well-known channel models such as Rayleigh and AWGN. Having a dedicate channel model for V2V communication was not accomplished, nevertheless this thesis has developed a dedicated V2V channel model and provided a predefined channel coefficients library, more details are found in Chapter (5).

2.6. VANET CHALLENGES

This section discusses some of the current key research challenges related to VANET communication that still need further solutions. Though some research e.g. Garg, (2014), Kirtiga *et al.*, (2014), Zelikman & Segal, (2015) and Amjad & Song, (2015) stated that VANET is classified as a sub-class of MANET and they do share some properties, however the behaviour of VANET and its characteristics are different in several ways, e.g. MANET routing protocols cannot be directly implemented in VANET (Katuka *et al.*, 2014). The key research challenges give the researchers an opportunity to study and investigate VANET characteristics deeply. As a result, new key factors will be obtained which can help to enhance the current applications or to invent a new technique which will be useful for the public transport system.

2.6.1. SPECTRUM ISSUE IN VANET

The spectrum of 75MHz at 5.9GHz (5.850 – 5.925GHz) is allocated by United States FCC (1992) for the vehicular communication V2V and V2I. Nowadays, the IEEE 802.11p standard (IEEE Vehicular Technology Society, 2014) is adopted by ITS project as the best proper technology using this spectrum. Car 2 Car Communication Consortium (C2C CC) proposed a similar approach in Europe C2C CC, (2015). Unlike the spectrum in the US, C2C CC allocated the spectrum of 2x10MHz at 5.9GHz for vehicular communication especially to safety application in VANET. Mace, (2013) showed that the non-safety applications could be supported by using additional spectrums to satisfy all the requirements of the applications such as 5GHz or 5.8GHz bands. However, the 5.9GHz is currently used for military radar system and satellite service (Daley, 2000). Alhammad, (2014) said that the Short Range Device Maintenance Group (SRDMG) recommended placing the 1st 10MHz control channel in (5.885 - 5.895 GHz). The purpose of this recommendation is to align the spectrum in the EU with the US approach. The SRDMG also recommended to place the 2nd 10MHz channel in the upper part of the Industrial, Scientific and Medical (ISM) band (5.865 - 5.875 GHz) (Jakubiak and Koucheryavy, 2008), where the other radiolocation service below 5.85GHz can benefit from it.

2.6.2. BROADCASTING ISSUE IN VANET

Broadcasting in VANET represents one of the key challenges for researchers (Indra and Murali, 2014). Information distribution among vehicles requires unique algorithms in order to manage the packet flooding which arises by the massive packet transmission in the network. Some of the broadcasting techniques were used in VANET research, these techniques include limited and unlimited bandwidth service solutions such as narrow bandwidth based on Frequency Modulation (FM) radio together with different wide band digital services such as Digital Audio Broadcasting DAB, Digital Video Broadcasting (DVB) and Digital Video Broadcasting – Handheld (DVB-H). Also, Rahim *et al.* (2009) stated that the Satellite - Digital Multimedia Broadcasting (S-DMB) digital service has been used due to its ability to give a real time traffic information service. IEEE 802.11-a DSRC standard (US Department of Transportation, 2015) used by VANET communication is not fully appropriate for handling broadcast transmissions due to the continual message collisions. These collisions make the vehicles to re-transmit the message frequently. Also, they affect the delivery rate and delivery time. Broadcasting techniques were found by Zeadally *et al.* (2010) to be associated with broadcast problems. To reduce or overcome the broadcast problem the concept of location aware broadcasting is required, where reducing the broadcast range is needed by reducing unnecessary network overhead. However, more efforts have been made by Zeadally *et al.* (2010) to innovate another approach which is called Clustering Approach. This approach has emerged as a promising solution, where neighbouring vehicles pose in the form of manageable groups (clusters) which limits the message broadcasting range. Ciccarese *et al.* (2010) defined a timer-based intelligent flooding scheme for VANET. The scheme operates on the MAC layer. It utilises a distributed contention mechanism on the basis of which it suffices that at least one contending node correctly receives the data packet for electing a forwarder. However, research in VANET broadcasting has recently started but still needs to provide high efficiency and reliable broadcasting techniques.

2.6.3. ROUTING PROTOCOLS ISSUE IN VANET

The dynamic nodes movement at high speed, where the network topology changes rapidly is considered the main challenge in VANET communication. This constant change leads to loss of the intermediate nodes between the source and destination most of the time (Katiyar *et al.*, 2014). In this manner, end-to-end connectivity cannot always be established. Although VANET is classified as a sub-class of MANET (Patel, 2013), the MANET routing protocols are inapplicable efficiently and effectively to the special vehicular environment due to frequently rapid change in the topology. However, this issue gives the researchers the motivation to find a suitable routing algorithm which can overcome the frequent path distributions caused by vehicle mobility. In this context, some research on the issue of routing protocols in VANET has been done. A power control algorithm based on local information Caizzone *et al.* (2005) assumes that the moving vehicle continuously keeps the data packet, without transferring it, unless it could find another vehicle closer to the destination. Also, no exchange of power-related signalling among nodes is required. Luo *et al.* (2008) proposed VANET routing protocol constructed mobility model called SUVnet. SUVnet utilises the global positioning information, GPS and Zone Routing Protocol ZRP. The goal is to predict an efficient path based on a temporary memory that saves the history of the movement information of intra-zone vehicles and destination location information. The results indicated that VANET could achieve a better routing performance by applying the General Packet Radio Service (GPRS) (ETSI, 1999) function on ZRP border nodes. The problem of spectrum access in VANET has been addressed in Chung *et al.* (2009) that deals with dynamics channel due to high mobility. A Cognitive MAC protocol (CMV) for VANET proposed by Chung *et al.* (2009) to support synchronised transmissions by means of allocating a channel for every beacon interval. CMV employs both long-term and short-term spectrum access which can provide a fair share, and increases the overall network throughput by exploiting multi user diversity. The results showed that CMV improves previous multi-channel MAC protocols throughput by up to 72% compared to the traditional dedicated and split protocols.

Okada et al (2009) introduced a selection scheme Expected Progress Distance EPD for the next hop node in VANET as a new metric link. The new metric link takes into consideration the quality of the transmission link and the forwarding distance. Okada *et al.* (2009)

concluded that the proposed scheme achieves better Packet Delivery Ratio (PDR) and a higher throughput than the conventional schemes, such as Beacon-less Routing Algorithms (BLR) (Cao & Xie, 2005), greedy perimeter stateless routing GPSR (Karp & Kung, 2000), contention-based forwarding and flooding-based geo-casting protocols (Ko, 2002). Ivan *et al.* (2009) discussed the evaluation of the Packet Error Rate (PER) performance of the WAVE physical layer. Ivan *et al.* (2009) deduce that the rapid changes of the channel pointedly affects the estimation process which is sternly affecting the performance of the PER, whereas the Inter-Carrier Interference (ICI) has no effect on the performance when the data rate is small. VANET exhibit continuous movement that lead to fast change in technology, fluctuation in communication and increased issues when new layout information is changed. To avoid these negative results and increase quality of communication, clusters can be built by classifying neighbouring vehicles driven in the same direction (Chen *et al.*, 2015).

2.6.4. PRIVACY ISSUE IN VANET

Privacy in VANET is another issue which requires to be improved and enhanced. The development of vehicular communication and the widespread use of computers on the vehicles promoted chances of networks on these vehicles being attacked by wireless worms. The properties of the movement, medium, media access control and passage of worms were analysed and theoretical models and rules of simulation were presented. In VANET communication, vehicles are required to broadcast an authenticated message continuously (Ibrahim, 2009). IEEE 802.11p (IEEE Vehicular Technology Society, 2014) allocated a 10MHz channel which is recommended to be used for safety messages. The broadcasting message includes all information regarding vehicles such as vehicle speed, vehicle position and verifiable identity. Dressler et al. (2011) and Yan, (2013) stated that the purpose of using safety messages in VANET is to prevent attacks from manipulating the authorised location tracking of vehicles. Attackers can easily get and spy on all broadcast messages due to the nature of wireless environment. There is therefore a need to protect the privacy location of vehicles. In this context, a number of research efforts have been made to improve the privacy issue in VANET. Serna *et al.* (2014) addressed the general security and privacy issue in VANET communication. Their approach is mainly focused on a framework which consists of an Authentication System (AS) which validates credentials in near real-time using the Online Certificate Status Protocol (OCSP) protocol (Adams & Lloyd, 2003), quantitatively. The introduced framework is used to address the challenges such as vehicle tracking and user profiling. The proxy mobile IPv6 (Hinden &

Deering, 2003) is designed by the Internet Engineering Task Force (IETF) to reduce the overhead of the signal, but it does not consider the security issue. Therefore, a local-based authentication and billing scheme was proposed by Yeh & Lin, (2014) to lessen the long-distance communication overhead. Their proposed scheme was designed to cover V2V and Vehicle - to - Infrastructure (V2I) communication. The authors concluded that the proposed scheme not only can reduce the long-distance signalling overhead in proxy mobile IPv6, also it reduces security weaknesses such as man-in-the-middle and impersonation attacks. More research related to the privacy issue in VANET communication can be found in (Li *et al.*, 2014 and Kim & Lee, 2014).

2.7. ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING OVERVIEW

Orthogonal Frequency Division Multiplexing (OFDM) is one of the key technologies that used in IEEE 802.11x, 3rd Generation Mobile Networks (3G), 4th Generation Mobile Networks (4G) and 5th Generation Mobile Networks (5G). Many authors including Wang *et al.* (2014) have highlighted the traditional single carrier transmission scheme, the bandwidth is allocated to transmit symbols sequentially for a relatively short period of time. OFDM transmits multiple symbols in parallel where each symbol is using a relatively narrow piece of bandwidth for a much longer period of time Figure (2.6).

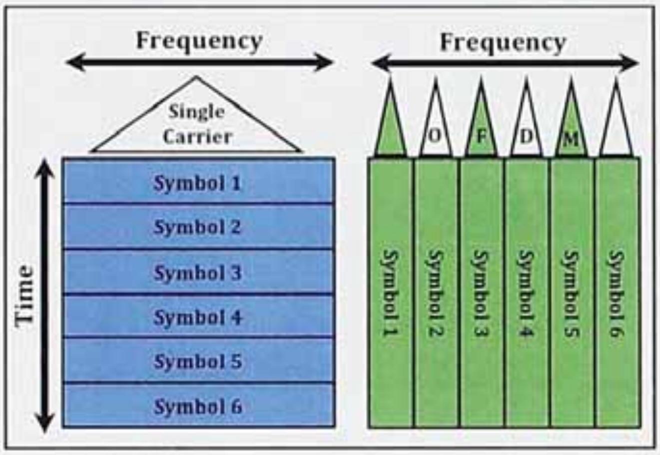


Figure 2.6: Traditional and OFDM Symbols Transmission Carrier.

Hartenstein & Laberteaux, (2010) stated that IEEE 802.11 standard based on OFDM, three channels are allocated to be used with the following bandwidths: 5MHz, 10MHz and 20MHz. The 10MHz channel will universally be used for VANET communication while the 20MHz is commonly used for 802.11a (Joshi, 2014). The OFDM channel basic parameters for the IEEE 802.11 at 10MHz bands are shown in Table (2.2):

Modulation	bit per subcarrier symbol
BPSK	1
QPSK	2
16 QAM	4
64 QAM	6

TABLE 2.2: The Basic Parameters of OFDM Channel in 802.11 at 10MHz.

The signal can come in 4 different types of modulation:

- Binary phase shift keying BPSK.
- Quadrature phase shift keying QPSK.
- 16-point quadrature amplitude modulation 16-QAM.
- 64-point quadrature amplitude modulation 64-QAM.

Each modulation technique illustrates a different number of bits encoded per subcarrier symbol as can be seen in Table (2.3).

Parameters	Values
Subcarrier Numbers	48
Pilot Subcarrier Numbers	4
Subcarrier no. + Pilot Subcarrier no.	52
Subcarrier frequency spacing	156.25 kHz
Guard interval	1.6 μsec
Symbol interval + guard interval	8 μsec

TABLE 2.3: The IEEE 802.11 OFDM Modulation Techniques.

The user bits are enhanced by the Forward Error Correction FEC Perişoară *et al.* (2008). This is because the FEC not only improves the probability of successful decoding but it also reduces the effective user bit rate as shown in Table (2.4). Three FEC codes can be utilised which are 1/2, 2/3, and 3/4. Twelve combinations between the four different modulations and the three FEC codes can be formulated, however only 8 out of these 12 combinations are actually allowed in the 802.11 OFDM.

Modulation	Coded bit rate (Mbps)	Coding rate	Data rate (Mbps)	Data bits per OFDM symbol
BPSK	6	1/2	3	24
BPSK	6	3/4	4.6	36
QPSK	12	1/2	6	48
QPSK	12	3/4	9	72
16 QAM	24	1/2	12	96
16 QAM	24	3/4	18	144
64 QAM	36	2/3	24	192
64 QAM	36	3/4	27	216

TABLE 2.4: Data Rate Options in a DSRC 10 MHz OFDM Channel.

2.8. CHAPTER SUMMARY

VANET is attracting a considerable attention from the research and the automotive industry fields, where it can help in supporting ITS in addition to driver and passenger assistant services. This chapter aims to provide a background with regard to VANET communication including: VANET architecture, standardisation, spectrum policy, signal propagation, VANET challenges and finally an overview about OFDM.

VANET is emerging as a new class of wireless networks (Moustafa & Zhang, 2009), spontaneously formed between moving vehicles, and allowing for a number of useful services for drivers and passengers, ranging from road safety applications to entertainment applications. In VANET communication, vehicles interconnect with each other via short radio signals i.e. DSRC (Chiu *et al.*, 2013). This inter-connection can cover up to 1000 meters in an urban area (Lu & Poellabauer, 2010). These communication can be categorized into four main types (Faezipour *et al.*, 2012; Da Cunha *et al.*, 2014):

- In-Vehicle Communication.
- Vehicle to Vehicle Communication V2V.
- Vehicle to Road Infrastructure Communication V2I.
- Vehicle to Broadband Cloud Communication V2B.

VANET standard was approved by the United States Federal Communication Commission (1992) FCC, which is allocated to support the Intelligent Transport System ITS applications in the licensed band of 5.9 GHz spectrum. Although many standard organisations are involved in the study and standardisation of VANET, this technology still remains under research in both scientist and industry fields. Besides the ongoing standardisation activities, this chapter discussed a number of technical challenges such as: spectrum issue, broadcasting issue, routing protocol issue and privacy issue in VANET. Finally, this chapter discussed the OFDM technology which is one of the key technologies that is used to enable MIMO systems as well as the new generation of mobile communication 4G.

Chapter Three
Channel Models and Simulators

3.1. INTRODUCTION

The development of real-time safety and non-safety applications for use in VANET calls for a good understanding of the dynamics that underlie network topology characteristics (Kumar *et al.*, 2013). This is mainly due to the fact that these dynamics influence the performance of any given application over the VANET model. Using several key metrics of interest, such as neighbour distribution, node degree, link duration, and number of clusters, all are important factors in order to get good results for VANET simulations (Akhtar *et al.*, 2015). The development of a more realistic simulation environment for VANET is critical in ensuring high performance. Any environment required for simulating VANET, needs to be more realistic and include a precise representation of vehicle movements, as well as passing signals between different vehicles. In order to achieve efficient results that reflect reality, a high computational power during the simulation is needed which consumes a lot of time. Having a precise movement model and channel model for vehicle communication is necessary to reflect the reality of VANET. Existing simulation tools cannot simulate the exact physical conditions of the real world, so results can be unsatisfactory when compared with real world experiments (Ku *et al.*, 2011). This chapter discusses the channel models which have been used by the research community to be utilised as a VANET channel model. In addition, the chapter gives an overview of the Spatial Channel Model (SCM) which was designed for cellular communication; this research relied on its development to be used as V2V channel model. Finally, the chapter reviews the existing simulation tools which have been used to simulate the VANET environment.

3.2. VANET CHANNEL MODELLING

It is noteworthy that many V2V network protocols are assessed through simulation e.g. (Korkmaz *et al.*, 2006; Baur *et al.*, 2010). In the majority of network simulators, Boeglen *et al.* (2011) said that the physical layer is often affected by an apparent lack of realism. Thus, Boban *et al.* (2011) said that the creation and implementation of realistic V2V channel modelling has become a critical issue in the field of ITS. Moreover, Viriyasitavat *et al.* (2015) mentioned that V2V channels exhibit specific features such as:

- Diverse environments where the communication happens.
- Combinations of different communication types: V2V, V2I, V2B, etc.
- The objects, both static and mobile that affect the vehicular communication, in combination, result in complex propagation.

According to Khairnar & Kotecha, (2014) in a simulation study, the researchers presented several deterministic and probabilistic propagation channel models that could be used in VANET environment. From an implementation perspective, these models can be either probabilistic or deterministic or a combination of both. This section aims at reviewing some deterministic and probabilistic channel models for VANET communication.

3.2.1. DETERMINISTIC CHANNEL MODEL

Deterministic model facilitates the computation of the received signal strength on the basis of real-time environmental characteristics such as the distance between a receiver and transmitters (Ali *et al.*, 2009). An example of this type of model is the Free Space Model Zhang & Chen, (2013), also known as the Friis Model Bryant & Newman, (1946) as showed in Equation (3.1).

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 \quad (3.1)$$

P_t: the power of the transmitting antenna.
P_r: the power of the receiving antenna.
G_t and G_r: the antennas gain.
R: the distance between antennas.
λ: the wavelength.

In the Free Space Model, the received power is dependent only on the transmitted power, distance between sender and receiver, and antenna gain. Thus, as the radio wave moves away from an omnidirectional antenna, power decreases relative to the square of the distance. Another example of the deterministic model is the Ray Tracing Model Choi *et al.*

(2012) which also accounts for a reflection through the ground in relation to the dielectric properties of the earth, as well as the LoS. Mitra, (2009) and Akhtar *et al.* (2015) showed that the Ray Tracing Model provides more accurate predictions at longer range as compared to the Free Space Model. The Ray Tracing Model is based on the evaluation of the VANET topology characteristics over space and time for a highway scenario. In order to achieve the objectives of the Ray Tracing Model, a road topology is utilised, real-time information obtained from the Freeway Performance Measurement System (PeMS) (Choe *et al.*, 2002; Aligawesa & Hwang, 2010) and integrate them into a microscopic mobility model which is integrate with VANET simulator in order to generate traffic flow along the highway. However, Chong, (2006) said that the Ray Tracing Model is often impractical due to the need for a detailed description of the specific propagation environment.

Yun & Iskander, (2015) stated that the Ray Tracing Model, Friis and Free Space Models are basic radio propagation models, where the physical layer is treated in a simplistic and consequently not quite realistic manner. It is noteworthy that representation of signal propagation among vehicles needs the reproduction of the actual physical radio propagation process for any given environment (Wang & Cheng, 2009). Akhtar *et al.* (2015) showed that this process is referred to as the generation of the impulse response of the channel through a determination of the possible paths from the transmitter to the receiver.

Gozalvez *et al.* (2012) stated that the channel modelling is a crucial mechanism for studying the performance of VANET. This mainly results from the dynamic environment, high cost and large resources needed for deploying vehicles in urban scenarios. Tripp-barba *et al.* (2014) aimed at evaluating the effect of the Packet Error Model as applied in VANET. The study was geared towards the measurement of losses, number of hops, and end-to-end delay scenarios. The simulation results showed that the basic Packet Error Model has the potential to generate similar results as those obtained through a realistic Packet Error Model, especially when the configuration and design of the former if precisely set at low or medium channel capacities (Tripp-barba *et al.*, 2014).

Gibb *et al.* (2002) and Shafiee *et al.* (2011) showed that stochastic models are not efficient in evaluating the radio communication between vehicles in a simulation environment for this reason Sommer *et al.* (2011) presented a computational simulation model for IEEE 802.11p in urban environments on the basis of real-time measurements through the use of IEEE 802.11p/DSRC devices, where they estimated the effects of building and other obstacle influence on radio communication between vehicles. The proposed model by Sommer *et al.* (2011) considers building geometry and sender/receiver positions, and its model relies on building outlines, which are commonly available in modern geo-databases as OpenStreetMap.

A study by Wang *et al.* (2014) focused on snapshot dispersion that results in operation in non-rural places having equal traffic by modelling movement patterns, communication channels, medium access control operations and worm passage process. In addition, Wang *et al.* (2014) simulated wireless worm passage which are self-replicating computer viruses that can spread in the network in changing traffic under the same observation as the traffic that does not change using a tool that model the network. They demonstrated the relationship between the effects of the preview and the results observed with time. An analysis of the results of the local variations in differences was conducted and how the rates affected the measurements of the networks. Wang *et al.* (2014) findings is valuable in assisting the engineers in developing techniques that can intelligently and automatically detect and prevent the proliferation of wireless worms in VANET.

3.2.2. PROBABILISTIC (STOCHASTIC) MODEL

The probabilistic models enable more sensible modelling of radio wave propagation. Kuntz *et al.* (2008) stated that the probabilistic model essentially utilises a deterministic model as part of its output parameters in order to achieve a mean transmission range. For each individual transmission, the power received is then drawn from a distribution. The outcome is a more diverse distribution of the successful receptions. A scenario can take place with a certain probability that two nodes that are close to each other cannot communicate, even though it can also take place with certain likelihood that communication can take place between two nodes that fall beyond deterministic transmission range (Kuntz *et al.*, 2008).

Rubio *et al.* (2006) showed that the probabilistic (stochastic) model determines the physical characteristics of the vehicular channel in a totally stochastic manner without making presumptions of any underlying geometry. The distance-dependent path loss, large-scale and small-scale fading distributions are the major parameters that need to be estimated. The surrounding obstacles may include mobile objects such as other vehicles or static objects such as buildings (Rubio *et al.*, 2006).

Zajic, (2013) stated that most of the modelling activities aim at addressing the additional attenuation brought about by the obstacles and this results in a log-normal distribution around the average received signal power, especially in urban areas.

When it comes to a vehicle mobility model, the realistic representation of vehicle mobility calls for the use of precise microscopic mobility modelling, real-data based traffic demand modelling, and real-world road topology (Harri *et al.*, 2009; Barcelo, 2010).

In an attempt to extend the development of analytical models and the utilisation of hybrid simulations, Baltzis, (2010) proposed an analytical model that encompasses distance-dependent losses, as well as small-scale fading (discussed in 4.3) and shadowing. Baltzis, (2010) presented some closed-form expressions of the packet reception probability, packet forwarding in circumstances where there are no simultaneous transmissions. A simplified approach for propagation of the signal assumes a deterministic attenuation of signal power in relation to the transmission distance (Baltzis, 2010). Thus, the packets are received with optimal certainty within the intended communication range, but reception becomes almost impossible at greater distances. In the same context, a study by Wu and Zheng, (2014) considered the fair access problem in VANET. The authors implemented an analytical framework for examining the performance of the Distributed Coordination Function (DCF), based fair channel access protocol by IEEE 802.11 (IEEE, 2012) in a less-saturated state. An association between the probability of transmission and the size of minimum contention window were established together with a relationship between transmission probability and the size of the smallest contention window. Based on Wu & Zheng, (2014) analytical framework, the smallest contention window size for a given velocity can easily be established with the aim of achieving fair access among the different vehicles.

Communication in VANET may occur between vehicles V2V or between vehicles and infrastructure V2I situated on the roadside. In VANET scenarios, multiple vehicles require access to the same infrastructure concurrently through a single channel, which in most cases causes data collision and the fair access problem. In order to avoid data collision and the fair access problems, Leng et *al.* (2009) mentioned that it is necessary to employ an efficient MAC protocol to organise the access of the channel to multiple vehicles. Among the most used MAC standards is the IEEE 802.11 standard (IEEE, 2012), where it is mainly applied in wireless communication networks. DCF is the primary method of access in the IEEE 802.11 standard (IEEE, 2012). DCF is a random access mechanism that is based on the Carrier Sense Multiple Access CSMA with collision avoidance.

Yousefi *et al.* (2006) and Li *et al.* (2013) stated that VANET exhibit unique properties in contrast to the traditional wireless networks like vehicular mobility constraints, application requirements such as a safety message broadcast period, and vehicular network connectivity. Wu & Zheng, (2014) said that the unique attributes make IEEE 802.11 DCF unable to align the access to the channel in VANET efficiently presenting new disputes in the MAC protocol design for VANET. One problem arising with VANET is the fair access problem (Harigovindan *et al.*, 2012) in which case, vehicles moving at higher speeds are not offered the same opportunity to communicate to the RSUs as vehicles travelling at lower speeds. Most existing MAC protocol designs do not take this problem into account.

In a comprehensive analysis Wang *et al.* (2014) proposed a new analytical model for highway inter-vehicle communication systems. An unsaturated VANET cluster was modelled using the Markov chain and the introduction of an idle state. The fading of the wireless channel was integrated with the mobility of the vehicle through the derivation of a joint distribution of the distances between vehicles. The suggested analytical framework precisely characterised the performance of the VANET. Wang *et al.* (2014) framework can be applied to the VANET clusters design and suggests numerous insights that present instructions for the design and the management of VANET. Extensive models depict that the proposed framework and the solutions precisely capture the VANET performance in terms of throughput and reliability over wide ranges of network sizes, spans and traffic volumes. However, Wang *et al.* (2014) showed that Markov chain is not yet able to make a clear relation with a real environment. A statistical channel framework, Sum-of-Sinusoids (SoS) is suggested by Aygun & Wyglinski, (2014) to utilises decode-and-forward relaying VANET. The authors have obtained the channel impulse response in a high traffic conditions in order to get the channel characteristics and they have conserved it to be used for future simulation. The proposed channel framework by Aygun & Wyglinski, (2014) was used in analysing the relay network capacity of VANET operational in highway traffic conditions. The output depicted that the channel model has a higher performance in relation to previous studies.

3.3. MIMO CHANNEL MODELS

The performance of MIMO systems is affected by the spatial characteristics of the radio channel (Almers *et al.*, 2007). The improvement of the SNR takes the advantage of multi-path effects in the form of spatial diversity. This improvement occurs by combining the outputs of de-correlated antenna arrays with low mutual fading correlation (Shiu *et al.*, 2000). Spatial multiplexing is another technique used to improve the system's gain by creating multiple parallel channels between the transmitter and receiver (Kumar, 2012). Tse & Viswanath, (2005) said that the capacity of MIMO systems is not only dependant on the number of channels, but it also depends on the correlation between the channels as well. This means that large MIMO gains can be achieved by low spatial correlation. Kizilirmak, (2010) stated that the other alternative method to achieve low correlation is to use antenna arrays with cross-polarisations such as antenna arrays with orthogonal polarisations. This section provides an overview about channel modelling which are used to develop MIMO channel models.

3.3.1. SPATIAL CHANNEL MODEL

Spatial channel model (SCM) is a Ray-based or Geometric model based on stochastic modelling of scatters. SCM is a part of the European Wireless World Initiative New Radio (WINNER) project (Eurescom GmbH, 2006), established in 2003 by the Partnership Project Standards Body (3GPP) (3rd Generation Partnership Project, 2014). It is commonly used for a MIMO wireless system channel as it can take account of the temporal correlation parameters of the communication channel. In other words, to simulate the wideband fast fading scenario. Baum *et al.* (2005) stated that SCM is dedicated to a Code Division Multiple Access (CDMA) system with 5MHz band and 2GHz frequency.

SCM considers that the position of Base-Station (BS) and the scatters presented in the transmission area are fixed, and that the time variation of the channels is only due to the movement of the Mobile Station (MS) in the wideband fast fading scenario. 3GPP defined three various cases environments for SCM-MIMO wireless propagation channel (suburban macrocell environment, urban macrocell environment, and urban microcell environment). 3GPP applied the concept of spatial and polarisation diversity assuming multiple antennas at both the transmitter and receiver. Urban microcell is distinguished in LoS and NLoS propagation. SCM allocated a fixed six paths in each scenario, where each path represents a delay domain, based on Dirac delta function, but these paths have up to twenty sub-paths according to the sum-of-sinusoids method. Probability Density Function (PDF) (Shapo,

2006) is used to define the random variables such as path delays, path and angular properties powers for both sides of the link. The parameters, called drops, are drawn independently in time but it is excluded for fast fading.

The transmit/receive signal between the BS and the MS faces a large number of phenomena such as the path loss, fast fading, shadow fading the Doppler shift etc., which affect the reception of the signal. The simulation results for each scenario should be reliable so that many variables and parameters need to be taken under consideration in the simulation level. A rough description of the environment and cases are presented (3rd Generation Partnership Project, 2014).

1) Environments And Channel Realisation

3GGP group (3rd Generation Partnership Project, 2014) proposed three environments for the simulation level which are: (the Suburban Macrocell, the Urban Macrocell and the Urban Microcell). The first two environments classified as Macrocell because they share statistical similarity and they follow up the same modelling process with some parameter adjustment. Generally, the three environments follow the same simulation steps. The following table shows some basic characteristics for each environment. Table (3.1).

Characteristics	Macrocell		Microcell
	Suburban	**Urban**	**Urban**
Distance	Up to 3 km distance BS to BS.		Less than 1 km distance BS to BS.
Antenna	BS antenna above rooftop height.		BS antenna is at rooftop height.
Path Loss Model	A modified COST231 Hata urban propagation model.		The COST 231 Walfish-Ikegami NLoS model.
Other Characteristics	Angle spread, Delay spread and Shadow fading will be treated as correlated, LN random variables.		Angle spread, Delay spread and Shadow fading will not be treated as correlated RV.

TABLE (3.1) Basic Characteristics for Macrocell and Microcell Environments.

2) Cases And Channel Realisation

SCM provides two cases for simulation. The two cases are different in terms of complexity, where case one is considered less complicated than case two. In this context, the simulation results can be obtained faster in case one, for this reason it is recommended to use case one for space diversity results or when the results are regarding the usage of directional antenna (Salo *et al.*, 2005). With respect to case two, it should be used for polarisation diversity or for mixed spatial and polarisation results Table (3.2).

CASE I	CASE II
The cross polarisation is not taken into consideration.	The cross polarisation is taken into consideration.
Only vertical polarisation sub-rays considered in BS and MS antenna transmit and receive.	Vertical and horizontal polarisation sub-rays are considers in BS and MS antenna transmit and receive.
BS antenna is assumed to be either directional or omnidirectional, while MS antenna is assumed to be omnidirectional.	BS and MS array elements will be assumed ideal dipoles or cross-polarised, co-located dipoles, forming dipole pairs.

TABLE 3.2: Comparison between Case I and Case II.

Note: different functions are used to design case one and case two so that some of their features are not the same. In case one, three types of antennas are assumed for the BS, therefore the signal's attenuation will also be dependent on the antenna's gain function.

To realise SCM channels a drop is defined as a single simulation run, where an array of (S) elements is used by the BS for transmitting to a moving MS using an array of (U) elements for a given number of time frames. In addition, an independent path (N) is used between the transmitter and the receiver, which is defined by its powers and delays. Therefore, (N) structure time developing (SxU) matrix and their sum would define the total channel realisation:

$$H_{S,U}(t) = \sum_{n=1}^{N} \int_{-\infty}^{+\infty} H_{S,U,n}(t, \tau_n)\delta(\tau - \tau_n)d\tau_n \quad (3.2)$$

$$H_{S,U,n}(t) = \begin{bmatrix} h_{1,1,n}(t) & \cdots & h_{S,1,n}(t) \\ \vdots & \ddots & \vdots \\ h_{1,U,n}(t) & \cdots & h_{S,U,n}(t) \end{bmatrix} \quad (3.3)$$

The aim is to produce the coefficients for every time frame.
Equation (3.3) is the statistical model representing (s,u) matrix component for $H_{S,U,n}(t)$ for all (Macrocell, Urban Macrocell and Urban Microcell) environments (3rd Generation Partnership Project, 2014).

$$h_{u,s,t}^{(l)}(t) = \sqrt{\frac{P_n\, \sigma SF}{M}} \sum_{m=1}^{M} \begin{bmatrix} \sqrt{G_{BS}(\theta_{n,m,AOA}}\, exp\left[i\left(kd_s \sin\left(\theta_{n,m,AOD}\right) + \Phi_{n,m}\right)\right] \text{x} \\ \sqrt{G_{MS}(\theta_{n,m,AOA}}\, exp\left[i\left(kd_u \sin\left(\theta_{n,m,AOA}\right)\right)\right] \text{x} \\ \exp(ik||v|| \cos\left(\theta_{n,m,AOA} - \theta_v\right)) \end{bmatrix} \quad (3.4)$$

Pn: is the power of nth path.

N: is the number of paths (clusters).

M: is the number of sub-paths per path.

S: is the number of the BS linear array antenna elements.

U: is the number of the MS linear array antenna elements.

$\boldsymbol{\Phi_{n,m}}$: is the phase of the mth subpath of the nth path.

$\boldsymbol{\theta_{n,m,AOD}}$: is the AoD for the mth subpath of the nth path.

$\boldsymbol{\theta_{n,m,AOA}}$: is the AoA for the mth subpath of the nth path.

$\mathbf{G_{BS}}(.)$: is the BS antenna gain of each array element.

$\mathbf{G_{MS}}(.)$: is the MS antenna gain of each array element.

i: is is the square root of -1.

ds: is the distance in meters from BS antenna element s from the reference (s = 1) antenna. For the reference antenna s = 1, d1 = 0.

k: is the wave number 2π/ λ where λ is the carrier wavelength in meters.

du: is the distance in meters from MS antenna element u from the reference (u = 1) antenna. For the reference antenna u = 1, d1 = 0.

v: is the magnitude of the MS velocity vector.

$\boldsymbol{\theta_v}$: is the angle of the MS velocity vector.

$\boldsymbol{\sigma SF}$: is the lognormal shadow fading.

Equation (3.4) is the statistical model which represents (s, u) matrix component for $H_{S,U,n}(t)$ for all (Macrocell, Urban Macrocell and Urban Microcell) environments (3rd Generation Partnership Project, 2014).

$$h_{u,s,n}(t)=\sqrt{\frac{P_n\sigma_{SF}}{M}}\sum_{m=1}^{M}\left(\begin{array}{c}\begin{bmatrix}\chi_{BS}^{(v)}(\theta_{n,m,AoD})\\ \chi_{BS}^{(h)}(\theta_{n,m,AoD})\end{bmatrix}^T\begin{bmatrix}\exp\left(j\Phi_{n,m}^{(v,v)}\right) & \sqrt{r_{n1}}\exp\left(j\Phi_{n,m}^{(v,h)}\right)\\ \sqrt{r_{n2}}\exp\left(j\Phi_{n,m}^{(h,v)}\right) & \exp\left(j\Phi_{n,m}^{(h,h)}\right)\end{bmatrix}\begin{bmatrix}\chi_{MS}^{(v)}(\theta_{n,m,AoA})\\ \chi_{MS}^{(h)}(\theta_{n,m,AoA})\end{bmatrix}\times\\ \exp\left(jkd_s\sin(\theta_{n,m,AoD})\right)\times\exp\left(jkd_u\sin(\theta_{n,m,AoA})\right)\times\exp\left(jk\|\mathbf{v}\|\cos(\theta_{n,m,AoA}-\theta_v)t\right)\end{array}\right)$$

(3.5)

$\boldsymbol{G_{BS}^{(x)}}(.)$, $\boldsymbol{G_{MS}^{(x)}}(.)$: are the BS and MS antenna gain of each array element for the x direction (either horizontal h or vertical v).

r1: is the power ratio of waves of the nth path leaving the BS in the vertical direction and arriving at the MS in the horizontal direction (v-h) to those leaving in the vertical direction and arriving in the vertical direction (v-v).

r2: is the power ratio of waves of the nth path leaving the BS in the horizontal direction and arriving at the MS in the vertical direction (h-v) to those leaving in the vertical direction and arriving in the vertical direction (v-v). Where: r2 = r1.

$\boldsymbol{\Phi}_{n,m}^{(x,y)}$: is the phase of the mth subpath of the nth path between the x component (either the horizontal h or vertical v) of the BS element and the y component (either the horizontal h or vertical v) of the MS element.

The following parameter angles are introduced to help with the spatial description of the BS and the MS (common for all environments and cases).

Ω_{BS} : is the BS antenna array orientation, defined as the difference between the broadside of the BS array and the absolute north (N) reference direction.

Ω_{MS}: is the MS antenna array orientation, defined as the difference between the broadside of the MS array and the absolute north (N) reference direction.

$\boldsymbol{\theta}_{BS}$: is the LoS AoD direction between the BS and MS, with respect to the broadside of the BS array.

$\boldsymbol{\theta}_{MS}$: is the angle between the BS-MS LoS and the MS broadside.

$\boldsymbol{\delta}_{n,AOD}$: is the AoD for the nth (n = 1 ... N) path with respect to the LoS AoD.

$\boldsymbol{\delta}_{n,AOA}$: is the AoD for the nth (n = 1 ... N) path with respect to the LoS AoA.

$\Delta_{n,m,AOD}$: is the offset for the mth (m = 1 ... M) subpath of the nth path with respect to $\delta_{n,AOD}$.

$\Delta_{n,m,AOA}$: is the offset for the mth (m = 1 ... M) subpath of the nth path with respect to $\delta_{n,AOA}$. In Figure (3.1):

$$\theta_{n,m,AOD} = \theta_{BS} + \delta_{n,AOD} + \Delta_{n,m,AOD} \quad (3.6)$$

$$\theta_{n,m,AOA} = \theta_{MS} + \delta_{n,AOA} + \Delta_{n,m,AOA} \quad (3.7)$$

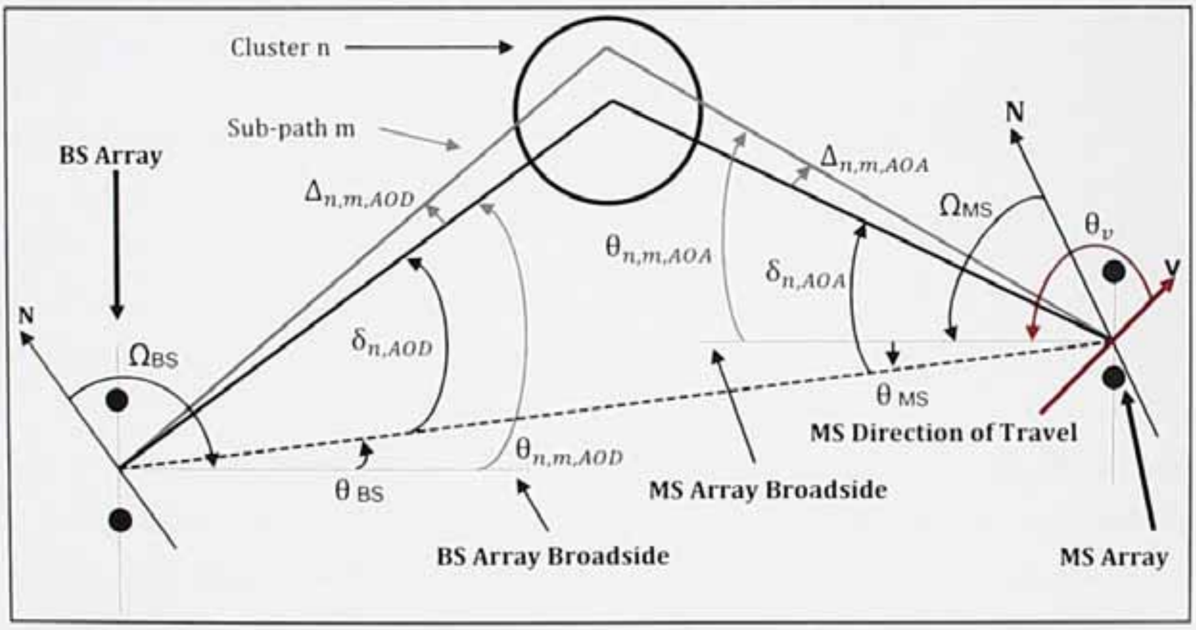


Figure 3.1: SCM Angles Parameters.

Clockwise angles are considered positive and anti-clockwise are considered negative. The negative values of the angles Ω_{BS}, Ω_{MS}, θ_{BS}, and θ_{MS} will be replaced by their positive values. For example, if $\theta_{MS} = -15^0$ we will assume that: $\theta_{MS} = 360^0 - 15^0 = 345^0$. This way we only handle positive angles. However, this does not apply to angles $\delta_{n,AOD}$, $\delta_{n,AOA}$, $\Delta_{n,m,AOD}$, $\Delta_{n,m,AOA}$which can also take negative values. Then: $\theta_{MS} = \Omega_{BS} - \Omega_{MS} + \theta_{BS} + 180^0$ (3rd Generation Partnership Project, 2014).

3.3.2. SPATIAL CHANNEL MODEL EXTENDED

SCM model described in section 3.2.1 is dedicated to a code division multiple access CDMA system with 5MHz band and 2GHz frequency. SCM-Extended model was made and used within the European WINNER project (Eurescom GmbH, 2006). SCME contains additional features compared to SCM. The extended version is broadening the channel bandwidth from 5 MHz to 100 MHz in the 2GHz and 5GHz frequency bands. In addition to NLoS option, LoS option is defined and included in this version. A K-factor model is now also available in all scenarios and it is active if the current "drop" is LoS. Equation (3.7) is a statistical model for LoS.

$$h^{LOS}_{s,u,n=1}(t) = \sqrt{\frac{1}{K+1}} h_{s,u,1}(t) + \sigma_{SF} \sqrt{\frac{K}{K+1}} \begin{bmatrix} \sqrt{G_{BS}\,(\theta_{BS})}\exp(jkd_s\, sin(\theta_{BS}))\ \times \\ \sqrt{G_{MS}\,(\theta_{MS})}\exp(jkd_u\, sin(\theta_{MS}) + \Phi_{LOS}\ \times \\ \exp(jk\|v\|\cos(\theta_{MS}-\theta_v)\,t) \end{bmatrix}$$

(3.8)

Where,

$\boldsymbol{\theta_{BS}}$: is the AoD for LoS component at the base.

$\boldsymbol{\theta_{MS}}$: is the AoA for LoS component at the terminal.

$\boldsymbol{\Phi_{LoS}}$: is the phase of LoS component.

$\boldsymbol{\theta_v}$: is the angle of the MS velocity vector.

$\boldsymbol{K}$: is the K-factor.

The 20 sub-paths of multi-path are divided into subsets, called mid-paths. These mid-paths define the intra-cluster delay spread and have different delays and power offsets relative to the original path. Each mid-path, consisting of a number of sub-paths, acts as a single tap (delay resolvable component). Grouping a number of sub-paths together makes the fading distribution of that tap approximately Rayleigh distributed. The Angle Spreads AS assigned to the mid-paths are optimised in such a way that the angular spread of all mid-paths combined is minimised. The resulting SCME impulse response has a good approximation to the respective SCM impulse response. Due to bandwidth extension, the number of tap delays increases from 6 to 18 or 20 depending upon the propagation scenario.

3.4. SIMULATION TOOLS

In VANET communication, the QoS is an essential aspect due to the dynamic environment and frequently topology changes (Saharan & Kumar, 2010). VANET simulation software allows the researcher to study and evaluate the performance of their proposed scenarios. Martinez *et al.* (2011) and Noori, (2012) said that the simulation of VANET requires three main components: VANET mobility generators, network simulators and VANET simulators. The first two component work separately. VANET mobility generators is used to provide a mobility model for the node of the VANET, while the network simulator is used for simulating the performance of the wireless network environment. Therefore, VANET simulators integrate both mobility generators and network simulators in order to evaluate effectively the performance of VANET. This section provides a comprehensive study of mobility models, network simulators and VANET simulators proposed for VANET. The study include the various available VANET simulators which are used by researchers in their studies.

3.4.1. VANET MOBILITY GENERATORS

The creation and implementation of realistic VANET simulation has become a critical issue in the field of ITS networks (Hou *et al.*, 2015). Thus, Vehicular mobility generators are needed to increase the level of realism in VANET simulations. This section presents the existing mobility generators and their features.

1- VanetMobiSim: is the extended version of the CANU Mobility Simulation Environment CanuMobiSim which is based on JAVA in order to generate vehicular mobility (Härri *et al.*, 2006). VanetMobiSim features automotive motion models at both macroscopic and microscopic levels, which can generate movement traces in different formats. The maps at the macroscopic level can be imported from the US Topologically Integrated Geographic Encoding and Referencing TIGER database (Census, 2015), or they could be generated randomly using Voronoi tessellation (Lee & Han, 2012). While, at the microscopic level, it supports mobility models such as Intelligent Driving Model IDM. VanetMobiSim is proposed to support different simulation tools such as GloMoSim (Zeng *et al.*, 1998), ns-2 (Fall and Varadhan, 2011) and QualNet (Scalable Network Technologies, 2011).

2- SUMO: Simulation of Urban Mobility (SUMO) is another VANET mobility generator which has the following features: an open source software, enabling large and highly portable road network traffic design (Krajzewicz *et al.*, 2012). SUMO can support collision free vehicle movement, different vehicle types, single-vehicle routing, multi-lane streets with lane changing, junction-based right-of-way rules, hierarchy of junction types, an open GL Graphical User Interface (GUI), and dynamic routing. SUMO can simulate large environments up to 10000 edges. Although SUMO is pure traffic generator designed to handle large road networks, it cannot be used directly as VANET network simulator where it can only create the mobility environment by converting the real world maps to simulation maps. In this case, SUMO required to be embedded with a compatible network simulator to be ready for VANET simulation such as ns-2, OMNEt++ and TraNS.

3- STRAW: STreet RAndom Waypoint (STRAW) is a vehicular mobility generator which is based on the operation of vehicular traffic to provide accurate simulation results (Choffnes and Bustamante, 2005). STRAW is one of the main resources that is used by the Car-to-Car Cooperation project. The STRAW mobility model constrains node movement to streets defined by map data for US cities and limits their mobility according to vehicular congestion and simplified traffic control mechanisms. Like the others VANET mobility models, STRAW mobility traces cannot be directly used by other network simulators.

4- CityMob: CityMob is proposed as VANET mobility generator and it is compatible with ns-2 network simulator (Martinez *et al.*, 2008). CityMob is designed to implement three different mobility models which are addressed as: Simple Model SM, Manhattan Model MM and Downtown Model DM. The SM is designed for vertical and horizontal mobility patterns without direction changes. In MM, the city is modelled as a Manhattan style grid with a uniform block size across the simulation area. All streets are two-way, with lanes in both directions. Car movements are constrained by these lanes. Vehicles will move with a random speed, within a user-defined range of values. DM model also simulates semaphores at random positions (not only at crossings), and with different delays. The DM adds traffic density in a way similar to a real town, where traffic is not uniformly distributed. Hence, there will be zones with a higher vehicle density. These zones are usually in the downtown, and vehicles must move more slowly than those in the outskirts. CityMob DM also has the following capabilities: (a) multiple lanes in both directions for every street, (b) vehicle queues due to traffic jams, and (c) the possibility of having more than a downtown.

The following table summarises VANET mobility generators.

	VanetMobiSim	SUMO	STRAW	CityMob
Source	Open	Open	Open	Open
Language	Java	C++	Java	Java
Traffic Model	Microscopic	Microscopic	Microscopic	Microscopic
Support Network Simulator	NS-2, GloMoSim, OMNeT++	NS-2, OMNeT++ and TraNS	JiST/SWAN	NS-2
Platform	Linux	Windows and Linux	Linux	Windows and Linux
GUI	Yes	Yes	Yes	Yes
Map Import	Real, User defined, Random	Real, User defined, Random	Real, User defined	Real, User defined
Setup and Usage	Moderate	Hard	Moderate	Moderate
Import different formats	Yes	Yes	Yes	No

TABLE 3.3: Comparison of Mobility Generators on VANET Environment.

3.4.2. NETWORKS SIMULATORS

Network simulators help researchers to observe the network behaviour under different conditions. Users can then customise the simulator to achieve their specific analysis needs. Compared to the cost and time involved in setting up real life hardware tests network simulators are relatively fast and inexpensive, they allow researchers to test scenarios that might be particularly difficult or expensive to emulate using real hardware, especially in VANET. Network simulators are particularly useful to test new networking protocols or to propose modifications to existing ones in a controlled and reproducible manner.

1- NS-2: The Network Simulator (NS-2) is developed by the Virtual InterNetwork Testbed VINT project research group at the University of California at Berkeley (Issariyakul and Hossain, 2009). It is widely used in the academic networking research, where it is an open-source discrete event network simulator that supports both wired and wireless networks. The core of NS-2 is written in C++ and users interact with NS-2 by writing OTcl scripts language. C++ is used to implement the detailed protocol and OTcl is used for users to control the simulation scenario and schedule the events. NS-2 separates control path implementations from the data path implementation. The Monarch research group at Carnegie Mellon University (Carnegie-Mellon University, 2001) extended NS-2 simulator by including: a physical layer with a radio propagation model, node mobility, radio network interfaces and the IEEE 802.11 MAC protocol. The OTcl script is responsible to: set up the network topology, initiate the event scheduler and tell traffic source when to start and stop sending packets through event scheduler. In NS2, the event scheduler keeps track of simulation time and release all the events in the event queue by invoking appropriate network components. All the network components use the event scheduler by issuing an event for the packet and waiting for the event to be released before doing further action on the packet.

2- NS-3: is another discrete-event network simulator which is in the academic networking research (Riley & Henderson, 2010). NS-3 is free software, licensed under the GNU GPLv2 license. It is not an updated version NS-2 since it is designed to replace the current popular NS-2. The core of NS-3 is written in C++ where Python programming language can be optionally used as an interface. The debugging in NS-2 is more complex since NS-2 is using two programming language C++ and OTcl. In addition, the performance of NS-3 is better than NS-2 in term of memory management. The emulation mode is included in NS-3 to allow the integration with real networks. A simulation script can be written as a C++ program, which is not possible in NS2. With modern hardware capabilities, compilation time was not an issue like for NS2, NS3 can be developed with C++ entirely. Automatic de-allocation of objects is supported using reference counting (track number of pointers to an object); this is useful when dealing with Packet objects. The buffer corresponds exactly to the stream of bits that would be sent over a real network. Information is added to the packet by using subclasses; Header, which adds information to the beginning of the buffer, Trailer, which adds to the end.

3- GloMoSim: Global Mobile system Simulator (GloMoSim) designed using the parallel discrete-event simulation capability to be used for wireless environments (Zeng *et al.*, 1998). It has been built as a set of library modules which is developed using PARSEC, a C-based parallel simulation language. Similar to the OSI layers GloMoSim is using layered approach, each of which simulates a specific wireless communication protocol in the protocol stack. GloMoSim is flexible where new protocols and modules can be programmed and added to the library using C-based parallel simulation language. To allow the rapid integration of models developed at different layers by different people, API standard is used between the different simulation layers. The commercial version of GloMoSim is widely used under the name of QualNet (Scalable Network Technologies, 2011).

4- OMNeT++: Optical Micro Networks Plus Plus (OMNeT++) is an object-oriented modular discrete event network simulator for wired and wireless environments (Varga & Hornig, 2008). It is an extensible, modular, component-based C++ simulation library and framework, new features and protocols can be supported through modules. Domain-specific functionality such as support for sensor networks, wireless ad-hoc networks, Internet protocols, performance modelling, photonic networks, etc., is provided by model frameworks, developed as independent projects. OMNeT++ offers an Eclipse-based IDE, a graphical runtime environment, and a host of other tools. There are extensions for real-time simulation, network emulation, database integration, Systems integration, and several other functions. Although OMNeT++ is not a network simulator itself, it is currently gaining widespread popularity as a network simulation platform in the scientific community as well as in industrial settings, and building up a large user community.

5- OPNET: OPtimised Network Engineering Tool (OPNET) is developed by OPNET technologies Inc. as a discrete event, object oriented, general purpose network simulator (Chang, 1999). In order to provide a comprehensive development environment supporting the modelling of communication networks and distributed systems, OPNET's engine consists of the combination between a finite state machine model and an analytical model. To define each characteristic of the system, OPNET uses a hierarchical model structure. The hierarchical model consists of three levels. The first level contains the network model which is used for topology design. The second level is for data flow models definition. Finally, the third level is specified for the process editor which handles control flow models defined in the second level. The three hierarchical levels are supported by including a parameter editor. The hierarchical models result in event queues for a discrete event simulation engine and a set of entities that handle the events. Each entity represents a node which consists of a finite state machine which processes the events during simulation. Over 25,000 university professors and students use OPNET products in Electrical Engineering, where it supports some simulation technologies such as:, Flow Analysis, ACE Quick Predict, Discrete Event Simulation (DES) and Hybrid Simulation within the DES environment. Finally, OPNET is only available in commercial form.

6- MATLAB: Matrix Laboratory MATLAB is the language of technical computing which is produced by the MathWorks, Inc. the leading developer of statistical computing software. MATLAB is a high-level language and interactive environment for numerical computation, visualisation, and programming. It enables the users to analyse data, develop algorithms, and create models and applications. The language, tools, and built-in math functions enable the user to explore multiple approaches and reach a solution faster than with spreadsheets or traditional programming languages (Sharma and Martin, 2009), such as C/C++ or Java™. MATLAB is widely used for a range of application, including signal processing, communication, test and measurement. More than a million engineers and scientists in industry and academia use MATLAB.

7- JiST/SWANS: Java in Simulation Time (JiST) is a high performance discrete event simulation engine that runs over a standard Java virtual machine. It is a prototype of a new general-purpose approach to building discrete event simulators, that unifies the traditional systems and language-based simulator designs (Barr *et al.*, 2005). It outperforms existing highly optimised simulation engines both in time and memory consumption. Simulation code that runs on JiST need neither be written in a domain-specific language invented specifically for writing simulations, nor must it be littered with special purpose system calls and 'call backs' to support runtime simulation. Instead, JiST converts an existing virtual machine into a simulation platform, by embedding simulation time semantics at the byte-code level. Thus, JiST simulations are written in Java, compiled using a regular Java compiler, and run over a standard, unmodified virtual machine. Scalable Wireless Ad hoc Network Simulator (SWANS) is built on top of the JiST platform. It was created primarily because existing network simulation tools are not sufficient for current research needs. SWANS contains independent software components that can be composed to form a complete wireless network or sensor network. Its capabilities are similar to ns-2 and GloMoSim, but SWANS is able of simulating much larger networks. SWANS leverages the JiST design to achieve higher simulation throughput, lower memory requirements, and run standard Java network applications over simulated networks. SWANS can simulate networks that are one or two orders of magnitude larger than what is possible with GloMoSim and ns-2, respectively, using the same amount of time and memory, and with a same level of detail.

8- SNS: A Staged Network Simulator (SNS) is proposed to improve the scale and run time performance of wireless mobile network simulators (Walsh & Sirer, 2004). Traditional wireless network simulators are limited in speed and scale because they perform many redundant computations both within a single simulation run, as well as across multiple invocations of the simulator. The staged simulation technique proposes to eliminate redundant computations through function caching and reuse. The central idea behind staging is to cache the results of expensive operations and reuse them whenever possible. SNS is a staged simulator based on ns-2. On a commonly used ad hoc network simulation setup with 1500 nodes, SNS executes approximately 50 times faster than regular ns-2 and 30% of this improvement is due to staging, and the rest to engineering. This level of performance enables SNS to simulate large networks. However, the current implementation is based on ns-2 version 2.1b9a (Martinez *et al.*, 2011), and it is not specifically designed to simulate VANET scenarios.

9- NetSim: Network Based Environment for Modelling and Simulation (NetSim) is a discrete event simulator developed by Tetcos, Inc. in 1999 (Veith *et al.*, 1999). NetSim is a leading network simulation software for protocol modelling and simulation, network R&D and defence applications. It has an object-oriented system modelling and simulation environment to support simulation and analysis of voice and data communication scenarios. It is also used simulates Cisco Systems networking and is designed to aid the user in learning the Cisco IOS command structure.

The following table summarises network simulators.

	NS-2	NS-3	GloMoSim	OMNeT++	OPNET	JiST/SWAN
License	Open Source	Open Source	Open Source	Open Source	Commercial	Open Source
Language	C++, OTCL	C++	Parsec C	C++	C++, Java	Java
Platform	Linux	Linux	Linux, Windows	Linux, Windows	Windows	Linux, Windows
GUI	Yes	Yes	Yes	Yes	Yes	Yes
Design	wireless and wired	wireless and wired	Only wireless	wireless and wired	wireless and wired	wireless and wired
LIMITATION						
NS-2	▪ Only two wireless MAC protocols are supported 802.11 and a single-hop TDMA protocol.					
NS-3	▪ Configuration and development is only text-based. ▪ The documentation of ns-3 is partially incomplete and difficult to handle. ▪ Root privileges are required when using the emulation feature, as it accesses system-level functions, which are not allowed to normal users.					
GloMoSim	▪ Effectively limited to IP networks due to the low-level design assumptions. ▪ Unavailability of new protocols.					
OMNeT++	▪ Not developed only for network simulations. ▪ Root privileges are required when using the emulation feature, as it accesses system-level functions, which are not allowed to normal users					
OPNET	▪ Quite complex tool, especially if specific component have to be developed.					
JiST/SWAN	▪ Low efficiency of simulation. ▪ The only MAC protocol provided for wireless networks is 802.11. ▪ Unnecessary run-time overhead.					

TABLE 3.4: Comparison of Networking Simulators on VANET Environment.

3.4.3. VANET Simulators

The driver response to the Inter Vehicle Communication (IVC) application is one of the important aspect in a simulation model for VANET (Sichitiu & Kihl, 2008), where the reaction of drivers in different situations could affect traffic throughput. The software that allows one to change the behaviour of vehicles, depending on a given application context is known as an integrated framework or simply a VANET simulator.

1- TraNS: Traffic and Network Simulation Environment (TraNS) is integrated simulation environment that integrates both a mobility generator and a network simulator in order to build VANET simulation environment (Piórkowski *et al.*, 2008). TraNS is an open source project providing an application-centric evaluation framework for VANET. It is written in Java and C++ where it works under Linux and Windows.
Currently, TraNS integrates the SUMO traffic simulator and the ns-2 network simulator to generate VANET simulation, which allows the information exchanged in a VANET to influence the vehicle behaviour in the mobility model. TraNS has several features including:

- Support IEEE 802.11p which is VANET standard.
- Automated generation of road networks from TIGER and Shapefile maps.
- Automated generation of random vehicle routes.
- Mobility trace generation for ns-2.

However, it supports the coupling between SUMO and ns-2 through the TraCI interface and possibility to simulate road traffic events. Also it provides ready-to-use VANET applications for road safety and traffic efficiency. Finally, TraNS can simulate large-scale networks (tested up to 3000 vehicles), and allows for Google Earth visualisation of simulations.

2- GrooveNet: GrooveNet is a hybrid simulator based on open-source Roadnav (Lynch, 2004) which enables communication between simulated vehicles, real vehicles and between real and simulated vehicles (Mangharam *et al.*, 2006). By modelling inter-vehicular communication within a real street map-based topography, it facilitates protocol design and in-vehicle deployment. GrooveNet's modular architecture incorporates mobility, trip and message broadcast models over a variety of link and physical layer communication models. GrooveNet can easily supports simulations of thousands of vehicles for US cities and to add new models for networking, security, applications and vehicle interaction. It supports multiple network interfaces, GPS and events triggered from the vehicle's on-board computer. Through simulation, GrooveNet has the ability to evaluate the message latency, and coverage under various traffic conditions. On-road tests over 400 miles lend insight to required market penetration.

GrooveNet supports three types of simulated nodes:

- Vehicles which are capable of multi-hopping data over one or more DSRC channels.
- Fixed infrastructure nodes.
- Mobile gateways capable of V2V and V2I communication.

Moreover, GrooveNet supports multiple message types such as GPS messages, which are broadcast periodically to inform neighbours of a vehicle's current position, and vehicle emergency and warning event messages with priorities. Multiple rebroadcast policies have been implemented to investigate the broadcast storm problem. GrooveNet is able to support hybrid simulations where the simulated vehicle position, direction and messages are broadcast over the cellular interface from one or more infrastructure nodes. Real vehicles communicate only with those simulated vehicles which are within its transmission range. GrooveNet generates street level maps for any place in the USA (Census, 2015) by importing TIGER files which are available free from the US Census Bureau.

3- EstiNet: is a world-renowned software tool for network planning, testing, education, protocol development, and applications performance prediction (EstiNet Inc., 2010). It is the commercial version of the National Chiao Tung University Network Simulator and Emulator NCTUns 6.0. It is both a network simulator and a network emulator and has worldwide customers and global impact. It is a very useful tool for studying cloud computing and various next-generation networks. Currently, it runs on the Linux operating system and supports the latest Fedora 20 Linux distribution.

EstiNet has important capabilities such as:

- OpenFlow network simulations.
- IEEE 802.11n network simulations.
- High-Level Architecture distributed emulations.
- Most up-to-date IEEE 802.11p/1609 VANET network simulations.
- Real-life emulations in which the client and server machines reside on two different subnets on the Internet.
- Realistic destination-oriented vehicle movement on the road VANET simulation. EstiNet network simulator and emulator has many useful features.

It can easily be used as an emulator since it supports seamless integration of emulation and simulation. It uses Linux TCP/IP protocol stack to generate high-fidelity simulation results. Supported networks include IEEE 802.11n networks, IEEE 802.11(p)/1609 WAVE wireless vehicular networks, IEEE 802.3 Ethernet-based fixed Internet, IEEE 802.11(a/g) wireless LANs, mobile ad hoc networks, IEEE 802.11(e) QoS wireless LANs and wireless vehicular networks VANET for Intelligent Transportation Systems ITS. EstiNet supports parallel simulations on multicore machines. By using an innovative parallel simulation approach, it supports parallel simulations for fixed networks on multi-core machines. It also provides a highly integrated and professional GUI environment (EstiNet Inc., 2010).

4- MobiREAL: MobiREAL is a network simulator for MANET. It provides a new methodology to model and simulate realistic mobility of nodes and enables to evaluate MANET applications in more actual environments (Osaka University, 2009). MobiREAL provides a new methodology to model and simulate realistic mobility of nodes and evaluate MANET applications. It is a network simulator that can simulate the mobility of humans and vehicles, and allow the changing of their behaviour depending on a given application context. MobiREAL (Osaka University, 2009) can easily describe mobility of nodes using C++. It adopts a probabilistic rule-based model to describe the behaviour of mobile nodes, which is often used in cognitive modelling of human behaviour. The proposed model allows one to describe how mobile nodes can change their destinations, routes and speeds/directions based on their positions, surroundings (obstacles and neighbouring nodes), and information obtained from applications. MobiREAL enables to simulate MANETs by adding mobility support facilities to the Georgia Tech Network Simulator GTNetS (Riley, 2008) where mobile nodes join/leave, their movement and packet collision among them are newly developed.

5- Veins: Vehicles in Network Simulation (Veins) is an open source framework for running vehicular network simulations (Sommer et al., 2011). It is based on two simulators: OMNeT++ (Varga and Hornig, 2008), an event-based network simulator, and SUMO (Behrisch et al., 2011), a road traffic simulator. It extends these to offer a comprehensive suite of models for IVC simulation. The Veins framework includes a comprehensive suite of models to make VANET simulations as realistic as possible, without sacrificing speed. The GUI and IDE of OMNeT++ and SUMO (Sommer, 2015) can be used for quickly setting up and interactively running simulations.

Veins has the following features:

- Allows for online re-configuration and re-routing of vehicles in reaction to network packets.

- Relies on fully-detailed models of IEEE 802.11p and IEEE 1609.4 DSRC/WAVE network layers.
- Relies on trusted vehicular mobility model and implementation done by Transportation and Traffic Science community.
- Can employ validated, computationally inexpensive models of shadowing effects caused by buildings as well as by vehicles.
- Can import whole scenarios from OpenStreetMap, including buildings, speed limits, lane counts, traffic lights, access and turn restrictions.

Road traffic simulation is performed by SUMO, which is well-established in the domain of traffic engineering. Network simulation is performed by OMNeT++ along with the physical layer modelling toolkit MiXiM, which makes it possible to employ accurate models for radio interference, as well as shadowing by static and moving obstacles (Sommer, 2015). Both simulators are bi-directionally coupled and simulations are performed online. This way, the influence of vehicular networks on road traffic can be modelled and complex interactions between both domains examined. Domain specific models for vehicular networking build on this basis to provide a comprehensive framework that is still easy to learn and use.

3.5. CHAPTER SUMMARY

The challenges faced by the conventional V2V communication models are represented by the signals propagation such as multi-path/sub-path fading and the dynamic environments. In addition, most of the obtained results that evaluate the channel performance in V2V are based on simulation, where these results hardly reflect the reality of the V2V channel performance. Many research and implementation works regarding VANET simulation have been done using different approaches and methods. The main reason behind these researches is how to find appropriate radio propagation model in order to be utilised in VANET communication. In this aspect, very basics radio propagation models are used Mitra, (2009) and Zhang & Chen (2013) e.g. the Ray tracing model and Friis model. On the other hand, deterministic channel models based on ray-tracing presented in Delahaye *et al.*, (2007) and Stepanov & Rothermel, (2008) were proposed to be used as VANET channel model. These models require very high computational times. Therefore, deterministic channel models are not suitable because of the high mobility, the diversity of the environment encountered, and the high number of communicating nodes. Wang *et al.* (2014) proposed a propagation model based on Markov chain elements and real world experiments is able to generate packet losses in a realistic way (Wang et al., 2014). However, Wang *et al.* (2014) model is not yet able to make a clear relation with a real environment. The nature of VANET environment adds more challenges to the communication between and among the vehicles. Therefore, a robust channel model for VANET is needed in order to reflect the reality and to overcome the high computational power which is needed during the simulation time. For this reason, this chapter discussed the Spatial Channel Model SCM and Spatial Channel Model Extended SCME to give an overview about the developed channel model V-SCME in Chapter (5).

CHAPTER FOUR
MIMO SYSTEMS: CHANNEL CODING

4.1. INTRODUCTION

Radio communication systems must continually provide higher data rates, whether to mobile radio 3G, 4G, etc. or Wireless Radio Networks (WLAN) communications (UK Essays, 2013). The increase of data rates can be achieved by providing larger bandwidths, the use of higher modulation types, the use of switching techniques, applying compression techniques or introducing multiple antenna systems (multiple links) which do not need additional bandwidths or increased transmit power (Swarnakar & Pant, 2013). MIMO terminology refers to Multiple-Input-Multiple-Output, which is a special robust class of smart antenna technology in the wireless systems where each single transmitter and receiver has multiple antennas (Marsch *et al.*, 2015). MIMO systems can support the communication performance of different applications by improving the efficiency (Xiangyi *et al.*, 2012), and also help to improve the connectivity by increasing the data rate to transmit several streams in parallel at the same transmit power (Halperin *et al.*, 2010). Furthermore, MIMO can also support efficiency in providing high mobility speeds such as: 3G, 4G, vehicular communications etc. MIMO systems can be employed for diversity gain. It also uses space and multiplexing for transmitting different information streams across it and this is known as spatial multiplexing. Spatial multiplexing literally means multiplexing parallel information streams in space. The unique aspects of MIMO systems are the increase in the data rate which is possible through multi-dimensional signal processing.

This chapter has covered a lot of ground including the principles of MIMO systems and their use over VANET technology. Sections (4.4), (4.5) and (4.6) respectively discuss the fading models and diversity schemes. Finally, the chapter presents a number of MIMO coding techniques which have been used with the proposed channel model in this research in order to improve the communication in V2V.

4.2. PRINCIPLES OF MIMO SYSTEMS

MIMO seems rather counter intuitive but it actually relies on lots of interference. That is the reason why a direct signal path between the BS and the subscriber station is not preferred. A good diversity in the signal propagation is needed for MIMO systems to work to its best advantage (Burr *et al.*, 2010). Therefore, Garg *et al.* (2013) showed that anything that interferes with the signal paths such as buildings and natural objects etc. will help in the overall efficiency and effectiveness of MIMO applications. MIMO systems consist of three main elements: the transmit signal process using Multiple Inputs (MI), the Radio Frequency (RF) channel and the receive signal process using Multiple Outputs (MO). The transmitter assigns the transmitted signal to antennas using pre-coding values which consider complex stages of processing such as Space-Time Block Code (STBC). After the whole process of preparation the signal is ready to be sent over the RF channel and that is why it is defined as multiple in MI that is the IN to the RF channel. In the receive side, the receiver may have multiple antennas so each receiver may have multiple receive channels which is called Multiple Out MO. Also these received signals have to be processed, so a way of combining the information from multiple receivers is needed in order to get the best information. Figure (4.1) illustrate conventional MIMO systems matrix.

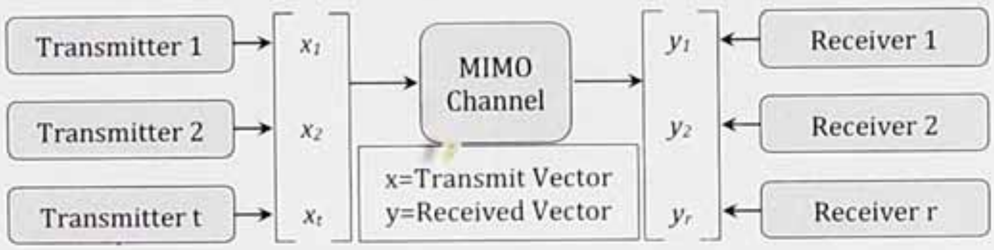


Figure 4.1: Conventional MIMO System Matrix.

x: represents the transmit vector, where, $x_1, x_2, \dots, x_t$ are the transmit symbols from $antenna_1$, $antenna_2$ and $antenna_t$.

y: represents the receive vector, where, $y_1, y_2, \dots, y_t$ are the receive symbols from $antenna_1$, $antenna_2$ and $antenna_t$.

So t is transmit dimensional vector and r is receive dimensional vector. The extended conventional MIMO systems can be represented as in Figure (4.2):

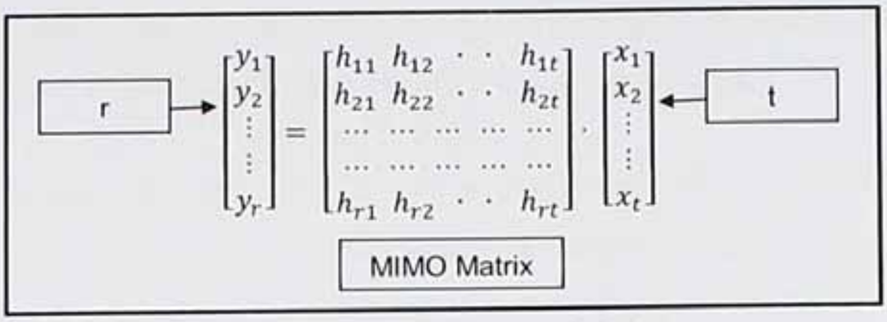


Figure 4.2: MIMO Systems Extended Matrix.

Each entry of the channel matrix $\boldsymbol{h_{r1}}$ $\boldsymbol{h_{r2}}$ $\boldsymbol{h_{rt}}$ are flat fading channel coefficients discussed in section (4.4.1). The MIMO channel matrix simplicity as:

$$y_1 = h_{11}x_1 + h_{12}x_2 + \cdots + h_{1t}x_t \quad (4.1)$$

$$y_2 = h_{21}x_1 + h_{22}x_2 + \cdots + h_{2t}x_t \quad (4.2)$$

Each transmit symbol $\boldsymbol{x_1}$ $\boldsymbol{x_2}$ …… $\boldsymbol{x_t}$ interfere at receive antennas $\boldsymbol{y_1}$, $\boldsymbol{y_2}$.

h_{ij} : is the channel coefficient between the i^{th} receive antenna and j^{th} transmit antenna.

h_{11} : R_x antenna 1 and T_x antenna 1.

h_{21} : R_x antenna 2 and T_x antenna 1.

MIMO systems model can be expressed as:

$$Y(t) = H(t) \cdot X(t) + N(t) \quad (4.3)$$

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ \vdots \\ y_r \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdot & \cdot & h_{1t} \\ h_{21} & h_{22} & \cdot & \cdot & h_{2t} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ h_{r1} & h_{r2} & \cdot & \cdot & h_{rt} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_t \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ \vdots \\ n_r \end{bmatrix} \quad (4.4)$$

Where,

Y: is r dimensional receive vector.

H: is r×t dimensional channel matrix.

X: is t dimensional transmit vector.

N: is r dimensional noise.

The noise is represented as ***r*** dimensional vector where ***n*** is the noise of each path which is equal to the number of receivers:

$$n = \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_r \end{bmatrix} \quad (4.5)$$

The power of each noise component is denoted by P. Formula (4.6) represents the power in each noise component for each receive antenna where σ is the variance:

$$P\ (\,|n_i|^2) = \sigma n^2 \quad (4.6)$$

The time varying impulse $h(t\,,\tau)$ can be used to characterise any linear wireless channel, where t is absolute time and τ is time lapse since impulse. Channel characterisation (Herbert *et al.*, 2014) in this way requires knowledge of the joint probability distribution of the channel over all t and τ, which in reality is not usually achievable. Instead it has been observed that many real world channels can be assumed to be Wide-Sense Stationary Uncorrelated Scattering (WSSUS) channels, which simplifies the analysis of $h(t\,,\tau)$. Furthermore, the noise processors at different receive antennas is assumed to be temporally uncorrelated (Hachem *et al.*, 2002). This assumption is considered since it is Gaussian independent, because there are different receive antennas so the noise processes are uncorrelated (Friedlander, 2008).

$$P\ (\,n_i\,n_j^*\,) = 0 \quad (4.7)$$

Equation (7.4) is the correlation between the noises at ***i, j*** receive antenna, where $\boldsymbol{n}^*$ is the opposite sign of the imaginary part. The multi-dimensional correlation of covariance matrix $P\ (\,nn^H\,)$ of this noise is represented as:

$$P\ (\,nn^H\,) = P\left(\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ \vdots \\ n_r \end{bmatrix} [n_1^*\ n_2^*\ \dots\ n_r^*]\right) = P = \left(\begin{bmatrix} |n_1|^2 & n_1 n_2^* & n_1 n_r^* \\ n_2 n_1^* & |n_2|^2 & n_2 n_r^* \\ n_r n_1^* & n_r n_2^* & |n_r|^2 \end{bmatrix}\right) \quad (4.8)$$

So it is observed that when the inspector operator P is taken each of the diagonal components represents σn^2:

$$|n_1|^2\ |n_2|^2 \dots\dots |n_r|^2 = \sigma n^2 \quad (4.9)$$

And each component in the off diagonal = 0.

$$n_1 n_2^*\ n_2 n_1^* \dots\dots = 0 \quad (4.10)$$

$$P(nn^H) = \begin{bmatrix} \sigma n^2 & 0 & 0 \\ 0 & \sigma n^2 & 0 \\ 0 & 0 & \sigma n^2 \end{bmatrix} \quad (4.11)$$

This is also termed as a white noise which is uncorrelated across antennas and time that has a covariance of:

$$P(nn^H) = \sigma n^2\, I \quad (4.12)$$

4.3. MIMO TECHNOLOGY IN VANET

There is a variety of significant research challenges which need to be overcome. These challenges are due to the fact that MIMO technique is exploited in wireless communications. (Yousefi *et al.*, 2006; Jakubiak & Koucheryavy; 2008; El-Keyi *et al.*, 2012) discussed some of the key research issues which include:

- Channel evaluation.
- The processing of space time signal in V2V.
- Channel modelling.

Bliss *et al.* (2005) said that MIMO systems provide considerable advantages including having a wider coverage area, enhancing the multi fading environments and improving higher data throughputs. Providing a high data rate at a high QoS in VANET communications system (Xue & Ganz, 2003; Dok *et al.*, 2010) is considered as the most important challenges in this research area. Due to the factors which could affect the signal strength like scattering, reflection and interference, the link reliability is needed to improve the QoS. However, Bolcskei, (2006) stated that MIMO technology can meet these issues in terms of increasing the inbound and outbound data traffic.

Darbari *et al.* (2010) showed that MIMO systems can be classified into two main categories which are smart antennas and spatial multiplexors. The function of smart antennas is that they utilise diversity gain, array gain and/or interference suppression to offer an increased Signal to Noise and Interference Ratio (SNIR) (Kapoor *et al.*, 1999). Each individual transmitter antenna sends the signals with a simple gain and delay differences which can be set appropriately so that an improved SNIR can be accomplished. From this technique, better spectral efficiency can be obtained i.e. greater range and/or decreased latency. Spatial multiplexors or coding are able to give an increased channel capacity directly (Tse & Viswanath, 2004). A single transmit antenna sends out an independent sub-stream signals with N transmit and N receive antennas.

4.3.1. BENEFIT OF MIMO TECHNOLOGY IN VANET

MIMO can provide a variety of prospective benefits that meet the major challenges. Furthermore, the benefits of MIMO can aid the exploitation of opportunities in the V2V applications. The benefits of MIMO to VANET are demonstrated below:

- **MIMO adaptability best matches various scenarios:** In order to obtain the highest possible data rate such as media streaming, spatial multiplexing would have to be used (Fleury & Qadri, 2012), while the short warning messages, in safety applications, require a diversity scheme. This adaptability is evident in the capability to constitute the multiple antennas in multiple modes, based on the interference intensity, propagation environment and the vehicular application of interest and to meet the safety requirements and satisfactory user experience applications. Furthermore, beam forming techniques focus the transmitted signal, expanding the communication range (Kadhim, 2014). In areas where vehicle density is relatively low, i.e. highway and rural areas, this longer scope of communication can be incredibly useful (Losilla *et al.*, 2011).

- **High dynamic network:** There is a highly dynamic V2V channel due to the fact to the multipath fading environment. Attia *et al.* (2012) stated that MIMO best invests this highly dynamic channel. In terms of MIMO, channel matrices are used to represent the intense multi-path fading. MIMO gathers or moves toward the theoretical diversity and multiplexing gains characterised, space-time signal processing coding scheme (Zhang *et al.*, 2008).
- **Video stream:** DSRC standard is unable to support High Definition Video HDV with 20 Mbps as it uses single input -single output radios. In addition, the radio won't be able to support high definition stream over internet protocol with 12-15 Mbps per stream, because of the limitation of the data rate (El-Keyi *et al.*, 2012). Using MIMO systems increase the channel capacity and data throughput and reduce the BER as well, so satisfying video streaming requirements.

4.4. FADING CHANNEL MODELS

Knopp & Li, (2005) and Intini *et al.* (2015) stated that the wireless communication signal faces challenges such as instability environment and fades due to multipath propagation, as a result this affects the signal's phase and amplitude. Nagel & Morscher, (2011) said that the scatterers like trees, buildings and vehicles which are within the environment of the transmitter and receiver leads to produce multipath of signals. In this case, Wong, (2000) said that the receiver will receive a multi copies of the transmitted signal form different paths. Each received signal copy has a different attenuation, delay and phase shift. The outcome could be constructive or destructive interference (Srivastava, 2010), in addition the signal power could be amplifying or attenuating which can be determined at the PHY of the receiver side using special signal processing techniques. Fading can be represented as large scale fading or small scale fading:

- **Large Scale Fading:** Large scale fading (Rappaport, 2001) is the outcome of the signal attenuation. Large scale fading occurs when the transmit signal propagate over large distance and the signal reflected by the surrounding objects in the transmitting path.
- **Small Scale Fading:** Small scale fading (Gibson, 2012) refers to the changes in signal amplitude and phase (small attenuation) caused by reflectors and scatterers (buildings, trees, vehicles ... etc.), which are present in the transmitting/receiving area. These changes cause the transmitted signal to arrive at the receiver as multiple versions and this leads to cause great variation within a half wavelength in the spatial position between transmitter and receiver.

4.4.1. RAYLEIGH FADING

Sklar, (1997) and Venkateswarlu & Jkr, (2014) stated that Rayleigh fading is classified as the worst case fading type because it is used to simulate the rapid amplitude changes when the direct ray component does not exist. Rayleigh fading is caused by multipath reception. According to Rayleigh distribution showed by Sharma *et al.* (2014), the magnitudes of the signals which are already transmitted via the transmission medium will fade randomly. During the transmission and when the receiver is traveling in a few wavelength distance a one ray model distribution scale is used as a small scale. One ray channel model distribution scale (Shiu *et al.*, 2000) is efficient to simulate the effects of rapid amplitude fluctuations. While the one ray exposed to scatterers is close to the receiver it produces a large number of rays which are arriving to the receiver from all different directions. The signals add in and out of phase giving rise to amplitude fluctuations that vary at a rate that is dependent on the speed of the receiver. Nikookar & Hashemi, (1993) used Rayleigh PDF as a statistical model to describe the amplitude variations of fading. The factor that lead to produce signal separation in the frequency domain is the receiver movement due to the Doppler effects. In general, waves arriving from the direction of motion cause a positive Doppler shift (Mathur, 2005) Figure (4.3), while waves coming from the opposite direction cause a negative Doppler shift.

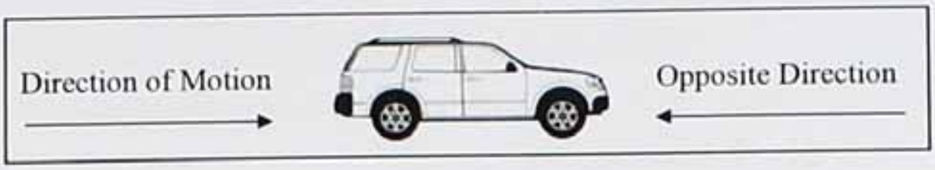


Figure 4.3: Waves Direction.

Equation (4.14) (Mathur, 2005) is showing the Doppler offset:

$$f_{D,n}(t) = f_m \cos(\theta_n(t)) \quad (4.13)$$

Where,

f_m = maximum Doppler frequency = v / λ.

λ is the wavelength of radio.

$\theta_n(t)$ is the angle between the objects that is changing over the time.

4.4.2. RICIAN FADING

The Rician model (Zheng & Beaulieu, 2003) is used to add LOS component in the received signal to the Rayleigh model. It considers that the main signal can be divided into two main signals such as LOS and the ground reflection so that the angle of arrival of LOS component can be adjusted. In addition, Rician fading (Ma & Zhao, 2007) add a bias to the Rayleigh PDF. K-factor is the definition for the ratio of the signal power in the LOS component to the local mean scattered power of the Rayleigh modulated component. This model is often used to simulate a rural environment which is common in microcellular systems. $K = 0$ transforms this model into the Rayleigh fading model and setting $K = \infty$ would transform it into a simple AWGN model with no fading.

4.4.3. SUZUKI FADING

The function of this statistical model is to provide the composite distribution of the log normal onto the Rayleigh distribution (Suzwi, 1977). Suzuki model is often useful to simulate and evaluate the link performance of slow movement or a stationary state. Due to shadowing effects, the average received power level fluctuates slowly so that the receiver has difficulty in averaging the effects of fading (Misra, 2013). The log normal is represented by the standard deviation of the average signal power level (Mobile Station MS speed) and a de-correlation length, which determines the rate at which the average power level changes. The de-correlation length determines the size of the shadow the receiver is moving through. "The de-correlation length along with the vehicle speed determines the actual rate at which the average signal power level changes at the receiver" (Keysight Technologies, 2014).

4.5. CHARACTERISATION OF FADING CHANNELS

A simple classification of fading radio channels (Biglieri, 2005) Figure (4.4) can be setup upon coherence bandwidth and coherence time of the physical channel.

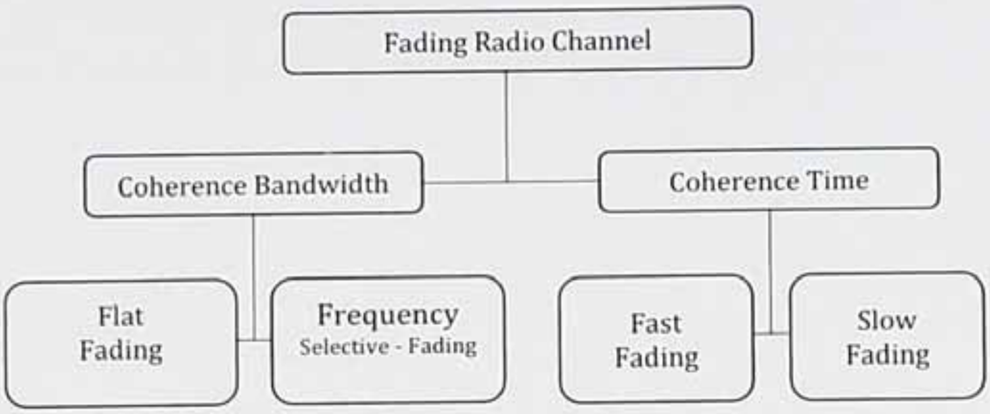


Figure 4.4: Classification of Fading Radio Channel.

4.5.1. COHERENCE BANDWIDTH

Coherence bandwidth discusses whether the fading is a flat fading or frequency selective fading.

- **Flat Fading**

Flat fading , also called narrow-band channels, occurs when the bandwidth of the signal B_S is smaller than bandwidth of the channel B_C , or the symbol period T_S is greater than the Root Mean Square RMS delay spread σ_τ (Richards, 2008). All the transmitted frequency components facing almost identical propagation delay and the received signal sampled at symbol rate is given by:

$$r(k) = \left(a_I + ja_Q\right).s(k) \quad (4.14)$$

Where,

$s(k)$: is transmitted symbol at sample k.

$r(k)$: received signal sample.

Gustafsson, (2003) mentioned that in flat fading the inter-symbol interference ISI is not existing but the channel coefficients can be still time varying, whereas a_I and a_Q are time varying fading. Time varying nature of a_I and a_Q is characterised by Doppler spectrum $S(f)$ and $a = \sqrt{{a_I}^2 + {a_Q}^2}$ is Rayleigh distribution fading.

- **Frequency Selective**

Frequency selective fading , also called wideband channels , (Taylor *et al.*, 2010) occurs when the bandwidth of the channel B_C (channel coherence bandwidth) is smaller than bandwidth of the signal B_S, or the root mean square delay spread σ_τ is greater than the symbol period T_S . In this case, the channel has different delays and gains for different frequency components, and symbol rate received signal sample is given by:

$$r(k) = \sum_{i=0}^{N-1} \left(a_{I,i} + j a_{Q,i}\right) \cdot s(k-i) \quad (4.15)$$

Where,

$s(k)$: is transmitted symbol at sample k.

$r(k)$: received signal sample.

In the frequency selective fading, channel introduces inter-symbol interference ISI, and an equaliser is required at receiver. Each component of the multipath fading represented as: $a_{I,i} + j a_{Q,i}$ which represents a Rayleigh fading, with $a_i = \sqrt{{a_{I,i}}^2 + {a_{Q,i}}^2}$ Rayleigh distribution. However, time varying rate of the channel depends on Doppler spread (Biglieri, 2005).

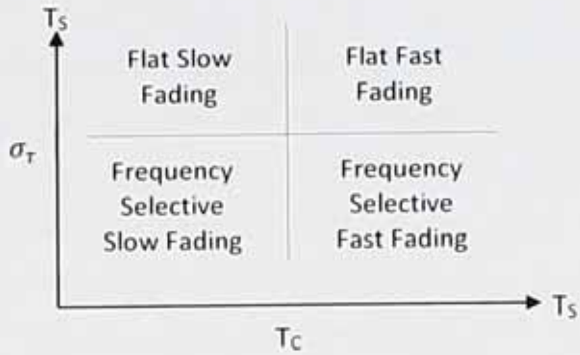
Coherence Bandwidth Fading Summary

T_S: Symbol Period.	B_S: Signal bandwidth.	B_D: Doppler Spread.
T_C: Coherence Time.	B_C: Coherence Bandwidth.	σ_τ: RMS Delay Spread.

Time Varying Rate Depends On:
T_S / T_C OR B_S / B_D.

Slow fading occurs when:
$T_S \ll T_C$ OR $B_S \gg B_D$.

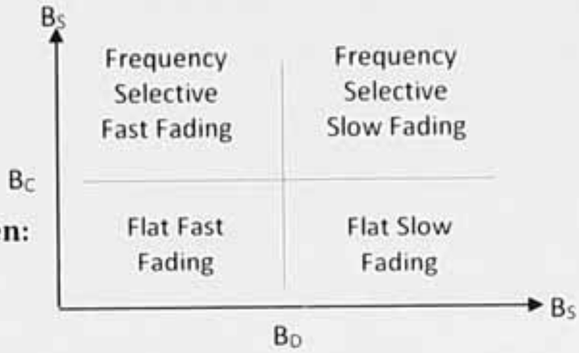
Fast fading occurs when:
$T_S > T_C$ OR $B_S < B_D$.



Frequency Selective Depends On:
T_S / σ_τ OR B_S / B_C.

Flat fading occurs when:
$T_S \gg \sigma_\tau$ OR $B_S \ll B_C$.

Frequency selective fading occurs when:
$T_S < \sigma_\tau$ OR $B_S > B_C$.



4.5.2. COHERENCE TIME

- **Slow Fading (Long Term Fading)**

Slow fading (Yarkoni *et al.*, 2006) can be caused by the large reflected and diffracted objects such as a hill or large building coming in the main path of the transmission. These obstruction causes path loss variation. However, slow fading (Richards, 2008) technically arises when the coherence time of the channel T_C is greater or relative to the delay constraint of the channel. "The amplitude and phase change imposed by the channel can be considered roughly constant over the period of use" (Yilmaz *et al.*, 2015). The movement of the MS to the distance objects is small and the propagation changes slowly.

- **Fast Fading (Short Term Fading)**

Fast fading (Yarkoni *et al.*, 2006) occurs due to reflection of local objects and the movement of MS from this objects. The MS movement for a short distance causes rapid fluctuations of amplitude. The coherence time of the fast fading channel T_C is smaller than the symbol time period of the signal transmitted T_S and the signal bandwidth B_S is lesser than Doppler spread B_D. In fast fading (Richards, 2008), the variations in the channel conditions is considered an advantage which can help the transmitter to increase reliability of the communication by using time diversity.

4.6. DIVERSITY SCHEMES

Diversity scheme (Khan *et al.*, 2007) is a very powerful techniques used in MIMO coding to combat fading in mobile/wireless communications channels. Researches studies (Tarokh *et al.*, 1999; Zheng & Tse, 2003; Kumar, 2012) on multiple antennas systems including channel capacity and the design of communication schemes demonstrates a great improvement of performance in the wireless communication system. The spectral efficiency in MIMO systems (Zheng & Tse, 2003) is much higher compared to the conventional single-antenna channels. Conventionally, the propagation issues such as channel fading significantly affect the reliability of wireless communication (Viriyasitavat *et al.*, 2015). Multiple antennas systems is used to increase the diversity in order to overcome the channel fading problem.

Singh & Eram, (2014) said that diversity scheme means improvement of the reliability of wireless signal massages. This improvement occur when multiple channels (Multiple antennas in the transmitters and/or receiver sides) with different characteristics are in use.

The replicas of the transmitted signal caused by MIMO needs to be provided with lowest consumption of the power, bandwidth and decoding complexity at the receiver which is an important issue. Another important issue (Jafarkhani, 2005) is how to use these replicas in order to receive the lowest of errors in the recipient. To achieve more reliable reception (Zheng & Tse, 2003) the transmitter sends signals that are carrying the same information through different paths, so that multiple independently faded replicas of the data symbol can be obtained at the receiver. Diversity (Bölcskei *et al.*, 2008) has important roles in channel interference, overcome multipath fading and avoiding error bursts.

4.6.1. ANTENNA DIVERSITY

Antenna diversity also known as space diversity is one of the diversities methods which is used to increase the link reliability in wireless communications (Garg *et al.*, 2013). This method involves installing a second diversity antenna below the first primary antenna at each location in the transmit/receive path Figure (4.5).

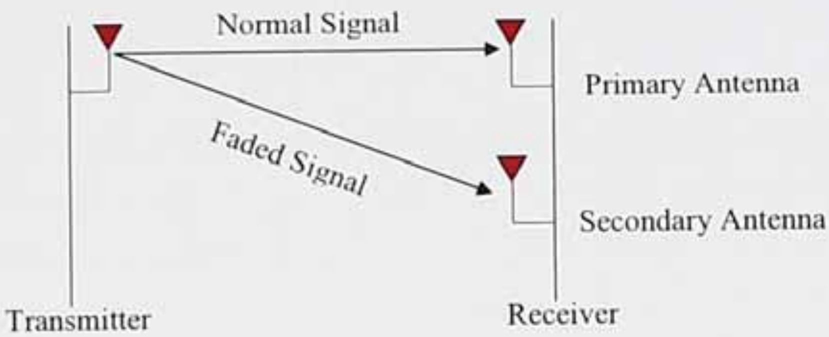


Figure 4.5: Antenna Diversity.

Antenna diversity acts against multi-path fading by automatic switch between primary and secondary antennas (Shoaib, 2010). This is done at the BER failure point or signal strength attenuation point to the secondary antenna that is receiving the transmitted signal at a stronger power rating. Valenzuela-Valdes *et al.* (2009) stated that it is important to have a vertical separation between the primary and secondary antennas in order to have a full gain. In more details, the diversity antenna will create another signal path between the two positions. "The new signal path is useful to specify which path to use. In the main path receiver switching and combining equipment are used to find out the fading. If fading occurs, the equipment switches to the diversity receiver" (Armintrout & Eimer, 2013). Consequently, the signal switches back to the main receiver when fading on the main path has subsided. Some factors that can cause the fading such as K-factor and signal reflection are discussed. K-factor is used to calculate signal propagation. The signal's propagation changes based on the weather, time of year and time of day.

Signal can take many different paths between sender and receiver due to reflection. It can cause fading because the reflected signal has the ability to interfere with the main signal and make it weak.

(Armintrout & Eimer, 2013) said that the best vertical separation between the primary and the secondary antennas needs to be calculated and optimised in both direction. Equation (4.16).

$$\text{ISD} = \frac{(7 * 10^{-5}) * f * s^2 * 10^{\frac{p}{10}}}{D} \qquad (4.16)$$

Where:

ISD: Antenna diversity improvement factor.

f: Frequency (GHz).

s: Vertical antenna spacing between antenna centres (feet).

D: Path length (miles).

p: is the fade margin associated with the second antenna.

In wireless communication system, the use of MIMO improves the performance (Bliss, 2008). Umar, (2004) said that the signal is propagated along different paths as a result it does not affect the same level of fading. Raoof *et al.* (2011) stated that the use of joint transmit and receive diversity is performed in multiple antennas systems, this allows multiple users to share a limited communication spectrum and avoid co-channel interference. The performance of spatial diversity scheme can be efficiently beneficial, once the T_x/R_x antenna array is properly configured to suit the propagation environment characteristic. Raoof *et al.* (2011) showed that this could be achieved by combining multiple branches in order to reduce the probability of fades in fading channels.

In MIMO systems, the provided gain can be classified in to two main categories: diversity and spatial multiplexing gains (Jr *et al.*, 2005). Zheng & Tse, (2003) stated that the researchers exerting their efforts to get either highest diversity gain or highest spatial multiplexing gain and it is not necessarily that maximising one type of gain will maximise the other. Vicario & Anton-Haro, (2005) proposed a cross-layer approach to overcome the switching problem between the two different types of gains. The proposed cross-layer approach showed a considerable performance gains while computational complexity still remains affordable.

a) Diversity Gain

The use of multiple antennas systems in transmit and receive sides will increase the reliability of communication system, this reliability is known as diversity gain (Jafarkhani, 2005; Prayongpun & Raoof, 2009). The diversity gain compares the BER versus the SNR. It measures the increase of BER against the SNR and could be expressed as the slope of the error rate as a function of SNR when SNR tends to infinity.

$$d = -\lim_{\mathrm{SNR}\to\infty} \frac{\log(P_e(\mathrm{SNR}))}{\log(\mathrm{SNR})} \qquad (4.17)$$

b) Spatial Multiplexing Gain

MIMO systems provide higher data rate than Single – Input – Single – Output systems (SISO). MIMO systems transmits different data stream from each transmit antenna in separate spatial dimensions to achieve the multiplexing gain. Multiplexing gain is a measure of the SNR improvement compared to a diversity system. The gain measured based on Shannon theorem (Shannon, 1948).

The theorem considers that the capacity for SISO links given by log $(1 + \mathrm{SNR})$ and MIMO links is given by:

$$\min(N_R, N_T) \log(1 + \mathrm{SNR}) \qquad (4.18)$$

Then, it is now a convention to refer to min (NR, NT) as multiplexing gain. The spatial multiplexing order is expressed as:

$$r = \lim_{\mathrm{SNR}\to\infty} \frac{\mathrm{R}(\mathrm{SNR})}{\log(\mathrm{SNR})} \qquad (4.19)$$

c) Diversity-Multiplexing Gain

The Diversity–Multiplexing trade-off (Zheng & Tse, 2003) is essentially the trade-off between the error probability and the data rate of a system. In this context the increase of link reliability against fading is required. This can be done by maximising the diversity gain and maximising the multiplexing gain in order to achieve the best spectral efficiency. The trade-off represented as:

$$d(r) = (N_T - r)(N_R - r); \quad r = 0, \dots, \min(N_T, N_R) \qquad (4.20)$$

This indicates that if r pairs of antennas are reserved for spatial multiplexing, it remains (NT - r) transmit antennas and (NR - r) receive antennas to be exploited for diversity gain. However, coding techniques (Freitas *et al.*, 2006) can adopt as a solution for inherent diversity-multiplexing trade-off.

4.6.2. FREQUENCY DIVERSITY

Awad *et al.* (2014) described Frequency diversity as it is implemented by using several channels to transmit the signal in different frequencies which refer to multicarrier transmission. As a result of this transmission different multipath are present. Multicarrier transmission has many techniques such as CDMA and OFDM (Taha & Salleh, 2009; Reiners

& Rohling, 1994). Frequency diversity is employed in line of sight LOS link which uses Frequency Division Multiplexing (FDM). Wideband *et al.* (2007) stated that the carrier frequency needs to be uncorrelated to each other so as not to experience the same fads. In order to minimise the correlated carrier frequencies, they should be separated by more than the coherence bandwidth of the channel. The uncorrelated channels could lead to simultaneous fading which is the result of the individual fading.

4.6.3. PATTERN DIVERSITY

In antenna diversity, the size and cost of antenna are challenges, and the antennas spacing is another major challenge, so that it may be deficient for the wireless communications (Khade & Badjate, 2013). However, the pattern diversity is considered useful among the other diversities techniques since it consists of the use of several collocated antennas with different radiation patterns (Lee *et al.*, 1996). The antenna is designed to provide a higher gain to radiate with orthogonal radiation patterns.

4.6.4. POLARISATION DIVERSITY

In polarisation diversity, vertical and horizontal polarised signals could be used to achieve diversity (Leach *et al.*, 1999). It does not consume extra bandwidth and there is no need for extra physical separations between the antennas. The signals are received at the same location, but with orthogonal polarisations. Unlike antenna diversity, polarisation diversity is commonly used because the two receiving antennas can be physically co-located (Brown *et al.*, 2007). In polarisation diversity, only one polarised antenna is used. In addition, polarisation diversity can only provide a diversity order of two and not more. However, at the MIMO receiver if the transmitted signal suffers propagation such as scattering which is not polarised during the transmission, the signal can be divided into two orthogonal polarisations to provide almost uncorrelated signals in this environment. The correlation between the polarised signals in the two receive antennas will determine the performance of the diversity scheme. To obtain the lowest correlation between the two antennas and the highest total output power, choice of two orthogonal polarisation components should be done. The vertical polarised mobile transmitted signal has a slight effect on polarisation due to the fact that the reflected signals from buildings and the ground are also vertically polarised. The interfered signals components leads to fading, as a result coupling will exist between polarisations but it is inconsiderable. In the receiving antenna, if a vertical/horizontal pair of polarisation is chosen then the vertical channels will receive most of the signal power and the rest horizontal channels will receive a much lower level. In real life, (Lempiäinen and Laiho-Steffens, 1998) the correlation between the orthogonal received polarisations depends on the transmitted polarisation and the extent of scattering of the signal in the transmission path. Scopingo *et al.* (2015) described the antennas polarisation in VANET communications as omnidirectional (vertical polarised ideal dipoles).

4.7. MIMO CHANNEL CODING

The objective of this section is to give an overview about MIMO channel coding. Section 4.6.1 begin with Alamouti scheme, which is a simple way of obtaining transmit diversity for the case of two transmit antennas. Section 4.6.2 is allocated to give a deep study about Vertical Bell Labs Layered Space Time (V-BLAST) coding in MIMO systems. The next two sections 4.6.3 and 4.6.4 are providing an overview about Spatial Modulation (SM) and Spatial Multiplexing.

4.7.1. ALAMOUTI SPACE TIME BLOCK CODE

Alamouti diversity scheme is the first Space-Time Block Code invented in 1998 by S. Alamouti (Alamouti, 1998). Alamouti is designed to provide a full transmit diversity for the systems using two transmit antennas to be used in 2x1 Multiple - Input - Single - Output (MISO) systems mode or 2x2 MIMO systems mode. It does not require transmit channel knowledge, and it is considered the only complex block code to achieve the maximum diversity gain. Figure (4.6) shows the complex orthogonal STBC Alamouti technique which is suitable for two antennas to encode two consecutive symbols.

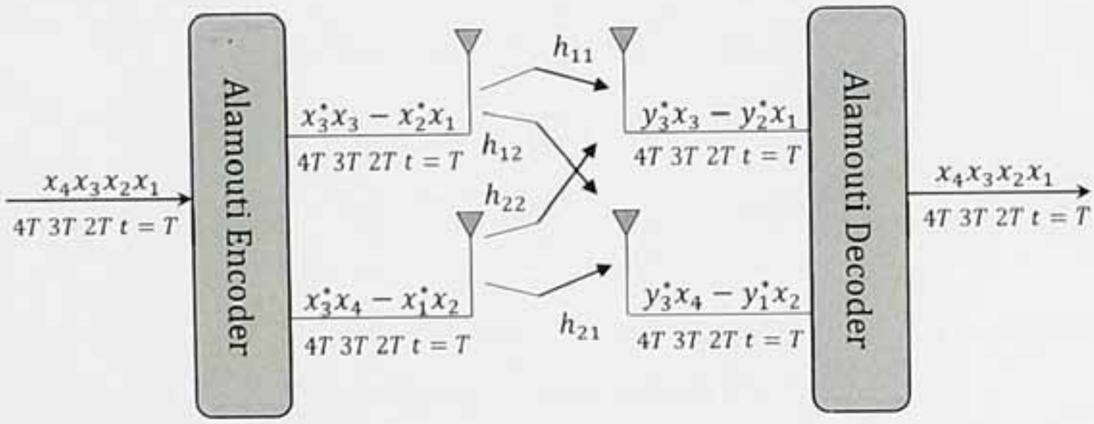


Figure 4.6: 2x2 MIMO Wireless Systems Using Alamouti Block Code.

Since the transmission is done over two periods of time, the decoding will also be done over two periods of time. Two symbols x_1 and x_2 are simultaneously transmitted from the two antennas then the two symbols $-x_2^*$ and x_1^* are simultaneously transmitted from the

two antennas again. Where as x_1^* is the complex conjugate of x_1 while $-x_2^*$ is the negative complex conjugate of x_2, i.e. if $x_2 = (1 + i)$ then $-x_2^* = -(1 - i)$ where $i = \sqrt{-1}$.
The overall mathematical model for Alamouti is illustrated in the following equations:

$$Y = H.X + N \quad (4.21)$$

As shown in Figure (4.4) the transmission has occurred over two period of time, so that the decoding also will be done over the same period of time. At the receiver the two periods are follows:

$$\begin{bmatrix} y1(t) \\ y2(t) \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} . \begin{bmatrix} x1(t) \\ x2(t) \end{bmatrix} + \begin{bmatrix} n1(t) \\ n2(t) \end{bmatrix} \quad (4.22)$$

In the first time instant, MIMO systems transmitting x_1 and x_2 where the system denoted as:

$$Y_{(1)} = [h_1 \; h_2] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + n_{(1)} \quad (4.23)$$

Where,

x_1 : Symbol transmitted from antenna 1.

x_2 : Symbol transmitted from antenna 2.

In the second time instant, MIMO system transmitting $-x_2^*$ and x_1^* where the system denoted as:

$$Y_{(2)} = [h_1 \; h_2] \begin{bmatrix} -x_2^* \\ x_1^* \end{bmatrix} + n_{(2)} \quad (4.24)$$

Where,

$-x_2^*$: Symbol transmitted from antenna 1.

x_1^* : Symbol transmitted from antenna 2.

In the receiver:

$$Y_{(2)}^* = [h_1^* \; h_2^*] \begin{bmatrix} -x_2 \\ x_1 \end{bmatrix} + n_{(2)}^* \quad (4.25)$$

$$Y_{(2)}^* = [-h_1^* \; h_2^*] \begin{bmatrix} x_2 \\ x_1 \end{bmatrix} + n_{(2)}^* \quad (4.26)$$

$$Y_{(2)}^* = [h_2^* \; -h_1^*] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + n_{(2)}^* \quad (4.27)$$

The combination of $Y_{(1)}$ and $Y_{(2)}^*$ which represents the first and the second time of transmission is results in the following system model at the receiver:

$$\begin{bmatrix} Y_{(1)} \\ Y_{(2)}^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_{(1)} \\ n_{(2)}^* \end{bmatrix} \quad (4.28)$$

Where, $\begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}$ equivalent to a 2x2 MIMO systems.

Let:

$$C1 = \begin{bmatrix} h_1 \\ h_2^* \end{bmatrix} \quad and \quad C2 = \begin{bmatrix} h_2 \\ -h_1^* \end{bmatrix} \quad (4.29)$$

In fact C1 is orthogonal to C2 which means in the receiver ***x1*** can be decoded from ***Y(1)*** through ***C1*** and ***x2*** can be decoded from ***Y*(1)*** through ***C2***. This can be proved by applying the Hermitian matrix to C1.

$$C_1^H = C_1 \quad (4.30)$$

$$C_1^H C_2 = h_1 * h_2 + (h_2)(-h_1^*) \quad (4.31)$$

$$C_1^H C_2 = h_1^* h_2 - h_1^* h_2 = 0 \quad (4.32)$$

Note that $\frac{C1}{||C1||}$ can employ as a receive beam former to detect x_1.

To represent the beam former, assume that $B_1 = \frac{C1}{||C1||}$ (4.33) .

$$B_1 = \begin{bmatrix} h_1 / ||h|| \\ h_2^* / ||h|| \end{bmatrix} = \frac{1}{||h||} \begin{bmatrix} h_1 \\ h_2^* \end{bmatrix} \quad (4.34)$$

$$B_1^H \bar{y} = \frac{1}{||h||} [h_1^* \, h_2] \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \bar{B}_1 \bar{n} \quad (4.35)$$

$$= \frac{1}{||h||} [||h||^2 \quad 0] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \bar{n}_1 \quad (4.36)$$

$$= ||h|| \, x_1 + \bar{n}_1 \text{, } where \; x_1 \; is \; decoded. \quad (4.37)$$

Similarly to decode x_2 the beam former $\bar{B}_2$ is given as:

$$\bar{B}_2 = \frac{C2}{||C2||} = \frac{1}{||.n||} \begin{bmatrix} h_2 \\ -h_1^* \end{bmatrix} \quad (4.38)$$

Then the same process which was used to decode x_1 should be repeated to decode x_2.

The SNR at the receiver:

$$SNR = \frac{||h||^2 \, P_1}{\sigma \, n^2} \quad (4.39)$$

$$SNR = \frac{||h||^2 \, P_2}{\sigma \, n^2} \quad (4.40)$$

Where,

P_1 is the power allocated for the symbol x_1.

P_2 is the power allocated for the symbol x_2.

$||h||^2$ is the diversity order.

As it was mentioned previously $[x_1 \;\; x_2]$ represents the transit vector, this indicate that there are two symbols transmitted every instant of time which means that the transmit power has been spilt between these two symbols.

The total transmit power is P which is fixed.

$$||h||^2 = \sqrt{|h_1|^2 + |h_2|^2} \quad (4.41)$$

$$\frac{P}{2} = P_1 = P_2 \quad (4.42)$$

$$SNR = \frac{P}{2}\frac{||h||^2}{\sigma n^2} = \frac{1}{2}\frac{P\,||h||^2}{\sigma n^2} \quad (4.43)$$

C1 and C2 are orthogonal. Also it has been observed that the Alamouti code belongs to a special class of codes termed as Orthogonal Space Time Codes (OSTBC), due to the coding across space and time Figure (4.7).

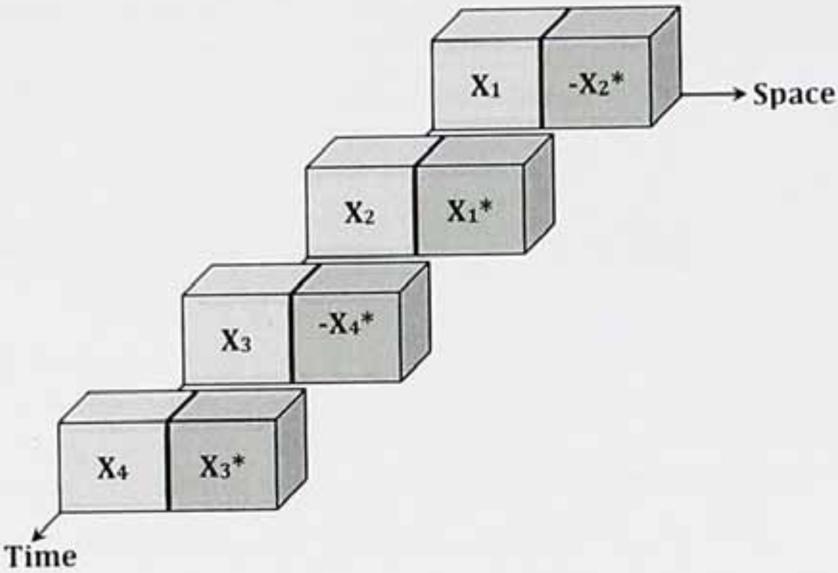


Figure 4.7: Alamouti Space-Time Diversity

4.7.2. SPATIAL MODULATION

In wireless communication systems, the evolution of smartphones and the data traffic generated by these devices is a challenge. Globally (Guglielmo, 2014), the total data traffic which is sent to the mobile networks will reach to 190 exabytes by 2018. In order to address this challenge Di Renzo et al (2014) said more radio frequency spectrums need to be allocated for these networks, but unfortunately these spectrums are not available. So in this case and to solve this problem the system is required to be more efficient in terms of producing more bits per hertz. Another challenge is how to make these systems more energy efficient. Cisco, (2013) showed that currently there are approximately 1.5 million outdoor base stations deploying worldwide, and this number is expected to reach up to 2 million by 2017 which means that more energy will be consumed. The total amount of energy that is consumed by these networks is equivalent or comparable to that of entail air traffic. A new technology has been developed to address the mentioned challenges, this technology called Spatial Modulation SM (Serafimovski *et al.*, 2013). SM uses multiple transmitter antennas to convent extra information bits. In particular Di Renzo *et al.* (2014) said that this extra information is encoded in the physical location of the transmitting antenna. As such it requires no addition of bandwidth yet still it results in increasing data rate. This makes the system more spectrally efficient (Di Renzo *et al.*, 2014).

In mobile communication, transmit and receive antennas are required, this will define the transmission link and certainly the goal is to transmit information. Spatial modulation uses a single antenna, broadcasting in any particular instance (one RF Chain). The path of the raise from transmitter antenna, to the receiver as one antennas is Figure (4.8).

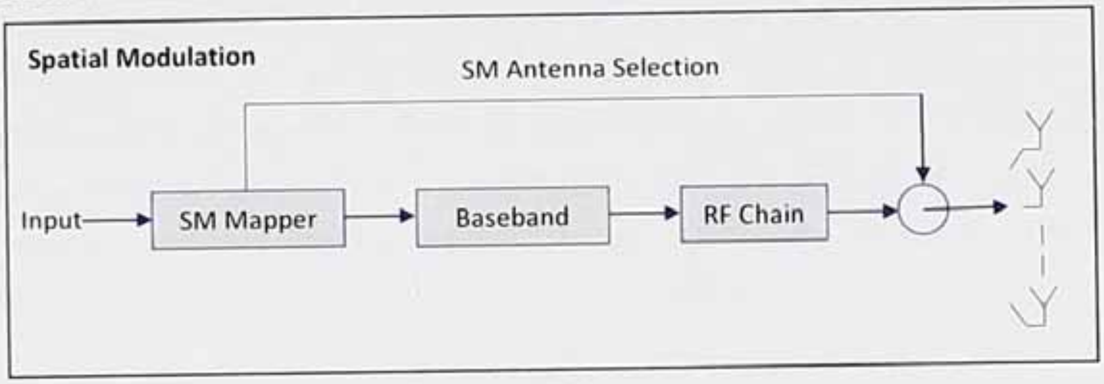


Figure 4.8: SM System.

Serafimovski *et al.* (2013) stated that the transmit antenna determination is important to verify which path is used to transfer the data used to arrive at the receiver. Thus, the receiver can determine which transmit antenna was active and it can extract the spatial information of spatial modulation. This can simply be done by having a physical separation of antennas where the raise coming from multiple antennas take different paths to the receiver. A physical separation of antennas enables spatial modulation to increase the information data rate and results in a more spectrally efficient system since it is requires no addition bandwidth.

- **SM Example**

In this example, a word consisting of four symbols W, O, R and D needs to be transferred from the transmitter to the receiver via a transmission link (wireless signal). The technology presupposes the existence of a signal space which has two parts, real part and an imaginary part. The idea is to link these symbols W, O, R and D to called constellation points as showed Figure (4.9). In this complex (real and imaginary parts) diagram the points will be allocated for these symbols. So there are four different signals and four different constellation points. The channel transmits only one of these symbols at a time. SM technology assumes that multiple antenna systems are available at the transmitter (Renzo *et al.*, 2011). These antennas have a unique position in that antenna array, and the location is defined as a spatial constellation point. So the signals constellation point is defined and also a spatial constellation point is defined. In the transmitter, the antennas are linked to the signals: T_{x1} is linked to signal W, T_{x2} is linked to signal O, T_{x3} is linked to signal R and T_{x4} is linked to signal D. Essentially a 3D constellation diagram is created and the 3rd dimension can extend as a space Figure (4.9). To transmit a random sequence of symbols such as RWOO, the way this works is to group these symbols into peers, where RW is the first peer and OO is the second peer. The first symbol R will transmits in a spatial domain and the second symbol W in first peer will be transmitted in the signal domain. The same operation will be applied for the second peer OO. As a result, in every transmission step two symbols are transmitted instead of transmitting one symbol. For example at the time instant t_1 RW will be transmitted and in the second time instant t_2 OO will be transmitted. However, the capacity of the system is doubled (Mesleh *et al.*, 2007).

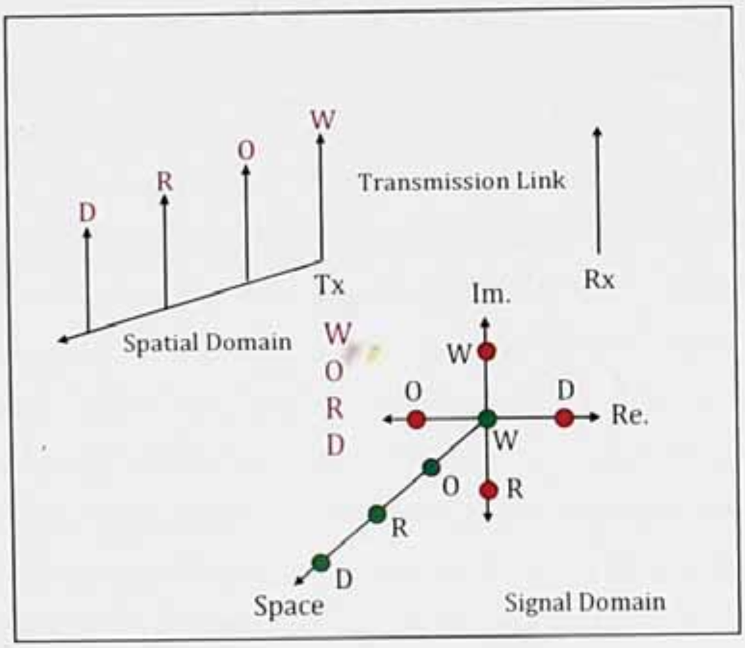


Figure 4.9: SM System 3D.

Figure (4.10) illustrates the principle block diagram of spatial modulation and the conventional MIMO systems. The diagram indicates that spatial modulation (Mesleh *et al.*, 2008) is activated in a single transmit antenna at any particular transmission instances, this mean it requires only a single (RF Chain) whereas in conventional MIMO systems multiple (RF Chains) are required.

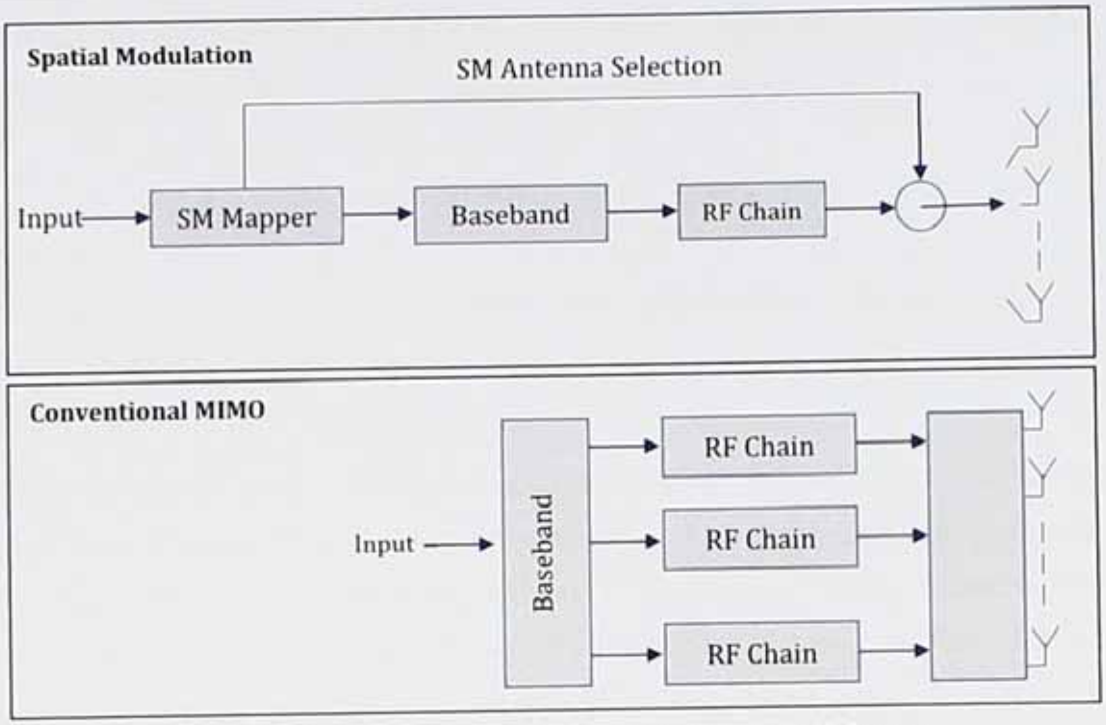


Figure 4.10: Block Diagram of SM and Conventional MIMO Systems.

4.7.3. SPATIAL MULTIPLEXING

In this chapter, several different uses of multiple antenna systems in wireless communication have been discussed, where multiple antennas are used to provide diversity gain and to increase the reliability of the wireless links in both receive and transmit antennas. This section is covering a technique called Spatial Multiplexing (Nalysis *et al.*, 2013), which is in simple terms a transmission technique used for MIMO wireless communication systems to transmit data streams where each spatial channel carries independent information, and separately encoded data signals. Thus, spatial multiplexing provides an additional spatial dimension for communication, which increases the data rate of the system capacity of the MIMO channel of transmit and receive antennas. In the spatial multiplexing approach, the signal date stream is de-multiplexed and encoded into two independent and separate sub-streams. The sub-stream is then transmitted at the same time over each transmit antenna. In the other side where the receive antenna is installed, a joint decoder is located to retrieve the original data stream. Hence, spatial multiplexing (Tse & Viswanath, 2004) requires one signal symbol stream at a time, it can only be used for the transmission of a Sphere Decoding (SD) representation of the source.

Viswanathan, (2014) showed that in spatial multiplexing, if the environment of the transmission link is rich enough with scatters, several independent sub-channels are created in the same allocated bandwidth, so no additional bandwidth or additional power cost is needed for multiplexing gain. Where, the multiplexing gain is also referred to as degrees of freedom with reference to signal space constellation.

$$SDoF = \min(N_T \ , N_R) \quad (4.44)$$

Where,

SDoF: is the number of degrees of freedom in a multiple antenna configuration.

N_T: is the number of transmit antennas.

N_R: is the number of receive antennas.

The overall capacity of the system is controlled by the degrees of freedom in MIMO configuration (Viswanathan, 2014). Conventional spatial multiplexing is illustrated in Figure (4.11). Two symbols data streams S1 and S2 are ready for transmission. To double the rate SIMO 1x2 antennas are used which are required for the two radio frequency chains. The idea is to transmit S1 and S2 in the same time slot. In other words, each bit of the data stream is multiplexed on two different spatial channels thereby increasing the data rate. Here, the diversity gain is 0 and the multiplexing gain is 2 (assuming 2×2 MIMO configuration).

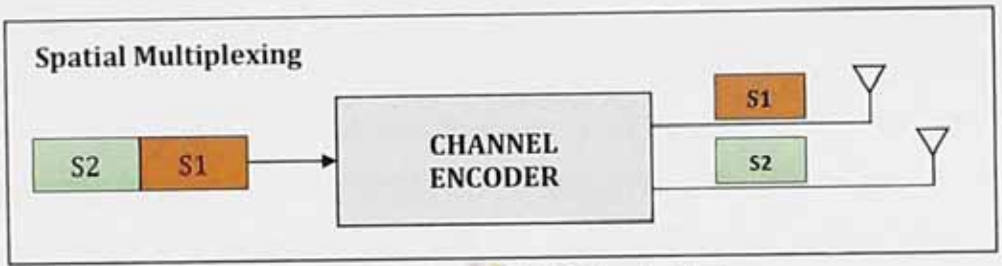


Figure 4.11: 1x2 Spatial Multiplexing System.

Although the rate has doubled but also interference between the symbols has been created, and these symbols need to be decoded at the receiver. Therefore, the use of such Alamouti or spatial modulation is recommended to prevent this interference.

4.7.3.1. VERTICAL BELL LABS LAYERED SPACE TIME

In the last few years MIMO systems have attracted significant attention due to their support of mobile and wireless radio communications by increasing the data rate (Ma, 2011). The received signal Rx processing algorithm is considered an important part of the wireless system. In 1996, Foschini, (1996) proposed the Diagonal Bell laboratories (D-BLAST) architecture which was the first designed algorithm by Bell labs for the received signal. Later on, V-BLAST algorithm was proposed by Golden *et al.* (1999), it is considered as the first practical implementation of MIMO systems communication in demonstrating a spectral efficiency as high as 40 bits/s/Hz in real time. Although D-BLAST achieves a full capacity in MIMO systems, V-BLAST is simplest in terms of vector encoding processes which are the essential difference between the two algorithms. The D-BLAST code blocks (Wolniansky *et al.*, 1998) are organised along diagonals in space-time, and specialised inter sub-stream block coding is used to introduce the redundancy between the sub-streams. V-BLAST is non – linear MIMO receiver detection algorithm to the receipt of multi antenna MIMO systems.

The principle of this algorithm (Wu *et al.*, 2011): V-BLAST employs successive interference cancellations SIC. At the beginning, the algorithm identifies the most powerful signal which has a highest SNR, the next step it regenerates the received signal from this user. The impact of each estimated symbol is cancelled from the received symbol vector so what does SIC roughly means. One symbol is estimated from the vector $x_1\ x_2\ x_3\ x_4$, for example x_1, then the impact of $x_1$will be removed from the receive vector y and the rest of the symbols are decoded similarly. After decoding every symbol the effect of it will be removed progressively in the receive symbol vector and so on to decode the other receive symbol.

The encoding and decoding process for each symbol in the vector represents a de-multiplex operation followed by independent bit-to-symbol mapping of each sub stream Figure (4.12). Inter sub-stream coding or any type of coding is not required, however conventional coding of the individual sub streams may be applied. Separating the signals an efficient way (Joshi *et al.*, 2011) requires a combination of the old and the new detection techniques, this combination can be achieved and utilised by V-BLAST. Also, it allows significant operation of the Shannon capacity and achieves large spectral efficiencies in the process.

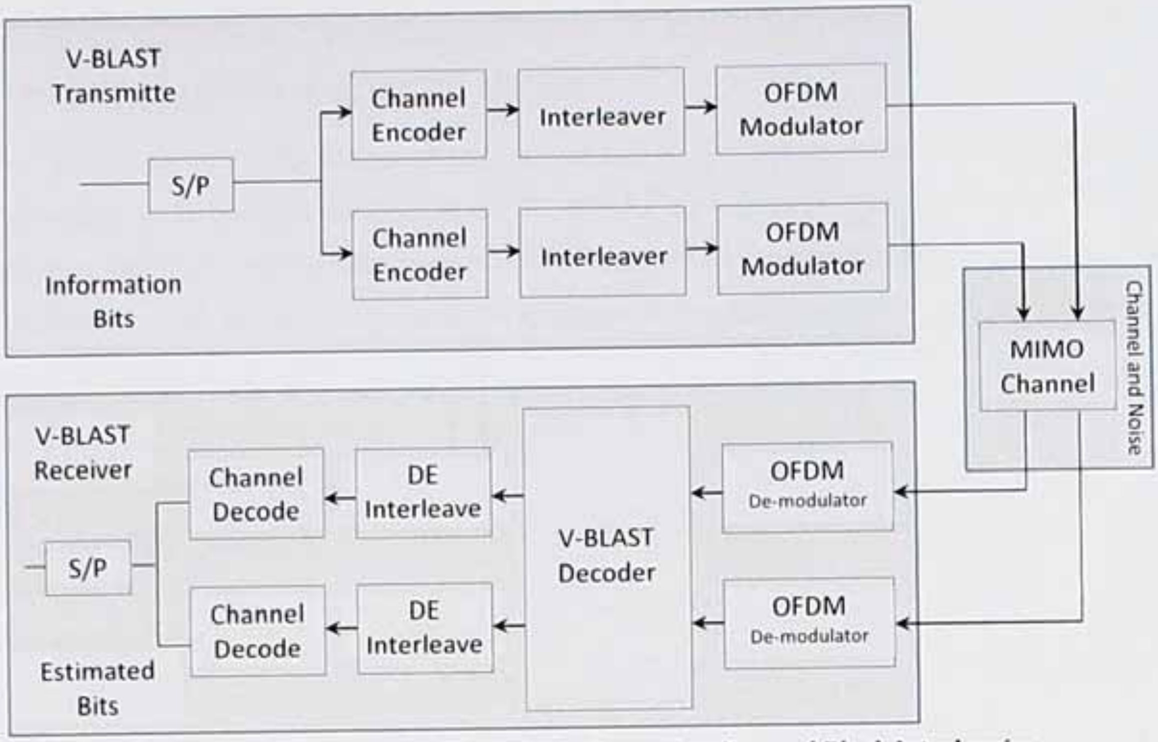


Figure 4.12: V-BLAST Transceiver with Channel Coding and Block Interleaving.

Wolniansky *et al.* (1998) said that symbol detection in MIMO systems requires the estimation of the channel coefficients from the received signal. In this context, the channel matrix estimate is supposed not to have any estimation errors. Nevertheless, the channel estimation errors do exists in the real system and they affect the system performance. "The BLAST approach differs from simply using traditional multiple access techniques in: First, unlike code- division or other spread-spectrum multiple access techniques, the total channel bandwidth utilised in a BLAST system is only a small fraction in excess of the symbol rate, i.e. similar to the excess bandwidth required by a conventional QAM system. Second, unlike Frequency Division Multiple Access (FDMA), each transmitted signal occupies the entire system bandwidth. Finally, unlike Time Division Multiple Access (TDMA), the entire system bandwidth is used simultaneously by all of the transmitters all of the time. Taken together, these differences are precisely what give BLAST the potential to realise higher spectral efficiencies than the multiple-access techniques. In fact, an essential feature of BLAST is that no explicit orthogonalisation of the transmitted signals is imposed by the transmit structure at all " (Wolniansky *et al.*, 1998). Instead, the propagation environment itself, which is assumed to exhibit significant multipath, is exploited to achieve the signal de-correlation necessary to separate the co-channel signals. V-BLAST utilises a combination of old and new detection techniques to separate the signals in an efficient manner, permitting operation at significant fractions of the Shannon capacity and achieving large spectral efficiencies in the process.

In V-BLAST system with N_t transmit antennas and N_r receive antennas ($N_r \geq N_t$) for MIMO communication systems (Golden *et al.*, 1999), the data stream is split into parallel sub-streams and each one is sent through a corresponding transmit antenna. Each receive antenna receives the signals from all N_t transmit antennas. Equation (4.45) describes the used discrete-time model:

$$\bar{y} = H_x + \bar{n} \quad (4.45)$$

H: is the channel matrix of:

$$[number\ of\ rows\ in\ receive\ antenna\ (r)] \times [number\ of\ rows\ in\ transmit\ antenna\ (t)]$$

and $r \geq t$.

The channel matrix of H can be illustrated as:

$$[\bar{h}_1\, \bar{h}_2\, \bar{h}_3 \dots\dots \bar{h}_t] \times [x_1\, x_2\, x_3 \dots\dots x_t] + \bar{n} \quad (4.46)$$

Where,

$\bar{h}_1\, \bar{h}_2\, \bar{h}_3 \dots\dots \bar{h}_t$: represents the transmitter columns.

$x_1\, x_2\, x_3 \dots\dots x_t$: represents the transmitter symbols.

$\bar{n}$: The noise.

The channel matrix H can be expanded to:

$$\bar{y} = \bar{h}_1 x_1 + \bar{h}_2 x_2 + \bar{h}_3 x_3 + \cdots\cdots + \bar{h}_t x_t + \bar{n} \quad (4.47)$$

The corresponding weight matrix is:

$$K = H^{\dagger} \quad (4.48)$$

Where $H^{\dagger}$ is the pseudoinverse of H or it is called the left inverse of H.

$$K = [k_1^H\, k_2^H\, k_3^H \cdots\cdots k_t^H] \quad (4.49)$$

Where, $H^{\dagger}$ (K) has the transmitter rows and H has transmitter columns.

$k_1^H\, k_2^H\, k_3^H \cdots\cdots k_t^H$ represents the transmitter rows.

$\bar{h}_1\, \bar{h}_2\, \bar{h}_3 \dots\dots\dots \bar{h}_t$ represents the transmitter columns.

$$I = K * H \quad (4.50)$$

Where I is the identity matrix which will be used in detection.

$$I = K * H = [k_1^H\, k_2^H\, k_3^H \cdots\cdots k_t^H] * [\bar{h}_1\, \bar{h}_2\, \bar{h}_3 \dots\dots\dots \bar{h}_t] \quad (4.51)$$

This essentially means:

$$I = \begin{bmatrix} k_1^H\bar{h}_1 & k_1^H\bar{h}_2 & k_1^H\bar{h}_t \\ k_2^H\bar{h}_1 & k_2^H\bar{h}_2 & k_2^H\bar{h}_t \\ \cdots & \cdots & k_t^H\bar{h}_t \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \; where: \begin{Bmatrix} k_1^H\bar{h}_1 = k_2^H\bar{h}_2 = 1 \\ k_1^H\bar{h}_2 = k_2^H\bar{h}_1 = 0 \end{Bmatrix} \; so \begin{Bmatrix} 1 \; if \; i = j \\ and \\ 0 \; if \; i \neq j \end{Bmatrix} \quad (4.52)$$

This indicates that k_1^H is orthogonal to $\bar{h}_2\,\bar{h}_3 \dots\dots\dots \bar{h}_t$ so this can be used to cancel the interference from $x_2\,x_3 \dots\dots x_t$ This could be represented as:

$$\bar{y} = \bar{h}_1x_1 + \bar{h}_2x_2 + \cdots\cdots + \bar{h}_tx_t + \bar{n} \quad (4.53)$$

To cancel the interference from $\bar{h}_2\,\bar{h}_3 \dots\dots\dots \bar{h}_t$:

$$\tilde{y} = k_1^H(\bar{h}_1x_1 + \bar{h}_2x_2 + \cdots\cdots + \bar{h}_tx_t + \bar{k}_1^H\,\bar{n} \quad (4.54)$$

At this point:
$\bar{k}_1^Hh_1 = 1 \;\; and \;\; \bar{k}_1^Hh_2 = 0.$

$$\tilde{y} = x_1 + 0 + \dots\dots + 0 + \bar{n} \quad (4.55)$$

So $\tilde{y} = x_1 + \bar{n}$ which is used to decode x1 and remove its effect from the receive vector the receive vector y.

$$\bar{y} - \bar{h}_1x_1 = (\bar{h}_1x_1 + \bar{h}_2x_2 + \cdots\cdots + \bar{h}_tx_t) + \bar{n} - \bar{h}_1x_1 \quad (4.56)$$

$$\hat{y}_2 = \bar{y} - \bar{h}_1x_1 \quad (4.57)$$

$$= \bar{h}_2x_2 + \bar{h}_3x_3 + \cdots\cdots + \bar{h}_tx_t + \bar{n} \quad (4.58)$$

Note: by cancelling x_1 from the receive vector y the matrix is effectively reduced to $[h_2\;h_3\;h_t]$ and this is represents a new matrix L.
Where:

$$\hat{y}_2 = L\,[x_2\;x_3x_t] + \bar{n} \quad (4.59)$$

To decode x_2 the previous steps need to be repeated.

4.8. CHAPTER SUMMARY

This chapter has covered a lot of ground. It is mainly focused on providing an information regarding the following:

1- Principles of MIMO Systems and the Use of MIMO in VANET:

In VANET communications (Abdalla, 2011) the advantages of having unlimited battery life and multiple antennas positions are strong factors in using MIMO systems with VANET. MIMO systems perform higher capacities compared to single antenna systems. However, there are significant challenges which need to be taken into consideration like: channel modelling, processing of space time signals in VANET and channel coding. MIMO provides considerable advantages including having wider coverage area, enhancing the multi fading environments and improving higher data throughputs (Nguyen & Aceves, 2011). Providing high data rate at high QoS in VANET communications system (Liu & Zhou, 2012), is considered as the greatest challenges in VANET research area. Due to the factors that could affect the signal strength such as scattering, reflection and interference, the bandwidth is needed to improve the QoS. To improve the bandwidth there are two approaches in general, in the first approach the diversity technique is used to improve link reliability in terms of improving the transmit diversity and/or the receive diversity. The use of higher modulations and efficient codes will increase the data rate which consequently leads to improving the reliability of the link. In the second approach (Bolcskei, 2006), MIMO systems are used in both transmitter and receiver, while each transmitting antenna transmits a separate stream of data. However, MIMO technology seems to meet these issues in terms of increasing the inbound and outbound data traffic.

2- Fading Channel Models:

The wireless communication signal faces challenges such as instability environment and fades due to multipath propagation (Knopp & Li, 2005), as a result this affect the signal phase and amplitude. The scatterers like trees, buildings and vehicles which are within the environment of the transmitter and receiver produce multi path of signals. In this case, the receiver will receive a multi copies of the transmitted signal form different paths. Each received signal copy has a different attenuation, delay and phase shift. The outcome could be constructive or destructive interference (Srivastava, 2010), in addition the signal power could be amplifying or attenuating which can be noticed at the receiver.

3- Diversity Schemes:

There are many different types of smart antenna diversity techniques, such as antenna diversity, polarisation diversity, time diversity and frequency diversity. Diversity scheme means to improve the reliability of wireless signal massages (Khan *et al.*, 2007). This improvement occur when multiple channels (Multiple antennas) with different characteristics are in use. The replicas of the transmitted signal needs to be provided with lowest consumption of the power, bandwidth and decoding complexity at the receiver which is an important issue. Another important issue is how to use these replicas in order to receive the lowest of errors in the recipient (Jafarkhani, 2005). To achieve more reliable reception (Zheng & Tse, 2003) the transmitter sends signals that are carrying the same information through different paths, so that multiple independently faded replicas of the data symbol can be obtained at the receiver. Diversity acts an important roles in channel interference, overcome multipath fading and avoiding error bursts (Bölcskei *et al.*, 2008).

4- MIMO Channel Coding:

This section discussed the most popular MIMO coding techniques such as Alamouti Space-Time-Block-Code, Vertical Bell Labs Layered Space Time, Spatial Modulation and Spatial Multiplexing to be utilised over the VANET channel model. The section has started with Alamouti, which is a complex orthogonal Space-Time-Block-Code technique suitable for two antennas that encodes two consecutive symbols (Alamouti, 1998). Alamouti designed to be used in 2x1 MISO mode or 2x2 MIMO mode. It does not require transmit channel knowledge, and it's considered the only complex block code to achieve the maximum diversity gain. The second MIMO coding technique discussed in this section is Spatial Modulation. Spatial Modulation (Serafimovski *et al.*, 2013) is a new technology that has been developed to address and overcome the spectrum limitation issue. Currently there are approximately 1.5 million outdoor base stations deploying worldwide, and this number is expected to reach up to 2 million by 2017 (Cisco, 2013) which means more energy will be consumed. The total amount of energy that is consumed by these networks is equivalent or comparable to that of entail air traffic. Spatial modulation uses multiple transmitter antennas to convent extra information bits. In particular this extra information is encoded in the physical location of the transmitting antenna. As such it requires no addition of bandwidth yet still results in increasing data rate. This makes the system more spectrally efficient. The third and the last MIMO coding technique discussed in this section is Spatial Multiplexing. Spatial multiplexing in simple terms (Nalysis *et al.*, 2013) is a transmission technique used for MIMO wireless communication systems to transmit data streams where each spatial channel carries independent information, and separately encoded data signals. Thus, spatial multiplexing provides an additional spatial dimension for communication, which leads to an increase in the data rate of the system capacity of the MIMO channel, transmit and receive antennas. In the spatial multiplexing approach, the signal date stream is de-multiplexed and encoded into two independent and separate sub-streams. The sub-stream is then transmitted at the same time over each transmit antenna. In the other side where the receive antenna is installed, a joint decoder is located to retrieve the original data stream. Hence, spatial multiplexing (Tse and Viswanath, 2005) requires one signal symbol stream at a time, it can only be used for the transmission of a Sphere decoding SD representation of the source. An example of spatial multiplexing is Vertical Bell Labs Layered Space Time V-BLAST. V-BLAST is Layered-Space-Time algorithm proposed by Golden *et al.* (1999), it is considered as the first practical implementation of MIMO systems communication in demonstrating a spectral efficiency as high as 40 bits/s/Hz in real time. V-BLAST employs successive interference cancellations SIC. At the beginning, the algorithm identifies the most powerful signal which has a highest SNR, the next step it regenerates the received signal from this user. The impact of each estimated symbol is cancelled from the received symbol vector. One symbol is estimated from the vector $\boldsymbol{x_1 x_2 x_3 x_4}$, for example $\boldsymbol{x_1}$ then the impact of $\boldsymbol{x_1}$will be removed from the receive vector y and the rest of the symbols are decodes similarly. After decoding every symbol the effect of it will be removed progressively in the receive symbol vector and so on to decode the other receive symbol.

CHAPTER FIVE
V-SCME: SIMULATION RESULTS AND DISCUSSION

5.1. INTRODUCTION

Over recent years, VANET communication has attracted a lot of attention due to its potential in facilitating the implementation of ITS. Vehicular applications need to be completely tested before deploying them in the real world. In this context, VANET simulations would be preferred in order to evaluate and validate the proposed model, where these simulations are considered inexpensive compared to the real world (hardware) tests. The main challenge in VANET communication is the high dynamic environment. Researchers should take this challenge into consideration in order to build a robust model which reflects reality. In fact, there are still unsolved problems linked to VANET simulations such as: channel modelling and channel coding as discussed in Chapters (3 and 4). It is noticeable that most of the time the outcome of mobility on the physical layer of VANET is treated in a simplistic and consequently not quite realistic manner as discussed in Chapter (3).

Developing a MIMO radio channel model for V2V communication with a robust coding technique is the important aspect of this chapter, this is needed in order to overcome different conditions for the VANET environment. This is precisely the target of this thesis. In addition, this thesis has the following contributions:

- Development of a V2V statistical channel model V-SCME which is based on an already existing approach; SCME for cellular communication.
- Provision of a predefined channel coefficients online library to be accessed by researches for future simulations.
- MIMO is a suitable choice for V2V communication and 2x2 MIMO is a good enough solution for V2V communication in terms of cost and complexity.
- V-BLAST is a robust coding technique to be utilised in MIMO systems with V-SCME in V2V communication. The use of V-BLAST coding is a good solution to deal with the dynamic environment when different distances and speeds are applied.

Definitions

- **Realistic channel model**

Realistic channel model is a statistical or mathematical formula which represents a certain communication channel and has been verified through real world tests. In order to provide a realistic channel model for V2V communication, intensive tests should be implemented inorder to obtain data sets for different scenarios which cover different speeds, distances, antenna spacing, multi-path for LoS and NLoS conditions. The obtained data sets should be used as a reference to verify any statistical model or mathematical model. To the best of my knowledge, there was no complete data set for V2V communication channel measurement to refer to.

- **Acceptable Error**

In this work the acceptable BER for V2V communication has been set between 10^{-2} and 10^{-3}. Although this BER range could be considered as a high error in wired and conventional wireless applications, this range is acceptable in V2V communication due to the high dynamic environment.

5.2. THE PROPOSED CHANNEL MODEL

Today's advanced simulators enable thorough studies on VANET. However, the choice of the V2V channel model in such simulators is a crucial issue due to the high dynamic in VANET environment. In this thesis, a novel channel model Vehicular – SCME (V-SCME) was developed for V2V communication. V-SCME was developed based on spatial channel model extended SCME for cellular communication (3rd Generation Partnership Project, 2014) which is a part of IST WINNER project (Eurescom GmbH, 2006) to represent the V2V channel model.

SCME for cellular communication is a MIMO model, which is designed to simulate three types of environments:

- Urban Macrocell.
- Suburban Macrocell.
- Urban Microcell.

In the situation of VANET communication, Urban Microcell was the optimum environment where the vehicles interconnection distance is up to one kilometre (3rd Generation Partnership Project, 2014).

The major differences between the cellular and V2V communication are:

1- Antennas positions: in cellular communication, the base-station antennas are most likely placed higher than the mobile station antennas.
2- Nodes mobility: another major difference is the mobility of nodes, where in V2V communication both nodes are moving while in cellular communication the base-station is fixed and only the mobile station is moving.
3- Transmission range: 3rd Generation Partnership Project, (2014) showed that the transmission range between the mobile station and a certain base-station in cellular communication is 3km while it is less than 1km in V2V communication.

Regarding the PHY layer in a VANET context, there exists the 802.11p standard IEEE Vehicular Technology Society, (2014) adopted by IEEE organisation. IEEE 802.11p has emerged as a vehicular standard which is an adaptation of the IEEE 802.11a IEEE, (2012) standard for DSRC between vehicles. It was designed to improve the robustness against channel frequency selectivity. In addition, Abdelgader & Lenan. (2014) said that the vehicular standard IEEE 802.11p (IEEE Vehicular Technology Society, 2014) doubling the OFDM symbol time degrades the robustness of the system against time selectivity which depends on the Doppler frequency shift directly related to the vehicles speed. The V-SCME channel model has been developed to satisfy the requirements of the IEEE vehicular standard, by fully integrating the IEEE 802.11p standard (IEEE Vehicular Technology Society, 2014) physical layer.

The novel statistical model V-SCME has taken into consideration both LoS and NLoS conditions. V-SCME has been simulated using Matlab R2013a simulator, where relevant scenarios and configuration parameters that showed in 3GPP cellular model (3rd Generation Partnership Project, 2014) are also considered. However, in this thesis specific scenarios and configurations for V2V communication were designed to develop the V-SCME novel model, these scenarios and configurations were directly related to: {antenna gain, wavelength, antenna spacing, angle of velocity, Angle of Arrival (AoA), Angle of Departure (AoD), distances between the vehicles and vehicles speeds}. Due to the nature of the V2V environment, V-SCME has taken into account the values of angles such as AoD and AoA. The vehicles are assumed to be travelling on the same road, where AoD and AoA are set at ($180° \pm 5°$) in Microcell Urban (up to 300 meters LoS and 1km NLoS coverage distance) (3rd Generation Partnership Project, 2014). The following configuration values were considered in order to obtain the estimated channel fading, channel capacity and the power delay for the vehicular standard IEEE 802.11p (IEEE Vehicular Technology Society, 2014):

- Different speeds were considered (10km/h-120km/h).
- 5.9GHz was the carrier frequency in different multi-path scenarios.
- The channel model was constructed under the condition of 2x2 MIMO and 4x4 MIMO systems for different disruptions levels (up to 18 multi-path and up to 20 sub-paths) (3rd Generation Partnership Project, 2014).

Figure (5.1) is a schematic diagram which shows the number of possible multi-path and the number of sub-path clusters associated with the derived SCME for cellular communication statistical model. The derived statistical model is utilised in V2V communication to estimate the channel parameters in Microcell Urban for both cases LoS and NLoS.

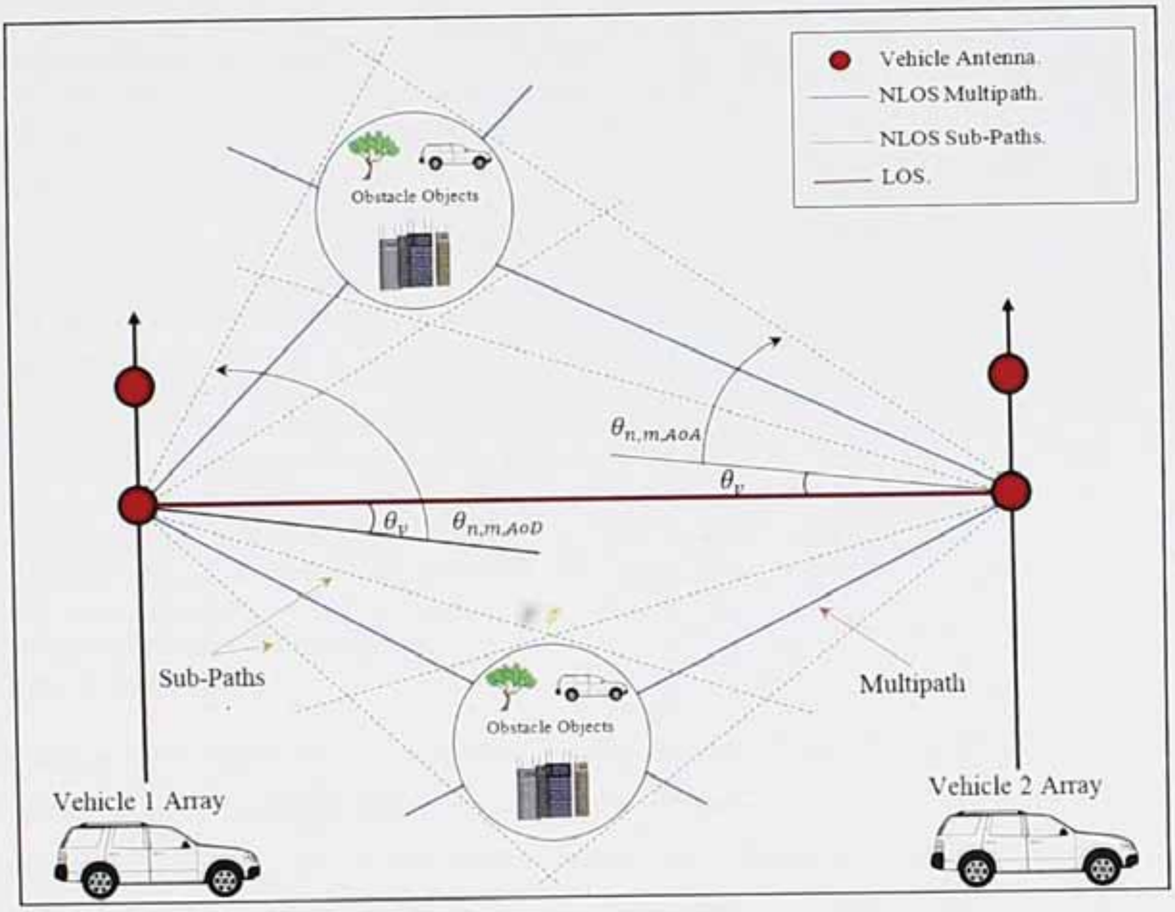


Figure 5.1: V2V Modelling Approach.

Equations (5.1) (5.2) respectively representing the SCME for cellular communication NLoS and LoS statistical model for MIMO systems (3rd Generation Partnership Project, 2014).

$$h_{u,s,n}^{(l)}(t) = \sqrt{\frac{P_n\,\sigma_{SF}}{M}} \sum_{m=1}^{M} \left[\begin{array}{c} \sqrt{G_{BS}(\theta_{n,m,AoD})}\exp(\,i\,[kd_s\sin(\theta_{n,m,AoD}) + \Phi_{n,m}]) \times \\ \sqrt{G_{MS}(\theta_{n,m,AoA})}\ \exp(ikd_u\sin(\theta_{n,m,AoA})) \times \\ \exp(ik||v||\cos(\theta_{n,m,AoA} - \theta_v)t) \end{array} \right]$$

(5.1)

$$h_{s,u,n=1}^{LOS}(t) = \sqrt{\frac{1}{K+1}}\,h_{s,u,1}(t) + \sigma_{SF}\sqrt{\frac{K}{K+1}} \left[\begin{array}{c} \sqrt{G_1(\theta_{AoD})}\,exp(ikd_s\,sin(\theta_{AoD})) \times \\ \sqrt{G_2(\theta_{AoA})}\,exp(ikd_u\,sin(\theta_{AoA}) + \Phi_{LOS} \times \\ exp(ik||v||\,cos(\theta_{AoA} - \theta_v)\,t) \end{array} \right]$$

(5.2)

Where,

P_n: is the power of the multi − path.
N: is the number of multi − path.
M: is the number of sub − paths per path.
S: is the number of the sender antenna element.
R: is the number of the receiver antenna element.
$\Phi_{n,m}$: is the phase of the sub − paths of multi − path.
$\theta_{n,m,AoD}$: is the AoD for the sub − paths of multi − path.
$\theta_{n,m,AoA}$: is the AoA for the sub − paths of multi − path.
θ_v: Angle of the velocity vector with respect to the V1 and V2 broadside.
G_{BS}: is the BS antenna ganis of each array element.
G_{MS}: is the MS antenna ganis of each array element.
i: is the square root of − 1.
k: is the wave number $2\pi/\lambda$.
d_s: is the distance in meters from the sender antenna.
d_u: is the distance in meters from the recipient antenna.
v: is the relative velocity between vehicles.
Φ_{LOS}: is the phase of the LoS component.
θ_{AoD}: is the AoD for the LoS component.
θ_{AoA}: is the AoA for the LoS component.
σ_{SF}: is the lognormal shadow fading.
K: is the K − Factor.

The next steps are showing the derivation for the developed model including the gain, distance, wavelength and the angles in V2V communication.

In V2V communication, the communicated vehicles have the same antenna gains if they are mounted at the same positions on the vehicles (Abbas *et al.*, 2013). Thus, this work considered the antennas were mounted at the same positions in $Vehicle_1$ and $Vehicle_2$.

Assumes that $Vehicle_1$ has G_1 gain which is equal to $Vehicle_2$ gain G_2 therefore:
$G_1 = G_2$.

$\sqrt{G_1} \times \sqrt{G_2} = G_v$.

Where, G_v is the vehicle gain.

The distance between the mounted antenna (antennas spacing) was identified based on 3GPP (3rd Generation Partnership Project, 2014) which are 0.5 λ, 4 λ and 10 λ.

According to Equation (5.1), ***ds*** is the distance in meters from the sender antenna and ***du*** is the distance in meters from the receiver antenna. In V2V case, (ds = du) = d where they have same value. This work considered the distances up to 300 meters LoS and up to 1000 meters NLoS (3rd Generation Partnership Project, 2014).

The value of $\boldsymbol{k}$ in Equation (5.1) represents the wavelength number. To compensate the value of k in the derived equation the wavelength in V2V need to be calculated.

$$\mathrm{k} = \frac{2\pi}{\lambda}$$

$\lambda = \frac{\mathrm{c}}{\mathrm{f}}$, where, c is the speed of light and f is the frequency.

$$= \frac{3 \times 10^8 \text{ m/s}}{5.9 \times 10^6 \text{ 1/s}} = \frac{300000000}{5.9 \times 10^6} = 50.847 \text{ m.}$$

$$\mathrm{k} = \frac{2\pi}{50.847} = 0.1235.$$

K-Factor is set to 1 in the LoS condition and it has been calculated based on Pythagoras theorem as shown in Figure (5.2):

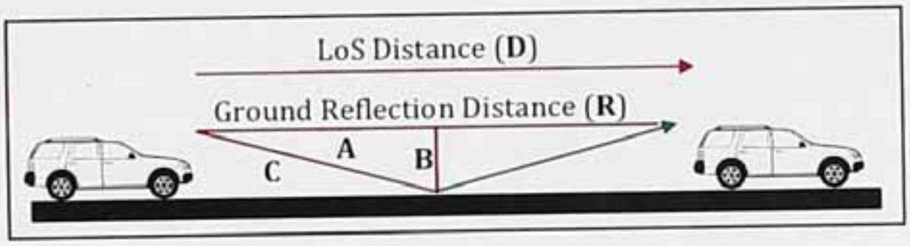


Figure 5.2: K-Factor in V2V.

$$K - Factor = \frac{D}{R}, which\ is\ approximately = 1.$$

The LoS distance $\boldsymbol{D}$ = 300m and the antenna height is = 1.5m.

Then $\boldsymbol{A}$ = 150m and $\boldsymbol{B}$ = 1.5m.

$$C = \sqrt[2]{(A)^2 + (B)^2} = \sqrt[2]{(150)^2 + (1.5)^2} = \sqrt[2]{22502.25} = 150.007m.$$

$\boldsymbol{R}$ = 150.007 + 150.007 = 300.014m.

$$K - Factor = \frac{D}{R} = \frac{300}{300.014} = 0.9999 \cong 1.$$

Due to the nature of V2V environment, the values of AoD and AoA were set at (180° ± 5°) in Microcell Urban. In most cases, the angle between the vehicles θ_v was set at 0 degree if the vehicles were travelling in the same directions and set at π if they were travelling in opposite directions. The V2V novel V-SCME statistical model for NLoS and LoS are shown in Equations (5.3) and (5.4) respectively.

$$h_{u,s,n}^{(I)}(t) = \sqrt{\frac{P_n\ \sigma_{SF}}{M}} \sum_{m=1}^{M} \left[\begin{array}{c} G_v \sqrt{(\theta_{n,m,AoD})(\theta_{n,m,AoA})} \\ \exp(j\,[0.1235\ d\ (\sin(\theta_{n,m,AoD}) + \sin(\theta_{n,m,AoA}) + \Phi_{n,m}]) \\ \times \exp(\pm j\ 0.1235\ v \cos(\theta_{n,m,AoA})t) \end{array} \right]$$

(5.3)

$$h_{s,u,n=1}^{LOS}(t) = \frac{h_{s,u,1}(t)}{\sqrt{2}} + \frac{\sigma_{SF}}{\sqrt{2}} \left[\left[\begin{array}{c} G_v \sqrt{(\theta_{AoD})(\theta_{AoA})} \\ \exp[j\ 0.1235\ d\ ((sin(\theta_{AoD}) + \ sin(\theta_{AoA})) + \Phi_{LOS}] \\ \times \exp(\pm j\ 0.1235\ v \cos(\theta_{AoA})\, t) \end{array} \right] \right]$$

(5.4)

5.3. CHANNEL CHARACTERISTIC IN V2V

In most of VANET simulation scenarios the channel modelling issue has been treated in a simple manner using Rayleigh channel model e.g. (Sharma & Malhotra., 2015; Akbar *et al.*, 2015; Abbasi *et al.*, 2015; Nyongesa *et al.*, 2015) as VANET channel model. In this sections, the time domain channel characteristic for V2V communication have been tested based on V-SCME channel model and Rayleigh channel model. The simulation results are illustrated in Figures (5.3) (5.4). The purpose of this scenario tests were to show the estimated channel fading using the parameter of the vehicular standard IEEE 802.11p. Three different speeds have been applied 30km/h for slow speed, 60km/h for medium speed and 90km/h for high speed. The vehicular standard IEEE 802.11p carrier frequency 5.9GHz and the bandwidth of 10MHz have been used in the simulation tests.

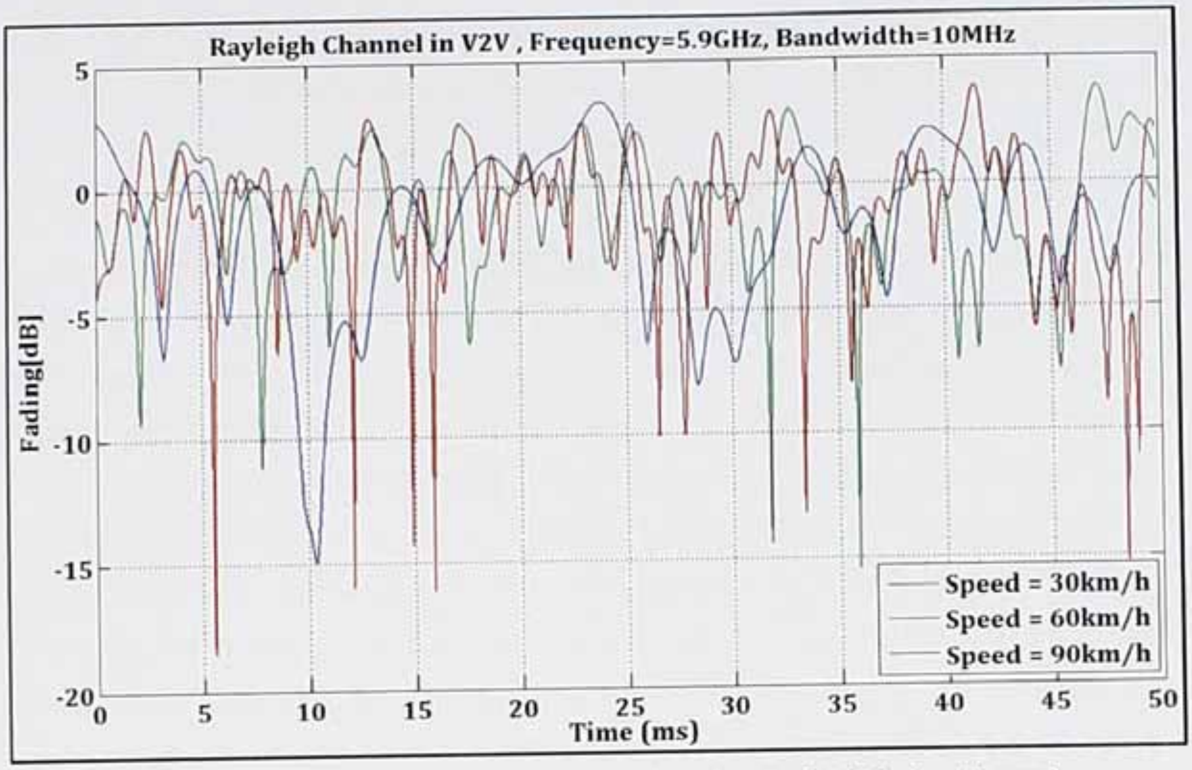


Figure 5.3: V2V Time Domain Characteristic based on Rayleigh Fading Channel.

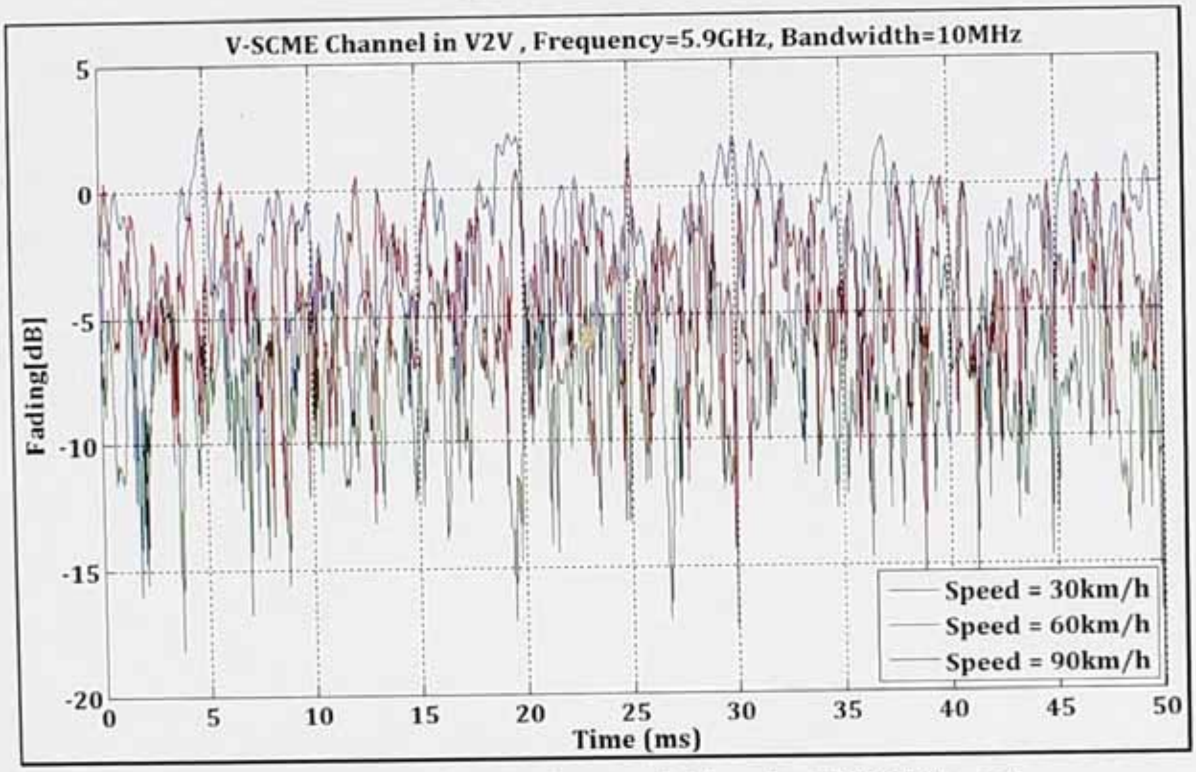


Figure 5.4: V2V Time Domain Characteristic based on V-SCME Channel.

As a comparison between Rayleigh and V-SCME channel characteristic for V2V channel, the time variant of the channel fading of the V-SCME shown in Figure (5.4) was higher than the time variant of the Rayleigh channel fading shown in Figure (5.3) for all different speeds. The number of parameters which were considered by the WINNER project (Eurescom GmbH, 2006) to represent the channel in cellular system was the result of their best efforts to provide a more realistic channel. Therefore, the obtained results in Figure (5.4) was appropriate to characterise the V2V channel than Rayleigh.

Achieving a higher data rate, robustness against multi-path fading and overcoming the inter symbol interference are the main features of OFDM technique. Zhao *et al.* (2013) stated that the physical layer of the vehicular standard IEEE 802.11p (IEEE Vehicular Technology Society, 2014) is based on the OFDM techniques. Sharma *et al.* (2014) said that OFDM techniques can improve the efficiency of spectrum and cope with severe channel conditions. Thus, OFDM is proposed to be used in VANET communication. The fading influences on the performance of the V2V communication and the use of SISO-OFDM will cope with such a channel. In digital transmission systems, the digital data (0 and 1) is translated into baseband signal when the data has to be transmitted over a medium that only allows for analogue transmission. Therefore, different modulation schemes such as BPSK, QPSK and QAM can be used to represent the translated data. Within this work the behaviour of the OFDM in two different channel models has been tested; with three different modulations schemes. Figure (5.5) shows the BER vs. SNR for V2V-OFDM in three different modulations schemes QPSK, 16-QAM and 64-QAM, in AWGN and Rayleigh channel models. The results showed that AWGN model needs less SNR power of approximately (30%) to achieve the same BER in Rayleigh channel which was used to represent the V2V channel other researchers. Although Rayleigh channel is consuming more power, OFDM could be a good solution for V2V communication as there is unlimited battery power generated during a vehicle journey.

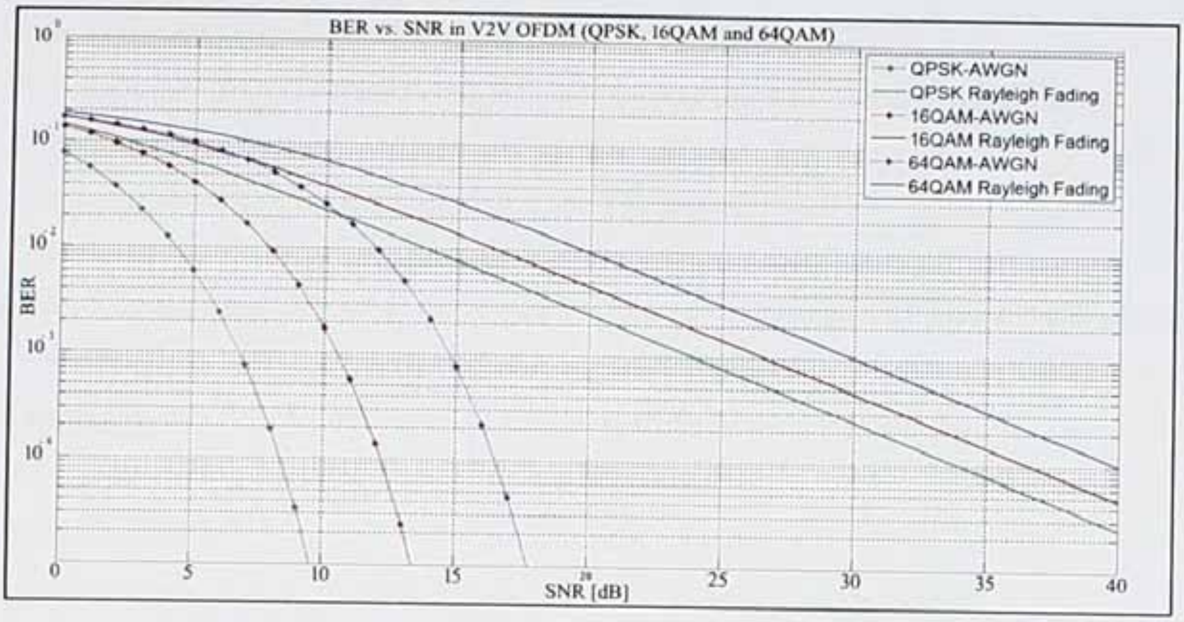


Figure 5.5: OFDM in AWGN/Rayleigh Channels for QPSK, 16QAM and 64QAM.

A V2V channel is a highly time variant channel as shown in Figures (5.3) and (5.4) and that caused a high BER as compared to other applications such as indoor Wi-Fi or less mobility outdoor application. Therefore a suitable technique will be intensively tested to satisfy an acceptable results for V2V application. However, in this work MIMO diversity techniques have been used to improve the error degradation with less transmission power. Figure (5.6) shows BER vs. SNR of using Alamouti 2x2 for V2V for Rayleigh Channel. The three modulations schemes have satisfied one Part Per Million (ppm) for BER in different SNRs [dB] which is better than the previous test in Figure (5.5). For QPSK, the SNR power was 60% less than the previous OFDM test while for 16QAM the SNR power was 25% less and it was almost the same for 64QAM.

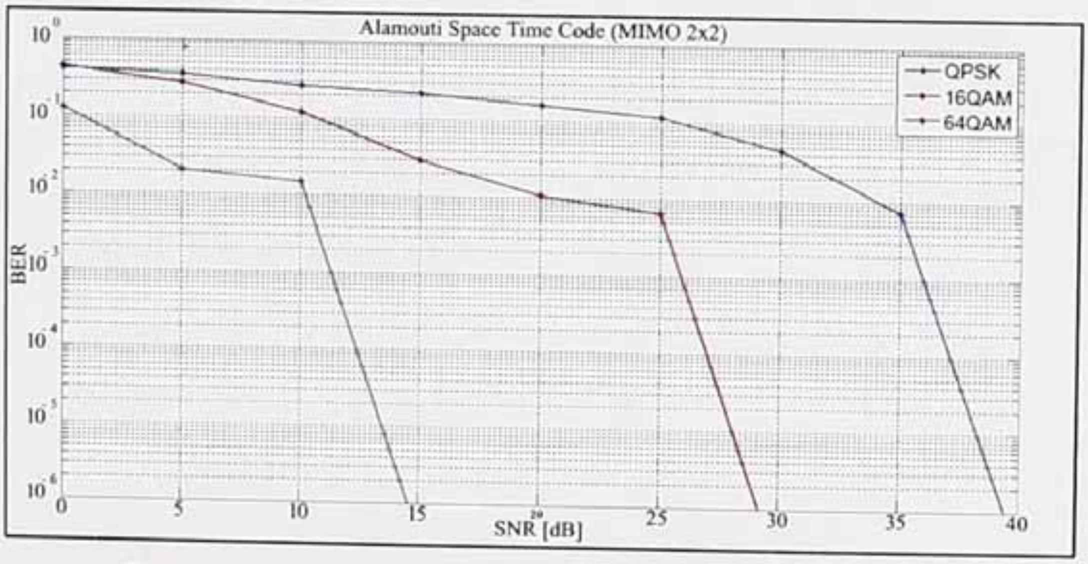


Figure 5.6: Alamouti/Rayleigh Channels for QPSK, 16QAM and 64QAM.

5.4. VALIDATION OF V-SCME IN V2V COMMUNICATION

The channel capacity of MIMO systems could be increased by compromising the number of antenna and the antenna spacing at the senders and receivers sides, in theory increasing the number of antenna and the spacing among them increase the channel capacity. In V2V communication, with such a dynamic environments, many parameters affect V2V signals and having a realistic V2V channel model is challenging. Most of the previous work e.g. (Dib, 2009; Bernadó *et al.*, 2010; Cheng *et al.*, 2013; Nuckelt *et al.*, 2013; Taimoor et al., 2013) used a simplified representation for V2V channel model by conveying Rayleigh fading or Ray tracing wireless channel without factual multi-path fading as discussed in Chapter (3).

5.4.1. VALIDATE THE CHANNEL CAPACITY OF THE PROPOSED MODEL

This thesis provides a predefined V2V channel coefficients based on a catastrophic signal fading. The validation focuses on the spectral efficiency of the predefined V2V channel coefficients library. Urban canyon microcell (COST 231 Final Report, 1999) was included to provide this library. Also, it has considered both LoS and NLoS for distances less than 300 meters this was based on the vehicular standard IEEE 802.11p (IEEE Vehicular Technology Society, 2014), while only NLoS was used for distances between 300 to 1000 meters 3rd Generation Partnership Project, (2014). Up to 18 multi-path for NLoS, while only 6 diffused signals for LoS. In MIMO system, Kim, (2015) said that the antenna spacing is one of the major factors which direct effects on the spectral efficiency and the channel capacity communication systems. In this context, three antenna spacing were selected 0.5λ, 4λ and 10λ to match the antenna spacing which is recommended by the 3GPP (3rd Generation Partnership Project, 2014) for evaluation. Cumulative Distribution Function CDF and the transmission rate of R bps/Hz were used to measure the performance of the V2V channel as shown in Figure (5.7, A-I). At SNR = 20[dB] for 2x2 MIMO and 4x4 MIMO, three distances {(100 and 300 meters LoS and NLoS) and (1000 meters NLoS)}, three speeds (20km/h, 40km/h and 60 km/h).

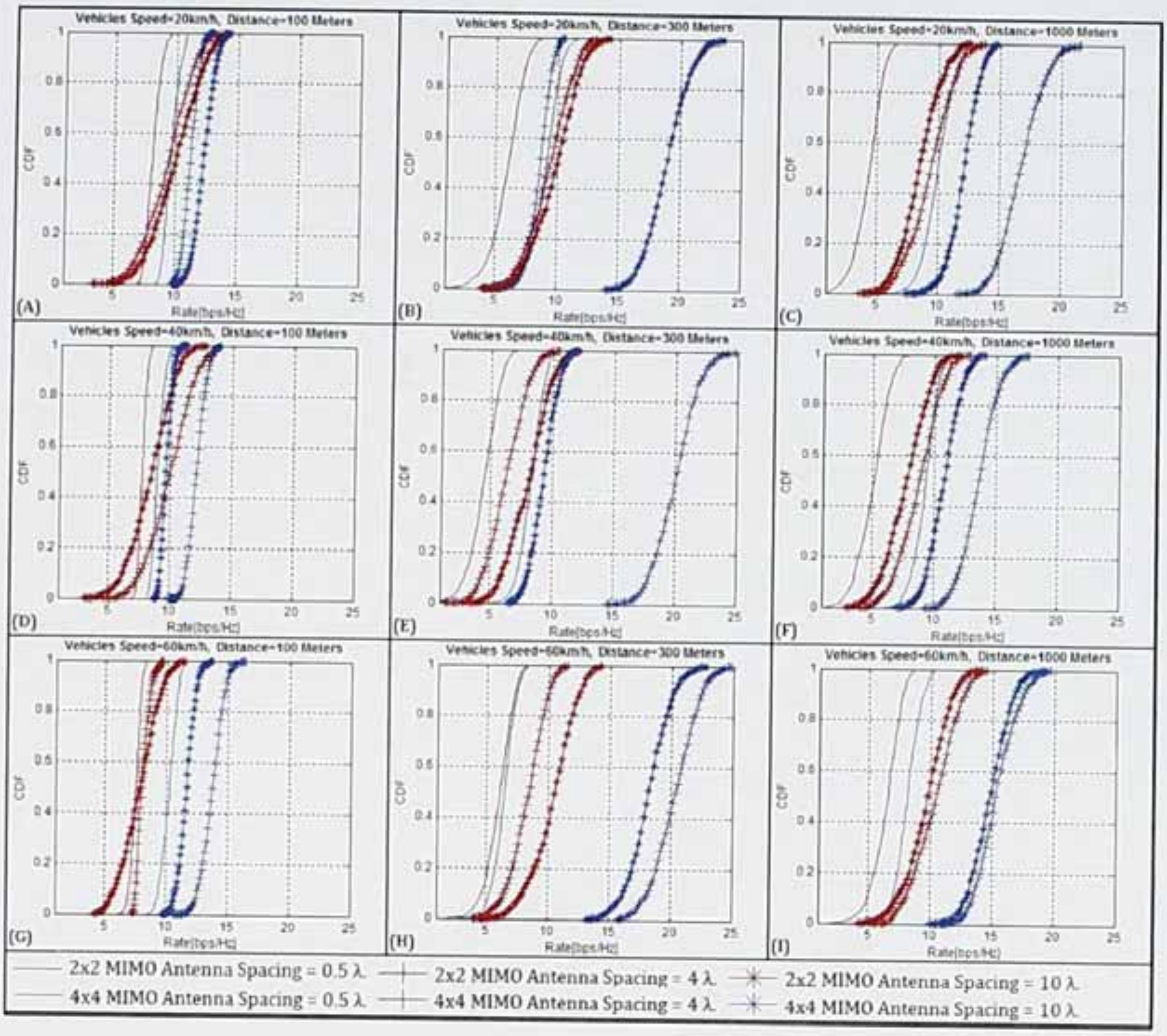


Figure 5.7 (A-I): CDF vs. Rate [bps/Hz] for V2V channel in urban canyon microcell scenarios with different 2x2 and 4x4 MIMO with three antenna spacing (0.5λ, 4λ and 10λ), three different speeds (20km/h, 40km/h and 60km/h) and three different distances (100m, 300m and 1000m).

The obtained results in Figure (5.7 A-I) varied from case to case, due to the urban Canyon Microcell scenarios. However, it can be seen from the obtained results that the higher number of antennas in MIMO systems the better transmission rate (bps/Hz).

Generally, at CDF=0.1, the longer distances between the vehicles the lower transmission rate, and the same observation for the vehicles speeds. Figure (5.7A) shows, at CDF=0.1, the 4x4 MIMO have better rate than 2x2 MIMO, while increasing the antenna spacing does not always improve the rate due to the nature of the signal disruptions at a certain time in this particular scenario. For example, 4x4 MIMO with 4λ spacing provided a better channel capacity rate than the 10λ spacing as shown in Figures {(5.7C), (5.7D), (5.7E), (5.7F), (5.7G), (5.7H) and (5.7I)}, but in general both 4λ and10λ spacing were better than 4x4 MIMO with 0.5λ spacing, while the channel capacity in 2x2 MIMO 10λ spacing was slightly better than 2x2 MIMO 4λ spacing and both were better than 0.5λ spacing as shown in Figure (5.7, A-I). The author recommended to use 2x2 MIMO with 4λ spacing as a good enough solution in terms of cost effective and complexity. This was one of the strong points of this library which could be more realistic representation of V2V channel and more details will be discussed in section (5.5). The library was built based on WINNER EU project Eurescom GmbH, (2006) to reduce the overall simulation time.

Transmission rate (bps/Hz) and the SNR were used to measure the performance predefined library as shown in Figure (5.8, A-I). For constituency, the same (distances, speeds, antenna spacing values and urban canyon microcell scenarios) were used to produce the results in Figure (5.8, A-I). However, it can be seen from the results that the higher the number of antennas in MIMO system the better is the transmission rate (bps/Hz). Generally, at SNR 20-30 [dB], the longer the distances between the vehicles the lower is the transmission rate.

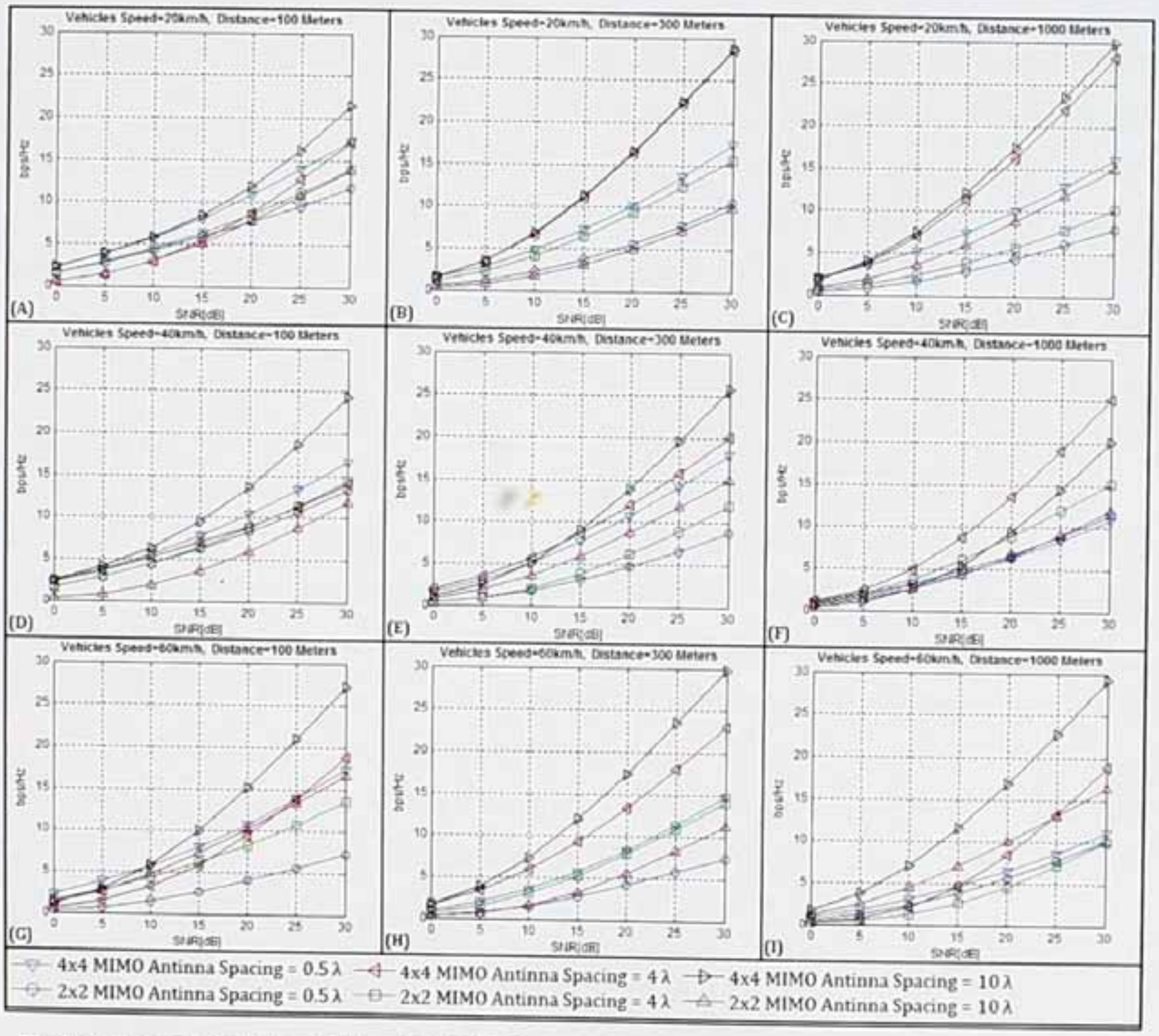


Figure 5.8 (A-I): Rate [bps/Hz] vs. SNR [dB] for V2V channel in urban canyon microcell scenarios with different 2x2 and 4x4 MIMO with three antenna spacing (0.5λ, 4λ and 10λ), three different speeds (20km/h, 40km/h and 60km/h) and three different distances (100m, 300m and 1000m).

Both LoS and NLoS were employed in 100 and 300 meters distances scenarios while only NLoS is employed in 1000 meters distances scenarios. The antenna spacing was the major key of shaping any MIMO system spectral efficiency, consequently for V2V communication that would be the main factor to achieve an optimum spectral efficiency and transmission rate with minimum cost. It's noticed from Figure (5.7 A-I) and Figure (5.8 A-I) that the effect of having wider antenna spacing functions was better in the longer vehicles' distances.

The methodology used in this work to measure and assess the performance of the predefined V2V channel coefficients library is consistent among all parameters and other variables. The results were simulated/produced using MATLAB R2013a and the V2V channel coefficient library as well.

5.4.2. NETS4CARS RESEARCH GROUP

Over the last two years the author was engaged with a relevant European research group called Nets4Cars which is an international workshop on communication technologies for vehicles (Vinel, 2015). This group meets regularly twice a year which's sponsored by IEEE and Springer. In Q1 2014, an initial result of developing SCM-MIMO as a V2V channel model was published as a novel idea in (Al-Khalil *et al.*, 2014).

In Q1 2015, the second participation was about identifying a suitable MIMO-Coding for SCM in V2V communication which was a challenge. The simulated V2V communication system showed that integrating V-BLAST MIMO-Coding over the SCM channel model achieved optimum results. This work was published in (Al-Khalil *et al.*, 2015).

In Q2 2015, as an outcome of the continuance engagements and discussions with Nets4Cars members, a research gap has been highlighted in VANET research community. Providing V2V channel coefficients during the simulation time is a time consuming process due to the high computational power. Therefore I have created a novel open access predefined channel coefficients library and the Nets4Cars group members have welcomed this accomplishment as it's going to reduce the simulation times and enables the researchers to handle a large scale VANET tests scenarios. This accomplishment published in Q4 2015 (Al-Khalil *et al.*, 2015).

5.4.3. COMPARING WITH RESCUE PROJECT RESULTS

The research area of wireless channel measurements and modelling for VANET communication have recently shown an increased interest. These authors are supported by the Intelligent Transportation Systems in order to satisfy the safety and security requirement for the VANET communication. RESCUE is a European project for communication technology that have recently delivered an initial results in their website (RESCUE Project, 2013) by (Kaske *et al.*, 2014) to measure V2V channel in real world. Kaske et al, (2014) approach was based on an extension of the GBSCM developed under the IST WINNER project (Eurescom GmbH, 2006) which was similar to this work approach that was based on a developed of 3GPP Extended (3rd Generation Partnership Project, 2014) under the same project. Kaske *et al.* (2014) stated that "Currently no attempts are available to extend a cellular system dedicated channel model to V2V applications". However, Kaske *et al.* (2014) published their initial results in Oct-2014 and at the same time the results of this work was published in Oct-2014 (Feasibility Study of Utilising SCM – MIMO Channel Model in V2V Communication. Published in The 7th International Workshop on Communication Technologies for Vehicles. St-Petersburg Russia Oct-2014) (Al-Khalil *et al.*, 2014). Kaske *et al.* (2014) mentioned that the use of MIMO systems over V2V is important, and only few MIMO data sets were focusing on the propagation issue in V2V channel which was a challenge. Another challenge was the scatterer e.g. (vehicles, trees, surrounding buildings and other objects) presenting in the transmission range that effects the propagated signals. These challenges have already been addressed in this thesis section (5.1) Figure (5.1).

Kaske *et al.* (2014) considered in their scenario the carrier frequecny of 2.5 GHz, where the vehicular standrd IEEE 802.11p (IEEE Vehicular Technology Society, 2014) allocated the carrier frequency band of 5.9 GHz to be used in the Intelligent Transportation Systems communication. Kaske *et al.* (2014) stated that due to manufacturing problems the antenna arrays for the 5.2 GHz band could not be finished before the channel sounding campaign was scheduled, and they left the carrier frequency of 5.9 GHz band for the future work as soon as the antenna arrays are available. In this thesis, both carrier frequencies 5.9 GHz and 2.5 GHz bands have been considered in the simulation tests. Kaske *et al.* (2014) ran their real world scenarios tests on the campus of Ilmenau University of Technology using two scenarios a main street and crossing street. RUSK HyEff Sounder manufactured by Medav GmbH have been used as a channel sounder. RUSK HyEff Sounder was capable to continuously record real-time wideband MIMO channel matrices (Kaske *et al.*, 2014) and it can emulate V2V network scenarios. Kaske *et al.* (2014) have set the bandwidth to 40MHz while within this thesis 10MHz bandwidth has been used in the simulation tests which was the recommended bandwidth by the vehicular standard IEEE 802.11p (IEEE Vehicular Technology Society, 2014). In addition, Kaske *et al.* (2014) have used different level of transmitted power of 24[dB], 27[dB] and 36[dB]m to cover different ranges within 5 meters. On the other hand, the mesurement results of CDF vs. SNR shows that the magnitude power used up to 15[dB]. In this thesis, 5[dB], 10[dB] and 15[dB] were used to compare the obtained results with their museared results. My results were quite similar to the same configration and environment. Two trolleys and two vehicles as scatterer have been used in Kaske et al, (2014) tests, the antennas were mounted on the top of the trolleys and their hight was 1.7 meters, while 1.5 antennas hight have been used in this thesis tests as it was recomemended by 3GPP (3rd Generation Partnership Project, 2014).

"The patch antennas possess two ports where one was primarily susceptible for horizontal (or φ-) polarisation and the other for vertical (or θ-) polarisation. In total each array was composed of 32 antennas port which leads to a 32x32 MIMO configuration" (Kaske *et al.*, 2014). It has been concluded that not all the 32 antennas were involved in the communication, but only two antennas were in charge to handle communication and the 32 antennas were mounted to cover 360°. Furthermore, 2x2 and 4x4 MIMO were considered in this work simulations tests, the simulation results showed that 2x2 MIMO was the optimum solution for V2V communication.

Regarding to the antennas spacing, Kaske *et al.* (2014) set the antennas spacing to 0.4 λ for horizantal spacing and 0.45λ for vertical spacing, while the 3rd Generation Partnership Project, (2014) set the vehicular antennas spacing to 0.5 λ. In this thesis simulation tests set the antennas spacing values to 0.5 λ, 4 λ and 10 λ. The reason of setting the antennas spacing values to of 4 λ and 10 λ is due to space availabity in the vehicle which would increase the channel capacity as shown in section (5.3.1).

"The main goal of the measurement campaign is to aid in the development of a V2V channel model. The data obtained can be used for the development of a V2V channel model as well as realistic channel measurements for system simulations." (Kaske *et al.*, 2014), which is similar to this thesis approach.

Kaske *et al.* (2014) proposed four different environments to run their realistic tests

- T1: wide grid static measurements.
- T2: dense grid static measurements.
- T3: moving cars measurements.
- T4: full dynamic measurements.

In this thesis, the 3rd and 4th tasks environments (T3 and T4) have been considered for a comparision which is often found in V2V communication. In addition, the full dynamic environment measurements cosiders the most complicated scnario due to the continuasly change of the topology.

In the verification of the obtained results, an important problem has been addressed by Kaske et al. (2014) which was "although the system seems to be working properly at the beginning it cannot be predicted to remain in this state up to the end of a campaign. Typical failures of the multiplexers caused by hard- and software errors lead to disordered, missing, or static switching sequences. A further problem may occur due to the loss of the synchronisation between the switches at both link ends." (Kaske *et al*,. 2014).

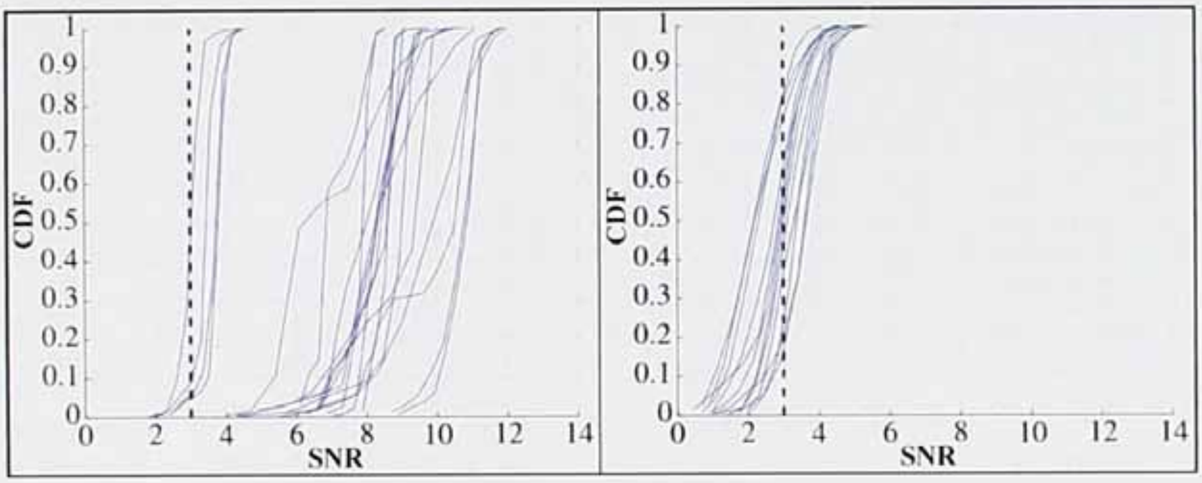


Figure 5.9: CDF vs. SNR: RESCUE Results for T3 and T4.

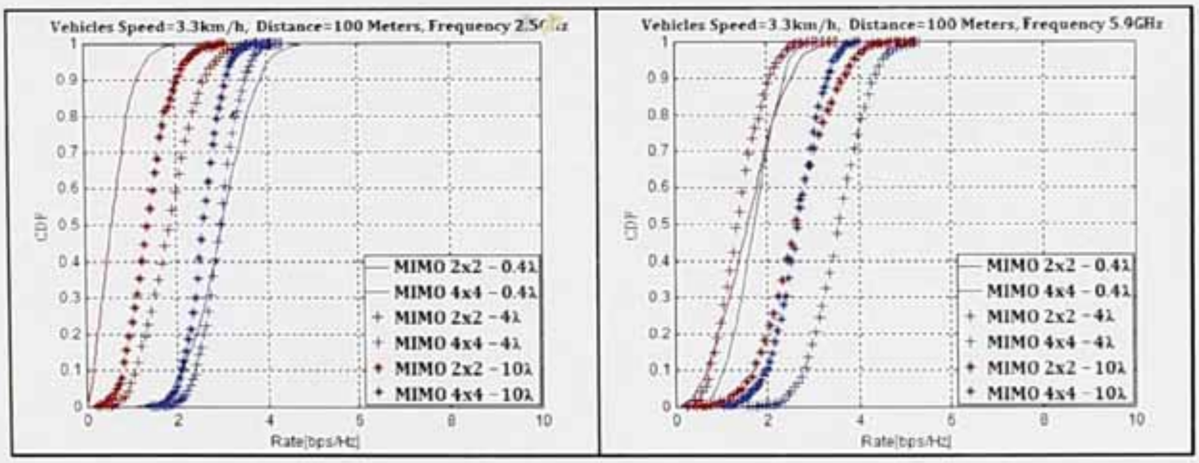


Figure 5.10: CDF vs. Rate [bps/Hz] for V2V channel in urban canyon microcell scenarios with different 2x2 and 4x4 MIMO with three antenna spacing (0.4λ, 4λ and 10λ) and SNR 5[dB].

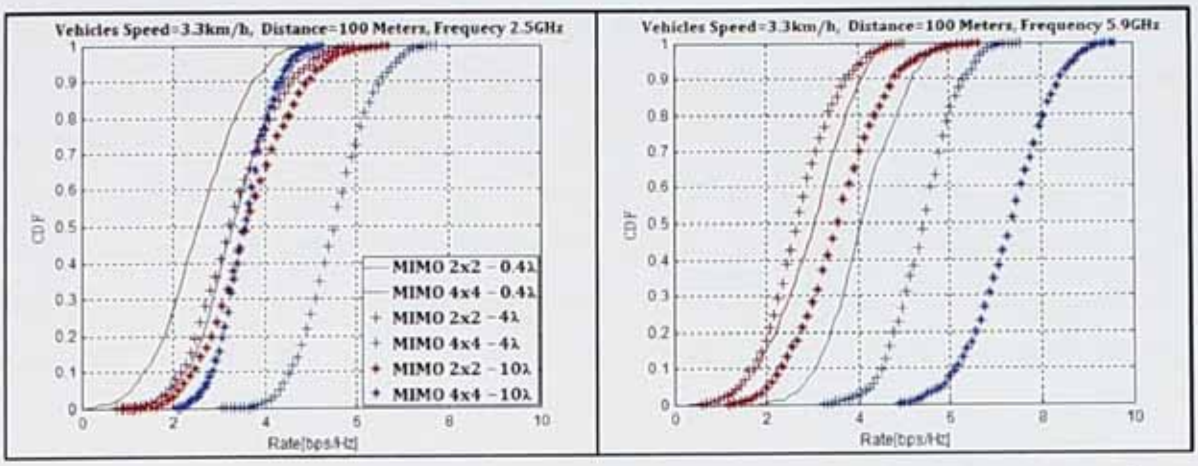


Figure 5.11: CDF vs. Rate [bps/Hz] for V2V channel in urban canyon microcell scenarios with different 2x2 and 4x4 MIMO with three antenna spacing (0.4λ, 4λ and 10λ) and SNR 10[dB].

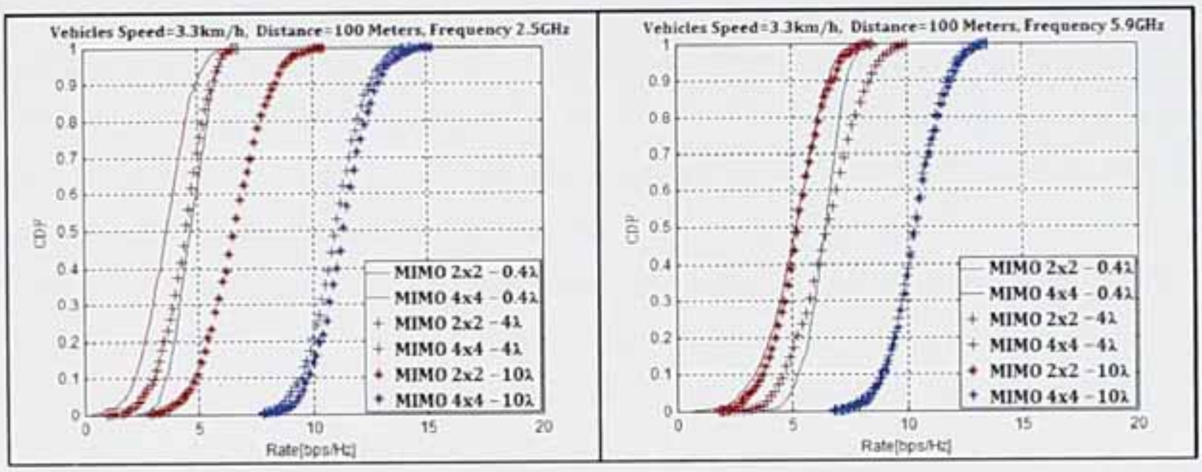


Figure 5.12: CDF vs. Rate [bps/Hz] for V2V channel in urban canyon microcell scenarios with different 2x2 and 4x4 MIMO with three antenna spacing (0.4λ, 4λ and 10λ) and SNR 15[dB].

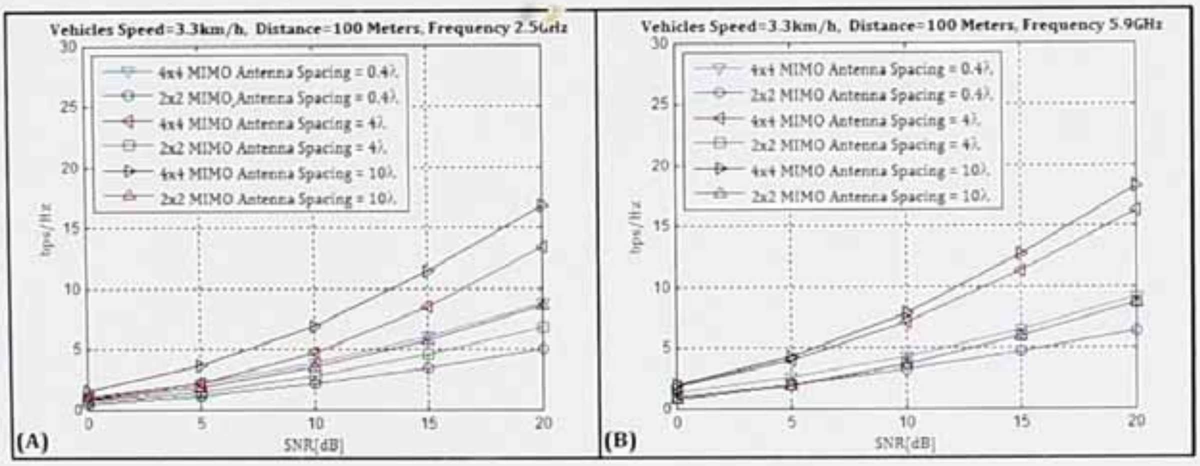


Figure 5.13: Rate [bps/Hz] vs. SNR [dB] for V2V channel in urban canyon microcell scenarios with different 2x2 and 4x4 MIMO with three antenna spacing (0.4λ, 4λ and 10λ).

As mentioned above, (Kaske *et al.* (2014) have used physical tests in their V2V channel measurement campaign. They are the first research group to provide real world test for V2V MIMO (RESCUE Project, 2013). The configuration of this campaign was done by considering vehicle speed 3km/h, up to 100 meters distance, 2.5GHz carrier frequency, 0.4λ 2x2MIMO antenna spacing and up to 15[dB] SNR. This section is allocated to validate the obtained simulation results using our novel V-SCME with the RESCUE project measurement campaign in T3 and T4 as shown in Figure (5.9). In this test, the same configuration was assigned to the V-SCME to compare the obtained results with the WP4 RESCUE project, where it was the only configuration that was considered in their report with very limited outcomes. Consequently, this work simulation results have showed a comparable results with their results as shown in Figure (5.10), (5.11) and (5.12) (MIMO 2x2/ 0.4 λ/ 2.5GHz).

In addition to the above, a wider range of configuration in terms of carrier frequency, antenna spacing and numbers of antennas were simulated as an additional self-validation process which is compatible with the vehicular standard IEEE 802.11p (IEEE Vehicular Technology Society, 2014). In Figure (5.10) two carrier frequencies were considered (2.5GHz and 5.9GHz) with 5[dB] SNR. The configured test (MIMO 2x2 / 0.4λ / 2.5GHz) showed a similar results to the RESCUE project as shown in Figure (5.9), while the other cases were the results of V-SCME simulation and were not considered in the RESCUE project. As a general observation the channel capacity (bps/Hz) is improved by increasing the antenna spacing, having more antenna arrays and increasing the SNR.

Although the RESCUE project have implemented the hardware of the V2V communication and produced some results it is limited to a certain configuration and there was no measurement for the channel capacity, MIMO diversity coding, multi-path, modulation and data throughput. I believe that making a V2V channel predefined open access library with wide range of configuration and environment is useful for the research community.

5.5. MIMO CODING

In wireless communication, coding over MIMO systems Wang et al, (2010) has been widely used in order to improve the reliability and achievable transmission rates. MIMO – Coding techniques can be classified into the following categories (Mahey & Malhotra, 2015):

1- Spatial Diversity: Spatial Diversity (Diggavi *et al.*, 2004) is used to increase the transmission reliability by transmitting the same stream from different antennas. The Alamouti Space-Time code (Alamouti, 1998) scheme is a typical example of this category.
2- Spatial Modulation: The spatial modulation technique (Yang et *al.*, 2014) introduced a third dimension instead of the normal two dimensional modulation in order to increase the efficiency. The third dimension represents the index of the antenna where the symbol is a released from. The fundamental of spatial modulation is that the transmitter can access multiple antennas but only one antenna is used to transmit in any given symbol interval. In other words, only one transmit antenna is active at each time instant. The receiver must ensure which antenna was selected for transmission. The use of only one antenna at each time instance will help to avoid ICI.
3- Spatial Multiplexing: Spatial Multiplexing (Kwon *et al.*, 2009) is intended to increase the channel capacity, where multiple independent streams are transmitted through different antennas at the same time and on the same frequency, so that the receiving antenna array receives a superposition of all the transmitted signals. Thus MIMO capacity rises linearly with a minimum (N_T, N_R) as compared to the SISO systems, where N_T and N_R is the number of transmitter and receiver antennas respectively. The V-BLAST (Foschini, 1996) is a typical example of spatial multiplexing.
4- Beamforming Technique: is a coding technique of MIMO technologies that are used to generate the radiation pattern of antenna array. Beamforming (Vouyioukas, 2013) considers the knowledge of the channels information at both the T_x and R_x. The signal is transmitted with the decomposed product of the channel matrix to achieve capacity gain. Precoding is a generalisation of beamforming to support multi-layer transmission in MIMO systems. Beamforming is a typical technology of this category.

The objective of this section is to compare between the existing MIMO - Coding techniques in order to find the optimum one for utilisation in V2V communication. Section (5.5) begins with Alamouti scheme which was a simple way of obtaining transmit diversity for the case of two transmit antennas in V2V communication. The next section (5.6) discusses the simulation results for V2V communication using Spatial Modulation. Finally, section (5.7) is allocated for discussing the obtained simulation results using V-BLAST coding in MIMO systems.

5.5.1. ALAMOUTI SPACE TIME CODING IN V2V COMMUNICATION

Alamouti Space-Time code is a complex orthogonal space-time block code technique suitable for two antennas that encodes two consecutive symbols (Alamouti, 1998). Two symbols x_1 and x_2 are simultaneously transmitted from the two antennas then the two symbols $-x_2^*$ and x_1^* are simultaneously transmitted from the two antennas again. Where as x_1^* is the complex conjugate of x_1 while $-x_2^*$ is the negative complex conjugate of x_2, i.e. if $x_2 = (1 + i)$ then$-x_2^* = -(1 - i)$. In this section, Alamouti tests were divided into two main categories: Alamouti symmetric channel tests and Alamouti asymmetric channel tests consider both LoS and NLoS tests.

In wireless communication systems, the MIMO channel coding is needed in order to enhance the performance of communication over a certain channel model. Although these channel models do not always reflect the reality (Kaske *et al.*, 2014) as they were based on a statistical formulas. They are still required to help the researchers to analyse the performance of proposed systems and getting valuable information according to their scenarios. In information theory, the actual channel is represented by a channel model. The symmetric and asymmetric channels are the common channel models used in MIMO systems. The symmetric channel is one of the simplest analysing MIMO channel that has been frequently used in the coding theory. Figure (5.14) shows a symmetric channel diagram in which the channel coefficients $h_{11} = h_{22}$ and $h_{12} = h_{21}$, while in asymmetric channel, the channel coefficients $h_{11} \neq h_{22}$ and $h_{12} \neq h_{21}$. An example of symmetric channel is the indoor WiFi while the VANET channel is considered as an asymmetric channel.

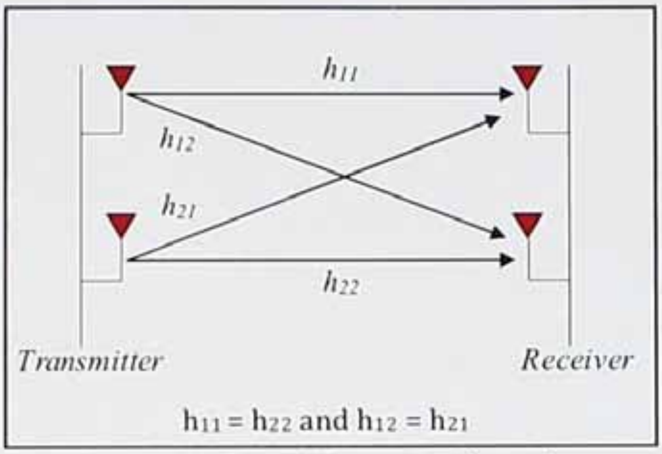


Figure 5.14: MIMO Symmetric Channel.

In VANET, the power azimuth and the Doppler spectrums (Tranter *et al.*, 2007) are both none uniform due to the scattering environments. As a result, V-SCME represents the summation of the incoming arbitrary arriving plane waves around the vehicle which can deal with various forms of vehicle speed. In this section, a sets of Alamouti Space Time Coding were applied to be utilised on V-SCME in order to evaluate the performance of the system. The tests are considered for both asymmetric and symmetric channels. For the symmetric channel, three distances were considered 100, 200 and 300 meters as the LoS distances. For each distance, three speeds were considered as shown in Table (5.1):

Distance	Vehicles speeds
100 Meters	10km/h, 50km/h and 90km/h
200 Meters	20 km/h, 60 km/h and 100 km/h
300 Meters	30 km/h, 70 km/h and 110 km/h

TABLE 5.1: Speed Groups for Alamouti tests

The simulation tests were constructed under the condition of MIMO and Alamouti-coding for four different modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

Figures (5.15), (5.16) and (5.17) shows the simulation results for the Alamouti symmetric channel based on the mentioned parameters above.

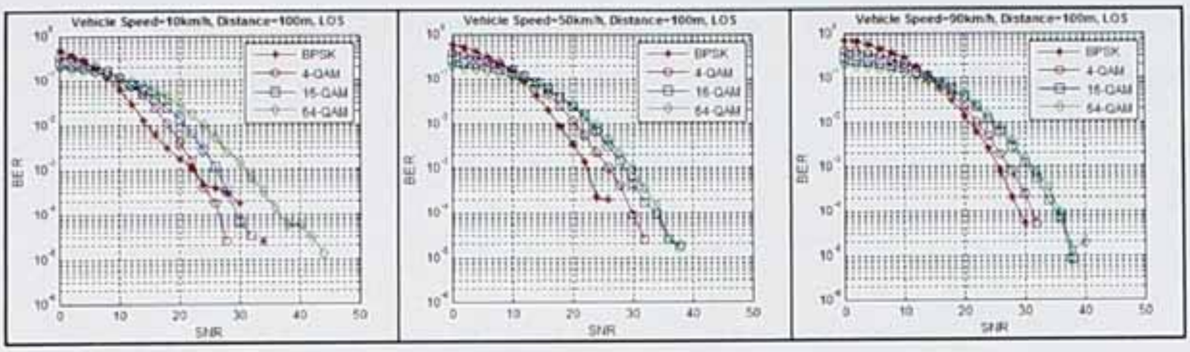


Figure 5.15: Alamouti Symmetric Channel: Vehicles Speeds: 10km/h, 50km/h and 90km/h. Distance between Vehicles 100 Meters. Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

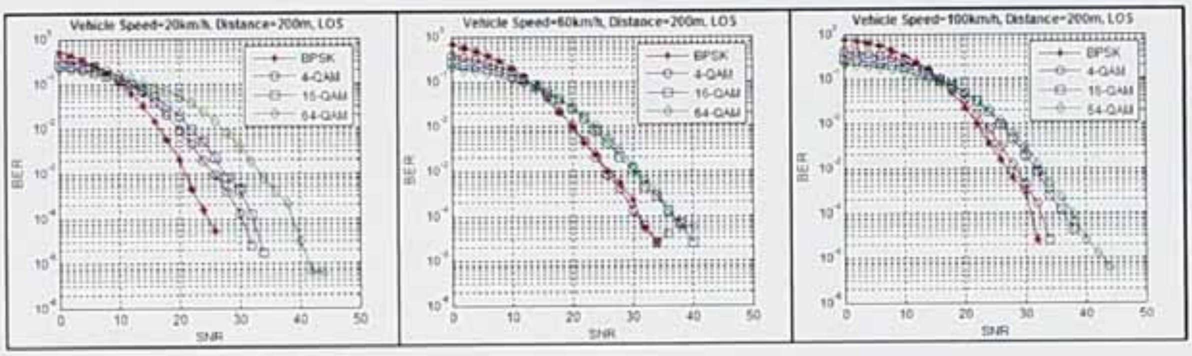


Figure 5.16: Alamouti Symmetric Channel: Vehicles Speeds: 20km/h, 60km/h and 100km/h. Distance between Vehicles 200 Meters. Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

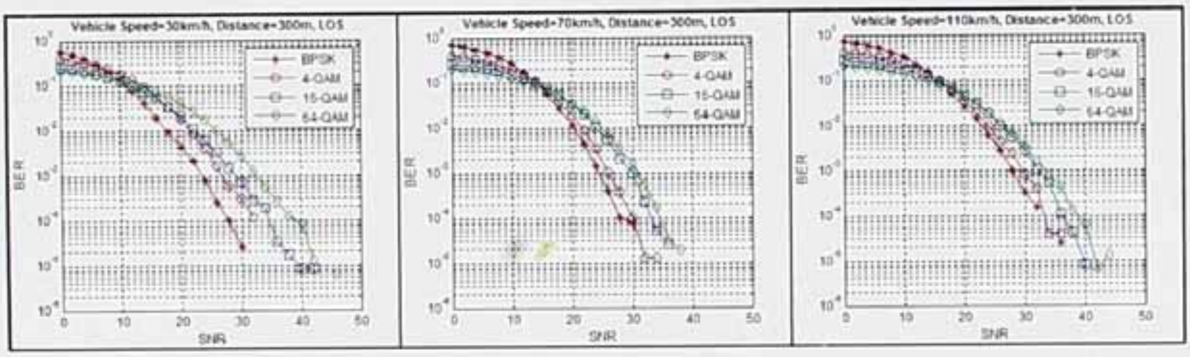


Figure 5.17: Alamouti Symmetric Channel: Vehicles Speeds: 30km/h, 70km/h and 110km/h. Distance between Vehicles 300 Meters. Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

The multi-fading and scattering adds challenges to estimate the channel characteristic in V2V communication. The simulation results in Figures (5.15), (5.16) and (5.17), showed that the BER vs. SNR have waterfalls shapes. Due to the high dynamic environment, different results were obtained at different times. In the first observation, all figures have an intersection point which represents the behavioural change of BER vs. SNR for the four different modulations (BPSK, 4-QAM, 16-QAM and 64-QAM). This behaviour was due to MIMO use in highly dynamic disruption environment such as V2V. The Alamouti Space Time Code was considered in this test, where, ***h*** represents the instantaneous channel parameter in MIMO 2X2 matrix (h_{11}, h_{12}, h_{21}, h_{22}) which was generated by V-SCM channel model over 10sec period of time. Tables (5.2), (5.3) and (5.4) compare the results SNRs [dB] in Figures (5.15), (5.16) and (5.17) at BER 10^{-2}.

Speeds	DISTANCE 100 Meters			
	BPSK	4-QAM	16-QAM	64-QAM
10km/h	15	19	21	23
50km/h	19	20	22	23
90km/h	21	22	23	23

TABLE 5.2: The SNRs [dB] at BER 10^{-2} Gained from Figure (5.15).

Speeds	DISTANCE 200 Meters			
	BPSK	4-QAM	16-QAM	64-QAM
20km/h	18	20	21	29
60km/h	20	20	22	22
100km/h	21	22	28	28

TABLE 5.3: The SNRs [dB] at BER 10^{-2} Gained from Figure (5.16).

Speeds	DISTANCE 300 Meters			
	BPSK	4-QAM	16-QAM	64-QAM
30km/h	19	21	22	27
70km/h	20	21	25	25
110km/h	21	22	28	28

TABLE 5.4: The SNRs [dB] at BER 10^{-2} Gained from Figure (5.17).

The simulation results shown in tables (5.2), (5.3) and (5.4) have an acceptable BER for V2V communication, for example the SNR results were 15, 19, 21 and 23 where the distance was 100 meters at speed 30km/h for BPSK, 4-QAM, 16-QAM and 64-QAM respectively. The results for each individual speed for BPSK, 4-QAM, 16-QAM and 64-QAM respectively are consistent. However, the simulation results in table (5.3) and (5.4) for the 64-QAM were inconsistent results.

Modulation	20 km/h	60 km/h	100 km/h
64-QAM	29	22	28

Modulation	30 km/h	70 km/h	110 km/h
64-QAM	27	25	28

In V-SCME the number of parameters that were chosen within a certain range, measured at a particular instant, might cause different results because of the multi-path problem, the vehicle position and the high time variant channel characteristics as shown in Figure (5.4). Although the simulation tests of Alamouti symmetric channel showed an acceptable results, V2V is an asymmetric channel so Alamouti coding is not appropriate for V2V communication as shown in Figure (5.18).

For the asymmetric channel tests, a distance of 100 meters was considered for three different speeds 20km/h, 60km/h and 100 km/h. Figure (5.18) shows the simulation results for the Alamouti asymmetric channel based.

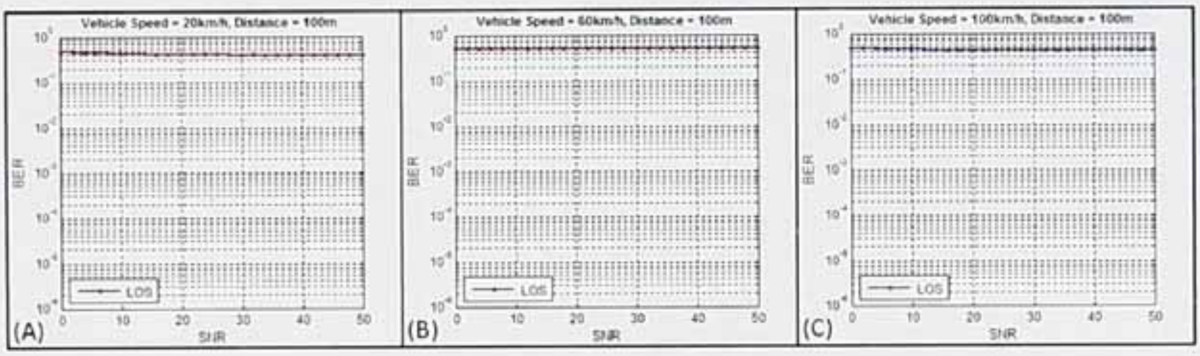


Figure 5.18: Alamouti Asymmetric Channel: Vehicles Speeds: 20km/h, 60km/h and 100km/h. Distance between Vehicles 300 Meters.

The simulation results showed a very high BER compared to the Alamouti symmetric channel. This indicates that Alamouti Space Time Coding is suitable for slow fading channel communication rather than mobility communication such as V2V.

5.5.2. PERFORMANCE OF SPATIAL MODULATION IN V2V

Globally (Guglielmo, 2014) the total data traffic which is sent to the mobile networks will reach to 190 exabytes by 2018. In order to address this challenge more of the radio frequency spectrum needs to be allocated for these networks, but unfortunately this amount of the spectrums is not available. To solve this problem a system is required to be more efficient in terms of producing more bits per hertz to improve the spectral efficiency. Another challenge is how to make these systems more energy efficient. Spatial Modulation (SM) (Serafimovski *et al.*, 2013) is a recently developed technology which is using multiple transmitter antennas to convey extra information bits in order to enhance the capacity of MIMO schemes. In particular this extra information is encoded in the physical location of the transmitting antenna. As such it requires no addition of bandwidth yet it still results in increasing data rate. This makes the system more spectrally efficient.

In this section, the performance of SM has been investigated by considering different scenarios over the V2V communication using V-SCME channel model. The simulation scenarios take into consideration the complex environment in V2V communication due to the high mobility. Table (5.5) shows the simulation scenarios.

Parameters	Values
Environment	Urban Microcell
Vehicles Antennas	Omnidirectional
Antennas Array	MIMO 2x2
AoD and AoA	180 ± 5
Carrier Frequency	5.9GHz
Signal Propagation	LoS and NLoS
Number of Multi-path	Up To 18.
Number of Sub-paths	Up To 20.
Vehicles Speeds: 1st group	10km/h, 60km/h and 110 km/h
Distances between Vehicles	100, 200 and 300
Modulations	BPSK, 4-QAM, 16-QAM and 64-QAM

TABLE 5.5: Simulation Setting for SM Performance in V2V Communication

Figures (5.19), (5.21) and (5.23) show the simulation results of the LoS for the Spatial Modulation based on the parameters setting in Table (5.6).

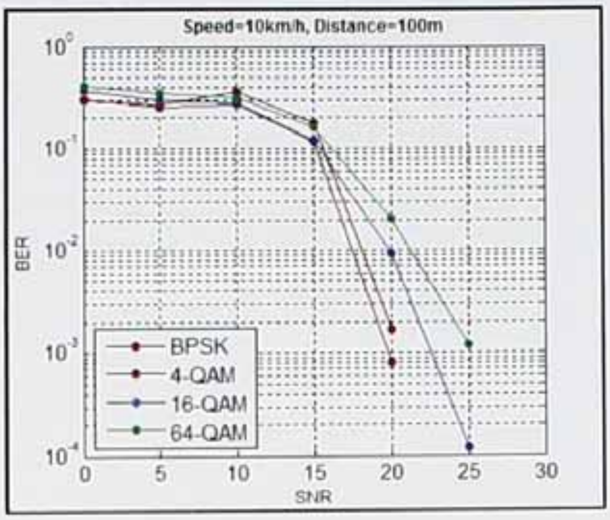


Figure 5.19: SM (LoS), Vehicles Speeds: 10km/h, Distance between Vehicles 100 Meters, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

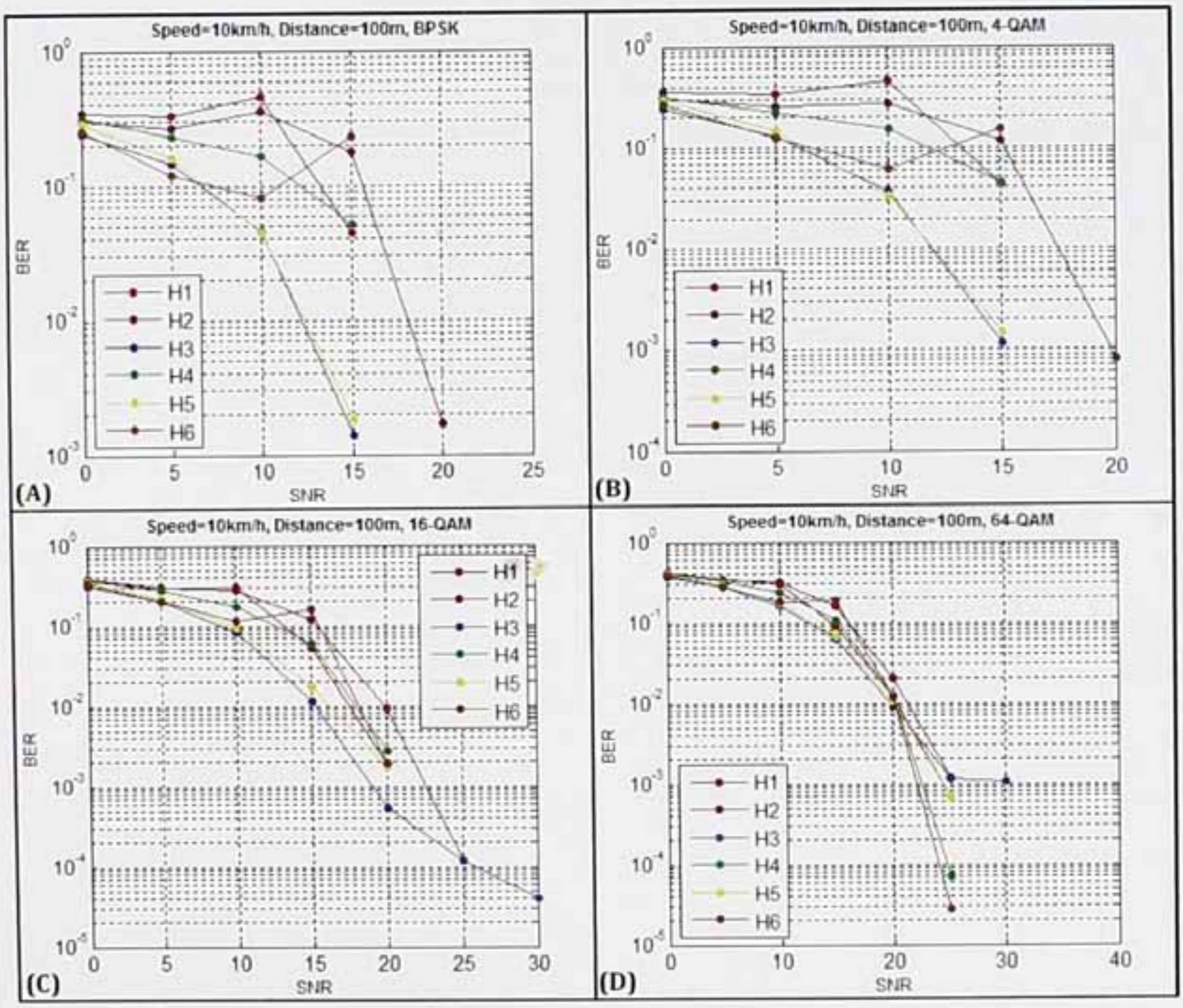


Figure 5.20 (A-D): SM (NLoS), Vehicles Speeds: 10km/h, Distance between Vehicles 100 Meters, Number of Multi-path 6, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

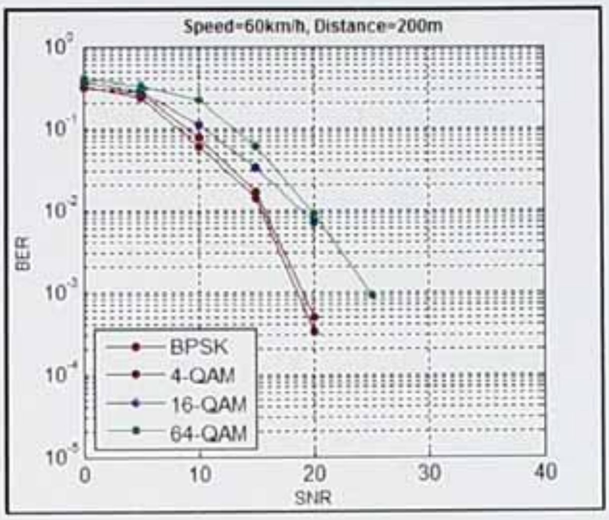


Figure 5.21: SM (LoS), Vehicles Speeds: 60km/h, Distance between Vehicles 200 Meters, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

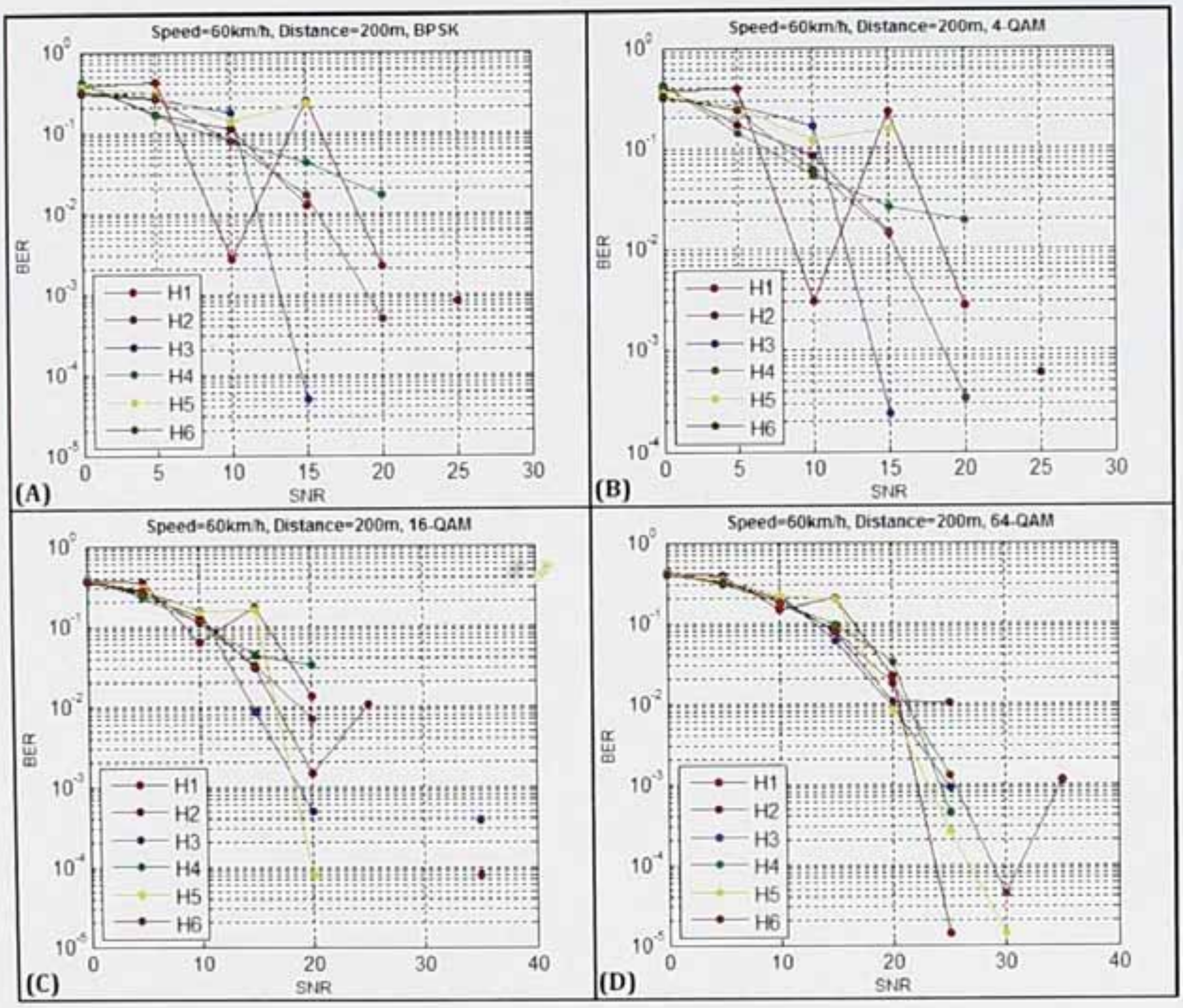


Figure 5.22 (A-D): SM (NLoS), Vehicles Speeds: 60km/h, Distance between Vehicles 200 Meters, Number of Multi-path 6, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

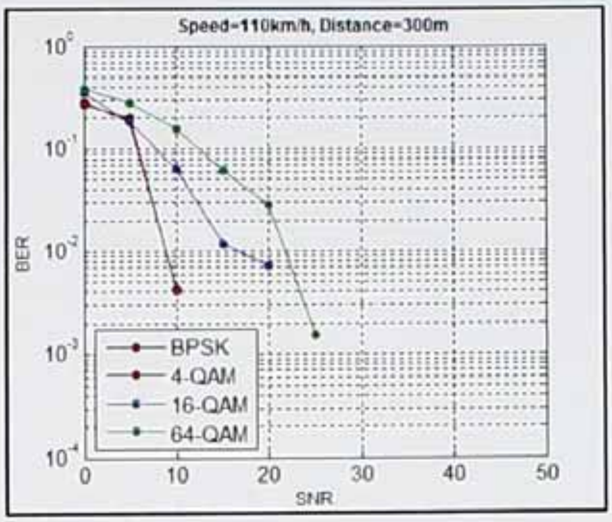


Figure 5.23: SM (LoS), Vehicles Speeds: 110km/h, Distance between Vehicles 300 Meters, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

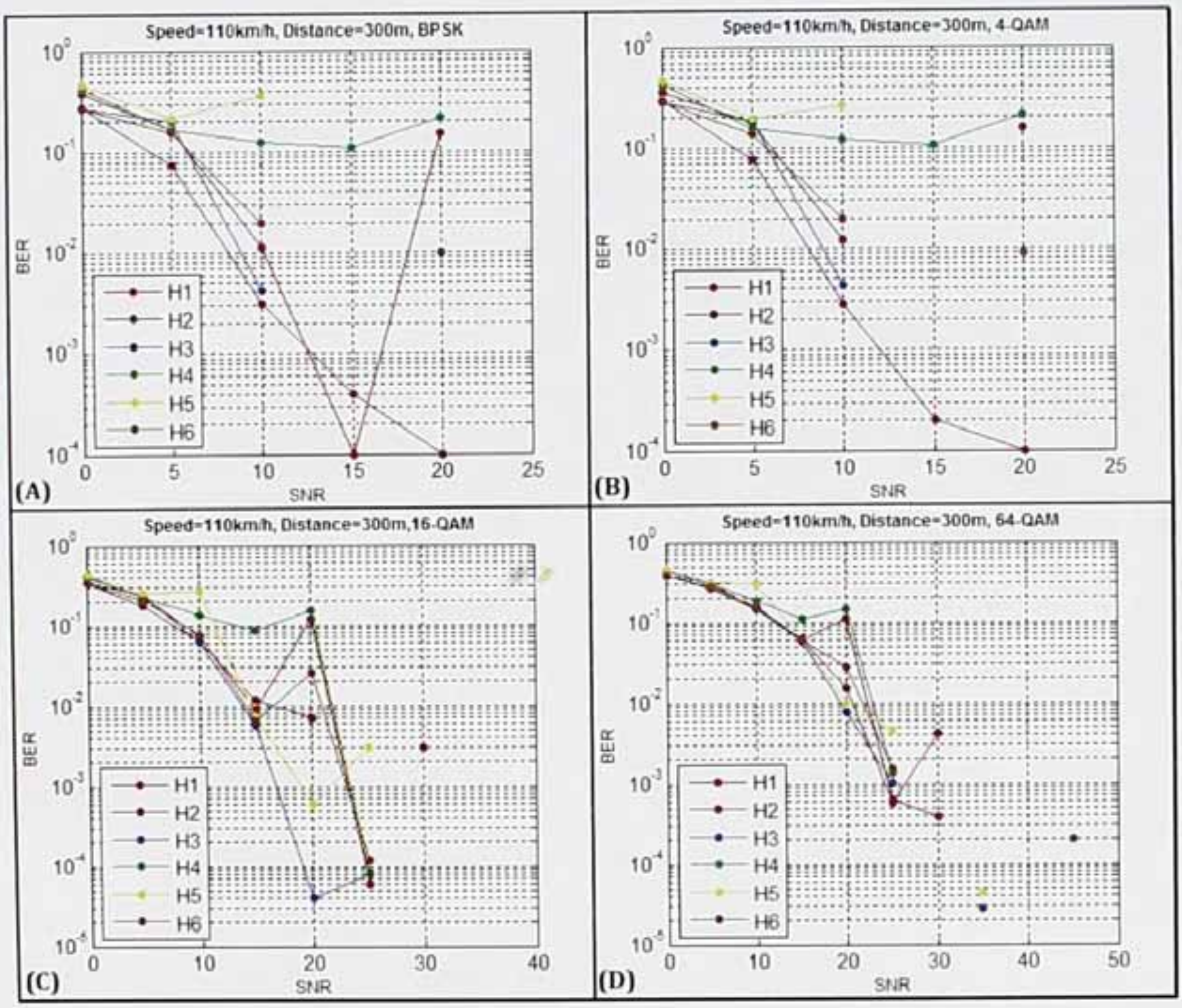


Figure 5.24 (A-D): SM (NLoS), Vehicles Speeds: 110km/h, Distance between Vehicles 300 Meters, Number of Multi-path 6, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

Figures (5.19), (5.21) and (5.23) show the performance of SM over V2V communication based on the simulation setting in Table (5.5). These settings followed the approach of the vehicular standard IEEE 802.11p (IEEE Vehicular Technology Society, 2014). The simulation tests were performed in three different scenarios:

1- Figures (5.19) and (5.20, A-D) respectively show the simulation results for both LoS and NLoS. In this scenario, the simulation tests considered the vehicles to be travelling in a relatively slow speed of 10km/h and the distance between the vehicles 100 meters.
2- Figures (5.21) and (5.22, A-D) respectively show the simulation results for both LoS and NLoS. In this scenario, the simulation tests considered the vehicles to be travelling in a relatively medium speed of 60km/h and the distance between the vehicles 200 meters.
3- Figures (5.23) and (5.24, A-D) respectively show the simulation results for both LoS and NLoS. In this scenario, the simulation tests considered the vehicles to be travelling in a relatively high speed of 110km/h and the distance between the vehicles 300 meters.

Table (5.6) compared the obtained results SNRs [dB] in Figures (5.19), (5.21) and (5.23) at BER 10^{-2} considering the LoS condition, where three different speeds were considered as slow, medium and high (10km/h, 60km/h and 110km/h), for three different distances between vehicles 100, 200 and 300 meters.

Speeds and Distances	MODULATIONS			
	BPSK	4-QAM	16-QAM	64-QAM
10km/h 100 Meters	18	17	20	21
60km/h 200 Meters	16	16	19	20
110km/h 300 Meters	09	09	16	21

TABLE 5.6A: Simulation Results for SM Performance in V2V Communication.

The simulation tests in table (5.6A) showed unacceptable results. For example, when the distance was 100 meters at a slow speed of 10km/h for the BPSK and 4-QAM modulations, the results were inconsistent, as the higher the modulation mode is the higher SNR should be. Still at the speed of 10km/h, the simulation results in Figures (5.20A) and (5.20B) for the NLoS tests show a high BER results. Unexpected SNRs [dB] results have been observed when the speed was 60km/h and the distance was 200 meters, where the SNRs was equal to 16[dB] for both BPSK and 4-QAM modulations, as expected to be greater than 16[dB] and less than 19[dB]. Still at the speed of 60km/h, the NLoS results in Figures (5.22A), (5.22B) and (5.22C) showed a high BER. Similarly, the obtained results in Figure (5.22) for a speed of110km/h and a distance between vehicles of 300 meters showed unexpected SNRs 9[dB] for both BPSK and 4-QAM. And the obtained results of the NLoS in Figures (5.24A), (5.24B), (5.24C) and (5.24D) for the same speed showed a high BER. Although the SM is a relatively new MIMO technology that can provide high data rate with reasonable spectral efficiency. Furthermore, inconsistent results were presented in Table (5.6A).

Modulation	Distance 100m Speed 10km/h	Distance 200m Speed 60km/h	Distance 300m Speed 110km/h
BPSK	18	16	09
4-QAM	17	16	09
16-QAM	20	19	16
64-QAM	21	20	21

TABLE 5.6B: Simulation Results for SM Performance in V2V Communication.

In addition the BER performance of SM systems under V-SCME channel models showed contradictory results, inconsistent results and a high BER in most of the NLoS results. The factors such as: different modulation schemes, different vehicles speeds, and different distances can affect the performance of SM over the V2V communication. This was due to the high dynamic environment in V2V communication which indicates that SM was unable to satisfy the requirement of V2V communication. In this case a more robust MIMO coding is needed in order to satisfy the requirement of V2V communication.

5.5.3. PERFORMANCE OF V-BLAST IN V2V COMMUNICATION

V-BLAST (Wu *et al.*, 2011) is a detection algorithm for MIMO systems at the receiver sides. The principle of V-BLAST is discussed in Chapter 4, first it detects the most powerful signal which has the highest SNR, and then it regenerates the 1st received signal. The regenerated signal is subtracted from the received signal in order to detect the 2nd most powerful signal, since it has already cleared the first signal and so on. Joshi *et al.* (2011) stated that these detections and subtracting gives less interference to a vector received. However, the vector encoding process is a demultiplex operation followed by independent bit to symbol mapping of each sub stream (Joshi *et al.*, 2011). The conventional coding of the individual sub- streams can certainly be applied. Therefore, no inter-sub stream coding or coding of any kind is required. V-BLAST utilises a combination of old and new detection techniques to separate the signals in an efficient manner. Symbols detections in MIMO system is based on the previously estimated channel coefficients from the received signal. However, the detection procedure assumed that the channel matrix estimate has no estimation error. On the other hand, the channel estimation errors exist in the real system, and they cause the degradation of system performance. As in other detection algorithms, channel estimation errors could bring the significant performance degradation. In this section, the performance of V-BLAST over the V2V communication using V-SCME channel model has been evaluated. The simulation setting in Table (5.7) takes into consideration the complex environment in V2V communication due to the high mobility.

Parameters	Values
Environment	Urban Microcell
Vehicles Antennas	Omnidirectional
Antennas Array	MIMO 2x2
AoD and AoA	180 ± 5
Carrier Frequency	5.9GHz
Signal Propagation	LoS and NLoS
Number of Multi-path	Up To 18.
Vehicles Speeds: 1st group	10km/h, 50km/h and 90 km/h
Vehicles Speeds: 2nd group	20km/h, 60km/h and 100 km/h
Vehicles Speeds: 3rd group	30km/h, 70km/h and 110 km/h
Distances between Vehicles	100, 200 and 300 meters
Modulations	BPSK, 4-QAM, 16-QAM and 64-QAM

TABLE 5.7: Simulation Setting for V-BLAST Performance in V2V Communication

Different scenarios and tests have been run using V-SCME (2x2 MIMO) based on the V-BLAST coding system in high dynamic disruption environments. Matlab simulation were run to generate channel coefficients using equations (5.3) for NLoS and (5.4) for LoS. A vector of generated data (x) to be transmitted over the generated V2V channel to generate a received vector (y) as in Equation (5.5). A MIMO coding technique (V-BLAST) is taking place during the simulation.

Equation (5.5) **H** is the instant channel parameter for 1 sec period in 2X2 MIMO matrix (h_{11}, h_{12}, h_{21}, h_{22}) and is periodically changed over the time to generate new **H**. for every single scenario e.g. LoS and NLoS (different speeds, different distances, different modulations and multi-path) are considered to compare the BER vs. SNR for MIMO coding evaluation and channel model validation.

$$Y = H.X + N$$

$$\begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} . \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ n_2(t) \end{bmatrix} \quad \text{..........................} \quad (5.5)$$

Whereas,

x is the transmitted symbol vector. ***y*** is the received symbol vector.

h is the channel characteristics matrix. ***n*** is the noise.

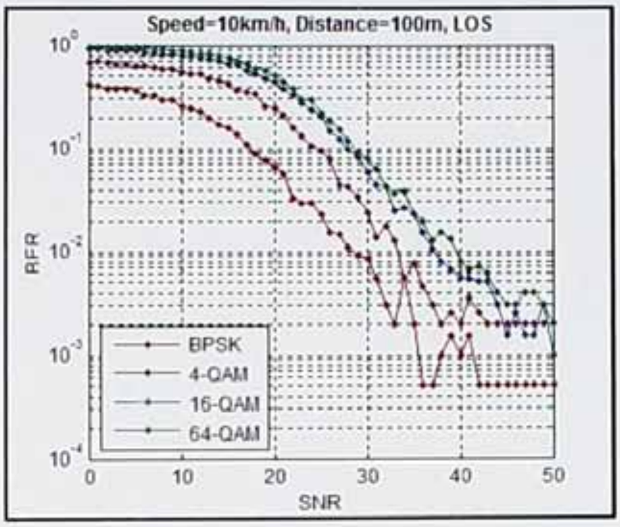


Figure 5.25: V-BLAST (LoS), Vehicles Speeds: 10km/h, Distance between Vehicles 100 Meters, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

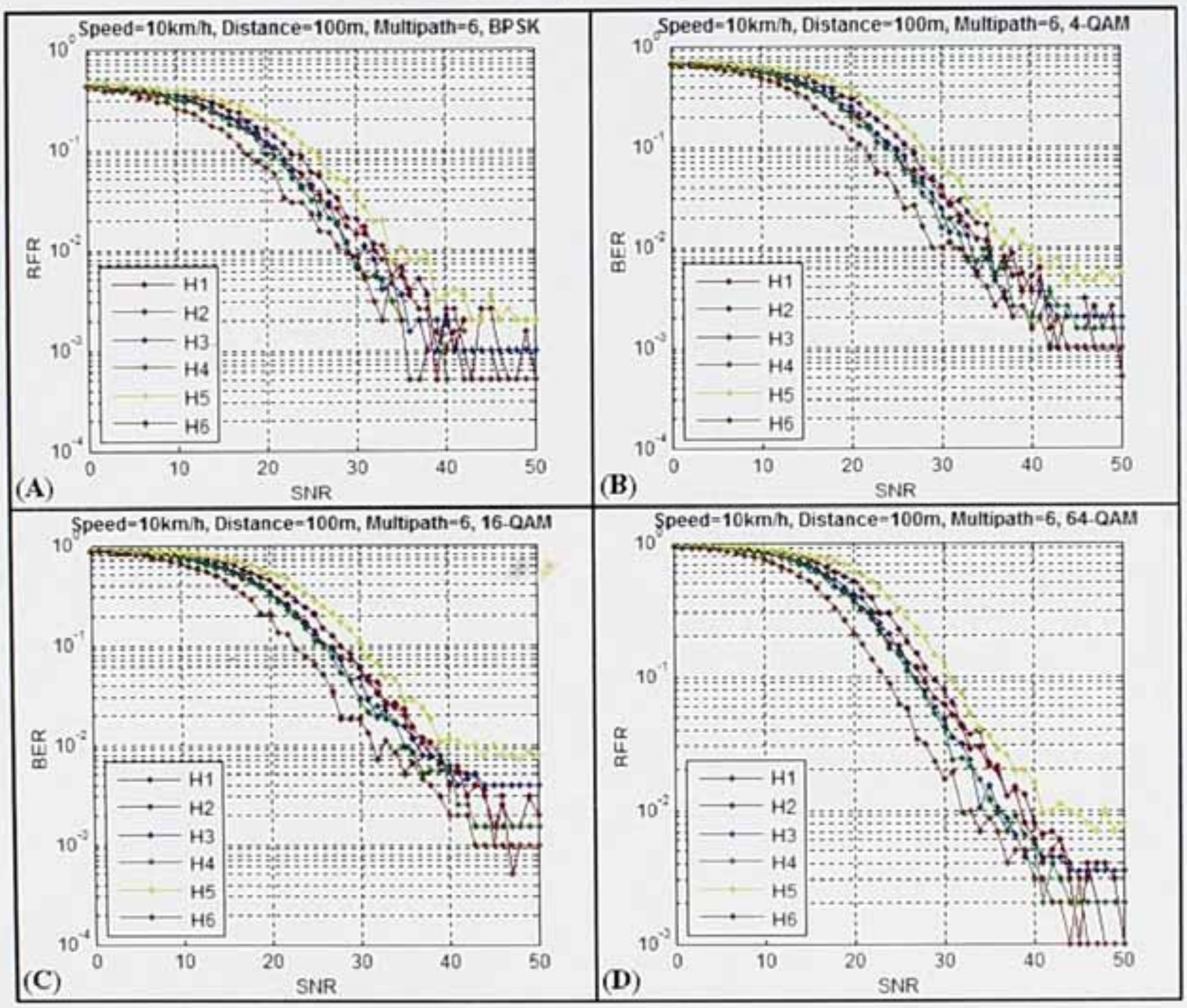


Figure 5.26 (A-D): V-BLAST (NLoS), Vehicles Speeds: 10km/h, Distance between Vehicles 100 Meters, Number of Multi-path 6, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

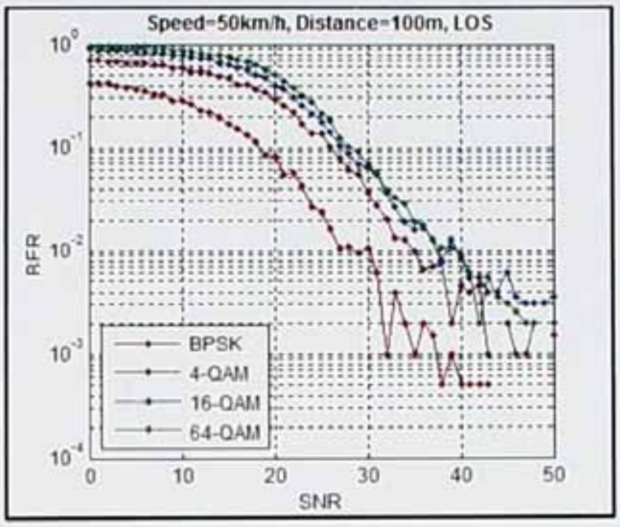


Figure 5.27: V-BLAST (LoS), Vehicles Speeds: 50km/h, Distance between Vehicles 100 Meters, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

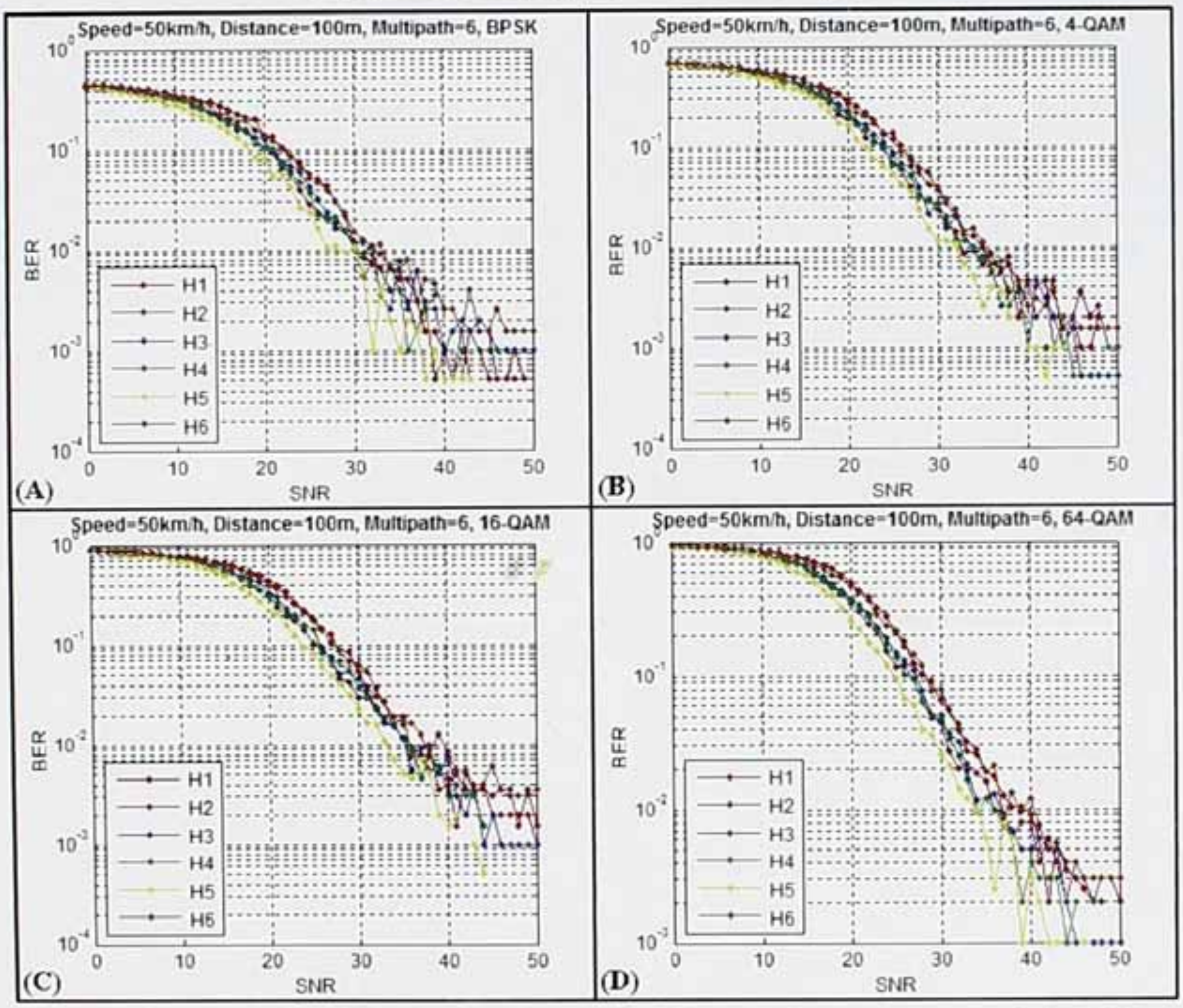


Figure 5.28 (A-D): V-BLAST (NLoS), Vehicles Speeds: 50km/h, Distance between Vehicles 100 Meters, Number of Multi-path 6, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

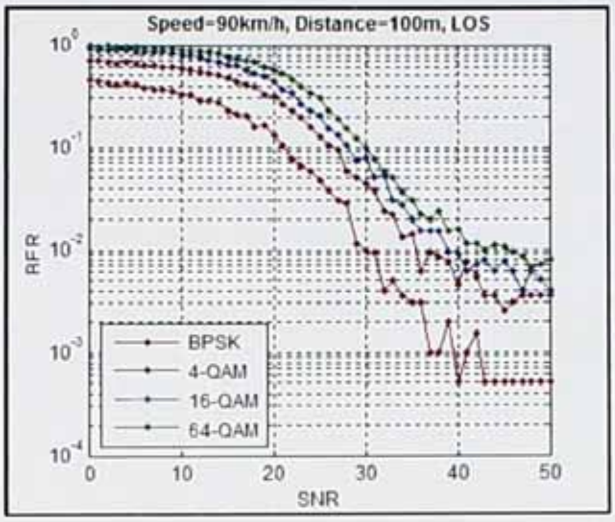


Figure 5.29: V-BLAST (LoS), Vehicles Speeds: 90km/h, Distance between Vehicles 100 Meters, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

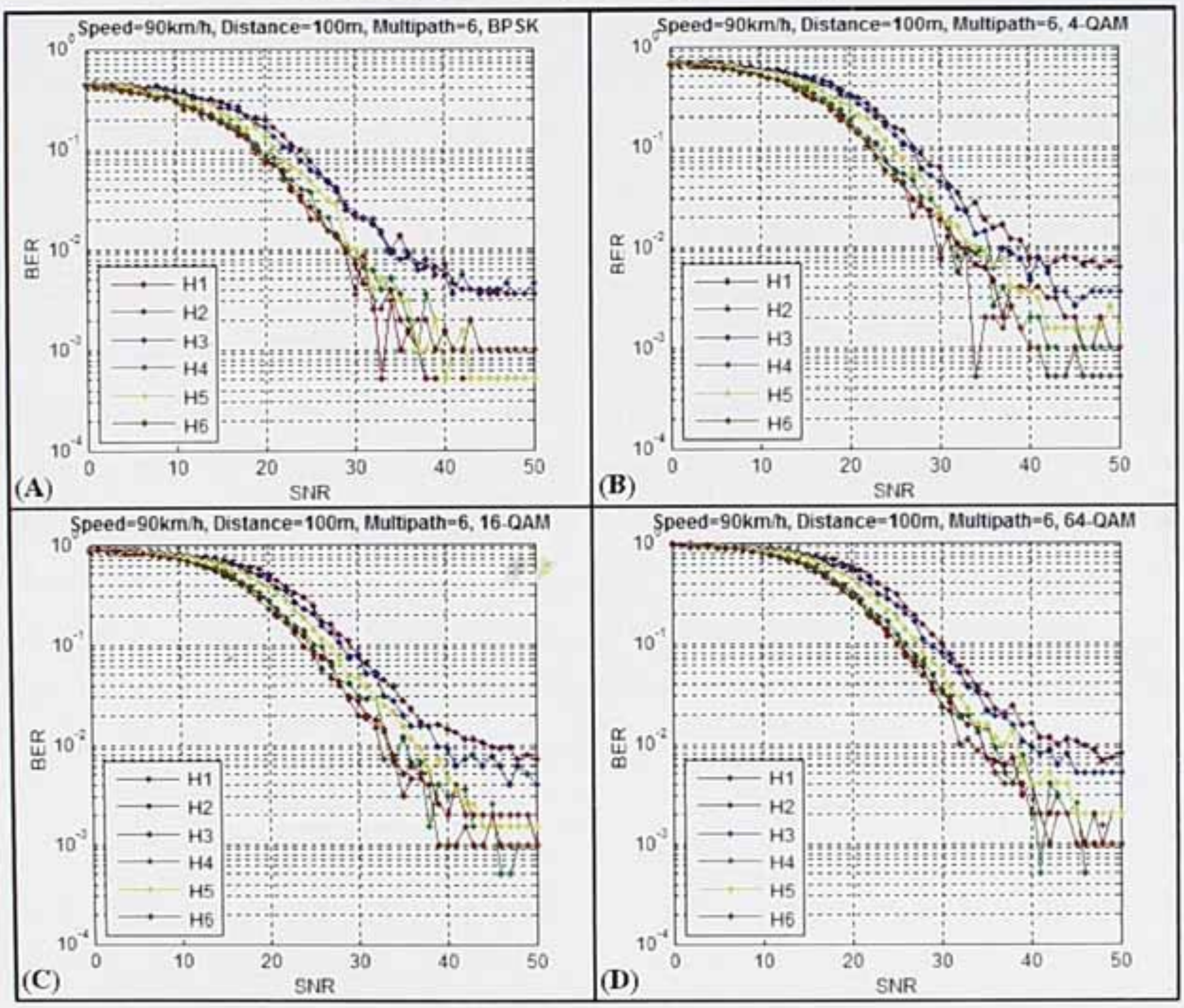


Figure 5.30 (A-D): V-BLAST (NLoS), Vehicles Speeds: 90km/h, Distance between Vehicles 100 Meters, Number of Multi-path 6, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

The simulation results for the LoS in Figures (5.25), (5.27) and (5.29) show the BER vs. SNR for three different vehicles speeds (10km/h, 50km/h and 90km/h), four different modulations BPSK, 4-QAM, 16-QAM and 64- QAM, and the distance between the vehicles of 100 meters. Table (5.8) compares the SNRs [dB] results at BER 10^{-2} and the simulation results were consistent when the V-BLAST coding is used.

Speeds	**Distance Between Vehicles 100 meters**			
	BPSK	**4-QAM**	**16-QAM**	**64-QAM**
10km/h	30	33	38	40
50km/h	30	35	38	40
90km/h	30	35	40	42

TABLE 5.8: The SNRs [dB] at BER 10^{-2} Gained from Figures (5.25), (5.27) and (5.29).

As shown in Table (5.8), as vehicles were traveling at different speeds: slow speed 10km/h, medium speed 50km/h and high speed 90km/h the results for the BPSK, 4-QAM, 16-QAM and 64-QAM modulations were consistent according to the levels of disruption. While comparing with the previous results for Alamouti coding and SM coding in sections (5.5) and (5.6), the obtained results were inconsistent and unacceptable due to the high BER with the same environment conditions. In other word, the V-BLAST coding over the V-SCME channel model was the optimum coding that satisfies the requirements of the dynamic environment for V2V communication.

The simulation tests for the NLoS are shown in Figures (5.26, A-D), (5.28, A-D) and (5.30, A-D), for three different vehicles speeds (10km/h, 50km/h and 90km/h), four different modulations BPSK, 4-QAM, 16-QAM and 64-QAM, and the distance between the vehicles of 100 meters. The simulation tests shows the SNRs [dB] results at BER 10^{-2}, where the number of multi-path was 6. In these tests the target was to show that the developed V-SCME channel model was not only considering the LoS but it's also considering the NLoS conditions.

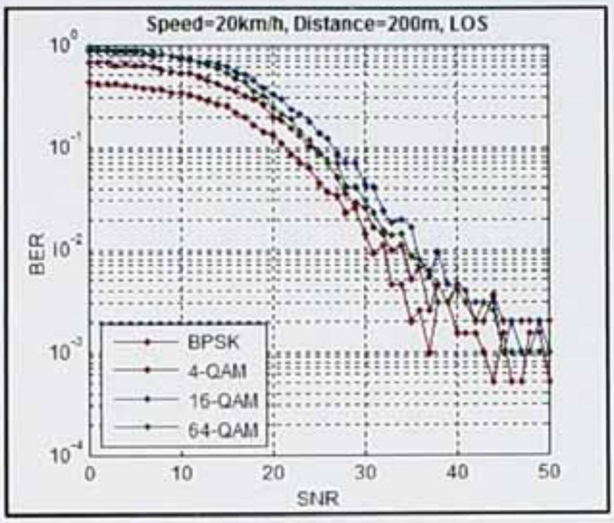


Figure 5.31: V-BLAST (LoS), Vehicles Speeds: 20km/h, Distance between Vehicles 200 Meters, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

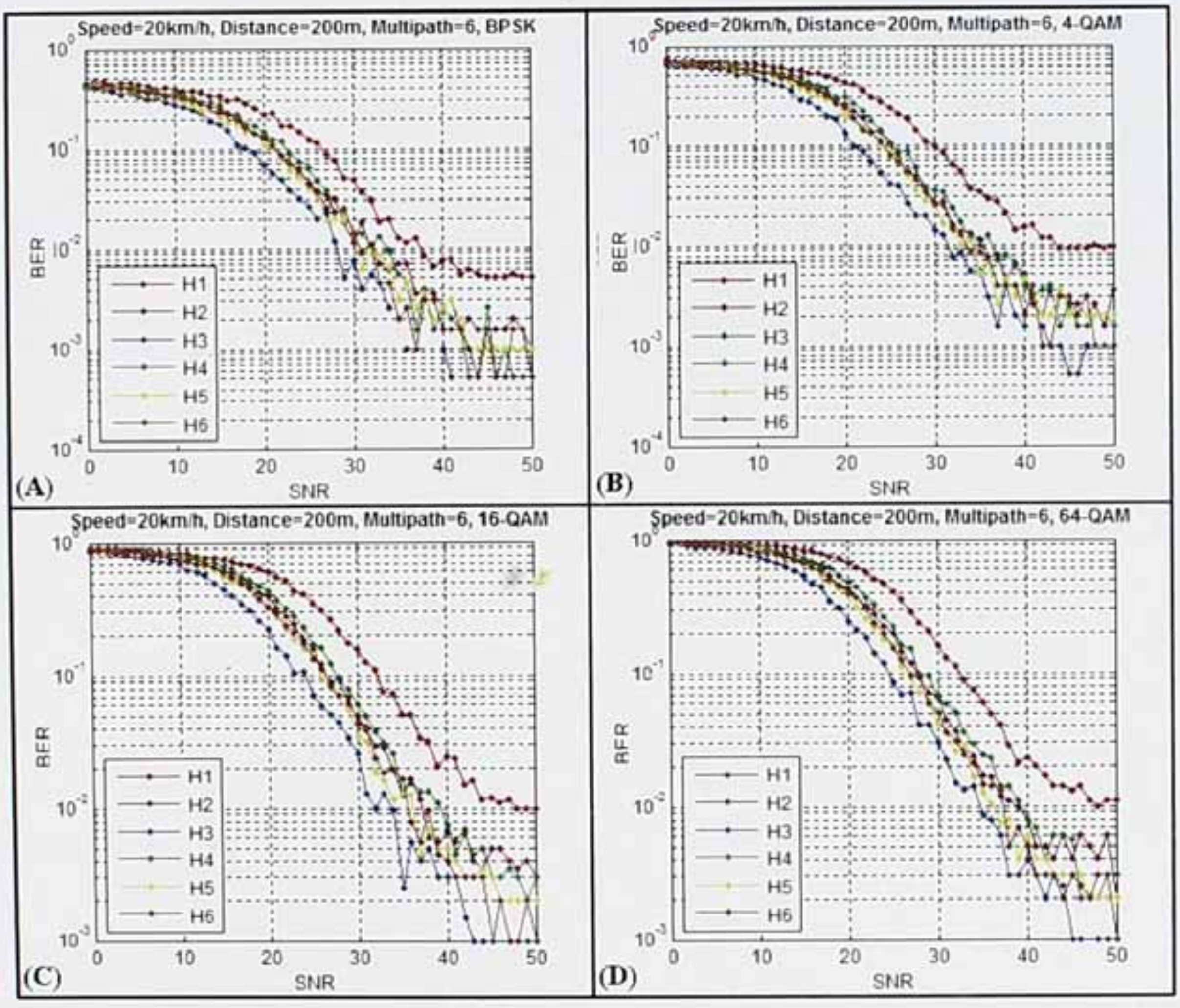


Figure 5.32 (A-D): V-BLAST (NLoS), Vehicles Speeds: 20km/h, Distance between Vehicles 200 Meters, Number of Multi-path 6, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

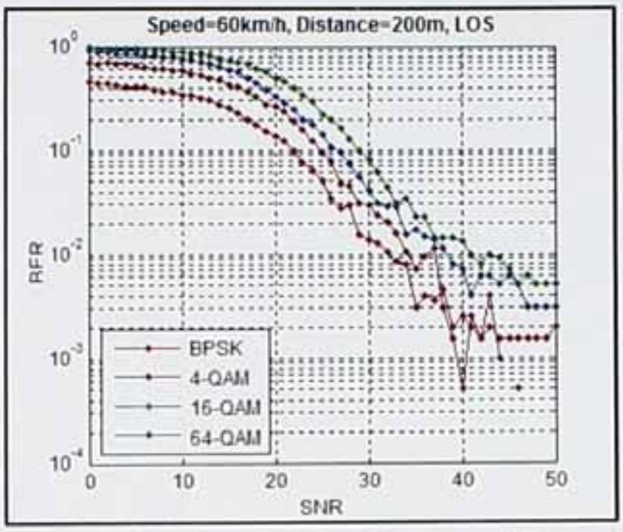


Figure 5.33: V-BLAST (LoS), Vehicles Speeds: 60km/h, Distance between Vehicles 200 Meters, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

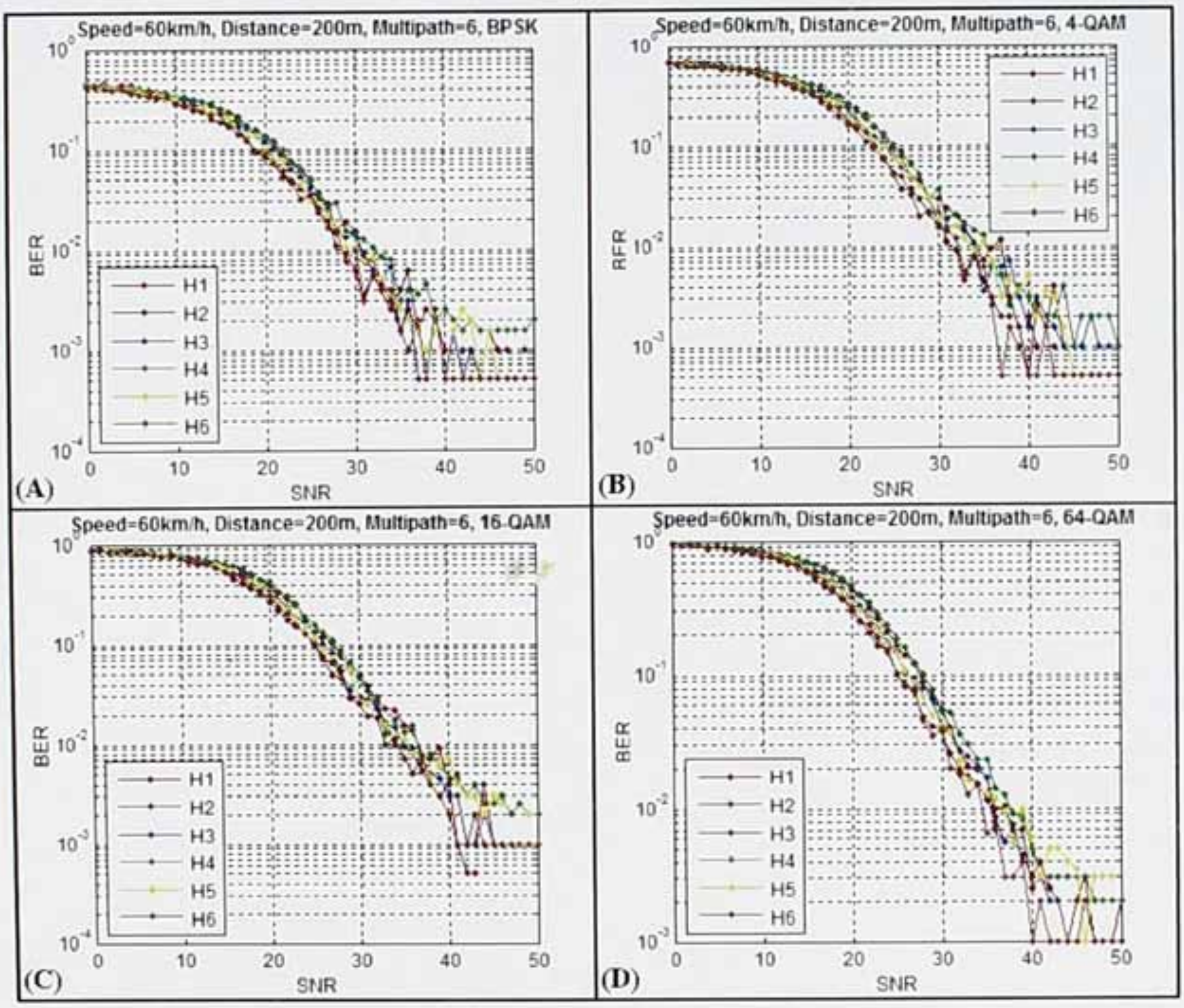


Figure 5.34 (A-D): V-BLAST (NLoS), Vehicles Speeds: 60km/h, Distance between Vehicles 200 Meters, Number of Multi-path 6, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

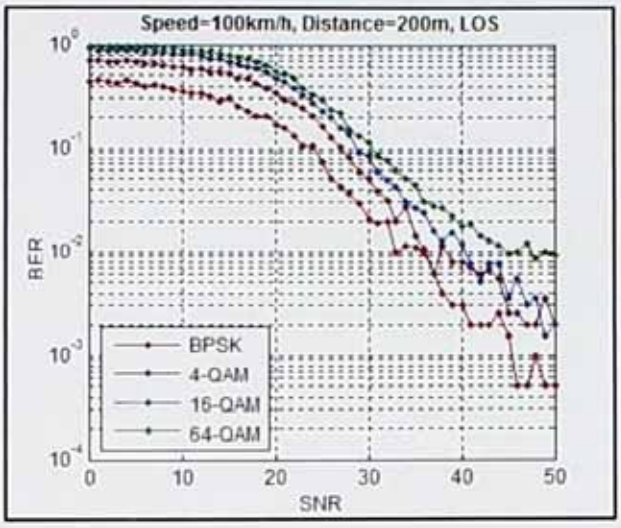


Figure 5.35: V-BLAST (LoS), Vehicles Speeds: 100km/h, Distance between Vehicles 200 Meters, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

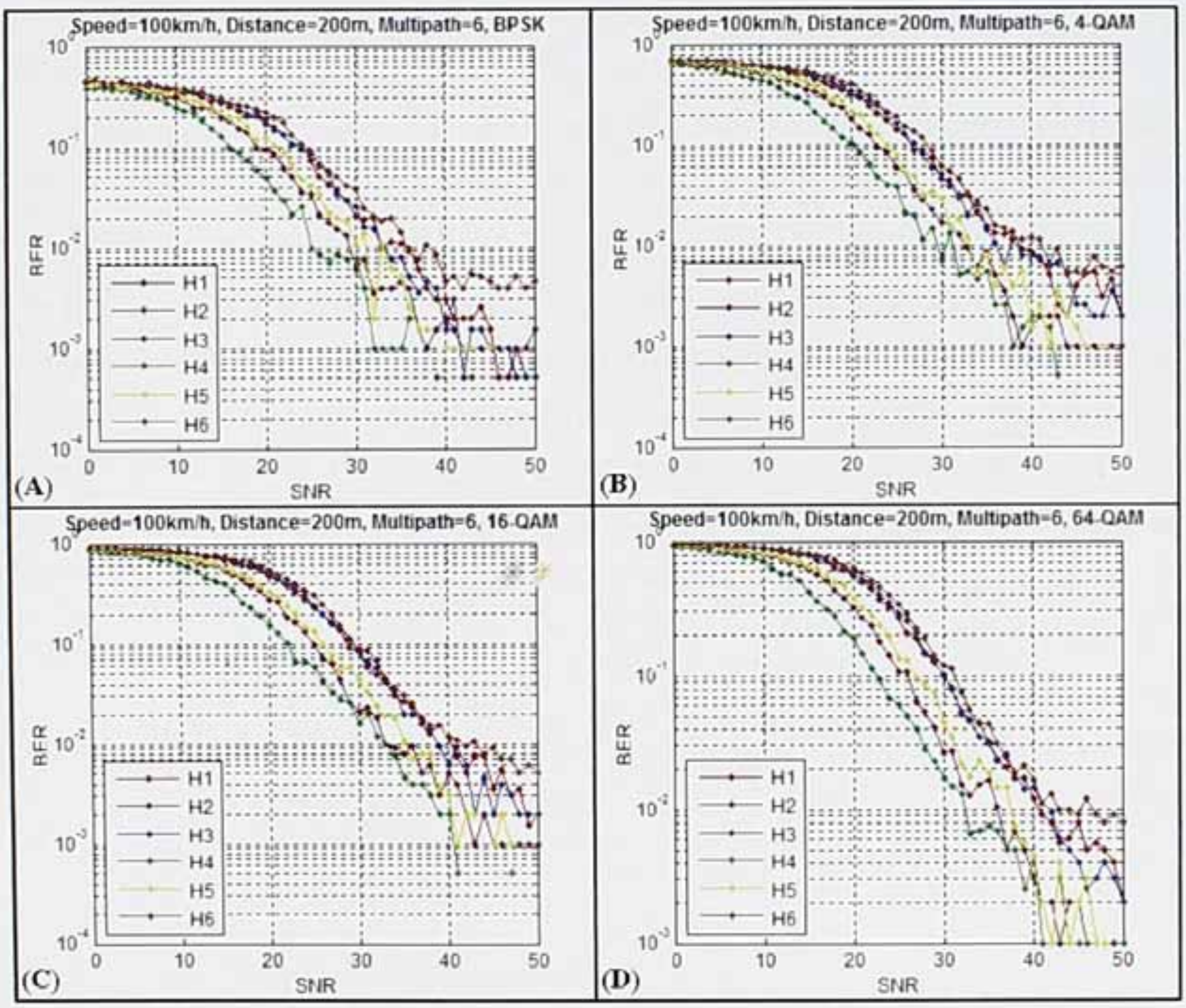


Figure 5.36 (A-D): V-BLAST (NLoS), Vehicles Speeds: 100km/h, Distance between Vehicles 200 Meters, Number of Multi-path 6, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

The simulation results for the LoS in Figures (5.31), (5.33) and (5.35) show the BER vs. SNR for three different vehicles speeds (10km/h, 50km/h and 90km/h), four different modulations BPSK, 4-QAM, 16-QAM and 64- QAM, and the distances between the vehicles of 100 meters. Table (5.9) compares the SNRs [dB] results at BER 10 and the simulation results were consistent when the V-BLAST coding is used.

Speeds	**Distance Between Vehicles 200 meters**			
	BPSK	**4-QAM**	**16-QAM**	**64-QAM**
20km/h	30	33	36	36
60km/h	31	33	39	41
100km/h	32	35	40	45

TABLE 5.9: The SNRs [dB] at BER 10^{-2} Gained from Figures (5.31), (5.33) and (5.35).

Similarly, Table (5.9) shows a vehicle traveling at three different speeds: slow speed 20km/h, medium speed 60km/h and high speed 100km/h. For example, Figure (5.31) shows the vehicle travelling at 60km/h. The simulation results were 31, 33, 39 and 41, which represents four different modulations BPSK, 4-QAM, 16-QAM and 64-QAM. The obtained results were consistent according to the levels of disruption. Compared to previous tests in Alamouti section (5.5) and SM section (5.6), the obtained results were inconsistent and unacceptable due to the high BER with the same environmental conditions.

The simulation tests for the NLoS are shown in Figures (5.32, A-D), (5.34, A-D) and (5.36, A-D), for three different vehicles with speeds of (20km/h, 60km/h and 100km/h), four different modulations BPSK, 4-QAM, 16-QAM and 64-QAM, and the distance between the vehicles of 200 meters. The simulation results show the SNRs [dB] results at BER 10^{-2}, where the number of multi-path was 6. In addition to the LoS tests, the NLoS conditions have been considered by the developed V-SCME channel model as well.

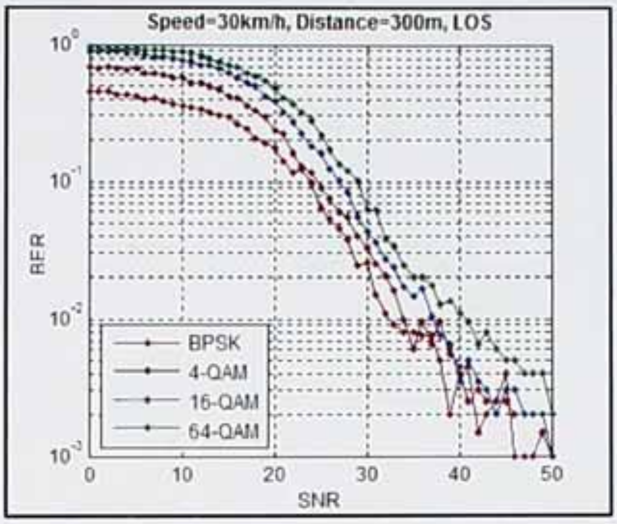


Figure 5.37: V-BLAST (LoS), Vehicles Speeds: 30km/h, Distance between Vehicles 300 Meters, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

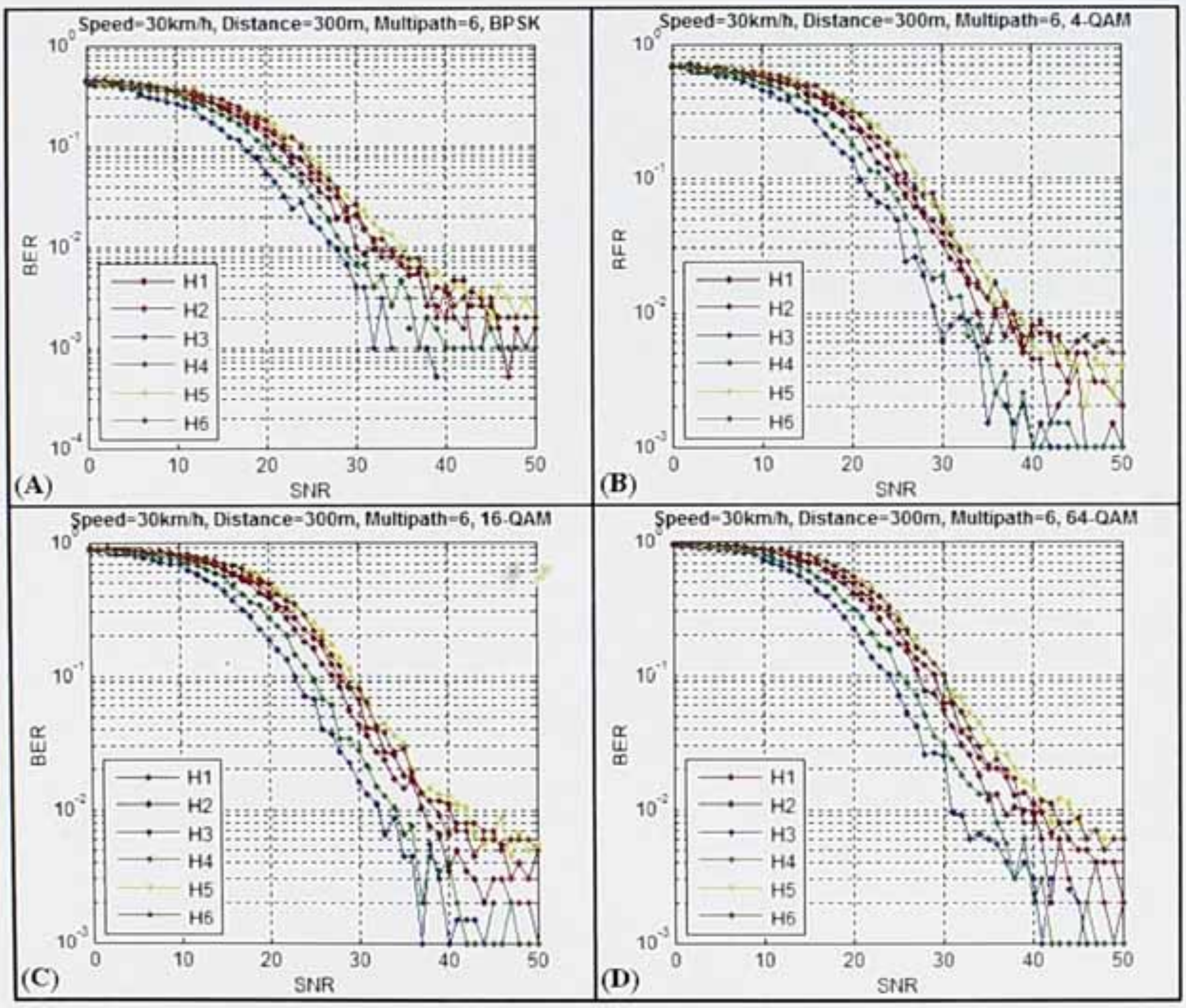


Figure 5.38 (A-D): V-BLAST (NLoS), Vehicles Speeds: 30km/h, Distance between Vehicles 300 Meters, Number of Multi-path 6, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

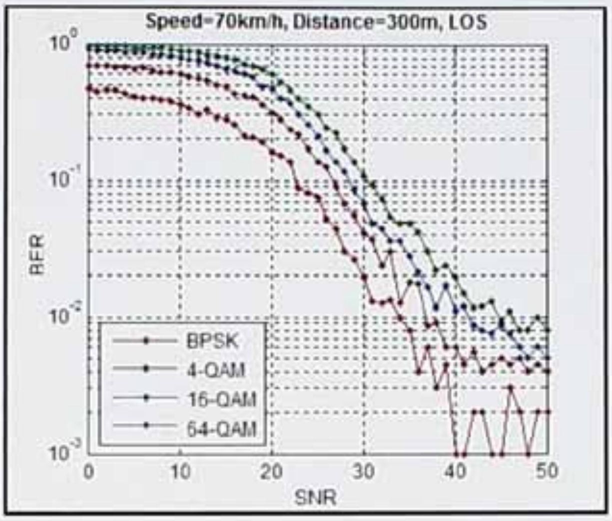


Figure 5.39: V-BLAST (LoS), Vehicles Speeds: 70km/h, Distance between Vehicles 300 Meters, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

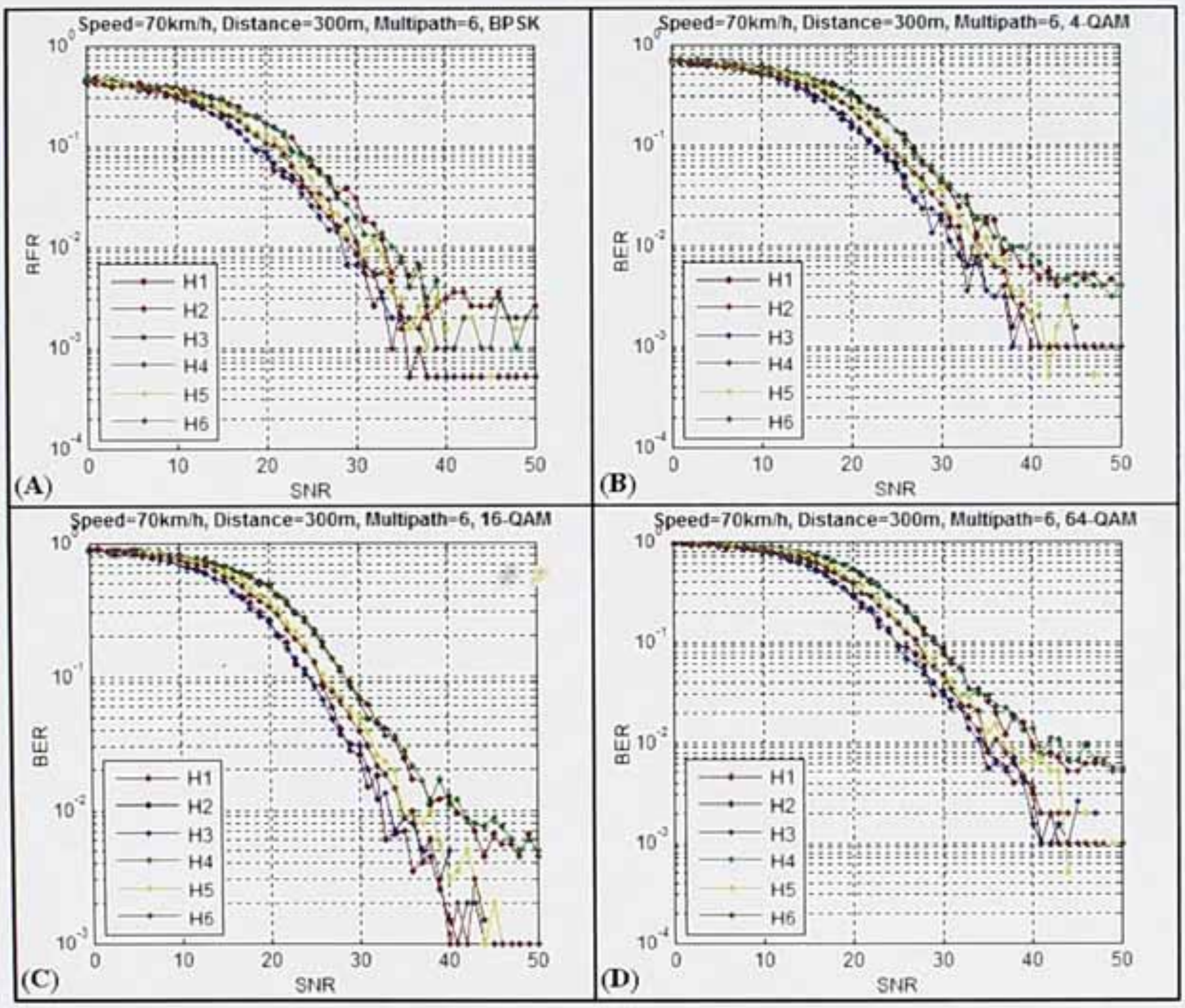


Figure 5.40 (A-D) V-BLAST (NLoS), Vehicles Speeds: 70km/h, Distance between Vehicles 300 Meters, Number of Multi-path 6, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

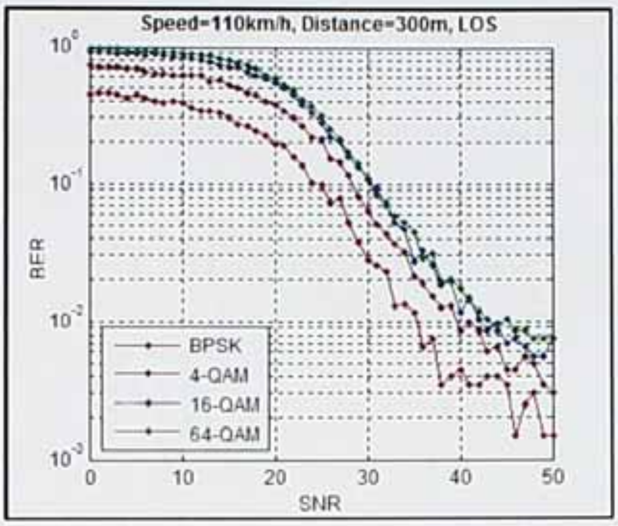


Figure 5.41: V-BLAST (LoS), Vehicles Speeds: 110km/h, Distance between Vehicles 300 Meters, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

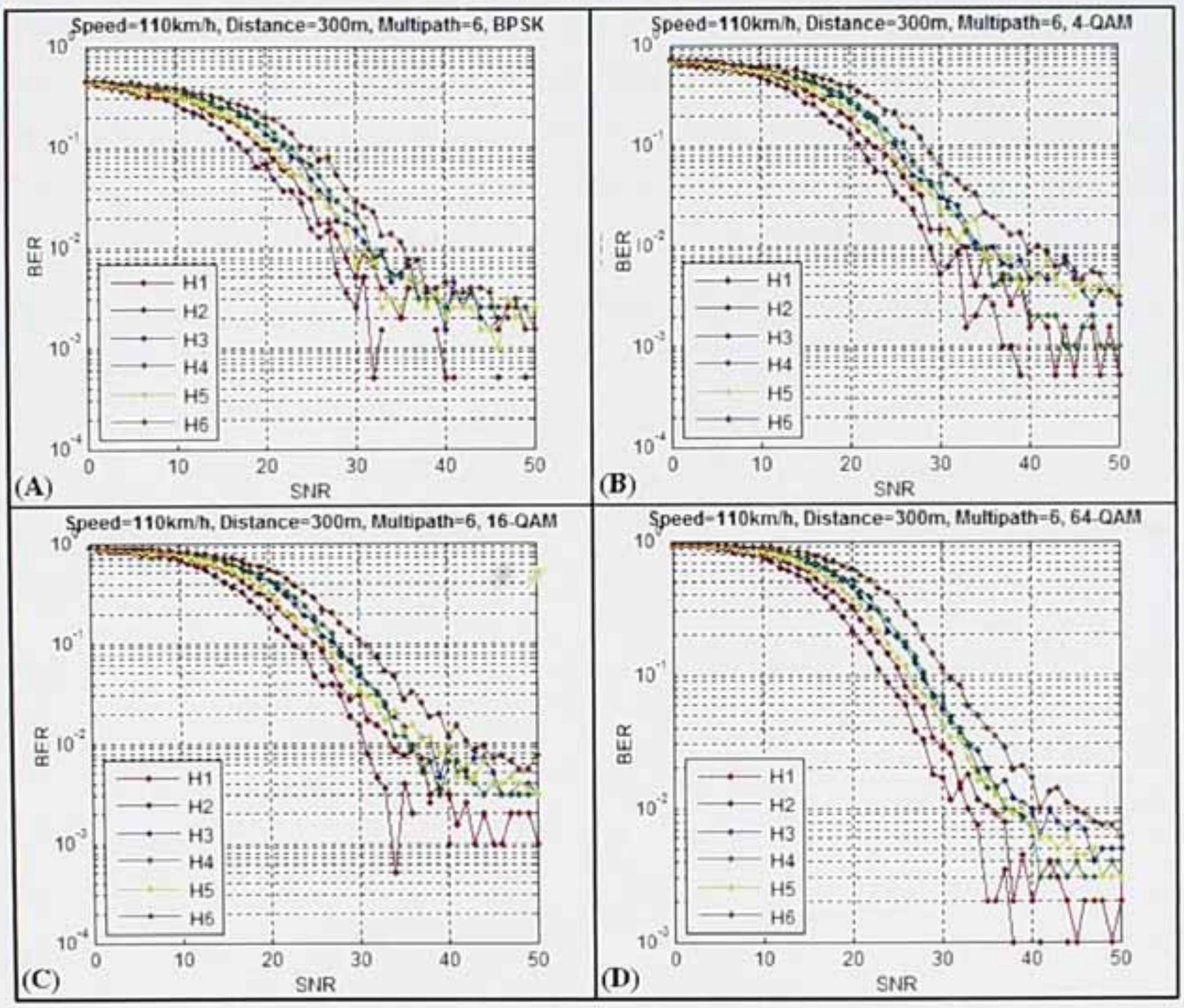


Figure 5.42 (A-D) V-BLAST (NLoS), Vehicles Speeds: 110km/h, Distance between Vehicles 300 Meters, Number of Multi-path 6, Modulations: BPSK, 4-QAM, 16-QAM and 64-QAM.

The simulation results for the LoS in Figures (5.37), (5.39) and (5.41) shows the BER vs. SNR for three different vehicles speeds of (30km/h, 70km/h and 110km/h), four different modulations BPSK, 4-QAM, 16-QAM and 64-QAM, and the distance between the vehicles of 300 meters. Table (5.10) compares the SNRs [dB] results at BER 10^{-2} and the simulation results are consistent (the SNR is increasing when the higher modulation mode used and vehicle speed is increased) when the V-BLAST coding is used.

Speeds	Distance Between Vehicles 300 meters			
	BPSK	4-QAM	16-QAM	64-QAM
30km/h	31	32	38	40
70km/h	33	38	41	46
110km/h	35	40	42	46

TABLE 5.10: The SNRs [dB] at BER 10^{-2} Gained from Figures (5.37), (5.39) and (5.41).

Table (5.10) shows the simulation results using V-SCME. The obtained results were acceptable. For example, by comparing the obtained results for each speed individually the SNRs [dB] for the three different speeds for the four different modulations were consistent. Even when comparing the speeds with each other the results were consistent e.g. the results for the 4-QAM modulation are shown in Table (5.10). The [dB] for the three different speeds 30km/h, 70km/h and 110km/h respectively are 32, 38 and 40. These results were acceptable due to high dynamic environment in V2V communication.

The developed V-SCME channel model has also considered the NLoS conditions. The simulation tests for the NLoS were showed in Figures (5.38, A-D), (5.40, A-D) and (5.42, A-D), for three different vehicles speeds (30km/h, 700km/h and 110km/h), four different modulations BPSK, 4-QAM, 16-QAM and 64-QAM, and the distance between the vehicles of 300 meters. The simulation tests show the SNRs [dB] results at BER 10^{-2}, where the number of multi-path was 6.

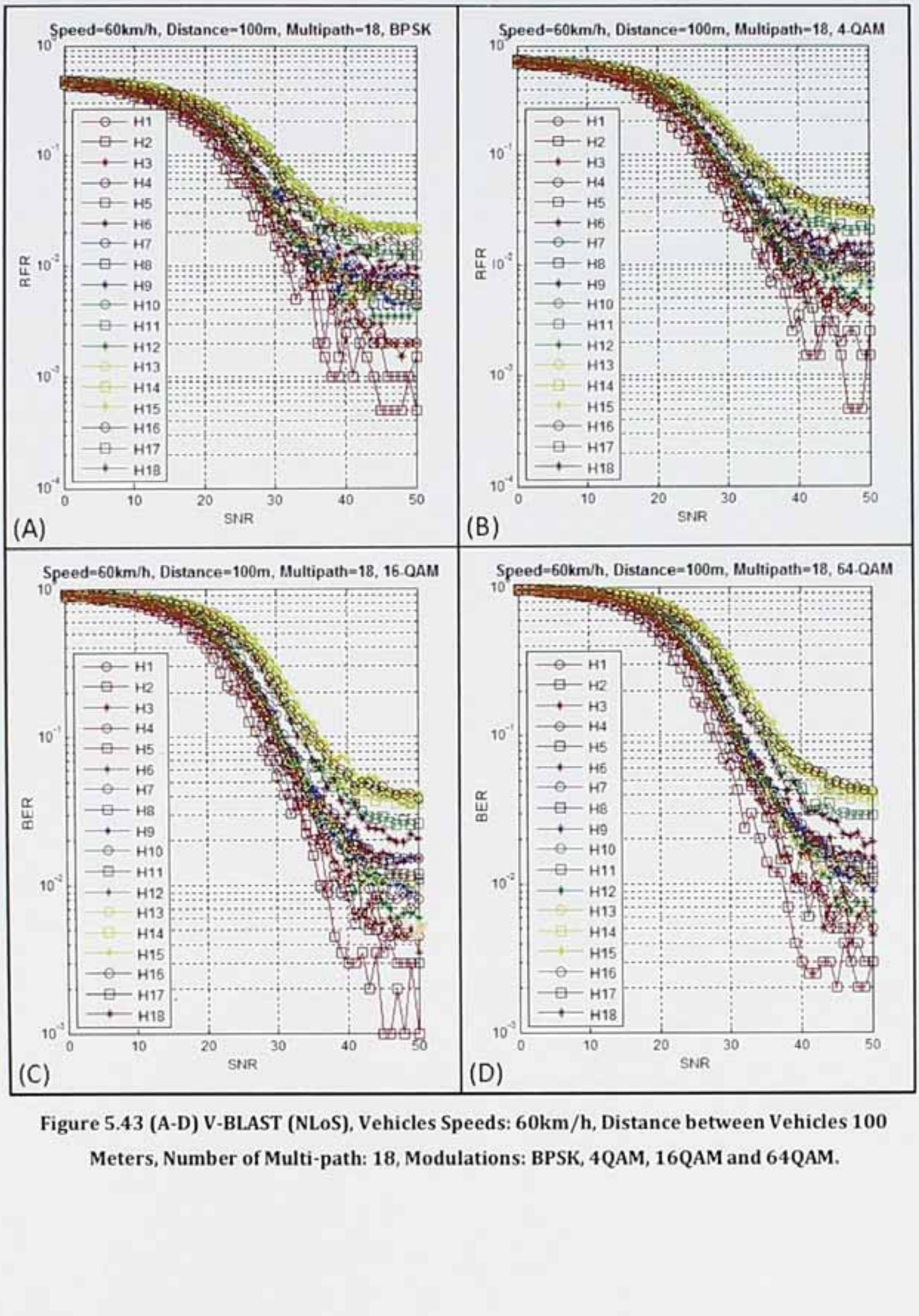


Figure 5.43 (A-D) V-BLAST (NLoS), Vehicles Speeds: 60km/h, Distance between Vehicles 100 Meters, Number of Multi-path: 18, Modulations: BPSK, 4QAM, 16QAM and 64QAM.

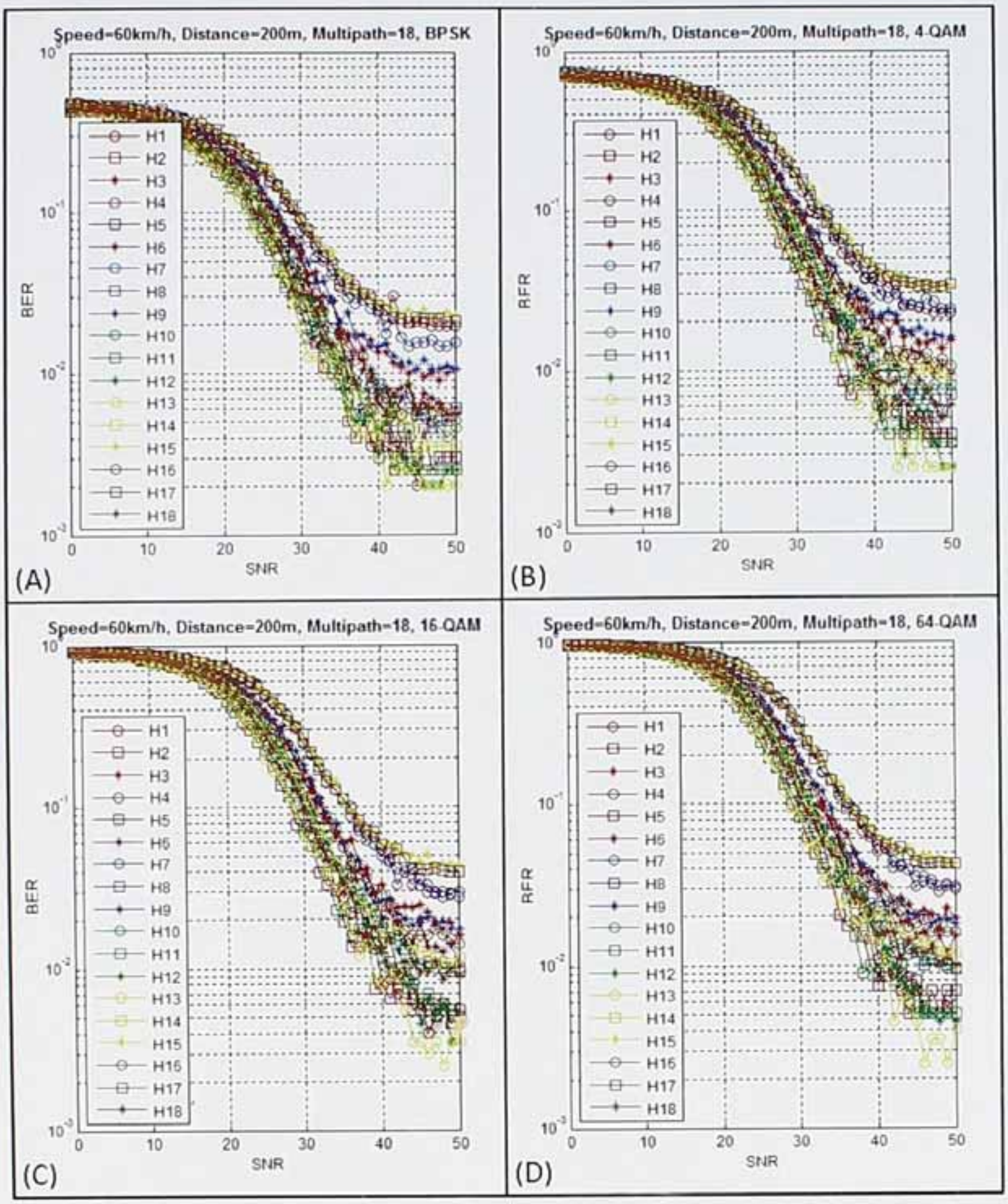


Figure 5.44 (A-D) V-BLAST (NLoS), Vehicles Speeds: 60km/h, Distance between Vehicles 200 Meters, Number of Multi-path: 18, Modulations: BPSK, 4QAM, 16QAM and 64QAM.

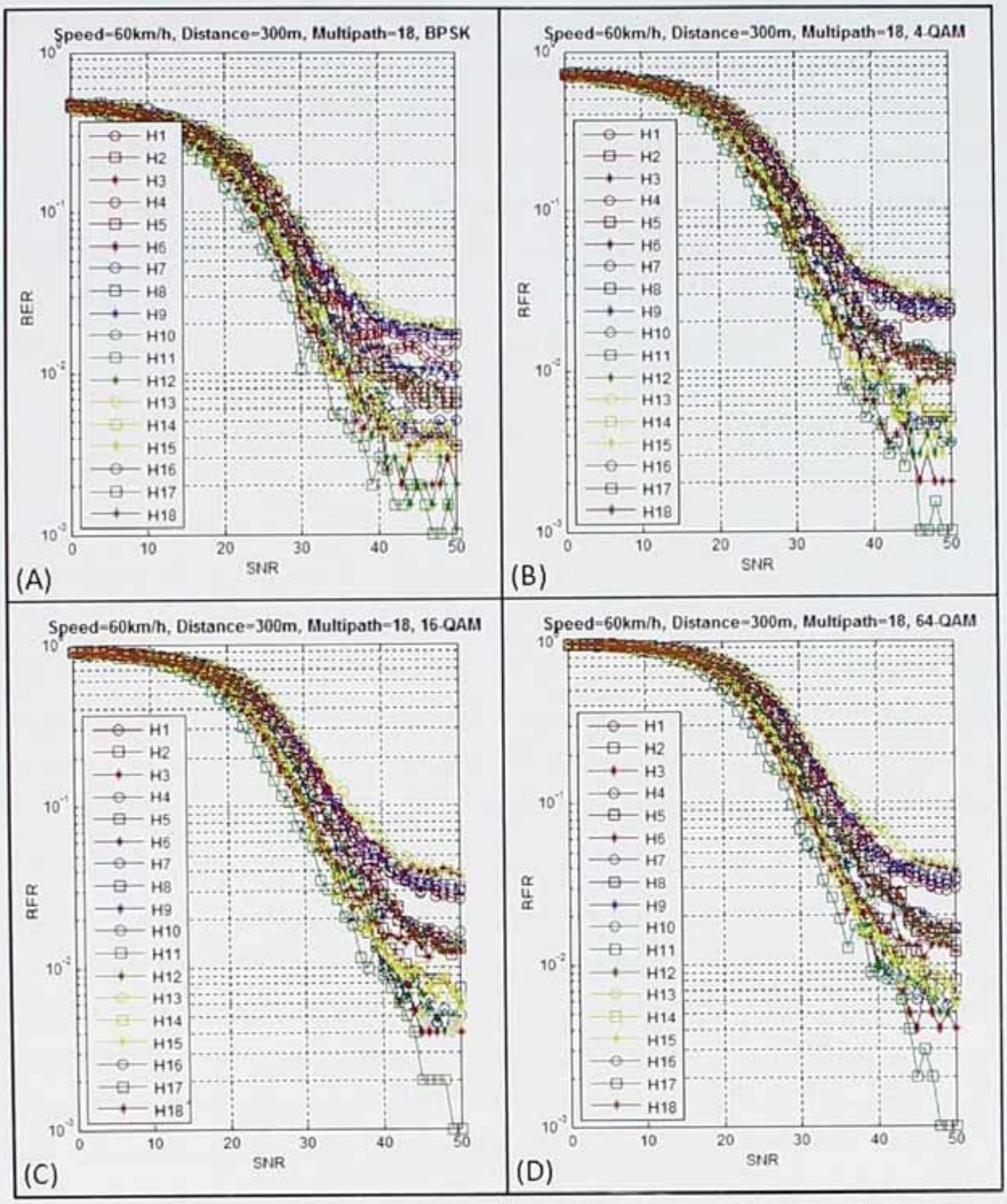


Figure 5.45 (A-D) V-BLAST (NLoS), Vehicles Speeds: 60km/h, Distance between Vehicles 300 Meters, Number of Multi-path: 18, Modulations: BPSK, 4QAM, 16QAM and 64QAM.

Figures (5.43, A-D), (5.44, A-D) and (5.45, A-D) show the performance of V-BLAST over the V-SCME channel model in V2V communication. The simulation tests considered the NLoS conditions for three different distances 100, 200 and 300 meters and different modulations. The results were considered for high level of disruption for 18 multi-path.

In this section, the V-BLAST over V-SCME channel model was used to improve the physical layer performance in V2V communication. Commercial interest in MIMO systems, which employ multiple antennas at both ends of the link, grew after the successful laboratory implementation of the well-known vertical Bell-Labs layered space-time architecture V-BLAST (Pupala, 2008). The aim of using a large number of parameters in V-SCME channel model was an attempt to mimic the highly dynamic disruption environment in V2V. The channel model with V-BLAST has improved the BER for the nodes moving at different speeds as compared to the previous works with Alamouti and SM coding.

5.6. CHANNEL COEFFICIENTS LIBRARY FOR V2V COMMUNICATION

In this thesis, the V-SCME performance with different coding techniques and in various propagation environments was validated. First, simulation results for transmission over the AWGN/Rayleigh channel were compared with analytical BER vs. SNR curves in order to verify accurate functioning of the simulator as discussed in section (5.2). Furthermore the system dependence is underlined on certain parameters of the propagation environment, e.g., number of multi-path components, frequency of channel time-variations, speed of vehicles, etc. Through this chapter the performance of the physical layer in V2V has been simulated by applying different coding techniques such as Alamouti, Spatial Modulation and V-BLAST.

One of the outcomes of this work has been the provision of an open access predefined channel coefficients library for V2V-MIMO communication. This library was determined based on V-SCME for NLoS and LoS respectively. The channel coefficients in 2x2 MIMO and 4x4 MIMO were formed as H_{2x2} and H_{4x4} matrices and they were varied over the time due to the dynamic environment of V2V-MIMO communication. Each signal path for LoS and NLoS has its own time variant channel coefficients. Specifying Urban Microcell V2V environments over ranges of speeds, distances, multi-path signals, different angle of arrivals and departures for LoS and NLoS was a very complex and time consuming process to determine the channel coefficients. Having precise channel model coefficients, a high computational power is needed to be determined during the simulation time, therefore there is a need to provide an open access predefined channel coefficients library for V2V channel to reduce the overall simulation time with a more realistic channel model for V2V. The open access library for 2x2 MIMO and 4x4 MIMO were structured according to two major parts: LoS and NLoS, each part has 12 different vehicle speeds (10km/h-120km/h), four different distances (100,300,500 and 1000 meters), up to 18 signal multi-path (N

≤18) for NLoS and up to 6 diffused signals for LoS and each signals has up to 20 sub-paths (M≤20) for both LoS and NLoS, and the channel coefficients sampling time 1ms (4000 channel coefficients per second for 2x2 MIMO and 16000 channel coefficients per second for 4x4 MIMO), more clarification is shown in Figure (5.46). The total channel coefficients for 2x2 and 4x4 MIMO in both NLoS and LoS was 73728000, and they are all available online (Al-Khalil, 2015).

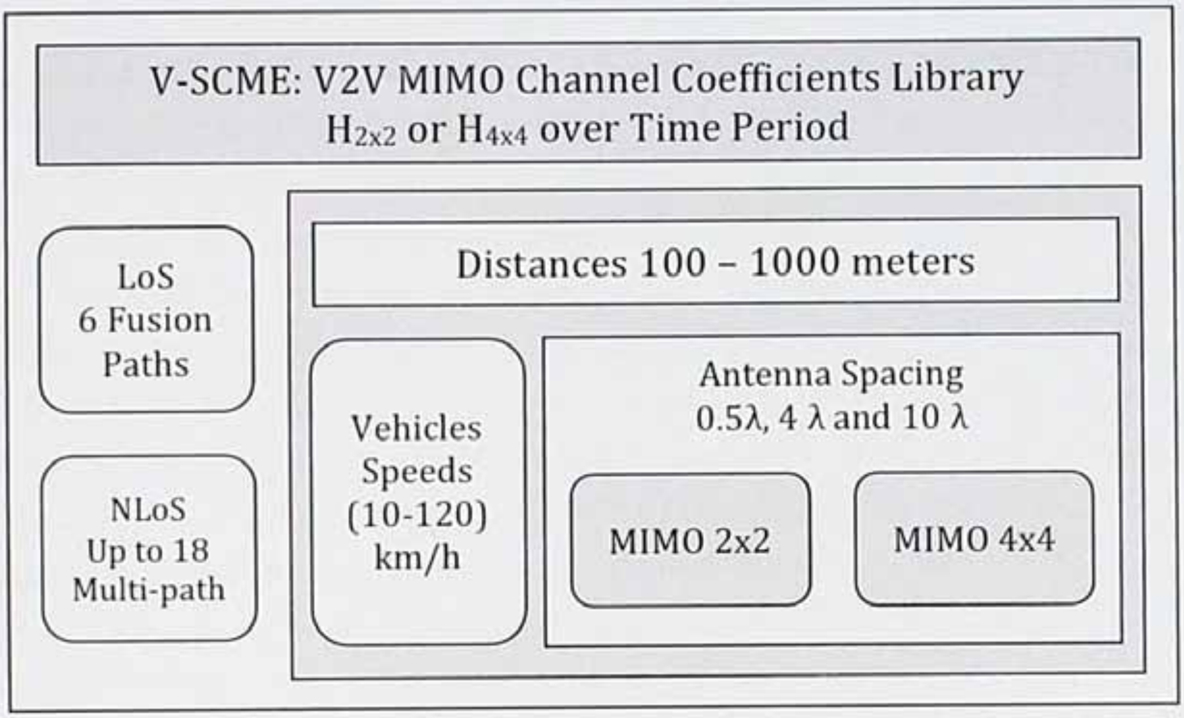


Figure 5.46: V2V MIMO Channel Coefficients Library Description.

5.7. CHAPTER SUMMARY

The chapter is about a simulation work to assess the performance of the PHY layer in vehicular environment using a novel model: Vehicular - Spatial Channel Model Extended V-SCME. Section (5.2) discussed the developed V-SCME channel model to be used in V2V communication. The proposed channel model was developed based on Spatial Channel Model Extended SCME for cellular communication (3rd Generation Partnership Project, 2014) to simulate the V2V communication in Urban Microcell environment. The developed model followed the approach of the vehicular standard IEEE 802.11p (IEEE Vehicular Technology Society, 2014), where 5.9GHz has been used as a carrier frequency and 10MHz for the bandwidth. The V-SCME has been simulated using Matlab R2013a simulator, where the scenarios and the configuration parameters showed the 3GPP cellular model (3rd Generation Partnership Project, 2014) were considered. However, within this thesis a specific set of scenarios and configurations for V2V communication were added in the developed novel model such as: antenna gain, wavelength, antenna spacing, angle of velocity, AoA, AoD, distances between the vehicles and vehicles speeds. Due to the nature of the V2V environment, V-SCME takes into account the values of angles such as angle of departure (AoD) and angle of arrival (AoA). The vehicles were assumed travelling on the same road, where AoD and AoA are set to ($180° \pm 5°$) in Microcell Urban (up to 300 meters LoS and 1km NLoS coverage distance) (3rd Generation Partnership Project, 2014).

The following configuration values were considered in order to obtain the estimated channel fading, channel capacity and the power delay for the vehicular standard IEEE 802.11p (IEEE Vehicular Technology Society, 2014) Different speeds were considered (10km/h -120km/h).

- 5.9GHz was the carrier frequency in different multi-path scenarios.
- The channel model was constructed under the condition of 2x2 MIMO and 4x4 MIMO systems for different disruptions levels (up to 18 multi-path and up to 20 sub-path) (3rd Generation Partnership Project, 2014).

The channel characteristics for the V2V communication were described in section (5.3). The simulation tests showed the behaviour of the V2V channel using two different channel models: Rayleigh channel model and the proposed novel V-SCME channel model. The obtained results showed that Rayleigh is a simple model which has been used in most of the research e.g. (Sharma and Malhotra, 2015; Akbar *et al.*, 2015; Abbasi *et al.*, 2015;

Nyongesa *et al.,* 2015) as a VANET channel, while it is not representing VANET channel model. In the same section, OFDM technique have been utilised in the highly dynamic V2V environments to achieve higher date rates with less bite error rate. The simulation result showed that consolidates OFDM have managed to reduce the BER in the multi-fading channel problems. MIMO - OFDM technique based on Alamouti Space Time Code has been utilised in V2V communication, in which the signal was transmitted through two antennas with different coding. Rayleigh or Ray tracing channels model were used as a V2V channels model. However, it was found that Rayleigh and Ray tracing were not representing the V2V channel model, where the amount of parameters which are considered in Rayleigh and Ray tracing channels model does not reflect the highly dynamic environment in V2V.

Section (5.4) showed the validation of the V-SCME which was one of the novel contributions of this thesis. The obtained results were compared with the RESCUE project result provided by (Kaske *et al.,* 2014) to measure V2V channel using hardware devices (real world).

Section (5.5) was another contribution in this thesis. The objective of this section was to compare between the obtained results of the existing MIMO – Coding techniques in order to find the optimum coding to be utilised in V-SCME to improve the V2V communication.

Alamouti Space Time Code simulation results were discussed in section (5.5.1). The simulation results obtained from V-SCME considered Alamouti Space Time Code for symmetric channel and asymmetric channel. The simulation results for Alamouti simulation tests showed an unacceptable BER. That indicated that Alamouti Space Time Coding is suitable for stationary communication rather than mobility communication. However, it was recommended to choose more robust space time coding techniques which are reliable in highly dynamic environment and mobility rather than Alamouti Space Time Code.

Section (5.5.2) presented the investigation of the performance of SM in V2V communication using V-SCME channel model. Although the SM is a relatively new MIMO technology that can provide high data rate with reasonable spectral efficiency. The BER performance of SM systems under V-SCME channel models showed unexpected results, inconsistent results and a high BER in most of the NLoS results. The factors such as: different modulation schemes, different vehicles speeds, and different distances can affect the performance of SM over the V2V communication. This is due to the high dynamic environment in V2V communication which indicate that SM is unable to satisfy the requirement of V2V communication. In this case a more robust MIMO coding is needed in order to satisfy the requirement of V2V communication.

In section (5.5.3), V-SCME channel model with V-BLAST coding system was used to improve V2V physical layer performance. Commercial interest in MIMO systems, which employ multiple antennas at both ends of the link, grew after the successful laboratory implementation of the well-known vertical Bell-Labs layered space-time architecture V-BLAST (Pupala, 2008). The aim of using a large number of parameters in V-SCME channel model was an attempt to mimic the highly dynamic disruption environment in V2V. The channel model with V-BLAST has improved the BER for the nodes moving at different speeds as compared to the previous works with Alamouti and SM coding.

Sections (5.6) discussed another novel contribution in this thesis which is the channel coefficients library for V2V communication. Almost all vehicular communication simulators use determined random channel coefficients during the simulation time which leads to (a) having a non-realistic channel representation (b) time consumption especially in large scale scenarios; therefore it is necessary to have a predefined library cities with thousands of vehicles which would be a very cost effective and a more accurate approach. The statistical model was derived to represent V2V communication channel model to estimate the channel parameters for both LoS and NLoS. Consequently, several distances, speeds, antenna spacing values and urban canyon microcell scenarios were intensively considered to produce and verify this library as well. Having such an open access library enables the researcher in relevant communities to test and evaluate several vehicular communication scenarios in wider manners with less time and efforts.

CHAPTER SIX
CONCLUSIONS AND FUTURE WORK

6.1. INTRODUCTION

This thesis provides a technical solution to V2V communication issues by developing a novel V2V statistical channel model called V-SCME and it has been tested within a simulated communication system such as MIMO coding with different types of modulations. V-SCME contributes to the wireless technology in V2V communications in general by enabling the research community to simulate larger scale VANET scenarios in a more realistic manner and a shorter time. The author was keen to work within the concept of the backward compatibility of wireless technologies.

The development of real-time safety and other applications for use in VANET, calls for a good understanding of the dynamics that underpin the network topology characteristics. This is mainly because these dynamics influence the performance of any given application over the VANET model.

The design and implementation of a channel model for V2V environment is critical for ensuring a high performance. Any vehicular network environment needs to be accurate and include a precise representation of vehicle movement as well as the passing of signals among different vehicles. In this thesis an efficient robust V2V channel model was developed and employed V-BLAST as MIMO channel coding. This developed channel model was compared with simulated and available real world results.

In V2V simulation, a high computational power during the simulation is needed and this consumes a lot of time. Having a precise movement model and channel model for vehicles communication is necessary to show the results in a more realistic manner as intensively discussed in section (5.5). There has been very little research done with physical V2V-MIMO until Kaske *et al.* (2014), so simulated results have been the only comparable techniques. The existing simulation tools discussed in this thesis (Chapter 3) could not simulate the exact V2V physical layer conditions as they have not used a verified system, therefore results can be unsatisfactory when compared with real world experiments. In this thesis the channel model was developed based on a verified system.

A research group Kaske et al (2014) which is part of the RESCUE European project for communication technology (RESCUE Project, 2013) have recently delivered some initial results to measure V2V channel in the real world. Their delivered results were based on a developed cellular system which is under the WINNER project (Eurescom GmbH, 2006). The developed model V-SCME is an attempt to extend an existing cellular system model (SCME) into a dedicated channel model for V2V applications. The author was keen to rely on a verified system such as the 3GPP project which is well established. The 3GPP research project group keeps verifying and considering several different types of scenario tests which are related to a mobile device and base-station. Therefore, as a conclusion the V-SCME is a robust, verified and reliable channel model for V2V communication.

In order to reduce the overall simulation time with a more realistic channel model for V2V, this work has provided an open access predefined channel coefficients library for V2V-MIMO communications. The channel coefficients are designed in 2x2 MIMO and 4x4 MIMO which are formed as H_{2x2} and H_{4x4} matrices and they are varied over time due to the dynamic environment of V2V-MIMO communication. The library is structured according to two major parts: LoS and NLoS, each part has 12 different vehicle speeds of (10-120km/h), four different distances (100,300,500 and 1000 meters), up to 18 signal multi-path ($N \leq 18$) for NLoS and up to 6 diffused signals for LoS and each signal has up to 20 sub-paths ($M \leq 20$) for both LoS and NLoS, and the channel coefficients sampling time 1ms (4000 channel coefficients per second for 2x2 MIMO and 16000 channel coefficients per second for 4x4 MIMO). The total channel coefficients for 2x2 and 4x4 MIMO in both NLoS and LoS is 73728000, they are all ready for downloading from (Al-Khalil, 2015).

6.2. V-SCME CHANNEL MODEL

The choice of the V2V channel model in VANETs simulators is a crucial issue due to the high dynamic environment and this is one of the conclusions of this work. Most of the reviewed channel models in this thesis e.g. Rayleigh, Rician and Ray tracing are basics radio propagation models, where the physical layer is treated in a simplistic and consequently not quite realistic manner as discussed in section (3.1.1). In addition, they are often impractical due to the need for a detailed description of the specific propagation environment. None of the literature to date has shown clear simulation attempts that discuss development of a cellular system channel model dedicated to V2V communications. Therefore, this missing element in the existing research literature, was part of the focus for this research.

In this thesis, a novel channel model V-SCME was specifically developed for V2V communications based on the verified SCME for cellular communications (3rd Generation Partnership Project, 2014) under IST WINNER project (Eurescom GmbH, 2006) to represent the V2V channel model. The WINNER project has been in use for a long period of time and is a verified one and, in addition to that, it is still considered in cellular system simulations for base-station – to – mobile communications. This gave me the motivation to develop the SCME for mobile – to – mobile (V2V) communications. An open access predefined channel coefficients library has been designed, based on the novel V-SCME, for V2V communications which is useful for the following:

- The library is initially built based on the 3GPP/WINNER channel model which is a verified channel modelling system for cellular communication.
- The library is offline and it will be beneficial for the future tests by reducing the overall simulation time.
- The library has a flexible design where it can provide customised scenarios for the future research such as increasing the number of antennas and vehicles speeds.

6.2. MIMO CODING TECHNIQUES

The MIMO coding techniques considered in this thesis are not only to improve the performance of the novel channel model V-SCME but also in order to provide a fully compatible system to satisfy the requirement of the V2V communications.

In MIMO systems, the diversity coding plays a major role in the communication process. Therefore, three different coding techniques have been tested over the V-SCME in this these: (a) Alamouti space code, (b) Spatial modulation and (c) V-BLAST coding technique. The simulation tests for Alamouti coding showed a very high BER results, which gave an indication that the Alamouti coding did not meet the requirement of the V2V communications due to the high dynamic environment. In other hand, the Spatial Modulation tests also did not meet the requirement of the V2V communications, where the obtained results were inconsistent due to the high dynamic environment in V2V communications. The V-BLAST coding technique is the optimum technique, where it has showed a reasonable consistent results for both LoS and NLoS conditions as compared to Alamouti and Spatial Modulation techniques. The simulation tests compared the SNR [dB] at 10^{-2} and 10^{-3} BER. Although the 10^{-2} and 10^{-3} BER are still considered high in the wired and wireless communications they are reasonable due to the nature of the V2V environment.

6.3. A Vision for Future Work

1- The main goal in this work was focused on developing V2V channel model based on the vehicular standard IEEE 802.11p. The next stage is to develop a V2I channel model based on an extended version of cellular system WINNER project (Eurescom GmbH, 2006), and design a predefined channel coefficients library by considering the suitable configuration setting.

2- Although V2V-MIMO statistical channel model was designed and developed in this thesis, a physical real world test with a complete communication system (with source coding, channel coding, modulation and RF) should be implemented to achieve a full validation process for V2V channel model.

3- Potential Long Term Evolution Advanced (LTE-A) technology could play an important role in wireless communication systems. LTE-A could be an alternative solution for V2V communications instead of the IEEE 802.11p as an open research topic to develop V2V and V2I channel models.

4- The use of 2x2 MIMO systems over the developed V2V channel model showed reasonable results. More channel capacity can be achieved by increasing the number of antennas i.e. 8x8 MIMO, 16x16 MIMO ... etc. which is a good solution, where this will give power spectral density for the use of video transmission.

5- Massive antennas with 5th generation mobile networks (5G) could be investigated for both V2V and V2I communications.

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