ADAPTIVE RADIO PROPAGATION MODEL FOR MODERN ROAD INFRASTRUCTURE UNITS IN VEHICULAR AD HOC NETWORKS

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ABSTRACT

Vehicular Ad Hoc Networks (VANETs) is an evolving field of wireless technology having a wide range of useful applications. The deployment and testing of new applications and protocols in VANETs is costly and labor intensive, so the simulation provides a cost effective solution for the evaluation of new applications and protocols. The Radio Propagation Models (RPMs) are employed in VANETs to predict signal attenuation and radio coverage. The RPMs require realistic detail due to restrictively fast mobility of vehicles, nature of network and the underlying road infrastructure units. Modern vehicular environment contains road infrastructure units such as confined curved roads, flyovers, underpasses, straight roads and tunnels. Two types of radio obstacles exist in vehicular environment that impede radio signals; static obstacles (such as buildings), and the moving obstacles (such as large buses). The radio signals in 5.9 GHz band (IEEE 802.11p) are less penetrating as compared to Wi-Fi and GSM which operate in 2.4 GHz and 1.8GHz band respectively. The radio obstacles have high impact on vehicular communication and maintaining the Line-Of-Sight condition among communicating vehicles improves vehicular communication. Hence, developing realistic RPMs in VANETs for the modern road infrastructure units is a challenging task. The existing RPMs do not inspect the impact of modern road infrastructure units on radio propagation in the presence of radio obstacles. Further, no set of rules exists for optimal positioning of Road Side Units (RSUs) on modern road infrastructure units to facilitate reliable communication. Accurate prediction of signal attenuation requires realistic RPM that is capable of addressing physical factors, models both static and moving radio obstacles, considers the modern road infrastructure units and utilize realistic traffic detail found in actual traffic environment. However, incorporation of the required level of detail in an RPM demands extensive computations. Therefore, a light-weight RPM for modern road infrastructure units is needed to predict signal attenuation

with acceptable accuracy. This research focuses on the development of an adaptive RPM with static and moving obstacle modeling that considers modern road infrastructure units to facilitate pragmatic simulation in VANETs and to provide reliable communication infrastructure. The proposed adaptive RPM selects among different modes of calculating signal attenuation depending upon the existing traffic conditions and underlying road infrastructure units along with the handling of radio obstacles. The adaptive RPM is evaluated on a small scale using real-world data obtained from extensive field measurement campaigns and also on a large scale using simulation. Optimal positioning of RSUs on modern road infrastructure units to maintain LOS condition among communicating vehicles is formulized using geometric concepts. Finally, a comparison is made between the two cases (presence and absence of RSUs at optimal distance) in terms of system evaluation metrics. This research redirects the existing efforts in the design of propagation models towards a novel perception by which to incorporate adaptability in propagation models as a benchmark towards realistic performance evaluation of new advancements.

ABSTRAK

Vehicular Ad Hoc Networks (VANETs) adalah medan berubah-ubah bagi teknologi tanpa wayar yang mempunyai pelbagai aplikasi yang berguna. Penggunaan dan pengujian aplikasi dan protokol baru dalam VANETs adalah mahal dan intensif tenaga kerja, oleh yang demikian simulasi menyediakan penyelesaian kos effektif bagi penilaian aplikasi dan protokol baru. Model Pengembangan Radio (RPM) digunakan dalam VANETs untuk meramalkan pengecilan isyarat dan liputan radio. RPM memerlukan keperincian realistik kerana kekangan pergerakan kenderaan yang sangat cepat, jenis rangkaian dan unit infrastruktur jalan asas. Persekitaran kenderaan moden mengandungi unit infrastruktur jalan raya seperti jalan raya terhad melengkung, jejambat, laluan bawah, bahagian jalan yang lurus, terowong jalan raya dan persimpangan kompleks. Dua jenis halangan radio wujud dalam persekitaran kenderaan moden yang menghalang isyarat radio daripada berkomunikasi kenderaan; halangan statik (seperti bangunan), dan halangan-halangan yang bergerak (seperti bas besar). Isyarat radio di 5.9 GHz band (IEEE 802.11p) kurang menembusi berbanding dengan Wi-Fi dan GSM yang beroperasi masing-masing pada 2.4 GHz dan jalur 1.8GHz. Halangan-halangan radio mempunyai kesan yang tinggi ke atas komunikasi kenderaan dan mengekalkan keadaan *Line-Of-Sight (LOS)* kalangan kenderaan yang berkomunikasi bagi memperbaiki komunikasi kenderaan tersebut. Oleh itu, pembangunan realistik RPM dalam VANETs bagi unit infrastruktur jalan moden adalah tugas yang mencabar. RPM sedia ada tidak memeriksa kesan unit infrastruktur jalan raya moden di perambatan radio di hadapan kedua-dua halangan radio statik dan bergerak. Tambahan lagi, tiada set peraturan wujud untuk kedudukan yang optimum untuk *Road Side Unit* (RSUs) di jalan infrastuktur yang moden untuk penyediaan komunikasi dipercayai di VANETs. Ramalan yang tepat isyarat pengecilan memerlukan realistik RPM yang mampu menangani faktor-faktor fizikal yang memberi kesan kepada

pembiakan radio, model kedua-dua halangan radio statik dan bergerak, menganggap unit infrastruktur jalan yang mudah, dan menggunakan perincian trafik realistik yang terdapat dalam persekitaran trafik yang sebenar. Walau bagaimanapun, penubuhan tahap yang diperlukan terperinci dalam RPM yang menuntut pengiraan luas. Oleh itu, pengkomputeran RPM murah untuk unit infrastruktur jalan raya moden yang diperlukan yang meramalkan tingkah laku isyarat radio dengan ketepatan yang boleh diterima. Kajian ini memberi tumpuan kepada pembangunan RPM penyesuaian dengan statik dan bergerak pemodelan halangan yang mempertimbangkan unit infrastruktur jalan moden untuk memudahkan simulasi pragmatik dalam VANETs dan untuk menyediakan infrastruktur komunikasi lebih dipercayai. RPM penyesuaian yang dicadangkan bijak memilih dan bertukar antara mod pandangan yang mengira pengecilan isyarat bergantung kepada keadaan lalu lintas yang sedia ada dan asas unit infrastruktur jalan. RPM penyesuaian yang dicadangkan mengendalikan semua halangan radio dalam unit infrastruktur jalan raya moden dan mengambil kira kesannya terhadap kekuatan isyarat yang diterima. RPM penyesuaian dinilai secara kecil-kecilan menggunakan data dunia sebenar yang diperoleh daripada kempen pengukuran lapangan yang luas dan juga secara besar-besaran menggunakan simulasi dan peta nyata. Kedudukan optimum RSUs pada unit infrastruktur jalan moden untuk mengekalkan keadaan *LOS* kalangan berkomunikasi kenderaan adalah formulasi menggunakan konsep geometri. Akhir sekali, perbandingan dibuat antara kedua-dua kes (kehadiran dan ketiadaan RSUs pada jarak optimum) dari segi metrik penilaian sistem yang termasuk pengecilan isyarat dan nisbah penghantaran paket. Kajian ini pelencongan usaha-usaha yang sedia ada dalam reka bentuk model perambatan terhadap persepsi novel yang digunakan untuk menggabungkan keupayaan menyesuaikan diri dalam model pembiakan sebagai penanda aras ke arah penilaian prestasi realistik aplikasi dan protokol baru.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

Acronym	Description
AOD	Average Optimal Distance
APL	Average Path Length
BDAM	Building and Distance Attenuation Model
BM	Building Model
BSM	Basic Safety Message
BSS	Basic Service Set
CCH	Control Channel
CEPT	Conference on European Postal and Telecommunications Administration
CSM	Constant Speed Motion
DAM	Distance Attenuation Model
DL	Delivery Latency
DM	Downtown Model
DSRC	Dedicated Short Range Communication
EDR	Event Data Recorder
ETSI	European Telecommunication Standard Institute
FCC	Federal Communication Commission
FIFO	First In First Out
FSPL	Free Space Path Loss
GHz	Gigahertz
GPS	Global Positioning System
IDM	Intelligent Driver Model
IDM-LC	Intelligent Driving Model – Lane Change
IEEE	Institute of Electrical and Electronics Engineers
IPv6	Internet Protocol version 6
ISO	International Standard Organization
ITS	Intelligent Transportation system
ITU	International Telecommunication Union
IVC	Inter-Vehicular Communication
JaDES	Java Discrete Event Simulator
JIST	Java In Simulation Time
LOS	Line of Sight
LIF	Line Intersection Flag
MAC	Media Access Control
MHz	Megahertz
MIMO	Multiple-Input Multiple-Output
MP	On Board Unit
NLOS	Non Line of Sight

pdf	Probability density function
OBU	On Board Unit
OCB	Outside the Context of BSS
OFDM	Orthogonal Frequency Division Multiplexing
ORP	Optimal RSU Positioning
PLCP	Physical Layer Convergence Procedure sub-layer
PLE	Path Loss Exponent
PDR	Packet Delivery Ratio
PMD	Physical Medium Dependent sub-layer
PTSM	Probabilistic Traffic Sign Model
RAV	Real Attenuation and Visibility
RCR	Reliable Connectivity Range
RIT	Road Infrastructure Type
RPMO	Radio Propagation Model with Obstacles
RPMs	Radio Propagation Models
RSS	Received Signal Strength
RSU	Road Side Unit
RUG	Real Urban Grid
RWP	Random Way Point
SCH	Service Channel
SHF	Super High Frequency
SISO	Single-Input Single-Output
SSM	Stop Sign Model
STRAW	Street Random Waypoint
SWANS	Scalable Wireless Ad Hoc Network Simulator
TIGER	Topologically Integrated Geographic Encoding and Referencing
TLM	Traffic Light Model
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UMM	Urban Mobility Model
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Both (V2I and V2V)
WAVE	Wireless Access in Vehicular Environment
Wi-Fi	Wireless Fidelity
WSM	Wireless Service Advertisements
WSMP	WAVE Short Message Protocol
WWM	Weighted Waypoint Mobility

CHAPTER 1: INTRODUCTION

1.1 Introduction

This chapter presents theoretical framework and motivation for the proposed research. It discusses the problem statement, states the research objectives and describes the methodology used for the proposed research. The chapter is divided into seven sections. Section 1.2 presents the background of the research. Section 1.3 highlights motivations for the proposed research by explaining the importance of the proposed work and significance of the proposed solution. Section 1.4 summarizes the problem statement by highlighting the research issues in the existing radio propagation models for vehicular ad hoc networks. Section 1.5 states the research aim and presents the research objectives. Section 1.6 summarizes the methodology used in this research and section 1.7 illustrates the layout of the thesis.

1.2 Background

Establishing reliable wireless communication among vehicles is the main focus of research in both the academia and the automotive industry as the exchange of information among moving vehicles is being exploited to provide various useful applications. Dynamic routing, GPS navigation, mobile sensing, emergency health care, traffic management, in-car entertainment and most importantly, the vehicular safety; are a few examples of worthwhile applications that utilize wireless communications among moving vehicles (Qureshi et al., 2015).

The federal communications commission (FCC) has allocated 75MHz of spectrum in the 5.9GHz band for vehicle to infrastructure (V2I) and vehicle to vehicle (V2V) communication, called dedicated short range communications (DSRC). IEEE is also working on the 1609 family of standards for wireless access in vehicular environments (WAVE) that states the architecture, standardizes the set of services and defines the interfaces that collectively enable vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) wireless communications.

For Physical and Media Access Control (MAC) layers, IEEE 802.11p standards are widely adopted (Cozzetti, Campolo, Scopigno, & Molinaro, 2012a), (Zhou, Wang, Cao, Shi, & Liu, 2015) in vehicular ad-hoc networks (VANETs). IEEE 802.11p is an adaptation of 802.11 working in 5.9 GHz frequency band which is suitable for VANETs mainly because of its ad hoc nature (Jiang & Delgrossi, 2008). MAC protocols for VANETs are more inclined towards fast topological changes rather than power constraints due to diverse communication needs in VANETs (Manui & Kakkasageri, 2008). With the help of VANETs, V2X (both V2I and V2V) communications are established that operate on a range of environments having distinct topological characteristics.

VANETs perform a significant role in establishing the Intelligent Transportation System (ITS) which aims to provide services related to safety and efficiency of the transportation system using advance electronics and communication technologies. The main objectives of ITS are; (a) to provide traffic safety, (b) to improve transportation efficiency by decreasing traffic congestion, and (c) to facilitate greener environment by reducing both the fuel consumption and the pollution. ITS relies on both wired and wireless communication to achieve its objectives. Therefore, vehicular communication systems are developed and vehicular communication is established as a part of ITS that consists of on-board units (OBUs) and road side units (RSUs).

1.3 Motivation

Deploying and testing VANETs are costly and labor intensive processes because they involve expensive resources and man power. Simulation is a cost effective solution to provide evaluation of new applications and protocols in VANETs. Radio propagation models are typically employed in VANETs to predict path loss and effective coverage area of the transmitter wherein the communication is possible. The choice of radio propagation model has significant impact on accessing the performance of any VANET application and new protocol because radio propagation models are utilized at the physical level.

A number of the existing radio propagation models are simplistic in nature (Martinez, Toh, Cano, Calafate, & Manzoni, 2009), (Martinez, Toh, Cano, Calafate, & Manzoni, 2011), (Marinoni & Kari, 2006), (Mahajan, Potnis, Gopalan, & Wang, 2007) which ignore one or more of the physical aspects that affect radio propagation in VANET environment. Physical factors that affect radio propagation in VANETs environment include path loss, shadowing, fading, reflection, absorption, diffraction, Doppler's effect and multipath propagation (Molisch, Tufvesson, Karedal, & Mecklenbräuker, 2009), (Hafeez, Zhao, Liao, & Ma, 2009), (Dhoutaut, Régis, & Spies, 2006). A radio propagation model in VANETs should consider all the physical factors and apply the effects of each factor on radio propagation in order to get reasonable detail to realistically simulate signal propagation in a particular communication environment.

The radio propagation models in VANETs require a high level of realistic detail due to restrictively fast mobility of vehicles, nature of network, limitations of the technology, urgency of information dissemination and the underlying complex road infrastructure units. Modern vehicular environment contains road infrastructure units such as curved roads, irregular roads, flyovers, underpasses, tunnels, elevated terrain and complex interchanges (Qureshi & Noor, 2013). To properly simulate a new application or a protocol in VANET, a radio propagation model should contemplate modern road infrastructure units and their effects on radio propagation.

Radio obstacles that impede radio signals in VANETs are categorized in two groups; namely, static radio obstacles and moving radio obstacles. Static radio obstacles include buildings, dense vegetation, traffic lights, and advertising boards etc. Moving radio obstacles include large vehicles such buses, trailers and delivery trucks etc. The antennas used in the vehicles have limited communication range and it is possible that the signal is weakened by these obstacles. A number of radio propagation models employed in VANETs (Xia, 1996), (Mughal, Wagan, & Hasbullah, 2011), (Zajic & Stuber, 2008), (Scopigno & Cozzetti, 2010) lack in handling radio obstacles which leads to unrealistic modelling especially in modern vehicular environment. However, the existing radio propagation models that are designed to handle obstacles for sensitive VANETS have limited characteristics. Moreover, applications that utilize V2X communications have diverse requirements that impose different needs in terms of modelling accuracy and level of detail. The study of the impact of these radio obstacles on V2X communications helps in providing more reliable communication infrastructure in VANETs.

Moreover, in order to provide reliable communication infrastructure, maintaining the Line-Of-Sight (LOS) condition among communicating vehicles can improve vehicular communication. However, the radio signals in the designated frequency band for VANETs (i.e. 5.9 GHz) are less penetrating as compared to Wi-Fi and GSM technologies because of relatively low wavelength. Hence, radio obstacles have relatively higher impact on vehicular communication as compared to other communication technologies.

1.4 Statement of Problem

Accurate prediction of signal attenuation and effective coverage area of communication in VANETs requires realistic and computationally inexpensive radio propagation model. The propagation model in VANETs should be capable of (a) addressing physical factors that affect radio propagation, (b) modelling both static and moving radio obstacles, (c) considers the modern road infrastructure units and their effect on radio propagation in assigned frequency band for VANETs and (d) utilizes realistic detail found in actual traffic environment such as road topology and relative speed of communicating vehicles. Therefore, developing a computationally inexpensive yet realistic radio propagation model suitable of predicting path loss with acceptable accuracy in modern VANET environment is a challenging task.

Although, a number of existing radio propagation models claim (Martinez, et al., 2009), (Otto, Bustamante, & Berry, 2009), (Giordano, Frank, Pau, & Gerla, 2011), (Sommer, Eckhoff, German, & Dressler, 2011), (Boban, Vinhoza, Ferreira, Barros, & Tonguz, 2011), (Gozálvez, Sepulcre, & Bauza, 2012) to be realistic but the absence of required level of detail (discussed below) is the critical aspect of currently used radio propagation models. The existing radio propagation models do not inspect the impact of modern road infrastructure units on radio propagation in the presence of both static and moving radio obstacles along with the consideration of realistic detail found in actual traffic environment. Further, to facilitate reliable communication in VANETs, a set of rules is required for the optimal positioning of RSUs on modern road infrastructure units.

The existing radio propagation models for vehicular communication lack required level of detail to accurately predict signal attenuation.

- The exiting radio propagation models either do not consider radio obstacles or simply fix the radio range to simulate the effect of static obstacles.
- The dimensions and speeds of the moving radio obstacles and their effect on communicating vehicles travelling at different speeds are not considered.
- The existing radio propagation models do not contemplate modern road infrastructure units and their effect on radio propagation in modern VANETs environment.
- No set of rules exists for optimal positioning of RSUs on modern road infrastructure units to facilitate reliable communication in VANETs

1.5 Research Aim and Objectives

The aim of this research is to propose a light-weight adaptive radio propagation model that considers both static and moving radio obstacles in modern road infrastructure units that predicts path loss with acceptable accuracy to provide reliable communication infrastructure in modern VANETs. The objectives are as follows.

1. To review state-of-the-art in radio propagation models in VANETs.

2. To investigate the impact of modern road infrastructure units on vehicular communication.
3. To propose adaptive radio propagation model that considers both static and moving radio obstacles in modern road infrastructure units.
    - To evaluate and analyze the performance of adaptive radio propagation model using received signal strength (RSS) and packet delivery ratio (PDR).
4. To optimize RSU positioning
    - To propose and validate optimized RSU positioning in modern road infrastructure units.
    - To compare the effect of optimal positioning of RSUs on radio propagation using proposed adaptive radio propagation model.

1.6 Proposed Methodology

We studied the state-of-the-art to identify issues in the existing radio propagation models for VANETs. A thematic taxonomy is proposed that categorized the existing radio propagation models and a qualitative comparison of existing radio propagation models is carried out. The issues in the current radio propagation models which negatively affect the accurate prediction of path loss in VANETs are also identified in this research work.

The research problem is investigated by studying radio propagation for VANET simulation environment and implementing existing radio propagation models to prove that the identified issues really exist. A simulation is performed by using the custom-built interactive Java analyzer to calculate important metrics such as path loss and packet delivery ratio. We utilize SUMO (simulation of urban mobility) package that serves as traffic generator for feeding traffic traces to custom-built Java analyzer. This collective environment (custom-built Java analyzer and SUMO) is employed for the evaluation of the impact of both types of radio obstacles and modern road infrastructure units on signal propagation in VANETs.

We propose an Adaptive Radio Propagation Model (ARPM) which is capable of inspecting the impact both static and moving radio obstacles on radio propagation along with the consideration of realistic mobility model in modern road infrastructure units. The proposed ARPM adapts to the underlying road infrastructure and traffic detail by applying specialized set of mathematical equations to predict signal attenuation in a particular scenario. Further, the calculation of the impact of optimal positioning of RSUs on vehicular communication in modern road infrastructure units using proposed ARPM is performed.

The proposed ARPM is evaluated using real world empirical data which is collected in a series of data gathering campaigns separately organized for multiple road infrastructure units. Further, we acquire quantitative results by modelling low level abstraction of the proposed solution performing empirical analysis using simulations. The maps of the selected road infrastructure units (where the data gathering campaigns were previously carried out) are obtained from OpenStreetMap (Haklay & Weber, 2008). The maps served as one of the inputs for mobility generation through an open source traffic simulation package SUMO (Behrisch, Bieker, Erdmann, & Krajzewicz, 2011). A custom built Java-based discrete event simulator JaDES is used to calculate important metrics after scanning the input from SUMO. Therefore, the evaluation of proposed ARPM in small scale is performed using extensive real world data gathering campaigns and the large scale evaluation is performed using simulation.

The comparison of ARPM with other state-of-the-art radio propagation models is also carried out in the simulation environment using important metrics such as RSS and PDR. The comparison of the quantitative results is made before and after optimal positioning of RSUs. The quantitative results are compared after the optimal positioning of RSUs using the proposed ARPM.

Figure 1.1 graphically represents the adopted research methodology that comprises of five major steps namely (a) review, (b) investigation, (c) proposal, (d) evaluation and (e) comparison.

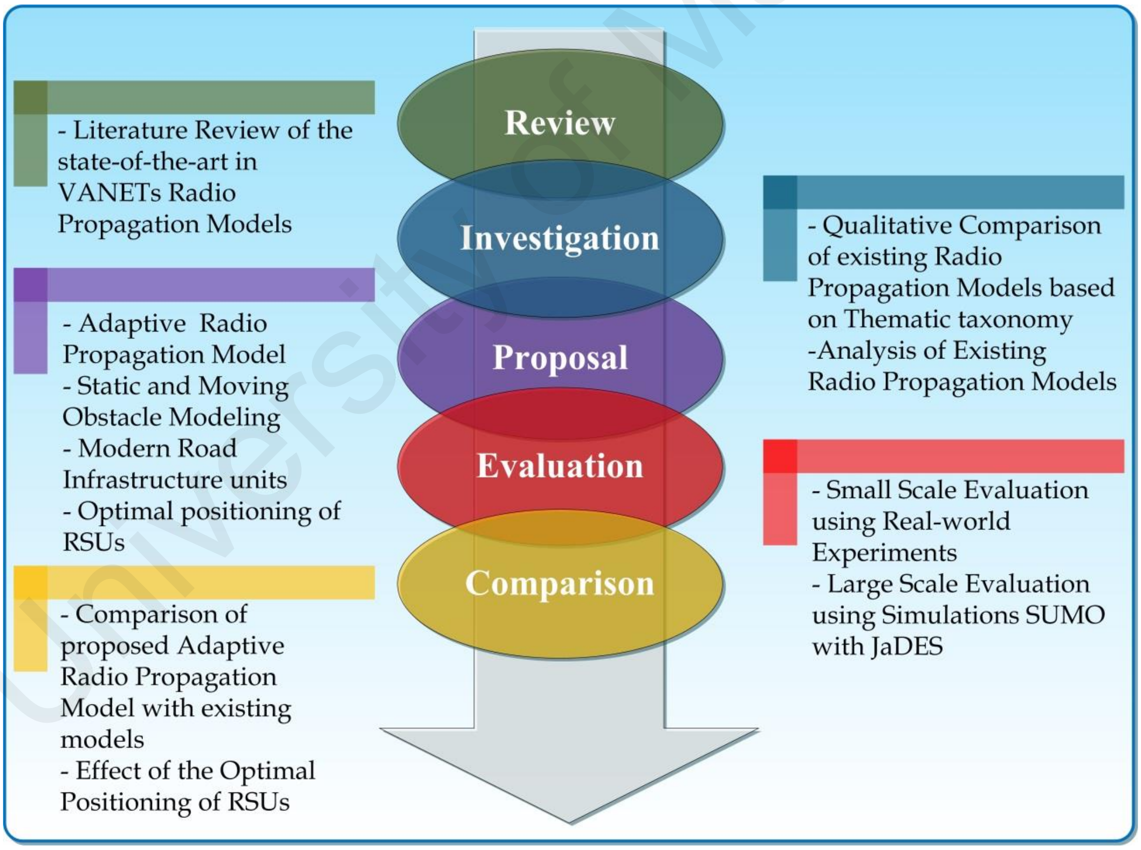

Figure 1.1: Research Methodology

1.7 Layout of Thesis

Chapter 2 presents the epistemology of VANETs and reviews the state-of-the-art in radio propagation for vehicular communication in modern traffic environment. It categorizes existing radio propagation models in VANETs on the basis of thematic taxonomy and compares those models using important metrics. The current challenges in existing radio propagation models and open issues for the development of realistic radio propagation models to predict path loss in VANETs are identified.

Chapter 3 analyses the existing techniques used in current radio propagation models for handling static radio obstacles. It expresses the preliminary simulation setup and experiments which are conducted to prove that large moving vehicles are the cause of signal attenuation in modern road infrastructure units. Further, this chapter inspects the propagation behavior in modern road infrastructure units and provides evidence that modern road infrastructure unit has an impact on radio propagation in designated frequency band for VANETs. The measurement parameters for problem analysis include; path loss, RSS and PDR.

Chapter 4 proposes an Adaptive Radio Propagation Model (ARPM) for VANETs. It explains the architecture of proposed model, and explains individual modules for information generation, static obstacle modelling, moving obstacle modelling and adaptive selection. The method of calculation of total signal attenuation depending upon diverse factor according to different scenarios is explained in this chapter.

Chapter 5 reports the method for the evaluation of proposed framework. It explains the tools used for testing the proposed ARPM, real world data acquisition, experimental results and statistical method used for the processing of data. It presents the usefulness of the proposed ARPM by analyzing the experimental results presented earlier. It also describes the significance of proposed ARPM by examining the experimental results in multiple scenarios.

Chapter 6 accomplishes the thesis by reporting on the reassessment of the research objectives. It elucidates the findings of the research work, describes the significance of the proposed solution, states the limitations of the research work and suggests future directions of the research.

Figure 1.2 shows the layout of this thesis.

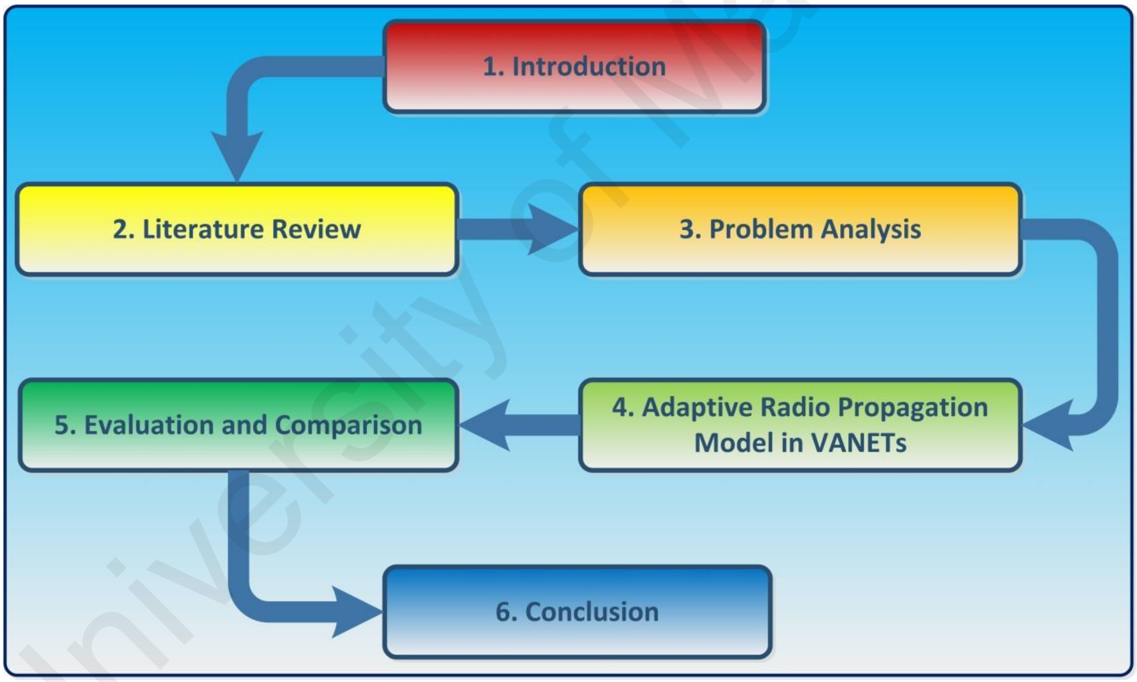

Figure 1.2: Organization of Thesis

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter describes epistemology of VANETs, reviews the state-of-the-art in radio propagation models and provides thematic taxonomy for existing radio propagation models in VANETs. Research challenges and open issues in existing radio propagation models are also discussed in this chapter.

The chapter is organized into twelve sections. Section 2.2 explains the fundamental concepts of VANETs and elaborate widely used communication standards. Section 2.3 gives an insight into the radio propagation in modern VANETs. Section 2.4 explains the basic radio propagation models utilized in VANETs. Section 2.5 presents thematic taxonomy of radio propagation models in VANETs. Section 2.6 reviews current radio propagation models and investigates the implications and critical aspects of the existing radio propagation models in VANETs. Section 2.7 compares existing radio propagation models by comparing the commonalities and deviations on the basis of significant parameters. Section 2.8 represents an analysis of existing radio propagation models while section 2.9 portrays the impact of modern road infrastructure units on radio propagation in typical VANET environment. Section 2.10 highlights the challenges and open issues in existing radio propagation models for VANETs while section 2.11 gives some useful recommendation on the basis of literature review. Finally, Section 2.12 summarizes the chapter with conclusive remarks.

2.2 Preliminaries

This section explains the basic idea of VANETs along with the information about some of the worthwhile applications and on-going projects in this area. Further, it discusses the standards used for the vehicular communication.

2.2.1 Vehicular Ad-Hoc Networks (VANETs)

VANETs is a challenging field of wireless technology that utilizes V2I (Q. Li, Qiao, & Yu, 2015), (Farah et al., 2012), (Korkmaz, Ekici, & Özgüner, 2010) and V2V (Kajackas, Vindašius, & Stanaitis, 2015), (Yin, Wang, & Zhang, 2013) communication to provide a wide variety of useful applications (Dynamic routing, GPS navigation, mobile sensing, emergency health care etc.). VANETs are expedient for such applications for the reason that they are equipped with the ability to handle rapidly changing topology and variable network density. Although VANETs are considered to be a special case of Mobile Ad Hoc Networks (MANETs); however, the protocols, techniques and standards relating to MANETs are inapplicable directly on VANETs due to varying node density, different mobility style and topological constraints (Manui & Kakkasageri, 2008). Further, VANETs have different security challenges as compared to MANETs (Xiong, Qin, & Li, 2010).

Figure 2.1 illustrates a typical VANET environment comprising of vehicles equipped with OBUs through which the vehicles in specific radio range can communicate with each other. An OBU is typically composed of Event Data Recorder (EDR), computational engine and a global positioning system (GPS) receiver. EDR archives the sent and received massages that can serve as a “black box” after an event (Sichitiu & Kihl, 2008). The GPS (Bevly, 2004), (Y Zhang et al., 2015) receiver provides geographical information about location, direction, and speed of the vehicle while the computational engine gives response to the received messages. OBUs are sometime equipped with radars that detect obstacles near the vehicle. RSUs are stationary devices mounted at road side, road intersections or may be embedded in traffic lights. RSUs are deployed in a typical VANET environment to provide communication with the infrastructure and with other OBUs (similar to wireless LAN accesses point) in order to support V2I communication. Similar to OBU, RSU typically consists of transceiver, computational engine and sensors (Pathan, 2010).

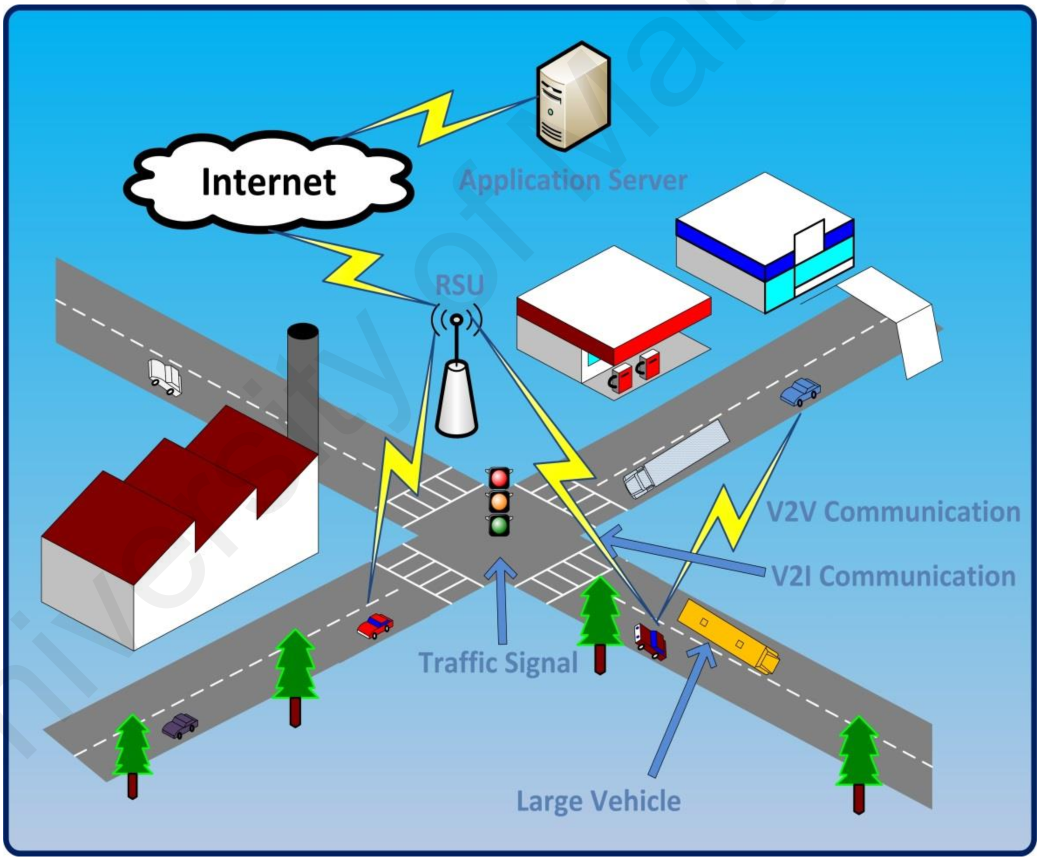

Figure 2.1: A Typical VANET Environment

Vehicles in VANETs have information about their own motion along with the detail about position, direction, speed and acceleration. This local information is periodically shared among other neighboring vehicles which are in radio range of a particular vehicle. Each vehicle stores the information about neighboring vehicles and broadcast this information to other neighbors and RSUs periodically; making it an ad-hoc distributed system (Lamport, 1978). Three type of messages are exchanged in VANETs; basic safety message (BSM) (Park & Kim, 2012), wireless service advertisements (WSA) (Campolo, Molinaro, & Vinel, 2011) and other network data such as text, audio or video in order to support a range of worthwhile applications in VANETs.

The automotive industry and international standard organization (ISO) (Zimmermann, 1980), (Guinée, 2002) are looking forward towards the advancement of technologies for the effective utilization of VANETs due to promising potential applications that involves V2X (both V2I and V2V) communications. With the help of VANETs, V2X communications are established in modern traffic environments with a range of distinct topological characteristics. Hence VANETs perform a significant role in the development of an effective ITS (Beresford & Bacon, 2006).

There is substantial research and innovation in the field of VANETs over the years. A variety of projects such as DRIVE C2X ("DRIVE C2X - Accelerate cooperative mobility," 2014), coopers ("Coopers," 2010), SCORE@F ("SCORE@F," 2014) and TeleFOT ("TeleFOT," 2014) etc. are going on by applying V2V and V2I communication for diverse applications, ranging from safety related applications to infotainment services. The evidence of the overwhelming demand of VANET applications is the fact that United States government announces decision to move forward with V2V communication technology and is planning to make this technology mandatory for every road legal vehicle by 2017 ("U.S Department of Transportation," 2014), ("VoA," 2014).

2.2.2 Communication Standard for VANETs

In United States, Federal Communication Commission (FCC) allocated 75 MHz of 5.9 GHz frequency band to dedicated short range communication (DSRC) of the ITS applications. Likewise, a breakthrough for the vehicular communication is the allocation of 50 MHZ band allocated by Postal and Telecommunication Administration (CEPT) in Europe. The protocol architecture conceived by IEEE is referred to as IEEE Wireless Access in Vehicular Environment (WAVE) and the architecture standardized by European Telecommunication Standard Institute (ETSI) is referred to as ETSI ITS. Both, the United States and European standards provide multiple channels in allocated bandwidth to support a wide variety of applications using vehicular communication including safety services, general purpose ITS services and commercial non safety applications (Campolo & Molinaro, 2013).

Figure 2.2 explains the protocol stack conceived by IEEE for DSRC. As, the vehicles in VANETs have to exchange periodic BSMs, SAE J2735 Message Set Dictionary Standards specifies a set of message formats and define message syntax to support BSMs at the top of the protocol stack. In the middle of the stack, DSRC utilizes a set of standards provided by IEEE 1609 working group; for instance, 1609.3 for Network services that includes WAVE Short Message Protocol (WSMP). It also supports renowned protocols for Network and Transport layers such as Internet Protocol version 6 (IPv6), Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). However, the requirements of a specific application determine the choice between using WSMP or IPv6+UDP/TCP (Kenney, 2011).

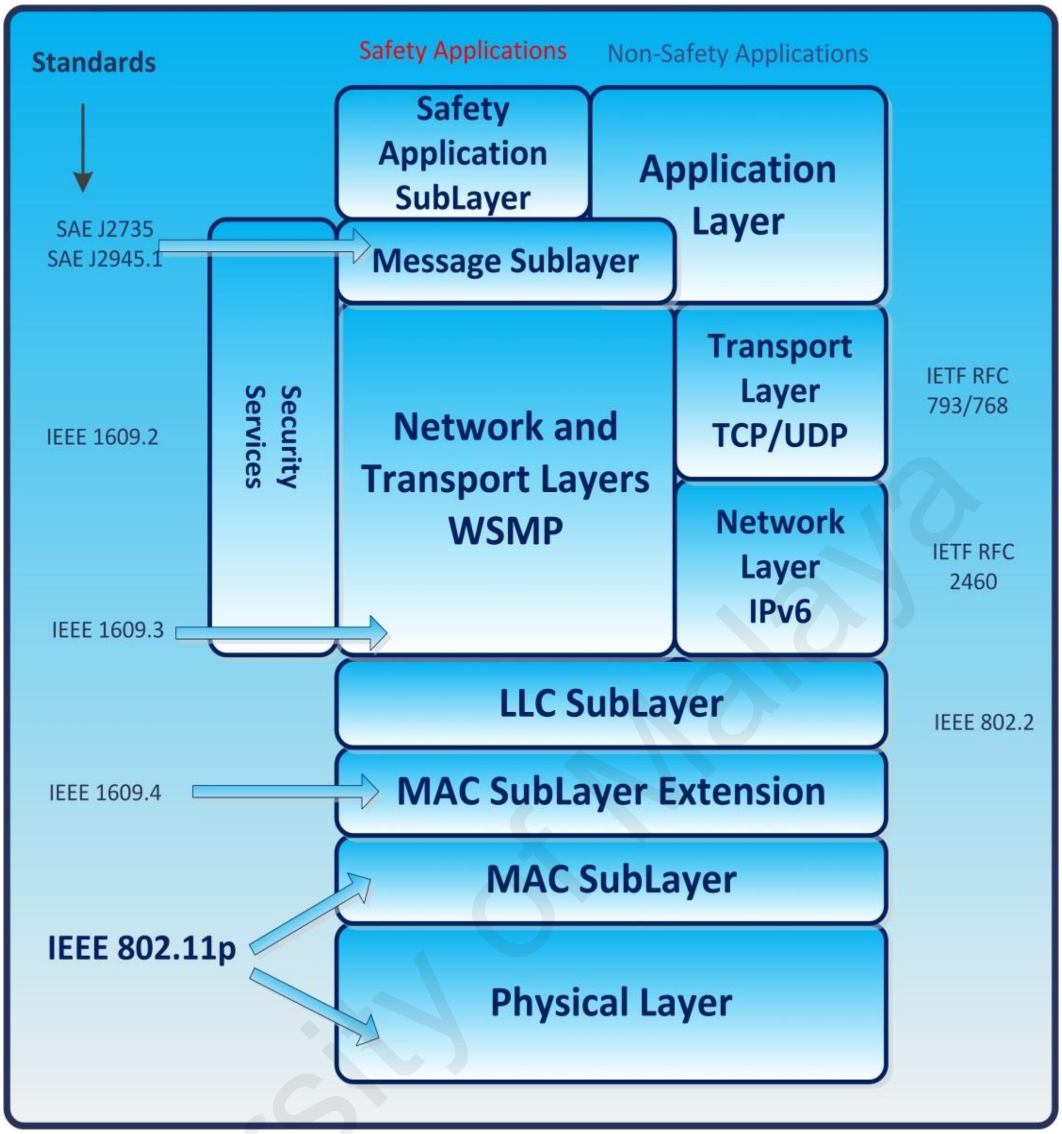

Figure 2.2: A Layered Architecture of IEEE WAVE for DSRC

For Physical and Media Access Control (MAC) layers, IEEE 802.11p WAVE standards are widely adopted which is modified version of IEEE 802.11 (WiFi) standard (Cozzetti, et al., 2012a). IEEE 802.11p is an adaptation of 802.11 working in 5.9 GHz frequency band which is suitable for VANETs mainly because of its ad hoc nature (Jiang & Delgrossi, 2008). The DSRC physical layer is further divided in two sub-layers namely; the physical medium dependent (PMD) sub-layer that communicates directly with the wireless medium and the physical layer convergence procedure (PLCP) sub-layer that supports mapping between MAC frame and PHY layer data unit. Orthogonal frequency division multiplexing (OFDM) is used by PMD to interface directly with the medium, therefore the unit of PHY layer data is OFDM symbol.

The allocated spectrum is divided into seven 10MHz channels with another 5 MHz guard band. Pairs of two consecutive 10 MHz channels can be combined to make 20 MHz channels. Each channel is either a service channel (SCH) or a control channel (CCH). MAC protocols for VANETs are more inclined towards fast topological changes rather than power constraints due to different communication needs in VANETs (Manui & Kakkasageri, 2008). The access rulers of the baseline 802.11 standard is utilized with simplified setup operations so as to allow a vehicle to transmit without being part of a basic service set (BSS) using a another mode called outside the context of BSS (OCB). The standard 1609.4 (Q. Chen, Jiang, & Delgrossi, 2009) stipulate extensions to the IEEE 802.11p MAC sub-layer to manage channel coordination for OCB enabled operations.

2.3 Background

The purpose of this section is to comprehend basics of radio propagation especially in modern VANET environment. Therefore this section contains a diverse variety of sub topics as it elaborates radio propagation concepts in VANETs along with the physical factors that affect radio propagation. Types of radio obstacles in vehicular environment are discussed along with a brief introduction of radio propagation models employed in modern VANETs. Modern road infrastructure units are explained in this section in order to develop an understanding that serves as a base-line in investigating the impact of modern road infrastructure units on signal propagation. Further, issues related to VANETs simulation is also presented in this section.

2.3.1 Radio Propagation in VANETs

The behavior of the radio waves while transmitting from one point to another in different atmospheric conditions is referred to as radio propagation. The behavior of radio waves varies at different frequencies (Parsons & Parsons, 2000). For instance, the radio waves below 20 KHz propagate as a single waveguide due to larger wavelength. However, in free space propagation, the amount electromagnetic energy carried by radio waves is inversely proportional to the square of the distance from its point source (Kapner et al., 2007).

The radio waves in VANET fall in super high frequency (SHF) electromagnetic waves that range from 3 GHz to 30 GHz according to International Telecommunication Union (ITU) categorization. The wavelength at 5.9 GHz (allocated bandwidth for VANETs) is approximately 5 centimeters that allow the waves to be directed in narrow beams by antennas; hence, these waves can be utilized for point to point communication and for the transmission of data. However, the radio waves in 5.9 GHz frequency band propagate entirely by line of sight as they are obstructed by radio obstacles in their path. These radio waves require the first Fresnel's zone (Athanasiadou, 2007), (Lindsey, 1989)to be cleared in order to get useful reception suitable for communication.

The radio signals in 5.9 GHz frequency band have relatively short wavelength, so the penetrating power of these signals is low as compared to other technologies like Wi-Fi and GSM. As a result, radio signals are obstructed by a variety of different types of obstacles in VANETs (Qureshi & Noor, 2013). Hence, the vehicles adopting IEEE 802.11p and ETSI standards have short communication range and the radio signal strength becomes weaker as different radio obstacles in the modern vehicular environment impede radio signals.

2.3.2 Physical Factors that Affect Radio Propagation

Wireless communication is largely affected by various physical factors and the radio signal is attenuated as a result of different phenomenon that include path loss, shadowing, fading (Prasad & Kegel, 1993), absorption, scattering (Beckmann & Spizzichino, 1987), multipath propagation (Turin, Clapp, Johnston, Fine, & Lavry, 1972) and Doppler's effect (Cox, 1972). Wireless communication is also effected by refraction and diffraction of the radio waves (Giordano, Frank, Pau, & Gerla, 2010). When a radio wave propagates in the space, there is a reduction in its power density that results in path loss and is sometimes represented by path loss exponent (PLE) (Erceg et al., 1999). The value of PLE usually ranges from 2 to 6 depending upon the medium; for instance, in free space, the value is approximately 2 and in an environment with building and other radio obstructions, the value of PLE is typically close to 6.

Fading is the change in attenuation that affects a radio signal over a particular propagation medium. Fading is caused by either shadowing from other radio obstacles present in the medium or multipath propagation. There are two types of fading; slow fading and fast fading (Hunter & Nosratinia, 2002). Slow fading is caused by events like shadowing when a large radio obstacle (e.g. building) disturbs the main signal path between the transmitter and the receiver because the coherence time of the channel is large as compared to the delay constraint of the channel. Coherence time is a measure of the minimum time within which magnitude or phase of the radio wave is predictable. Fast fading arise when the coherence time of the channel is trivial as compared to the delay constraint of the channel that results in considerable amplitude and phase change. Fading is often modelled as a random process. As, the signal can reach its destination using different paths, the multiple radio signals can partially cancel each other's effect due to destructive interference and is called as radio propagation anomaly. In wireless systems, when fading is due to shadowing from obstacles, it is called as shadow fading and when the cause of fading is multipath propagation, it is referred to as multipath induced fading (Andrusenko et al., 2008).

A radio signal is reflected, diffracted, absorbed and scattered by certain obstacles in its path. Wet and metallic surfaces cause reflection of the radio signals thereby affecting the wireless communication. However desert environment can absorb radio signal causing variation in path loss prediction (Saunders & Aragón-Zavala, 2007). Radio waves refract when traveling from an area of one refractive index to another (Budden, 1988) but this phenomenon is experience rarely especially in case of short range communication such as Wi-Fi (J.-S. Lee, Su, & Shen, 2007) and Dedicated Short Range Communication (DSRC) (Morgan, 2010), (Kenney, 2011). A radio signal is diffracted when it encounters an obstacle in the path of the receiver as it tends to bend around it because every point on wave front acts as the starting point for the another wave front enabling the waves to propagate around edges. A radio wave may scatters in all directions when it encounters a small object (compared to its wavelength) resulting in reduction of its intensity.

Doppler shift is a change in the frequency of a radio wave for the receiver, when transmitter and receiver are moving relative to each other. The Doppler's spread measures the spectral broadening due to the relative motion of sender and receiver. Doppler shift is observed in VANETs environment due to the nature of the network and the mobility of both the transmitter and receiver nodes (Asefi, Mark, & Shen, 2012).

2.2.3 Radio Obstacles in VANETs

Radio obstacles (Nešković, Nešković, & Paunović, 2000) that impede radio signals in vehicular environment are divided into two categories namely static obstacles (Meireles, Boban, Steenkiste, Tonguz, & Barros, 2010) and moving obstacles (Boban, et al., 2011). Static obstacles include buildings, dense vegetation traffic lights, and advertising boards etc. Moving obstacles include large vehicles such buses, trailers and delivery trucks. The static and moving radio obstacles block radio signals in V2V and V2I communications. The study of the impact of such obstacles on V2X communications helps in providing more reliable communication infrastructure in VANETs. Figure 2.3 shows a typical environment with different static and moving obstacles.

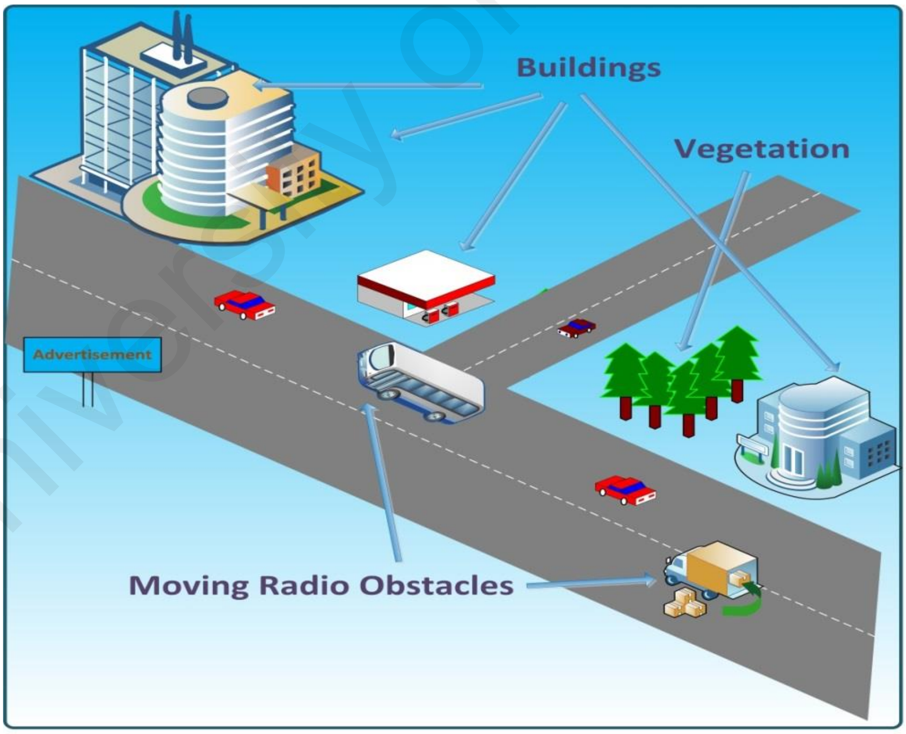

Figure 2.3: Radio Obstacles in VANETs

2.2.4 Radio Propagation Models

Radio propagation model is an empirically calculated/validated mathematical formulation used for the representation of the behavior of radio waves as they propagate through a medium. Although, this mathematical formulation is typically a function of frequency of the wave and the distance between sender and receiver, it may include other environmental factors as well. In telecommunication, every link has to bear different conditions such as path, terrain and obstructions; therefore, it is difficult to characterize the exact path loss in a single mathematical equation valid for all telecommunication systems. Hence, there exist multiple radio propagation models suitable for dissimilar telecommunication systems under different conditions such as separate models are employed for indoor and outdoor radio communication applications.

Radio propagation models for VANETs focus on apprehension of path loss along with a secondary task of calculating the effective coverage area of the transmitter wherein the communication is possible. These models are developed using large set of data acquired from specific propagation environment to predict realistic behavior of radio waves that may change dynamically depending upon different situations.

In vehicular environment, predicting the path loss is particularly challenging, since the radio signals of high speed vehicles are obstructed by different types of radio obstacles. The radio signals in vehicular communication have limited penetration power and it is possible that the signal is weakened by these obstacles. Moreover, there are road infrastructure units such as straight roads, curved roads, road tunnels, flyovers, underpasses, elevated terrain, irregular roads and complex interchanges in modern vehicular environment that may have varied impact on radio propagation.

It is difficult for a particular radio propagation model to consider all propagation aspects, road infrastructure detail and all mobility features of the vehicle due to the inherent complexity found in the VANETs environment. Further, the VANETs simulators have certain limitations. A simulator in VANETs captures traffic traces from real world and then simulates the effect of applying a particular radio propagation model that has an enormous impact on valuing important metrics such as RSS, PDR, Delivery Latency (DL), and Average Path Length (APL). Hence, the choice of radio propagation model affects MAC and higher layers in simulation.

The prediction of path loss has significant impact on accessing the performance of any VANETs application. A number computationally feasible radio propagation models (Martinez, et al., 2009), (Martinez, et al., 2011), (Marinoni & Kari, 2006), (Mahajan, et al., 2007) exists but they ignore one or more of the physical factors that affect radio propagation. Further, there are number of radio propagation model in VANETs (Mughal, et al., 2011), (Zajic & Stuber, 2008), (Scopigno & Cozzetti, 2010) which lack in including obstacle modelling consequently leading to unrealistic modelling. However, the existing radio propagation models that are designed to handle obstacles for sensitive VANETS have limited characteristics for instance; they do not consider modern road infrastructure units. Moreover, applications that utilize V2X communication have diverse requirements that impose different needs in terms of modelling accuracy and level of detail. Attempts such as (B. X. Wang, Adams, Jin, & Meng, 2010) are made to investigate the information propagation in V2V and V2I communication but they lack in modelling radio obstacles and they do not consider modern road infrastructure units.

2.2.5 Modern Road Infrastructure Units

The modern complex transport infrastructure especially in urban areas contains road infrastructural units such as flyovers, underpasses, tunnels, irregular streets, dead-end-roads, curvatures and complex interchanges. Each road infrastructure unit has a unique impact on radio propagation. This section explains the modern road infrastructure units in terms of radio propagation and also highlights the challenges in maintaining LOS conditions among communicating vehicles travelling on modern road infrastructure units.

Previous studies on radio wave propagation in vehicular environment focused on Manhattan style architecture, where the roads are organized parallel and perpendicular to each other in a grid like architecture (Giordano, Frank, et al., 2010), (Cozzetti, Campolo, Scopigno, & Molinaro; Giordano, Frank, et al., 2010). However, modern road infrastructure not only includes grid architecture but also utilize other road infrastructure units as well. Figure 2.4 shows some of the modern road infrastructure units.

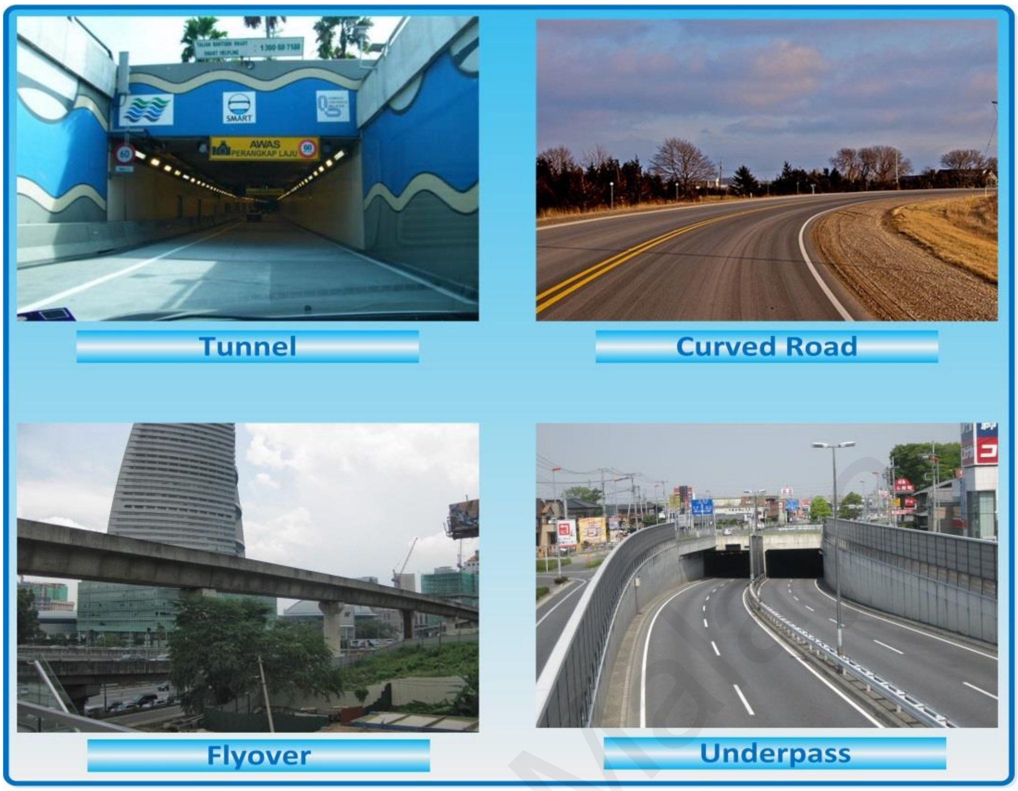

Figure 2.4: Modern Road Infrastructure Units

2.2.5.1 Curve Roads

In modern road infrastructure, curve road provides a transition between two roads which are tangent to each other. This allows a vehicle to perform a gradual turn instead of a sharp cut. Most of the curve roads are semi-circles in order to provide constant turning in accordance with the laws of physics. Vehicles maintaining specific distances among them are in LOS with each other on a straight road are no longer in LOS while using the curve road as shown in Figure 2.5. Therefore, a loss of power of the radio signals occur because the nearby building in urban environment and dense vegetation in highway environment may obstruct the radio signals. It results in loss of RSS values among communication vehicles that in turns may cause decrease in PDR.

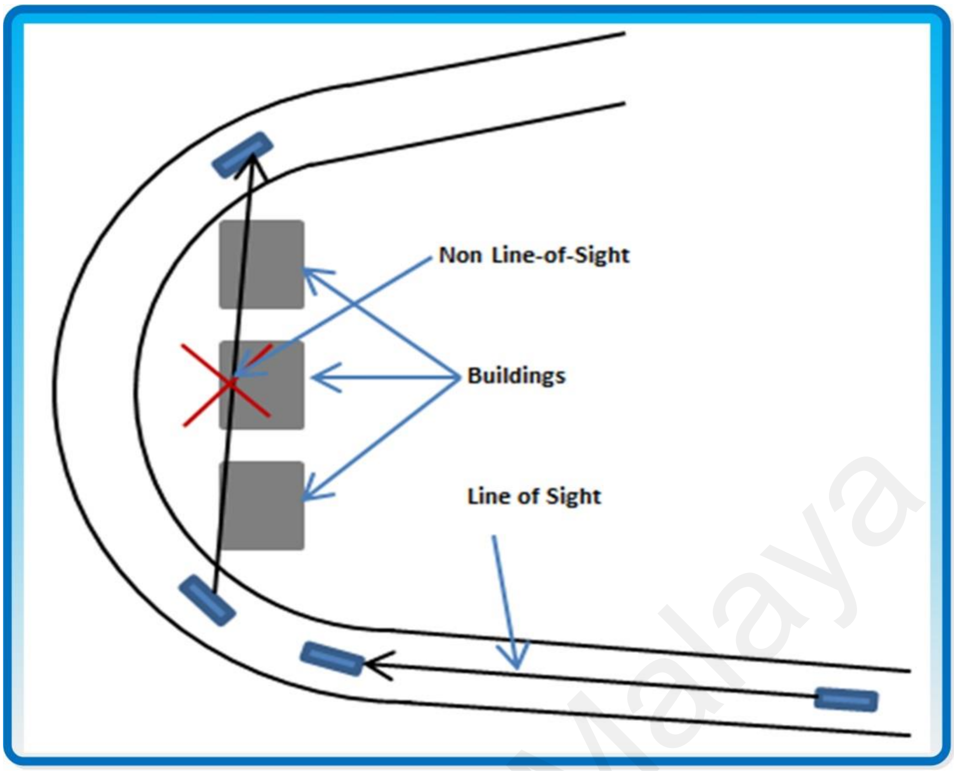

Figure 2.5: Curve Road

2.2.5.2 Road Tunnel

A road tunnel is an underground pathway for the vehicles that is totally enclosed from all four sides (top, bottom, left, and right) as shown in Figure 2.6. The openings of the tunnel are on start and end only that are used for entrance and exit. If the tunnel is composed of a straight road, vehicles outside the tunnel are potentially in LOS with the vehicles inside the road tunnel. However, if a road tunnel is composed of a curved road inside, the vehicles can no longer maintain LOS among them. Previous studies of radio propagation in tunnels showed that the radio propagation depends mainly upon shape of the tunnel (Shinozaki, Wada, et. al, 1995), (S.-H. Chen & Jeng, 1996), (Kasashima & Hirai, 2003). In LOS scenario, the path loss in tunnels is even less than free space but the path loss may suddenly increase when an NLOS condition arises.

A road tunnel can be considered as a waveguide due to its geometry and the conductivity, so, the radio propagation in tunnels is sometimes modelled using waveguide properties. According to existing research, the transverse dimensional tunnels which are much larger than the radio signal's wavelength experience waveguide properties (Deryck, 1978), (Y. P. Zhang, 2003). Therefore, signal attenuation in tunnels is smaller as compared to signal attenuation in free space probably due to the waveguide effect. However, the waveguide model is only suitable for calculating accurate signal attenuation in straight tunnels.

Two-slope propagation models for tunnels are empirical propagation models based on two-ray ground model suitable for LOS conditions among communicating vehicles. The path loss curve is divided into near and far regions in two-slope propagation models. In the near region, there is a rapid decrease in path loss slope usually modelled as free space propagation while the path loss slope is reduced in the far region due to waveguide effect. The point where the near and far regions can be separated from each other is called break point. The location of the break point depends upon the wavelength of the radio signal, the dimensions of the tunnel, the antenna and the relative permittivity (Z. Sun & Akyildiz, 2010) . However, the exact identification of break point is only determined experimentally.

The parameters that affect the radio propagation in tunnels include the tunnel geometry, electromagnetic properties of the material used to build the tunnel, antenna characteristics and radio obstacles (Hrovat, Kandus, & Javornik, 2014). The early research on radio propagation inside the tunnels proved that the dimensions of the tunnels have a significant impact on the signal attenuation (Yamaguchi, Abe, & Sekiguchi, 1989), (Didascalou, Maurer, & Wiesbeck, 2000), (Yang & Lu, 2007). However, the influence of conductivity on the radio propagation can be neglected in most of the tunnels (Jiping, Lingfei, & Xiaoyang, 2004). Moreover, the signal attenuation inside the tunnels also depends upon radiation pattern, polarization and position of transmuting and receiving antennas (Z. Sun & Akyildiz, 2010), (Lienard, Stefanut, & Degauque, 2009), (S. Wang, 2010), (Huo, Xu, Zheng, & Zhou, 2009).

Moving radio obstacles in the tunnel cause additional signal attenuation. One of the earlier studies (YP Zhang, 1999) showed that the additional path loss in tunnels caused by moving radio obstacles can reach up to 50 dB for 900 MHz frequency band. Another experimental study (Yamaguchi, et al., 1989) showed that the additional path loss in VHF band caused by moving radio obstacles in tunnels depends predominantly on size and quantity of moving radio obstacles. Furthermore, the shape and dimension of the tunnel's cross section (circular or rectangular) has an impact on the rate of signal attenuation (Hrovat, et al., 2014). However, another study (Changsen & Yan, 2006) suggested that the rate of attenuation in ultra-high frequency (UHF) band is not dependent on the shape and dimension of the tunnel, if the tunnel cross section is fifteen time larger than the wavelength of the radio signal.

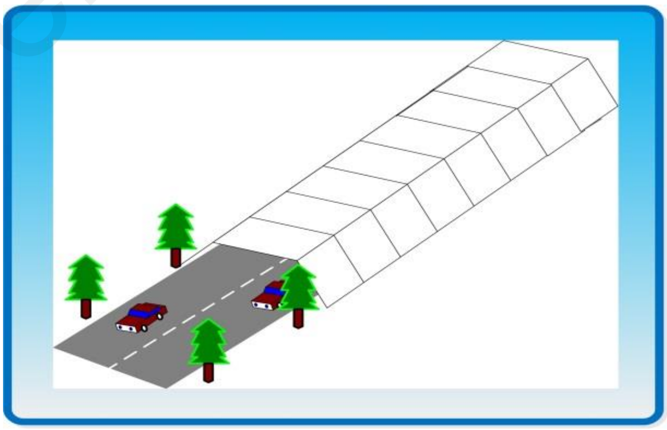

Figure 2.6: Tunnel

2.2.5.3 Flyover

A flyover is a bridge like structure that crosses over an intersection or another roadway. Flyover is a pivotal unit of modern urban road infrastructure because it is an attempt to make urban vehicular environment signal free. A flyover consists of two concrete edges and multiple pillars depending upon its length. Therefore, vehicles at different positions using a flyover may lose LOS among them because of the varying respective heights along the flyover and possible radio signal obstructions due edges and pillars. It is not possible to maintain LOS among vehicles at two different ends of flyover because the flyover itself behaves like a radio obstacle. Hence, the flyover causes packet loss in vehicle to vehicle communication. This scenario is explained in Figure 2.7. However, radio propagation characteristics for the vehicles travelling along a flyover are yet to be explored in designated frequency band for VANET.

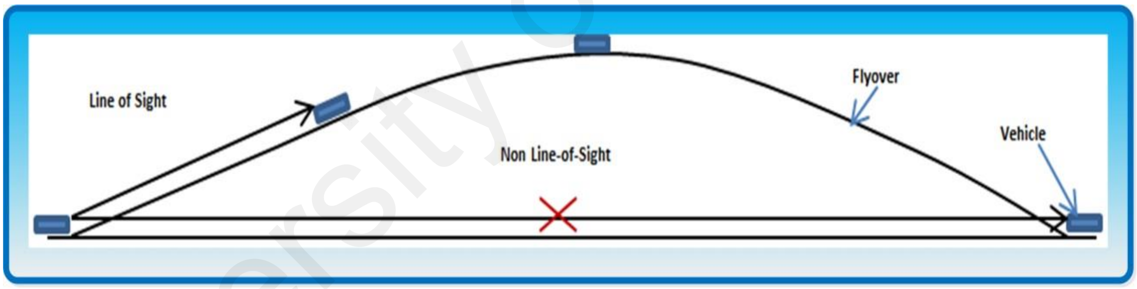

Figure 2.7: Flyover

2.2.5.4 Underpass

The underpass is a sort of a small road tunnel also incorporated to make the modern urban road transport environment signal free. The typical length of the underpass varies from 20 meters to 60 meters depending upon the width of the road that runs on top of the underpass orthogonally. The radio propagation characteristics inside an underpass theoretically resemble the radio propagation properties inside a road tunnels. However due to relatively short length of the underpass, radio waves might behave differently as compared to road tunnels. A typical underpass is shown in Figure 2. 8. The radio propagation characteristics inside an underpass are yet to be discovered in designated frequency band for VANETs.

Figure 2. 8: A typical underpass

2.2.5.5 Irregular Roads

Irregular roads do not follow Manhattan style grid architecture. The streets are arranged at different angels at each other. In irregular roads, LOS depends upon length of the streets and angular difference between the two streets where the communicating vehicles are travelling (Martinez et al., 2010). If the angular difference between two communicating vehicles on different streets is less than a threshold value, the two vehicles are considered in LOS otherwise the vehicles in different streets are in NLOS with each other as shown in Figure 2.9. It means that vehicles travelling on different streets on irregular roads are potentially in NLOS except when the angular difference between the two adjacent streets is less than a predefined threshold value.

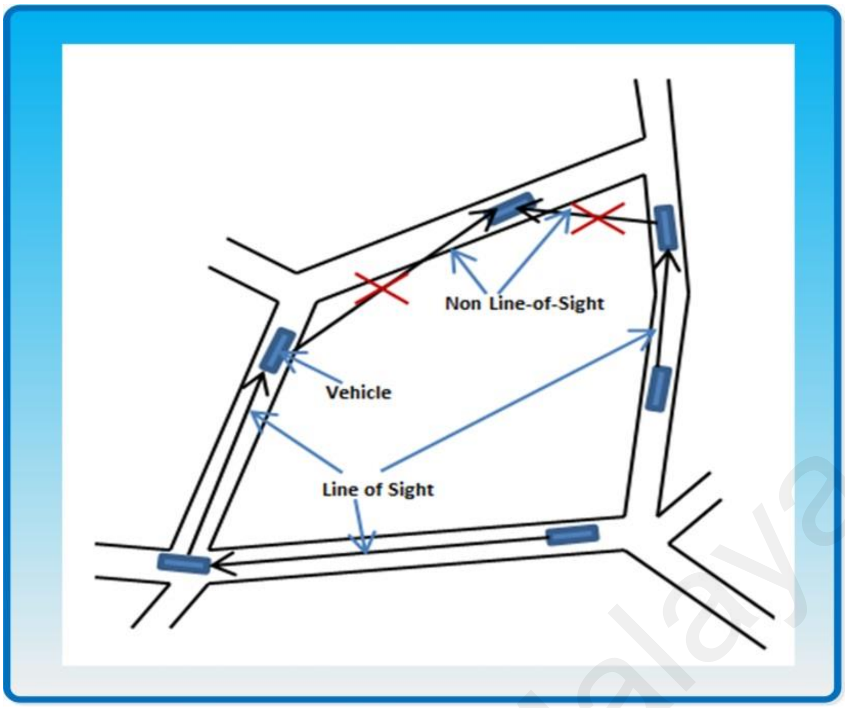

Figure 2.9: Irregular Roads

2.2.5.6 Complex Interchange

Nowadays, road traffic especially in urban areas and motorways utilized complicated and massively intertwined road traffic interchanges. One such complex traffic interchange (Los Angeles Highway Interchange) sometimes known as spaghetti junction is shown in Figure 2.10. These complex interchanges are composed of many different types of modern road infrastructure units such as curved roads, flyovers and underpasses. Together, these road infrastructure units form a complex structure to facilitate signal free and smooth traffic flow. LOS among communicating vehicles travelling on complex interchanges depends upon the structure of the individual infrastructure unit along with the position of the infrastructure unit in composite structure of complex interchange. However, radio propagation in complex interchanges is yet to be studied in designated frequency band for VANET.

Figure 2.10: Complex Interchange

2.2.6 Issues related to VANET simulation

VANETs simulators need to incorporate vehicular movement which is restricted by road infrastructure. In order to accurately simulate individual vehicle's behavior in VANETs, either the real world maps are used or a topology is created inside the simulator itself. The former approach is considered realistic and U.S Census Bureau's Topologically Integrated Geographic Encoding and Referencing (TIGER) maps (C.-C. Chen, Knoblock, Shahabi, Chiang, & Thakkar, 2004) are usually used for this purpose. Abrupt changes such as braking and acceleration of individual vehicles according to human driving behavior along with intersection / junction management is another demand of realistic VANETs simulator. Obstacles that obstruct the radio signals and vehicular movement such as buildings, large vehicles, stop signs and traffic signals need to be considered along with the communicating vehicle's characteristics such as vehicle speed and dimensions. All features related to urban traffic, their relationship with time and mechanism such as lane change management makes the simulation task complex and cumbersome to handle (Stanica, Chaput, & Beylot, 2011).

Generation of vehicular traces according to a selected mobility model is only one critical aspect of VANETs simulation. A network simulator such as NS-2 (Issariyakul & Hossain, 2011) is required that feeds on the real vehicular traces, simulates and yields network metrics such as PDR, delivery latency (DL) and average path length (APL). This approach is simple in nature and involves fewer amounts of computations as it only requires reading from a file that contains real traffic traces. However, it is difficult to get the real vehicular traces.

Another approach that provides data for literally all possible situations is to synthesize mobility traces using a traffic simulator. This approach requires interaction between a traffic simulator and a network simulator that involves implementing another module that serves as an interface between traffic and network simulators. Complexities involved in the development of such an interface lead to the concept of dedicated VANET simulator.

One of the methodologies for the VANET simulation is the use of hybrid simulation framework that uses a bidirectional coupling of network simulation and road traffic simulator that helps in the evaluation of inter-vehicle communication (IVC) protocols. The mobility model affects the result of VANET simulations; therefore, a representative model is needed for generating eloquent evaluation outcomes. An example of hybrid simulation framework is Vehicles in Network Simulation (Veins) (Sommer, German, & Dressler, 2011), that comprises of the network simulator OMNeT++ (Malekzadeh, Ghani, Subramaniam, & Desa, 2011) and the road traffic simulator SUMO (Behrisch, et al., 2011) .

2.2.7 Mobility Models in VANETs Simulation

The movement of mobile nodes is represented in simulation environment by using mobility models. A mobility model must be capable of representing velocity, acceleration/deceleration and location of mobile nodes which is continuously changing over time along with the consideration of modern road topology. When simulating a technique, a protocol or a new concept in VANETs, a mobility model has to be developed or at least selected from the existing models based upon its suitability to the actual and simulation environment (Madi & Al-Qamzi, 2013).

A mobility model can either be characterized as macroscopic or microscopic (Harri, Filali, & Bonnet, 2009). A macroscopic mobility model views the factors of interest as gross quantities such as vehicular density and average velocity in accordance with the fluid dynamics. Macroscopic mobility models are relatively less complex and easy to implement in simulation environment but they lack important detail such as individual driver behavior. Hence macroscopic models are not suitable for highly realistic modelling for sensitive VANETs environment where the effect of individual parameters for every node is significant and effect heavily on the simulation results. Urban VANETs environment (Zhu et al., 2011) demands every node and their mutual interactions to be considered individually for realistic modelling. In microscopic mobility model (Harri, et al., 2009) each node is treated as an individual and unique entity hence providing a detail view of the environment. However, adding realistic detail in microscopic model comes at a cost of increased computational complexity. A combination of both macroscopic and microscopic views of the environment is implementable and hence it provides a trade-off between realism and computational complexity.

Development of mathematical mobility models is an attempt to realistically model the mobility in VANETs. These models can further be classified into five groups as characterized in (Fiore, Harri, Filali, & Bonnet, 2007), namely (a) stochastic models, (b) traffic stream models, (c) car following models, (d) queue models and (e) behavioral models. In stochastic model, every aspect is viewed as a random value whereas traffic stream models make use of hydrodynamics. In car following models, the behavior of each node is dependent upon the behavior of the nodes ahead in a microscopic manner. Mobility models based on queues utilize first in first out (FIFO) structure treating every node as a client. One such model is defined in (McDonald & Znati, 1999). Behavioral models (Camp, Boleng, & Davies, 2002) required a deep study of human psychology and driving behavior. There are four steps in establishing a mathematical model; (a) to understand a particular movement pattern, (b) to develop a mathematical model, (c) to validate and (d) to reproduce it. However, the nature of mathematical models and the development steps make these models complex to develop, handle and simulate.

Due to the complexity of mathematical models, approximation models are developed. Approximation models do not exactly imitate the mobility pattern hence they are less complex as compared to mathematical models. Survey based models, trace based models and traffic simulator based models are the examples of approximation mobility models (Harri, et al., 2009). Random and deterministic behavior at macroscopic level is represented with the help of survey based models using statistical approach; however, the use of statistical techniques only provide coarse grained mobility which is not sufficient for detailed and realistic representation.

General mobility patterns are extracted from mobility traces in trace based models making the approach less complex. However extrapolation of the mobility patterns that cannot be directly observed from the traces is a challenging task. Fine grained traffic simulator based mobility models at microscopic level are implemented in realistic traffic simulators. Microscopic traffic simulators are developed by refining the mathematical models, extensively validating the models using real world traffic traces and incorporating the user behavior.

2.4 Basic Radio Propagation Models in VANETs

This subsection describes the basic radio propagation models that are adopted to simulate radio propagation behavior in VANETs. Basic radio propagation models can be classified in two major groups; (a) deterministic radio propagation models and (b) probabilistic radio propagation models from implementation point of view (Van Eenennaam, 2009). Figure 2.11 shows implementation based classification of basic radio propagation models.

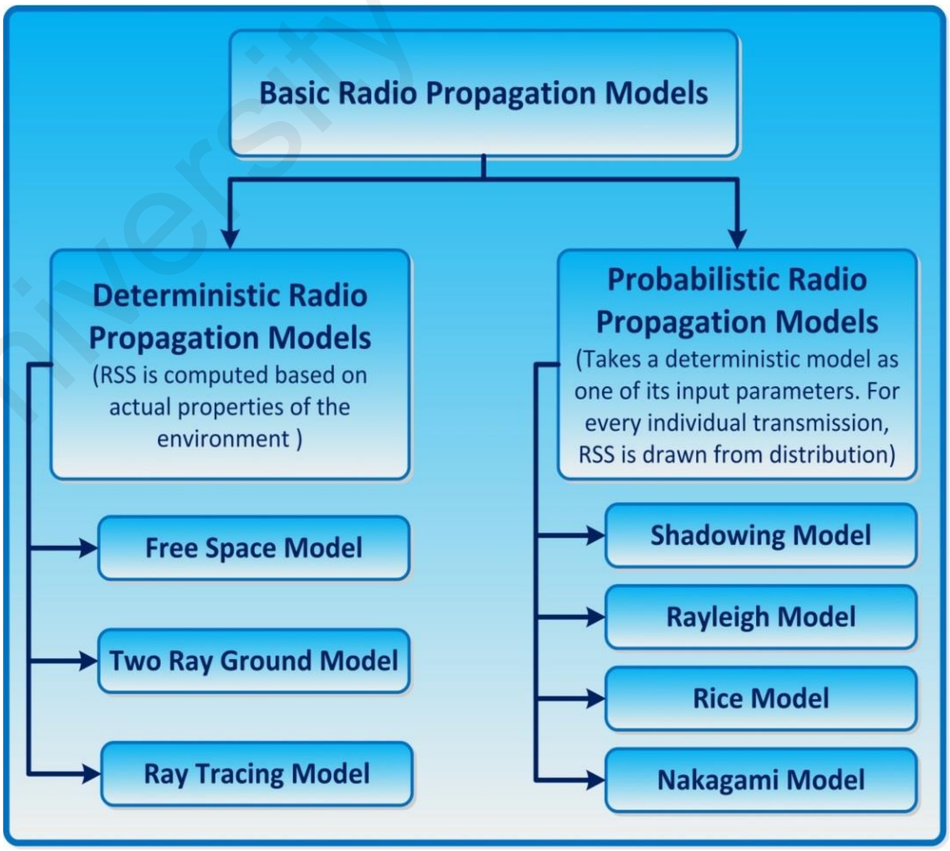

Figure 2.11: Implementation based classification of Basic radio propagation models

2.4.1 Deterministic Radio Propagation Models

A deterministic radio propagation model calculates the path loss and computes RSS based upon real properties of the environment such as speed of the communicating vehicles and inter vehicle distance etc. Some of the deterministic radio propagation models are very simple in nature and computationally feasible as they consider only basic properties of environment, for instance, distance between sender and receiver. However, simple deterministic radio propagation models overlook one or more the important characteristic of the environment resulting in unrealistic prediction of path loss. Free space model and two ray ground model are the examples of simple deterministic radio propagation models.

On the other hand, there are some complex deterministic radio propagation models which are difficult to implement as they considered more advanced properties of the environment; for instance, multipath propagation effects making them computationally complex. Ray tracing models are example of computationally complex deterministic radio propagation model that employs exact location of communicating nodes and individual characteristics of environment; such as conductivity, permittivity and thickness of radio obstacles etc. Therefore, complex deterministic radio propagation models are rarely implemented in VANETs.

2.4.1.1 Free Space Radio Propagation Model

The Free space model (Friis, 1946), (Ishimaru, 1978), (Ripoll, Schulz, & Ntziachristos, 2003) is a large scale propagation model which assumes that only a single LOS path exists between the sender and receiver. In free space propagation an ideal condition is assumed the existence of only LOS path between the sender node and receiver node. It considers the nodes to be floating in the free space. The calculation of RSS is based on sender and receiver distance and the transmitted power. Because of the simplicity and computational feasibility of free space radio propagation model, it is still used in various simulation environments to predict path loss. However, the effect of radio obstacles in vehicular environment along with certain other factors such as multipath propagation is not considered in free space model. The received signal power $P_r(D)$ as calculated by free space model is given in 2.1 ("Understand the path loss prediction formula," 2014)

$$Free\ Space\ Pr(D) = \frac{P_t\, G_S\, G_r\, \lambda^2}{(4\pi)^2 D^2 L^2} \tag{2.1}$$

$$\text{Where } G = \frac{4\pi A_e}{\lambda^2} \tag{2.2}$$

In equation 2.1, $\boldsymbol{P_t}$ represents power of the transmitted signal, $\boldsymbol{G_s}$ and $\boldsymbol{G_r}$ are antenna gains of sender and receiver nodes, $\boldsymbol{\lambda}$ represents wavelength and $\boldsymbol{L}$ is the system loss. $\boldsymbol{D}$ is the distance between the sender and the receiver. In equation 2.2, $\boldsymbol{A_e}$ is effective aperture related to the physical size of the antenna $\boldsymbol{G_s}$, $\boldsymbol{G_r}$ and $\boldsymbol{L}$ are often set to 1 to represent matched antennas and no system loss. Free Space Path Loss (FSPL) is computed in free space model and is considered to be directly proportional to the square of the distance between sender and receiver nodes. The free space path loss FSPL in decibel (dB) is given by equation 2.3 which represents a simplified version of path loss calculation where $\boldsymbol{f}$ represents the frequency of the signal in MHz and $\boldsymbol{D}$ is the distance in km.

$$PL_{freespace}[dB] = 20\log_{10}(D) + 20\log_{10}(f) + 32.44 - G_t - G_r \tag{2.3}$$

2.4.1.2 Two Ray Ground Radio Propagation Model

Two-Ray Ground Model (Andersen, Rappaport, & Yoshida, 1995), (Fall & Varadhan, 2005), (Mughal, et al., 2011) utilizes direct LOS path and the reflected path from the ground and predicts RSS for large distances, however, it is not suitable for short distances due to the oscillations caused by constructive and destructive interference of the two rays (Van Eenennaam, 2009). Two-ray ground model predicts the RSS based on (a) distance between sender and receiver, (b) transmitted signal power, (c) antenna gains, (d) height of transmitting and receiving antennas, and (e) system loss. It only computes RSS at the receiving end as the collection of direct LOS path and reflected path without the consideration of signal obstruction from radio obstacles. However, the predicted path loss by the model is relatively accurate for longer distances as compared to free space model for the reason that the two ray ground model also considers reflection from the ground in addition to direct LOS path (Rappaport, 1996). The received signal power $P_r(D)$ as calculated by two ray ground radio propagation model is given in equation 2.4 ("Indian institute of Technology Guwahati," 2014).

$$Two\ Ray\ Pr(D) = \frac{P_t\ G_t G_s\ h_s^2\ h_r^2}{D^4 L} \tag{2.4}$$

In equation 2.4, P_t represents power of the transmitted signal, $\boldsymbol{G_s}$ and $\boldsymbol{G_r}$ are antenna gains of sender and receiver nodes, $\boldsymbol{h_s}$ and $\boldsymbol{h_r}$ are the respective heights of sender and receiver antennas and $\boldsymbol{L}$ is the system loss. $\boldsymbol{D}$ is the distance between the sender and the receiver.

2.4.1.3 Ray Tracing Models

The two ray ground model considers direct path between the sender and the receiver along with the reflected path from the ground, therefore, it can be extended to multi-ray schemes simply by adding more rays that result from the reflection from different paths. Multi ray (typically six rays) schemes are more suitable in sub-urban and urban scenarios where there are many obstacles obstructing the radio propagation. A detailed view of the system including position of the nodes, orientation, and electrical properties of individual static radio obstacles in the environment is considered in the ray tracing models. These models are based on the physical factors of radio wave propagation i.e. rules of reflection and diffraction of radio waves. A complex impulse response ***h(t)*** is obtained that constitute *N* time-delayed impulses which are attenuated and phase shifted versions of the original signal (Turin, et al., 1972).

$$h(t) = \sum_{n=1}^{N} A_n \, \delta(t - \tau_n) e^{-j\vartheta_n} \tag{2.5}$$

In equation 2.5, $\boldsymbol{A_n}$ represents amplitude of the signal, $\boldsymbol{\tau_n}$ represents arrival time and $\boldsymbol{\vartheta_n}$ denotes the phase. Snell's law and Maxwell equations are utilized to calculate the values of these variables. The ray tracing models can also consider the detailed characteristics of the objects in the environment such as permittivity and thickness along with the radiation pattern of the antennas. The value of ***h(t)*** has to be re-calculated upon any change in the environment. Consequently, ray tracing models are suitable only for the environments with fix antennas. Due to rapid and continues movement of transmitters and receivers, the ray tracing model become computationally expensive in VNAETs.

2.4.2 Probabilistic Radio Propagation Models

Probabilistic radio propagation models provides more realistic modelling as they are based on (a) one of the simple deterministic models, (b) environmental characteristic and (c) statistical methods to estimate the path loss. There is always a probability that any two vehicles with in a transmission range of each other cannot communicate due to certain environmental conditions or an abrupt change such as presence of a moving obstacle obstructing the LOS. In the same way, two vehicles can communicate beyond the defined transmission range due to certain environmental factors; for instance propagation in a road tunnel. Therefore, probabilistic radio propagation models are well equipped for modelling these types of effects and the RSS is determined for every single transmission from a statistical distribution that results in diverse distribution of effective receptions. Brief descriptions of widely used individual probabilistic radio propagation models are presented in the following sub-sections.

2.4.2.1 Shadowing Model

The received signal power at a distance can be represented by random variable if the multipath propagation effects are considered. The shadowing model introduces a random variable along with the path loss component arguing that RSS at a certain distance from the sender can only be represented by a random variable because of fading effects from multipath propagation. As a result, random variation in the received signal power over certain distance is contemplated by shadowing model. The path loss component predicts the received power over a certain distance between sender and receiver, and secondly, normal distribution is used with variance σ for the distribution of in logarithmic domain (Log Normal Shadowing). The path loss ***PL(D)*** as calculated by shadowing model is represented in equation 2.6 (Rappaport, 1996).

$$PL(D)[dB] = \overline{PL}(D_o) + 10n\log\left(\frac{D}{D_0}\right) + X_\sigma \qquad (2.6)$$

Where $\boldsymbol{\overline{PL}(Do)}$ is the average path loss measured at a close-in reference distance $\boldsymbol{D_0}$ near the transmitter, $\boldsymbol{n}$ is the path loss exponent and $\boldsymbol{X\sigma}$ is a Gaussian random variable with zero mean (in dB) having standard deviation $\boldsymbol{\sigma}$. The received signal power ***Pr(D)*** using a shadowing model can be expressed using equation 2.7.

$$Pr(D)\,[dBm] = P_t[dBm] - PL(D)[dB] \tag{2.7}$$

2.4.2.2 Rayleigh Propagation Model

In no dominant LOS condition among communicating vehicles, the Rayleigh propagation model is utilized. This model is based on the assumption that the signal varies greatly due to constructive and destructive interference resulting from multipath propagation and the signal is modelled using Rayleigh distribution. Rayleigh distribution describes the statistical time varying nature of the received signals. The received signal is considered to be the sum of n waves with different amplitude and phase. The Rayleigh distribution has a probability density function (pdf) as expressed in equation 2.8 (Rappaport, 1996).

$$P(r) = \begin{cases} \frac{r}{\sigma^2}\exp\left[-\frac{r^2}{2\sigma^2}\right] & (0 \le r \le \infty) \\ 0 & (r < 0) \end{cases} \tag{2.8}$$

Where $\boldsymbol{r}$ is the envelope amplitude of the received signal, and $\boldsymbol{2\sigma}^2$ is the power of the multipath signal before envelop detection.

2.4.2.3 Rice Propagation Model

Rice propagation model (Kuntz, Schmidt-Eisenlohr, Graute, Hartenstein, & Zitterbart, 2008) is a probabilistic radio model that incorporate the radio propagation anomaly which usually occurs when one of the signals coming from one path is stronger than the signal received from all other paths. Unlike Rayleigh propagation model, Rice model takes advantage of LOS path. In case of no LOS component in the wireless channel, Rayleigh propagation model can be employed. Thus, Rayleigh fading is a specialized model for Rice fading in no LOS signal condition (Adeane, Rodrigues, & Wassell, 2005). When there is no LOS component in the wireless channel, the Rayleigh Fading model can be employed. The signal is modeled using Rician distribution as expressed in equation 2.9 (Rappaport, 1996).

$$P(r) = \begin{cases} \frac{r}{\sigma^2} e^{-\frac{(r^2+A^2)}{2\sigma^2}} I_0 \left[\frac{Ar}{\sigma^2}\right] & (A \geq 0,\ r \geq 0) \\ 0 & (r < 0) \end{cases} \tag{2.9}$$

In equation 2.9, $\boldsymbol{A}$ denotes the dominant signal amplitude and $\boldsymbol{I_0}$ is the modified zero-order Bessel function of first kind. The Rician distribution is described using a Rician factor $\boldsymbol{K}$ which is the ratio of dominant signal power and variance of multipath. $\boldsymbol{K}$ is defined in terms of dB in equation 2.10.

$$K(dB) = 10\ log \frac{A^2}{2\sigma^2}\ (dB) \tag{2.10}$$

2.4.2.4 Nakagami Model

Nakagami model (Nakagami, 1960) is a probabilistic radio propagation model that incorporates fading effect by modelling a wide class of fading channel conditions using configurable parameters and it follows a gamma distribution as represented in equation 2.11. The model includes a fading parameter; which is determined by taking the inverse of normalized variance of square of the channel amplitude.

$$Nakagami\ \Pr(D; m) \sim Gamma(m, \frac{Pr_{det}\ (D)}{m}) \tag{2.11}$$

Nakagami propagation introduces configuration parameters that can model multiple channel conditions including Rayleigh and Rice model. Rayleigh distribution becomes a special case of Nakagami model and it closely approximates rice distribution depending upon certain values of fading parameter. Nakagami Model is best suited for mobile multipath propagation (Pajala, Isotalo, Lakhzouri, & Lohan, 2006). However, simulation of Nakagami model involves complex mathematical processes (Yip & Ng, 2000).

The summary of basic radio propagation model is presented in Table 2. 1.

Table 2. 1: Summary of Basic Radio Propagation Models

Radio Propagation Model	Main Feature(s)	Calculation of RSS
Free Space Model	• Assumes only LOS path between the sender and the receiver.	The RSS depends upon 1. Transmitted power 2. Distance between sender and receiver 3. Antenna gains 4. System loss
Two-Ray Ground Model	• Considers direct path between the sender and the receiver node along with the reflected path from the ground.	The RSS depends upon 1. Transmitted power 2. Distance between sender and receiver 3. Height of antennas 4. Antenna gains 5. System loss
Shadowing Model	• Introduces a random variable along with the path loss component to predict fading effects resulting from multipath propagation. • Contemplates random variation in the received signal power over a certain distance.	• The path loss component predicts the received power over a certain distance between sender and receiver. • Normal distribution is used with variance σ for the distribution in logarithmic domain.
Rayleigh Model	• Assumes that the signal varies greatly due to constructive and destructive interference resulting from multipath propagation. • Models a situation where there is no dominant LOS condition among communicating vehicles	• The received signal is considered to be the sum of n waves with different amplitudes and phases. • Signal is modelled using Rayleigh distribution.
Rice Model	• Takes advantage of LOS path • Considers single exact path and multiple reflected signals.	• It follows the Rayleigh distribution but also takes advantage of positive effects of LOS path.
Nakagami Model	• Includes fading effect and it models a wide class of fading channel conditions using configurable parameters	The RSS depends upon 1. Amplitude 2. Average fading power 3. Fading parameter • It follows gamma distribution
Multi Ray Models	• Consider detailed view of the system including position of the nodes, orientation, and electrical properties of individual static radio obstacles in the environment. • These models utilize the physical factors of radio wave propagation such as rules of reflection and diffraction of radio waves	A complex impulse response is obtained that constitutes N time-delayed impulses which are attenuated and phase shifted versions of the original signal

2.5 Thematic Taxonomy of Radio Propagation Models for VANETs

The existing radio propagation models for VANETs utilize a range of approaches to model radio propagation and to predict path loss in different situations pertaining to multiple traffic scenarios. There is a need to classify the current radio propagation model in order to develop a better understanding about different methods that are utilized to model the radio propagation in VANETs environment. To provide a guideline for the future research in the area, discussion about the advantages and limitations of existing radio propagation models are also necessary.

Therefore, this subsection presents the proposed thematic taxonomy for the classification for existing radio propagation models. It categorized the existing radio propagation models for VANETs into multiple categories on the basis of the proposed thematic taxonomy. Further, it describes the main features, merits and demerits of existing radio propagation models employed for VANETs based on the following parameters: RSS, PDR, DL, and APL. Seven attributes namely, (a) Implementation Genre, (b) Obstacle Modelling Pattern, (c) Road Infrastructure Support (d) Propagation Scenario (e) Mobility Model, (f) Road Congestion Level, and (e) Result Verification Approach are considered in the taxonomy. Taxonomy of radio propagation models for VANETs is shown in Figure 2.12.

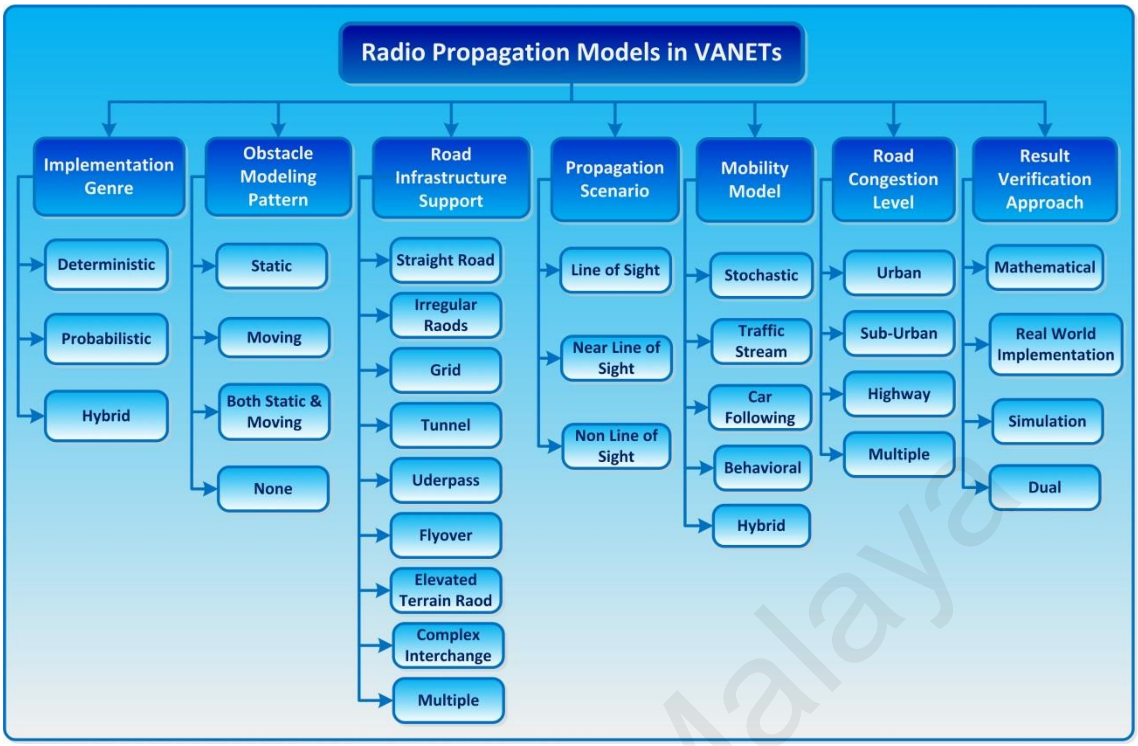

Figure 2.12: Taxonomy of Radio Propagation Models in VANETs

2.5.1 Implementation Genre

The attribute "*Implementation Genre*" indicates the basic approach that is adopted by a particular radio propagation model to implement radio signal propagation. This attribute constitute one of the following approaches; (a) ***Deterministic,*** (b) ***Probabilistic,*** and (c) ***Hybrid***. Radio propagation models are characterized either as a ***deterministic*** model or ***probabilistic*** model. Deterministic radio propagation models calculate the path loss depending upon certain properties of the communication environment while probabilistic radio propagation models apply statistical methods to estimate the path loss. A radio propagation model which implements a combination of multiple propagation schemes for different scenarios or adds factors such as reflection or diffraction in basic radio propagation models is represented by the ***hybrid*** in this taxonomy.

2.5.2 Obstacle Modelling Pattern

The attribute ***Obstacle Modelling Pattern*** represents the way obstacles are handled in a particular radio propagation model. In VANETs, the obstacles that impede radio signals are classified into static and moving obstacles. A radio propagation model in VANETs environment should be designed to handle radio obstacles in order to realistically model radio propagation especially in case of urban scenario. Four types of obstacle handling schemes are presented, (a) ***Static***; wherein only static obstacles such as buildings, advertisement boards and vegetation are considered, (b) ***Moving***; wherein only the moving obstacles such as large buses and trailers are considered, (c) ***Both;*** in which both static and moving obstacle are modelled, (d) ***None;*** wherein no radio obstacle is considered by a particular radio propagation model.

2.5.3 Road Infrastructure Support

As earlier stated, modern day vehicular environment contains road infrastructure units such as irregular roads, grid, flyovers, underpasses, road tunnels and complex interchanges (Qureshi & Noor, 2013). The Road Infrastructure Support represents the type of road infrastructure units that are selected by a particular radio propagation model for the measurement of data, validation of results and modelling of signal attenuation. Most of the existing radio propagation models in VANETs utilize grid structure with junctions, parallel and perpendicular roads in urban settings while a straight road is considered in highway settings. However, the modern road infrastructure units are very much different in nature than the infrastructure units covered by most of the existing radio propagation models (such as junction, straight roads).

In the taxonomy, the attribute ***Road Infrastructure support*** includes (a) ***Straight Road,*** (b) ***Irregular Road,*** (c) ***Grid***, (d) ***Road Tunnel,*** (e) ***Underpass,*** (f) ***Flyover,*** (g) ***Elevated Terrain Road,*** (h) ***Complex Interchange*** and (i) ***Multiple***. These road infrastructure units except ***Elevated Terrain Road*** and ***Multiple*** have already been explained in Section 2.2.5. Roads built for the mountainous terrain are represented in the taxonomy as ***Elevated Terrain Road*** as they follow a curvy and elevated path way. LOS conditions among communicating vehicles in mountainous terrain road are different from other road infrastructure units because the LOS in these roads is not dependent on the road distance among the communicating vehicles. Two vehicles at mountainous terrain road travelling at a certain distance from each other may experience LOS suddenly. These short-lived potential opportunities of LOS conditions have to be considered for vehicular communication while utilizing the mountainous terrain road. The value ***Multiple*** represents a road scenario where more than one road infrastructure units are utilized for the measurement of required data. ***Road Infrastructure Support*** is an important attribute in the taxonomy because it determines the degree of realism of a particular radio propagation model in context of modern traffic environment.

2.5.4 Propagation Scenario

Three possible methods are considered against the attribute ***Propagation Scenario*** in the taxonomy that represents the type of propagation used by a particular radio propagation model namely (a) ***Line of Sight,*** (b) ***Near Line of Sight,*** and (c) ***Non Line of Sight.*** Some radio propagation models assume that the communication is only possible when the transmitting vehicle (Tx) and the receiving vehicle (Tr) are in clear view of each other and there is no radio obstacle impeding the LOS between them. This propagation scenario is represented by the ***Line of sight*** in the taxonomy. ***Near Line of***

Sight is a propagation scenario that represents a situation where a virtual source makes communication possible even if there is no LOS between sender and receiver nodes like in knife edge effect (Luebbers, 1984) wherein an obstruction serves as a secondary source. ***Non Line of Sight*** scenario assumes that communication is possible between Tx and Tr even in the presence of obstacles that partially obstruct radio signals.

2.5.5 Mobility Model

The attribute ***Mobility Model*** in the taxonomy represents the choice of mobility model that is considered in a particular study to measure the results of applying propagation formula in a certain VANET environment. Mobility model is particularly important in VANET simulation because it affects the calculation of metrics such as PDR. Moreover, the mobility model carries significant importance because in VANETs, not only the communication is dependent on the topology and vehicular movement but also some of the vehicles act as radio obstacles for other communicating vehicles. The Mobility Model introduces five different schemes; (a) ***Stochastic,*** (b) ***Traffic Stream,*** (c) ***Car Following,*** (d) ***Behavioral,*** and (e) ***Hybrid.*** The first four types of mobility model are explained in previous section. The ***hybrid*** mobility scheme represents a combination of two or more mobility schemes which are utilized by an individual radio propagation model.

2.5.6 Road Congestion Level

Radio propagation in VANETs is also influenced by the traffic density and speed of the vehicle. The traffic is dense and moves at relatively low speed in urban environment; whereas, the traffic is relatively sparse in highway scenario and moves with comparatively greater speed. The road congestion level attribute represents a general conception about the traffic density and average speed. The road congestion level includes (a) ***Urban***, (b) ***Sub-Urban***, (c) ***Highway***, and (d) ***Multiple***.

2.5.7 Result Verification Approach

The attribute ***Result Verification Approach*** in the taxonomy represents the way results are collected and verified in one of the four possibilities. The result verification approach includes (a) ***Mathematical***, (b) ***Real World Implementation***, (c) ***Simulation***, and (d) ***Dual***. Results are collected and verified by existing radio propagation model using either the simulation or carrying out real world implementation. Some of the radio propagation models simply rely on mathematical modelling. Due to the financial infeasibility of implementation in the real world at a large scale, the results are often prepared by using real hardware at a lower scale (only 2 to 5 nodes) and then simulator is used to extrapolate the results at a higher scalability level (from 100 to 1000 nodes). The results verified by using both the real world implementation and simulation are represented by ***Dual*** in the taxonomy.

2.6 Review on the Existing Radio Propagation Models in VANETs Based Upon Proposed Thematic Taxonomy

This section presents a review on the existing radio propagation models based upon the proposed thematic taxonomy. The presence of buildings, advertisement boards and dense vegetation is the main cause of radio signal obstructions in V2X communication especially in urban environment. Large vehicles can also obstruct radio signals. This section presents a review of the existing radio propagation models by categorizing them into three broad categories; (a) Radio Propagation Models with no Obstacle Handling,

(b) Radio Propagation models with Static Obstacle Handling and (c) Radio Propagation Models with Moving Obstacle Handling according to the proposed thematic taxonomy.

Radio propagation models with static obstacle handling refer to those models that handle the static obstacles such as buildings, sign board and vegetation. The radio propagation models that consider the static obstacles and also include some innovative idea of obstacle handling are covered under innovative radio propagation models sub-category. The radio propagation models that are able to handle moving obstacles such as large buses and are able to depict the impact of moving obstacles are referred here as radio propagation models with moving obstacle handling. Figure 2.13 shows the classification of radio propagation models based on Obstacle Modelling Pattern.

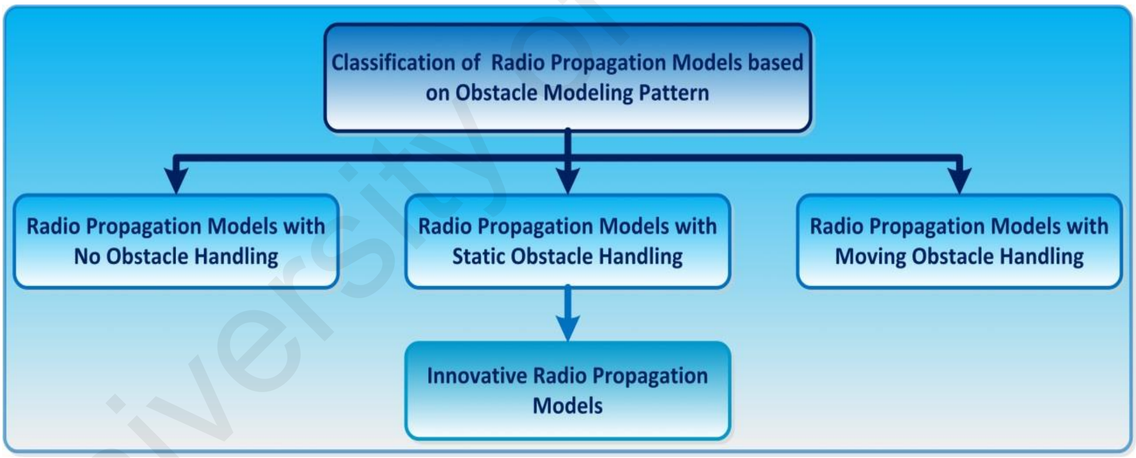

Figure 2.13: Classification of Radio Propagation Models based on Obstacle Modelling Pattern

The basic radio propagation models (explained in section 2.4) fall in the category of those models which do not consider any type of radio obstacle due to the fact that the basic radio propagation models do not explicitly consider the effect of static and moving radio obstacles on radio propagation. The subsequent sub-sections explain the categorization of radio propagation models with static obstacle handling, Innovative radio propagation models (sub-category), and radio propagation models that also handle moving radio obstacles. Table 2.2, Table 2.3, and Table 2.4, show the important features and present the summaries of respective radio propagation models that fall into a specific broad category.

2.6.1 Radio Propagation Models with Static Obstacle Handling

The existing radio propagation models that handle static radio obstacles are summarized in this subsection. Table 2.2 represents a summary of radio propagation models that handle static radio obstacles.

Table 2.2: Summary of the Radio Propagation Models with Moving Obstacle Handling

Model / Study	Main Feature(s)	Strengths	Weaknesses	Frequency Band / Standard
RPMO	• Improvement is made on the two-ray ground model • Proved that obstacle has great impact on radio propagation • Enhanced NS-2 simulator	• UMM showed better results than RWP • Metrics used: Packet Delivery Ratio, End-to-End Delay, Path length, Routing overhead	• Results based upon simulation only • Square buildings • Uniform distance between buildings • Distance attenuation is not considered • Small simulation area	——
DAM	• Signal attenuation vs. PL • NS-2 Simulator • More Realistic DM mobility model	Considers distance attenuation	• Restrictive Scheme • Results based upon simulation only	• 5.9 GHz
BM	• LOS scenario • NS-2 Simulator • Realistic mobility model	• Simplistic approach	• Non-LOS	• 5.9 GHz
BDAM	• Combination of DAM and BM • NS-2 Simulator • More Realistic DM mobility model	• Non-Uniformly distributed traffic density • Better performance compared with the Two-Ray ground model	• Restrictive Scheme • Only 100 nodes used in simulation	• 5.9 GHz
RAV	• Combination of attenuation and visibility models	• Irregular Paths • Angular Difference	• Low performance compared to Two-Ray Ground Models	• IEEE 802.11p
Otto's Study	• Shadowing effect is considered in various scenarios • Results are experimentally measured	• Real-World Study • Consideration of LOS and NLOS scenarios	• The Epidemic Data Dissemination Protocol is used	• IEEE 802.11b
Hosseini's Study	• Contribution in terms of more realistic NLOS scenario	• Consideration of phase distortion and signal scattering	• Pessimistic results when compared to the Two-Ray Ground Model	• 5.9 GHz
Biddlestone's Study	• Separate modeling of LOS and NLOS scenarios	• Consideration of Reflection and Diffraction in NLOS scenario	• Constructive and Destructive Interference is not modeled • Reflection from other vehicle is not considered	• IEEE 802.11p
Cozzetti's Study RUG model	• A new propagation model with the evaluation of NLOS scenario	• LOS and Non-LOS scenario consideration	• Effect of other vehicles on propagation is not modelled	• 5.9 GHz

2.6.1.1 Radio Propagation Model with Obstacles (RPMO)

RPMO proposed by (Marinoni & Kari, 2006) is an improvement of the Two-Ray Ground model that incorporates modelling of static radio obstacles. The model is an attempt to introduce realism in the simulations and it resolute that the presence of static radio obstacles has a great impact on the radio propagation especially in urban environment. A total of *m* obstacles are considered that totally obstruct the signal propagation in the simulation. However, in reality, the obstacles partially allow the radio signals to pass through them causing the variation in signal attenuation. The model considers small area (1200 m^2) and claims that performance results are independent of speed variations. For simulation, NS-2 simulator is employed by applying certain enhancements. RPMO is regarded to be unrealistic for the reason of considering following assumptions; square obstacle shapes, same distance between obstacles, and the obstacles totally obstruct the radio signals between two vehicles on parallel streets only.

RPMO behaves like a Two-Ray model in the absence of obstacles. The performance parameters namely PDR, end to end delay, path length and routing overhead are considered by RPMO; however, the model neglects important parameter, the signal attenuation; in all the measurements. Moreover, this study also introduces a mobility model named Urban Mobility Model (UMM) and compares it with Random Way Point (RWP) (Bettstetter, Resta, & Santi, 2003), (Bettstetter, Hartenstein, & Pérez-Costa, 2004). The study claims that UMM is more realistic than RWP which is considered to be unsuitable for the VANET simulations (Yoon, Liu, & Noble, 2003). Important characteristics of RWP are refined in (Rojas, Branch, & Armitage, 2005). RWP is refined by proposing Weighted Waypoint Mobility model (WWM) that incorporates preference criterion (Hsu, Merchant, Shu, Hsu, & Helmy, 2005). However, RPMO is not tested and compared using WWM.

2.6.1.2 Martinez's Models

In another attempt to propose realistic radio propagation models for VANETs, three models are introduced (Martinez, et al., 2009); (a) Distance Attenuation Model (DAM), (b) Building Model (BM), and (c) Building and Distance Attenuation Model (BDAM) to handle only the static obstacles in urban environment. DAM considers signal attenuation due to inter-vehicular distance. Under specified channel condition, the packet error rate to distance is utilized to estimate the impact of signal attenuation on packet losses. This scheme is although very simple but it is more restrictive in terms of packet loss calculations.

BM only covers the LOS scenario, arguing that in the 5.9 GHz frequency band, (of the 802.11p standard) the signal is highly directional and has less penetration. According to the authors of BM, the communication between vehicles is only possible whenever they are in LOS. However, the two important scenarios (a) Near LOS and (b) non LOS are not considered. Finally, DAM and BM are combined to develop BDAM for establishing a realistic radio propagation model with static obstacles. These models show better accuracy as compared to two-ray ground models in terms of warning notification time and packet delivery ratio.

In the simulation setup, the authors used their own proposed mobility model called Downtown Model (DM) (Martinez, Cano, Calafate, & Manzoni, 2008), in which streets are arranged in Manhattan style grid with a uniform building size, hence making the model restrictively specific. However, a positive aspect of the proposed models is the non-uniformly distributed traffic density consideration and the divisions of vehicles into two groups; (a) vehicles in warning mode that generate warning messages and (b) vehicles in normal mode that simply relay the messages. Additionally, an important parameter, namely, number of blind vehicles is considered.

Attenuation and visibility models are combined in a model referred to as Real Attenuation and Visibility (RAV) (Martinez, et al., 2010) that considers irregular paths by calculating the angular distance between streets. The vehicles are supposed to be capable of communicating whenever the difference is equal or greater than a pre-defined threshold value. An algorithm for determining LOS path is also proposed and simulated using the NS-2 simulator using 802.11p standard. RAV assumes that the RSS is dependent upon inter-vehicular distance and obstacles. Moreover, the probability of packets which are successfully received at any given distance is determined by the introduction of a probability density function in attenuation scheme of RAV. Then the visibility scheme determines the existence of obstacles between two vehicles. BDAM (Martinez, et al., 2009) is enhanced by adapting the real city map containing streets and intersections. The model shows better simulation results using warning notification time and the average of blind vehicles. However, the performance of visibility schemes is lower than two-ray ground model, Nakagami and BDAM.

2.6.1.3 Otto's Study

A real experimental study (Otto, et al., 2009) is conducted to investigate the impact of realistic radio propagation models on VANETs-based systems. In the work, probabilistic shadowing model is utilized to measure the IEEE 802.11b signal propagation in V2V communication for urban, suburban, and open road scenarios. Even the experiments are conducted on static obstacles (buildings) using Java in simulation time/Scalable Wireless Ad Hoc Network Simulator (JIST/SWANS) (Kargl & Schoch, 2007) wireless simulator and street random waypoint (STRAW) (Karnadi, Mo, & Lan, 2007) as mobility simulator. The experimental results showed that the readings are very much similar on the open roads during peak working hours and late night. However, worst performance is achieved for the uniform combined configuration of LOS and NLOS scenarios in urban settings.

2.6.1.4 Hosseini's Study

In another attempt of realistically modeling the propagation behavior in VANETs (Hosseini Tabatabaei, Fleury, Qadri, & Ghanbari, 2011), the authors focus their work on NLOS propagation in urban environments. They argued that existing radio propagation models do not consider the effect of shadowing including (a) reflection, (b) diffraction, (c) absorption, and (d) scattering caused by the obstacles. The authors further argued that the radio propagation models that have shown good accuracy in terms of path loss are often computationally complex. The main contribution of their work is (a) the modification of path loss component in terms of NLOS scenario as presented in another work (Q. Sun, Tan, & Teh, 2005), (b) the consideration of phase distortion, and (c) the consideration of signal scattering from obstacles. The Intelligent Driver Model (IDM) (Treiber, Hennecke, & Helbing, 2000) was incorporated in this work and the results are more pessimistic as simulated by GloMoSim (Jiang & Delgrossi, 2008), (Zeng, Bagrodia, & Gerla, 1998) when compared to two ray ground model in terms of packet loss ratio. However, the study disregards the modelling of moving obstacles.

2.6.1.5 Cozzetti's Study

In another study (Cozzetti, et al., 2012a), a scalable propagation model called Real Urban Grid (RUG) for urban scenario is proposed that introduced three conditions which are (a) LOS, (b) near LOS, and (c) Non LOS. The integration of NS-2 with RUG is also performed in the study. The authors of the study empirically argued that multiple corners could change the results in terms of RSS and PDR significantly or it may completely prevent the reception. However, the focus of this work is not on modelling of vehicles as obstacles.

2.6.1.6 Biddlestone's Study

Vehicular communication into VatSim (Redmill & Ozguner, 1999) using NS-3 (Henderson, Lacage, Riley, Dowell, & Kopena, 2008), (Marinoni & Kari, 2006) is unified in (Biddlestone, Redmill, Miucic, & Ozguner, 2012). The work highlighted urban environmental challenges in vehicular communication and simulation such as multiple propagation paths and oscillations. The simulation consisted of three components; (a) propagation calculation, (b) network stack emulation, and (c) traffic micro-simulation. The environment is divided into two types of square tiles (ground tile and wall tiles) that form a grid for the propagation modelling. Ground tiles represented vehicles and wall tiles represented buildings.

Transmitter tile sends a ray to a receiver tile and if it encounters no wall tile in the way, the scenario is considered to be LOS. In case of LOS, a two ray ground model is employed to predict the path loss. On the other hand, diffraction and reflections from wall tiles are modelled in NLOS situation. However, interference (constructive and destructive) which results from multiple reflections and diffractions in NLOS scenario is not taken into consideration. Moreover, the simulation did not include reflections from other vehicles (moving obstacle).

2.6.2 Innovative Radio Propagation models

The radio propagation models covered in this sub-section employ innovative techniques in terms of obstacle modelling. Mahajan's Model, CORNER (Giordano, et al., 2011), and Sommer's Model are tagged as innovative radio propagation models. Multiple mobility schemes with different levels of realistic detail are utilized and compared using important metrics such as delivery ratio, end-to-end delay, vehicle speed, wait time at intersections, block size and number of nodes in the Mahajan's model. Instead, the concept of reverse geocoding with the introduction of three different scenarios: LOS, NLOS1 and NLOS2 are exploited in CORNER. Sommer's model is a computationally inexpensive radio shadowing model that employs real data from OpenStreetMap and presents resemblance to real-world measurement data and simulation/model results. Table 2.3 shows the summary of Innovative radio propagation models in VANETs.

Table 2.3: Summary of Innovative Radio Propagation Models

Model /Study	Main Feature(s)	Strengths	Weaknesses	Frequency Band /
Mahajan's Model	• Enhancement in Two-ray Ground distance attenuation • Considers and compares multiple mobility schemes using important metrics	• Real urban data • Performance evaluation of sparse and dense VANETs	• Wi-Fi network only • Simulation uses 100 nodes	• IEEE 802.11b
CORNER	• An attenuation formula is used • Three possible situations LOS, NLOS1, NLOS2 • For simulation: Qualnet, VERGILIUS, CORSIM	• Correlation between mobility and propagation	• Does not consider shadowing effect from large vehicles	• IEEE 802.11p
Sommer's Model	• Radio Shadowing in urban environment	• Real-world study	• Short lived transmission opportunities ignored	• IEEE 802.11p

2.6.2.1 Mahjan's Study

An innovative model based on two-ray ground model is proposed in (Mahajan, et al., 2007) by including the obstacle factor and distance attenuation for the 802.11b environment. The impact of various obstruction factors on radio signals was determined by using real urban data. The focus of the study is on three mobility models: (a) Stop Sign Model (SSM), (b) Probabilistic Traffic Sign Model (PTSM), and (c) Traffic Light Model (TLM). SSM is a simple mobility model based on the car-following model and assumes that in an intersection, every vehicle must wait at a stop sign for a specific time period that is configurable. PTSM is a refined version of SSM in which the stop signs are replaced with traffic signals and probabilistic approach is utilized to estimate the behavior of traffic signals. Like SSM, any type of coordination among vehicles at an intersection is not incorporated in PTSM. TLM is a relatively detailed model compared to SSM and PTSM that focuses on environment details like coordinated traffic lights, the acceleration and deceleration of vehicles, and multiple lanes.

However, the three models introduced in Mahajan's study lack microscopic detail related to vehicle mobility. The empirical data in this study consists of two parameters: (a) distance from access point and (b) signal strength. Signal strength variation is measured by placing an 802.11b linksys wireless access point at the corner of a building block and the Wavemon tool (Mughal, et al., 2011) is utilized to measure the signal strength from various locations near the building. This model is an enhanced version of the two-ray ground model as it considers two parameters: (a) obstacle distance and (b) RSS. Besides, the study highlighted that VANET performance depends on routing decisions.

Moreover, the performance of sparse and dense VANETs in terms of ad hoc routing and a wireless backbone is compared and the results exhibited that performance in dense VANETs improves when using a wireless backbone, whereas performance in sparse VANETs improves when using ad hoc routing. The results are obtained by simulating only 100 nodes. Variation in results may be evident when considering a real urban scenario in which the number of nodes at peak hours exceeds the 100 node threshold. Consequently, this simulation setup requires scalability in order to claim the mentioned results. Additionally, this entire study was based on 802.11b, so the results might not specify the same when the same study is performed using 802.11p for a VANET environment.

2.6.2.2 CORNER

An urban propagation model CORNER was proposed in (Giordano, et al., 2011) that implements a propagation attenuation formula. This formula is based on path loss prediction and requires knowledge of the position of nodes relative to the underlying road network. Attenuation scenarios for the considered pair of nodes are classified using the formulae. This study covers three possible situations; (a) LOS, (b) Non Line of Sight with one corner separating the two nodes (NLOS1), and (c) Non-Line of Sight with two corners between the two nodes (NLOS2). Three steps for path loss prediction are covered in this radio propagation model: (a) Reverse geocoding, (b) Propagation situation classification, and (c) Formula application.

Reverse geocoding determines the path the signal must traverse between sender and receiver. Propagation situation classification is for identifying if the nodes are in LOS using geometrical properties. The propagation attenuation formula (Q. Sun, et al., 2005) is applied based on the collected knowledge. Then, the Qualnet (Subramanya & Shwetha, 2011) physical layer statistical model utilized the resulting attenuation to determine channel properties. In the next step, trace analysis was performed for different propagation schemes using connectivity index, average hops, average node degree and average link duration. The VERGILIUS (Giordano, De Sena, Pau, & Gerla, 2010) urban traffic scenario generator was used to generate mobility patterns and the resulting pattern was fed to corridor simulation CORSIM to obtain a mobility trace that lasts for 300 seconds. The VERGILIUS trace analyzer serves to extract relevant metrics from mobility traces.

CORNER also provides a correlation between mobility and propagation. The negative aspects of the model are (a) disregarding the shadowing effect from large vehicles, (b) neglecting small scale fading effects, and (c) utilizing only urban grids like infrastructure. However, Mangel et al. (Mangel, Michl, Klemp, & Hartenstein, 2011) illuminated that there is a lack of understanding in terms of NLOS modelling in the 5.9 GHz band and an agreed-upon NLOS channel model is not available. As a result, the general ability of adequate NLOS reception is questionable. Furthermore, CORNER simply utilizes free-space model to predict path loss in LOS scenario.

2.6.2.3 Sommer's Model

In another model (Sommer, Eckhoff, et al., 2011) which is widely utilized for static obstacle handling in VANETs simulation, the authors designed a model for IEEE 802.11p radio shadowing in a real urban scenario for evaluating safety applications in VANETs to estimates the effect of buildings on vehicular communications. The model utilized real-world data using 802.11p transceivers and real urban data for validation purpose. To simulate signal propagation in real urban environments, an empirical model for static obstacles was developed and the simulation results revealed that the model is efficient in terms of computational complexity. The model introduced certain calibration factors such as signal attenuation due to exterior of a building and the approximation of path loss because of the internal structure of the building. Moreover better results are obtained in terms of realistic modeling of radio propagation although it does not cover short-lived transmission opportunities.

2.6.3 Radio Propagation Models with Moving Obstacle Handling

Literature review (Martinez, et al., 2010), (Otto, et al., 2009), (Cheng, Henty, Stancil, Bai, & Mudalige, 2007), (Sen & Matolak, 2008),(Boban, et al., 2011) has reinforced that large moving vehicles significantly affect V2V communication in urban environments. The LOS between two communicating vehicles is exposed to a high risk of interruption by large vehicles such as buses and trucks. A realistic radio propagation model for highly dynamic VANETS is computationally expensive and moving obstacles make them even more complicated as highlighted in (Boban, et al., 2011). The summary of radio propagation models with moving obstacle handling is shown in Table 2.4.

Table 2. 4: Summary of Radio Propagation Models with Moving Obstacle Handling

Model / Study	Main Feature(s)	Strengths	Weaknesses	Frequency Band / Standard
Cheng's Study	• Analysis of V2V propagation • Introduction of speed-separation diagram for analyzing V2V environment	• Real-world study • Considers fading	• Only presents narrow- band measurement of V2V propagation	• 5.9 GHz
Sen and Matolak's Study	• Statistical Channel Models for Delay Spread, Amplitude Statistics and Correlation for Multiple V2V Environments • Identification of issues related to the development of Statistical Channel Models	• Consideration of multiple scenarios • Real-world study	• Limited V2V environment • Limited traffic density • Measurements are taken at 5.12 GHz	• 5 GHz
Karedal's MIMO model	• Generalization of geometry-based stochastic channel model techniques	• Model explains time varying properties of V2V propagation	• The observations are based on the highway scenario only	• 5.2 GHz
Boban's Study	• Moving vehicles are considered physical, three-dimensional obstacles that affect V2V communication	• Real-world data obtained by stereoscopic aerial photography	• Observations are based on the highway scenario only	• 5.9 GHz
Gozalvez's Study	• Extensive field testing campaign	• Introduction of Reliable Connectivity Range	• V2I communication only	• 5.9 GHz
Akhtar's Study	• The spatial and temporal evolution of VANET topology characteristics was analyzed using channel models by incorporating log-normal shadowing and obstacle-based channel modelling	• Incorporate log-normal shadowing and obstacle-based channel modelling	• Only the highway scenario is considered	• 5.9 GHz

2.6.3.1 Cheng's Study

Cheng et al. (Cheng, et al., 2007) performed narrow-band measurements of a moving V2V radio propagation channel using the 5.9 GHz frequency band. The experiment is conducted using DSRC radios and a slope piecewise linear channel model. Later, a speed separation diagram for analyzing V2V propagation characteristics is also developed.

2.6.3.2 Sen and Matolak's Study

The two-way high and low traffic densities of urban, sub-urban, and highway scenarios are extensively analyzed by Sen and Matolak (Sen & Matolak, 2008). The experimental results showed significantly different V2V channel properties using the 5 GHz band in low and high traffic conditions considering both urban and highway scenarios. The measurements were taken at 5.12 GHz, which is an aeronautical radio navigation band. They proposed several statistical channel models based on these measurements for different parameters such as delay spread, amplitude statistics and correlations for multiple V2V environments. However, the problems with these models are the limited V2V environment and traffic density.

2.6.3.3 Karedal's MIMO Model

In another attempt (Karedal et al., 2009), a wide-band Multiple-Input Multiple-Output (MIMO) model is proposed in which extensive measurements is performed in sub-urban and highway scenarios using the 5.2 GHz frequency band. In this work, a generalization of generic geometry-based stochastic channel model techniques is proposed to distinguish between discrete and diffuse scattering contributions by randomly placing the vehicles, obstacles and distinct signal components such as discrete components from mobile or static objects, LOS, and diffuse scattering. It is argued by the authors that the wide-sense stationary uncorrelated scattering assumption does not work for the V2V channel. Later, Renaudin et al. (Renaudin, Kolmonen, Vainikainen, & Oestges, 2013) validated the previous work by describing a wideband Single-Input Single-Output (SISO) channel model for V2V communication.

2.6.3.4 Boban's Study

To satisfy essential requirements for V2V communication, such as realistic mobility patterns, accurate positioning, controllable complexity, and realistic radio propagation characteristics a model is proposed in (Boban, et al., 2011). The model considered moving vehicles as physical, three-dimensional obstacles that affect V2V communication. The study analyses the overall impact on LOS obstruction, packet reception rate and received signal power by conducting extensive measurements.

The proposed model's performance is evaluated using two real-world datasets on a highway, obtained through stereoscopic aerial photography and the results supported that moving vehicles obstruct radio signals, generate major attenuation and packet loss. However, the model was only tested on a highway scenario; nonetheless, it still requires extensive measurements to determine the impact of obstructing, moving vehicles on vehicular communication in different urban and sub-urban scenarios with low, medium and high node densities for both 2.4 GHz and 5.9 GHz bands.

2.6.3.5 Gozalvez's Study

In (Gozálvez, et al., 2012), substantial field testing campaigns were carried out covering both LOS and NLOS scenarios using IEEE 802.11p equipment. It was argued that vehicular communication in urban environments requires efficient deployment of roadside units (RSUs). They introduced Reliable Connectivity Range (RCR) as a parameter describing distance where communication is reliable in terms of PDR. The optimal antenna height mounted at RSU was taken into account. When LOS with no trees or dense vegetation is considered, increasing antenna height also increases RCR, but the communication range decreases in the presence of dense vegetation. According to the results, high traffic density increases V2I communication link variability but does not reduce RCR. In addition, communication range is negatively affected by large vehicles that serve as obstacles to wave propagation.

2.6.3.6 Akhtar's Study

In a recent attempt (Akhtar, Coleri Ergen, & Ozkasap, 2014), the spatial and temporal evolution of VANET topology characteristics is analyzed using channel models by incorporating log normal shadowing and obstacle based channel modelling proposed in (Boban, et al., 2011). The node degree, neighbor distance distribution, number of clusters and link duration were considered in the study as system metrics. It was argued in the study that tuning the parameters and introducing time correlation for the Gaussian random variable in the log-normal shadowing model provides a good match with computationally expensive obstacle based models. However, only the highway scenario was considered in this study.

2.7 Comparison of Existing Radio Propagation Models in VANETs

This section compares existing radio propagation models in VANETs by using the proposed thematic taxonomy presented in section 2.5. Table 2.5 represents a comparison of radio propagation models based on the information shown in Table 2.2,

Table 2.3, and Table 2.4 using the proposed thematic taxonomy. Commonalities and deviations in existing radio propagation models are discussed on the basis of the proposed thematic taxonomy using the following comparison parameters: (a) Obstacle Modelling Pattern, (b) Nature of Radio Propagation Model, (c) Mobility Model, (d) Road Infrastructure Support (e) Radio Transmission Method (f) Scheme, and (e) Result Verification Approach. These parameters are discussed in Section 2.5.

Most of the radio propagation models which model only static obstacles are either based on free space or two-ray ground models. However, the hybrid approach was employed in (Cozzetti, et al., 2012a), (Hosseini Tabatabaei, et al., 2011), (Otto, et al., 2009), (Biddlestone, Redmill, Miucic, & Ozguner, 2012) by unifying other components with either free space or two-ray ground models in different scenarios. However, the shadowing and diffraction components are considered in some radio propagation models with a static obstacle modelling pattern as well. Although different mobility models are used by different radio propagation models; however, all mobility models utilized by the radio propagation models with a static obstacle modelling pattern are based on the random approach to model node mobility.

Hence, it is inferred that all radio propagation models with a static obstacle modelling pattern make use of the stochastic mobility model except (Hosseini Tabatabaei, et al., 2011). Grid is the only road infrastructure support in all radio propagation models with static obstacle modelling pattern excluding (Martinez, et al., 2010) that supports multiple road infrastructure units. LOS, non-LOS and near-LOS are considered radio transmission methods in different radio propagation models with static obstacle modelling pattern; however, only the urban scheme is covered by these radio propagation models except for (Otto, et al., 2009) that also includes the sub-urban scenario. Although, only (Otto, et al., 2009) with static obstacle modelling pattern is verified by a real-world measurement campaign.

Innovative radio propagation models only consider the static obstacle modelling pattern by employing original techniques in modelling these static obstacles. All innovative radio propagation models are hybrid in nature as they include reflection, diffraction and shadowing components in path loss prediction using either the free space or two-ray ground models. Innovative radio propagation models are based on both LOS and non-LOS radio transmission methods and a real-world study is conducted or real urban data is utilized in innovated radio propagation models to verify the results. However, the critical issue with innovative models is the support of only the grid as a road infrastructure unit and they only utilize urban schemes.

The nature of radio propagation models with moving obstacle modelling pattern is either Nakagami or Shadowing and is based on real-world implementations. Consequently, no mobility model is utilized in these radio propagation models. Multiple road infrastructure units such as straight roads, irregular streets, grids and terrain elevation are covered by radio propagation models with moving obstacle modelling pattern. Radio propagation models with moving obstacle modelling pattern contemplate both urban and highway schemes except for (Boban, et al., 2011) that only focuses on the highway scheme. Radio transmission methods, namely LOS, Non-LOS and Near-LOS are used in models with moving obstacle modelling pattern.

The majority of radio propagation models only cover static obstacles, whereas moving obstacles are modelled by a few. Hence, free space and two-ray ground models are not suitable for modelling moving obstacles. Most models (Cozzetti, et al., 2012a), (Martinez, et al., 2009), (Marinoni & Kari, 2006), (Hosseini Tabatabaei, et al., 2011) that rely on simulation and use the urban scheme only utilize grids as road infrastructure units as shown in Table 2.5.

Table 2. 5: Comparison of Radio Propagation Models based upon the Proposed Thematic Taxonomy

Model / Study	Obstacle Modelling Pattern	Implementation Genre	Mobility Model	Road Infrastructure Support	Propagation Scenario	Road Congestion Level	Result Verification Approach
RPMO	Static	Two-Ray	Stochastic (UMM)	Grid	LOS and Non-LOS	Urban	Simulation
DAM	None	Free Space	Stochastic (DM)	Grid	LOS	Urban	Simulation
BM	Static	Free Space	Stochastic (DM)	Grid	LOS	Urban	Simulation
BDAM	Static	Free Space	Stochastic (DM)	Grid	LOS	Urban	Simulation
RAV	Static	Free Space	Stochastic	Multiple (Grid Irregular Streets)	LOS	Urban	Simulation
Otto's Study	Static	Hybrid (Free Space, Shadowing)	Stochastic	Grid	LOS and Non-LOS	Multiple (Urban, Sub-Urban)	Dual
Hosseini's Study	Static	Hybrid (Free Space, Re-flection and Diffraction)	Behavioural (CSM, IDM-LC)	Grid	LOS and Non-LOS	Urban	Mathematical and Simulation
Biddlestone's Study	Static	Hybrid (Two -Ray, Diffraction)	Stochastic	Grid	LOS and Non-LOS	Urban	Dual
Cozzetti's RUG model	Static	Nakagami	Stochastic	Grid	LOS, Non-LOS and Near-LOS	Urban	Simulation
Mahajan's Study	Static	Hybrid (Free Space,Two -Ray)	Car-Following, Hybrid (SSM, PTSM, TLM)	Grid	LOS and Non-LOS	Urban	Dual
CORNER	Static	Hybrid (Free Space, Re-flection and Diffraction)	Stochastic	Grid	LOS, Non-LOS and Near-LOS	Urban	Dual
Sommer's Model	Static	Hybrid (Free Space, Two-Ray, Shadowing)	None	Grid	LOS and Non-LOS	Sub-Urban	Dual
Cheng's Study	Moving	Nakagami	None	Multiple (Straight Road, Irregular Streets, Grid)	LOS and Non-LOS	Multiple (Urban, Highway)	Real-world Implementation
Sen and Matolak's Study	Both	Nakagami	None	Multiple (Straight Road, Irregular Streets, Grid)	LOS and Non-LOS	Multiple (Urban, Highway)	Dual
Karedal's model	Moving	Shadowing	None	Multiple (Straight Road, Irregular Streets, Grid)	LOS and Non-LOS	Multiple (Urban, Highway)	Dual
Boban's Model	Moving	Shadowing	None	Straight Road	LOS, Non-LOS and Near-LOS	Highway	Dual
Gozelvez's Study	Moving	——	None	Multiple (Straight Road, Irregular Streets, Terrain Elevation)	LOS and Non-LOS	Multiple (Urban, Highway)	Real-world Implementation

2.8 Analysis of Radio Propagation Models in VANETs

This section provides an analysis of radio propagation models using parameters that include: (a) RSS, (b) PDR, (c) DL, and (d) APL. Table 2.6 displays an analysis of existing radio propagation models based on above mentioned metrics.

The information extracted from Table 2.6 shows that RSS is mainly dependent upon the distance between sender and receiver and its time correlation calculated by different radio propagation models. The analysis of all considered radio propagation models in VANETs reveals that RSS has a negative correlation with the distance between the sender and receiver. Hence, an optimal distance can be determined, which is suitable for V2V and V2I communications in different scenarios wherein communication is possible.

As expected, existing research exhibits that PDR is largely dependent on (a) vehicle density, (b) inter vehicular distance, and (c) type of obstacle between sender and receiver. Interestingly, PDR is independent of vehicular speed, at least in urban areas with an upper limit on speed. DL remains unchanged if roadway width increases. Although, vehicular density plays an important role in determining DL, multiple lanes have literally no effect on DL. This is an important finding for the future.

Table 2. 6: Analysis of Radio Propagation Models

Model /Study	RSS	PDR	DL	APL
RPMO (Marinoni & Kari, 2006)	----	↔ VS ↔ SB	↔ VS ↑ SB	↑ VS ↑ SB
DAM, BM, BDAM (Martinez, et al., 2009)	----	↓ NoV ↔ SB	↑ NoV	----
RAV (Martinez, et al., 2010).	----	↑ a BDAM	↓ a BDAM	----
Otto's Study (Otto, et al., 2009)	----	↓ a Op & Sub	↑ CDFMD	----
Hosseini's Study (Hosseini Tabatabaei, et al., 2011)	↓ D	↓ NoV	↓ NoV up to a certain value	----
Biddlestone's Study (Biddlestone, Redmill, Miucic, & Özgüner, 2012)	↓ D	↓ DR	----	----
Cozzetti's RUG model (Cozzetti, Campolo, Scopigno, & Molinaro, 2012b)	----	↓ D	----	----
Mahajan's Study (Mahajan, et al., 2007)	↓ D	↔ ML ↓ NoV	↔ML	----
CORNER (Giordano, et al., 2011)	----	↓ TN	----	----
Sommer's Model (Sommer, Eckhoff, et al., 2011)	↓ D	----	----	----
Cheng's Study(Cheng, et al., 2007)	↓ D	----	----	----
Boben's Model (Boban, et al., 2011)	↓ D	↓ D	----	----

Legend:
----: Not Considered,
↑: Increases with respect to / increase,
↓: Decreases with respect to / decrease,
↔: remains constant with respect to s,
a: As Compared to,
CDFMD: Cumulative Distribution Function of Message Delivered,
D: Distance between communicating nodes,
DR: Data Rate,
ML: Multiple Lanes,
NoV: Number of Vehicles,
Op: Open Area,
T: Time correlation,
SB: Size of Building,
Sub: Suburban Area,
TN: Travelling Nodes ,
VS: Vehicle Speed

2.9 Consideration of Modern Road Infrastructure Unit

Studies are conducted in the VANET literature to determine optimal positioning of the RSUs to optimize vehicular communication. However, there is no previous study that focused on modern complex road infrastructure units such as curve roads, flyovers, irregular roads. Most of the studies (Giordano, et al., 2011), (Mahajan, et al., 2007), (Hosseini Tabatabaei, et al., 2011) deal only with the grid as road infrastructure unit.

In another study (P. Li, Huang, Fang, & Lin, 2007), optimal placement of gateways is studied that connects RSUs to internet. However, this study only considered one aspect that is, minimizing number of hops from RSUs to gateways. Similarly, genetic algorithms are deployed to identify optimal placement of RSUs by minimizing travel time based on traffic information (Lochert, Scheuermann, Wewetzer, Luebke, & Mauve, 2008). A study (J. Lee & Kim, 2010) is also conducted that introduced RSU placement scheme based on the grid infrastructure where each junction is considered as a potential optimal position for the placement of RSU. However, the optimal position of RSU is selected on the basis of traffic density for individual RSU. In (Aslam & Zou, 2011), the authors unified vehicle speed and vehicle density for the placement of RSUs along the highway.

2.10 Challenges and Open Research Issues

This section presents the challenges and open research issues in the development of a realistic radio propagation model for VANETs. Most prior studies (Martinez, et al., 2009), (Marinoni & Kari, 2006), (Sommer, Eckhoff, et al., 2011), (Hosseini Tabatabaei, et al., 2011), (Martinez, et al., 2010), (Biddlestone, Redmill, Miucic, & Ozguner, 2012), (Giordano, et al., 2011) are based on Manhattan style architecture, which is commonly known as a grid environment with parallel and perpendicular streets, junctions, similar building architecture and uniform distance between two adjacent buildings. This approach tends to abstract away from the real urban architecture of modern cities. A number of existing radio propagation models also consider irregular pathways and non-LOS scenarios; however, a realistic approach necessitates the actual study of modern urban traffic scenarios. To the best of our knowledge, no prior study has been conducted that focuses on modern day, real urban traffic environments.

A possible scenario covered by most radio propagation models with minor variations is shown in Figure 2.14. Figure 2.15 illustrates a real urban scenario that is yet to be examined in terms of radio propagation models. It is noted that the real urban scenario is very different than the scenario considered by most existing models. The real urban scenario consists of complex traffic infrastructure, heavy traffic flow during peak hours and irregular building styles. Therefore, in-depth coverage of shadowing and fading effects in radio propagation model is necessary.in order to accurately predict path loss and effective coverage area or communication wherein the communication is possible.

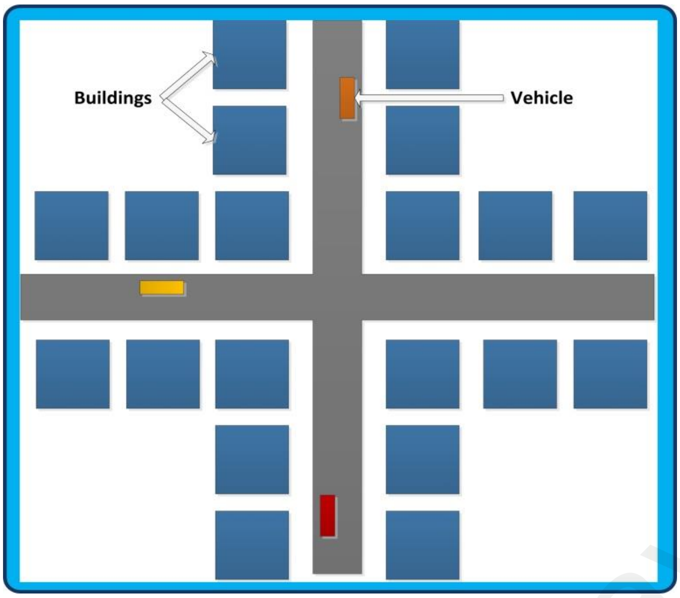

Figure 2.14: Urban Grid Architecture

A major hurdle in the development of realistic radio propagation models for urban environments is the acquisition of real urban data. Most studies are based on assumptions relating to traffic densities at different time periods throughout the day and night. As it is clear from the literature review that moving vehicles behave like obstacles and impact radio propagation, a realistic urban radio propagation model requires real urban data in order to accurately model radio propagation. Depending on the traffic density, multiple conditions can be formulated and the model can change its behavior accordingly.

Another consideration in the development of realistic radio propagation models in VANET environments entails simulation-related issues on account of the financial aspect of testing the models using hardware. Realistic modelling of urban environments requires microscopic models in which entities and their interactions must be modelled with realistic detail (Stanica, et al., 2011). Two simulators with different capabilities are needed for VANET simulation: (a) a traffic simulator in which real urban data is fed and it makes mobility/traffic traces, and (b) a network simulator that receives traffic traces from the traffic simulator and then displays the required results. Consequently, there is a need for a simulator that covers the two above-mentioned aspects dynamically (for all urban scenarios) and maintains a tradeoff among realism, accuracy and computational complexity. It is challenging because microscopic models are inherently complex.

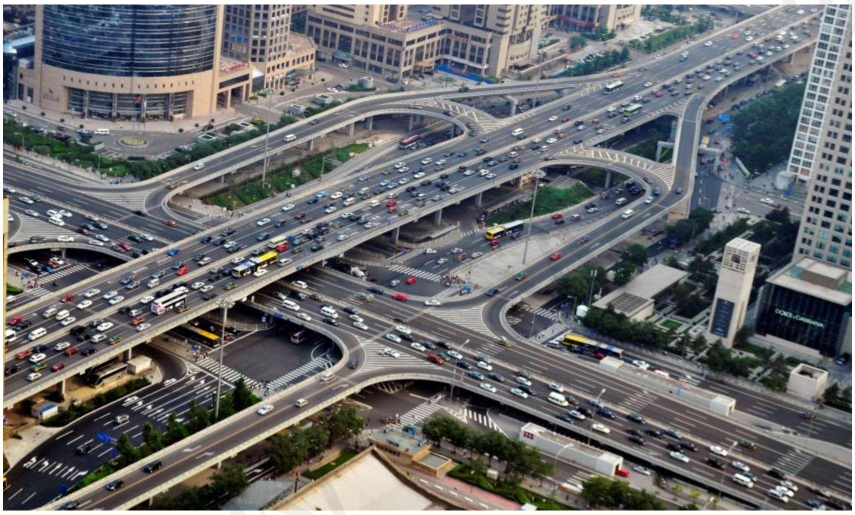

Figure 2.15: Real Urban Scenario (Campolo, et al., 2011)

2.11 Recommendations

Obstacle modelling is the most important issue relating to the development of realistic radio propagation models. A radio propagation model is still required that is capable of accurately modelling both LOS and non-LOS conditions in a real urban environment and accurately emphasize on modern day traffic environments including both static and moving obstacles.

V2I and I2V communication can play an important role when modelling obstacles in real urban scenarios, as suggested by (Gozálvez, et al., 2012). An analysis of existing radio propagation models recommends that a study can be conducted to identify the average optimal distance (AOD) between two RSUs at which the RSS is suitable for V2I communication as well as to identify the optimal position of infrastructure units along roadsides in different real-world scenarios. Keeping in view AOD and its formulation with existing models, a radio propagation model can be designed for modelling both static and moving obstacles. This approach can potentially make a radio propagation model (a) accurate, (b) simplistic, and (c) computationally less complex, because the physical area under consideration for radio propagation will be reduced.

When irregular roadways are considered, one way to effectively model such scenario is to utilize angular difference among multiple straight segments in order to determine the LOS between sending and transmitting vehicles. Moreover, there is a need to model (a) underpasses, (b) flyovers, (c) tunnels (d) curvatures, (e) complex interchanges, and (f) dead-end roads found in modern urban traffic environments. A virtual map placed/created on top of a real urban map can be used to virtually join each dead-end road with the nearest roadway, making the model more realistic. The AOD can then be calculated according to the virtual map.

However, comprehensive understanding of moving obstacles and their correlation with time is required. The task of introducing a more realistic radio propagation model also demands in-depth coverage of (a) every type and shape of static obstacles, (b) the impact of each type of obstacle on radio propagation, (c) the driver behavior (due to the structured mobility) (Angkititrakul, Miyajima, & Takeda, 2012), (d) shadowing effect and (e) impact of modern road infrastructure units on signal propagation. Further, a dynamic, lightweight simulator is required for VANETs that can perform accurate and computationally less complex simulations.

2.12 Conclusion

This chapter presents a discussion of the significance of realistic radio propagation models in VANETs. The factors affecting the design, development and evaluation were also explained. A review of existing radio propagation models employed for VANETs was conducted by comparing and categorizing them according to the proposed taxonomy. Critical issues and limitations were identified, which include the inappropriate selection of mobility models, lack of real urban data, and the scalability of acquired results in conformance with real urban traffic scenarios, simulation-related problems, unrealistic modelling of radio propagation obstacles and ignoring the impact of modern road infrastructure units on radio propagation. The most important issue stressed was in fact the modelling real urban scenarios that include modern road infrastructures such as curved road, underpasses, flyovers, road tunnels and complex interchanges. This led to the identification of challenges involved in the development of a more realistic radio propagation model that involves modelling all types of radio obstacles.

The chapter emphasized that a more realistic radio propagation model is required to meet the challenges of a futuristic ITS covering all types of radio propagation obstacles in VANETs. Based on the review and critical analysis of current radio propagation models, some recommendations were made that can serve as a starting point towards designing, developing and testing an innovative radio propagation model that is simple, accurate, less computationally complex and at the same time realistic.

CHAPTER 3: PROBLEM ANALYSIS

3.1 Introduction

The literature review presented in the previous chapter highlighted several open issues in the design and development of a computationally inexpensive radio propagation model in VANETs which can meet the challenges of a futuristic ITS by predicting the path loss with acceptable accuracy especially in urban scenario that comprises of modern road infrastructure units. However, investigation of all the identified issues is beyond the scope of this work. Therefore, to limit the scope of our research work, we selected three major issues for the investigation; (a) the effect of static radio obstacle on radio propagation, (b) the influence of moving radio obstacles on the signal attenuation and (c) the impact of modern road infrastructure units on RSS and path loss in vehicular environment.

Hence, this chapter investigates the issues in the design of a realistic radio propagation model which is suitable for multiple real world traffic scenarios. The chapter is organized into five sections. Section 3.2 investigates the effects of static radio obstacles on typical radio transmission in VANETs. Section 3.3 analyses the impact of moving radio obstacles on the RSS in VANET environment. Section 3.4 describes the impact of modern road infrastructure unit on vehicular communication and finally Section 3.5 summarizes the chapter with conclusive remarks.

3.2 Investigating the Impact of Static Radio Obstacles

In the absence of obstacles, radio signals travel in a straight line from sender to receiver. However, these signals have a tendency to reflect/diffract in the presence of radio obstacles. Some obstacles can absorb the radio signals as well. As a result, a radio signal may reach the destination out of phase causing the degradation of the received signal strength. The degradation of RSS up to a certain extent has a negative effect on PDR because the data carried by the radio wave is not delivered properly.

The impact of static radio obstacles such as buildings is very prominent when two communicating vehicles are travelling on the parallel or perpendicular roads separated by irregular buildings of different shape and sizes. The channel conditions for the transmission between the two communicating vehicles might change abruptly; alternating between LOS transmissions and strong shadowing (NLOS) resulting from the presence of buildings. Figure 3. 1 shows the deterioration in RSS as the transmission from a vehicle is blocked by multiple buildings. The RSS depends upon the position of the communicating vehicles and dimensions of the static obstacles. In Figure 3. 1, a red arrow shows that the signal is completely blocked by the presence of multiple buildings, while yellow and light green arrows show a partial obstruction of radio signals resulting from one or more buildings. Subsequently, the green arrows show a near-perfect lossless transmission. For the investigation of the impact of building on vehicular communication, we conducted a real world experiment whose details are shown in subsequent sub-sections.

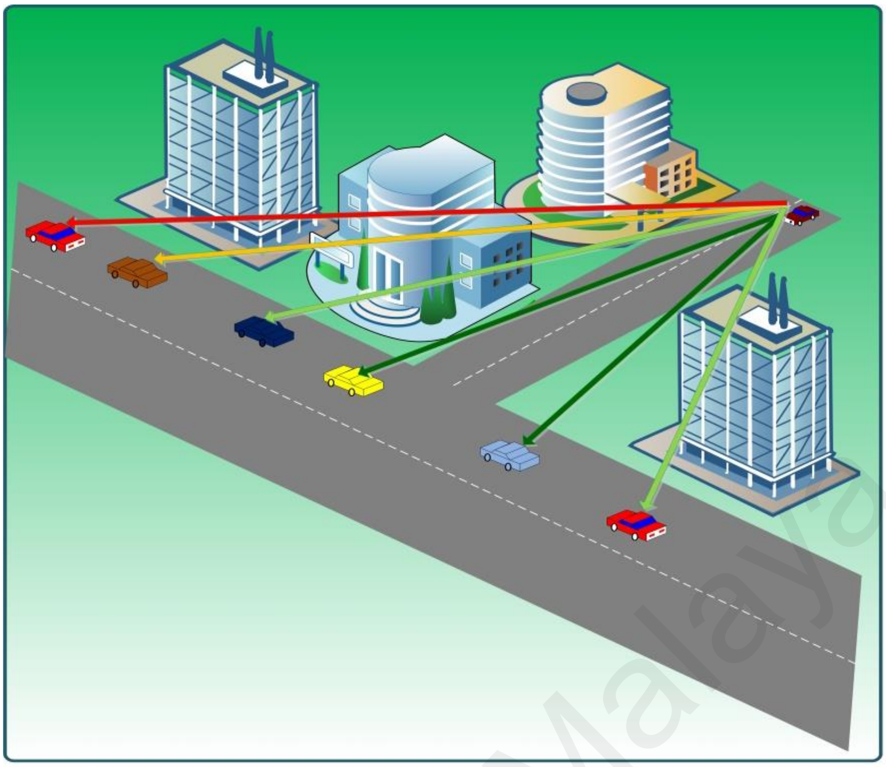

Figure 3. 1: Decrease in RSS due to presence of buildings.

3.2.1 Measurement (Impact of buildings on radio signals)

We conducted a field experiment to measure the impact of static obstacles on the radio transmission and to collect the data from continues transmission at 5 GHz using Wifi 802.11 n transceivers. The location for the experiment has the latitude: 33.56322, and the longitude: 73.15074. The selected building was square in shape having the following dimensions; length ~65 meters and width: ~ 20 meters. The exact location of the field experiment as obtained by Google Earth (Patterson, 2007) is shown in Figure 3.2. The sending vehicle (Tx, height: 1.47 m) is parked at the position shown by the green dot in the Figure 3.2 and another vehicle (Tr, similar height) is driven on the path shown by red dots in a cyclic manner so that the signal from Tx are obstructed by a five-story building (height: ~16.5 m).

Figure 3.2: Physical site for measuring the impact of static obstacles.

We have taken readings multiple times while driving around the building shown in Figure 3.2. The deterioration in RSS is observed when the signals from the source vehicle are obstructed by the building walls. The abrupt decrease in RSS is observed as soon as the receiving vehicle makes the first turn around the building and it keeps on decreasing when the receiver is travelling at the backside of the building. Figure 3.3 shows the RSS values monitored as Tr is driven around the building. The x-axis in Figure 3.3 shows the time scale of gathered RSS value while Tr completes a cycle around the selected building. Degradation in RSS is observed as the RSS the NLOS condition aroused due to the presence of building between Tx and Tr. This is clear evidence that the signals in 5 GHz frequency band are obstructed by the static obstacles that hinder the transmission among the communicating vehicles.

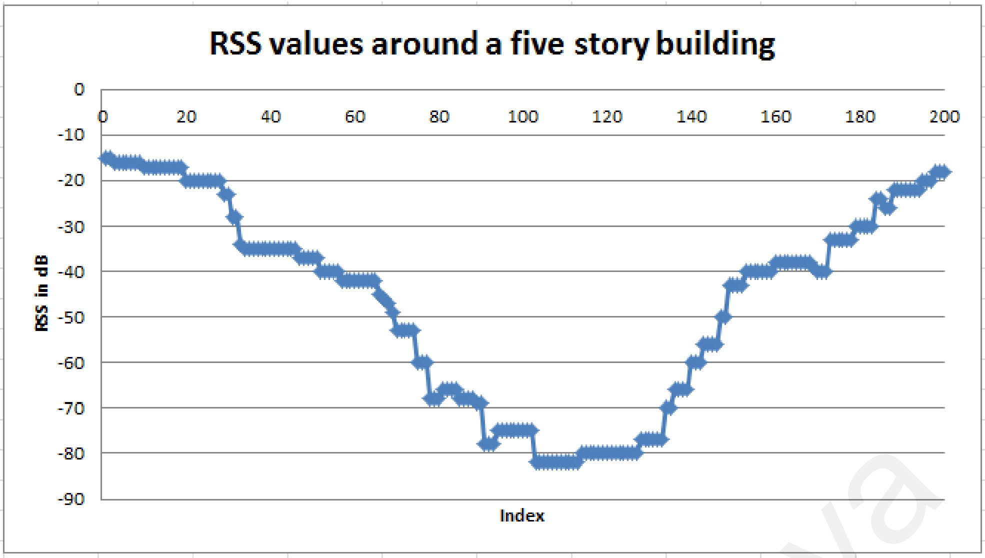

Figure 3.3: RSS values around a five story building.

3.2.2 Validation

The rectangular building shape is selected for the sake of simplicity of this preliminary experiment. The loss effect due to the static radio obstacles during the transmission depends upon the effective length of the static obstacles that block the line-of-sight (*d*) and the number of times the border of the obstacle is intersected by the line-of-sight (*n*) as shown in equation 3.1.

$$L_{Obs} = f\ (n, d) \tag{3.1}$$

This phenomenon is also described in (Sommer, Eckhoff, et al., 2011), where an obstacle model is presented by utilizing the basic radio propagation models (such as two ray ground and log normal shadowing models) and incorporating the impacts of static radio obstacles. The total received power is calculated by summing the transmit power with the antenna gains and subtracting all the loss effects. Therefore, it is observed that the static obstacles impede the radio signals of communicating vehicles and these obstacles are the cause of deterioration in RSS. Similar results as monitored during the data gathering campaign around the five story building can be obtained by further formulating equation 3.1.

3.3 Investigating the Impact of Moving Radio Obstacles

The moving radio obstacles such as large buses, delivery trucks and trailers may also affect the vehicular communication. One of the methods to observe the influence of moving radio obstacles on radio communication is to calculate the Fresnel's zones. Any obstacle that lies within the Fresnel's ellipsoid between sending and receiving vehicles has a potential to obstruct radio signals. Therefore, in case of unobstructed communication, the Fresnel's ellipsoid needs to be cleared. If 60 % of the first Fresnel's zone is free from obstacles then LOS between sending and receiving vehicles is considered unobstructed (Boban, et al., 2011) otherwise an NLOS condition between the communicating vehicles is considered. A typical condition which arises due to a large moving vehicle (obstacle) between two vehicles of relatively smaller size is illustrated in Figure 3. 4 where ***D*** denotes the distance between sender and receiver nodes, ***d1*** is the distance between sender and obstacle and ***d2*** represents the distance between obstacle and receiver.

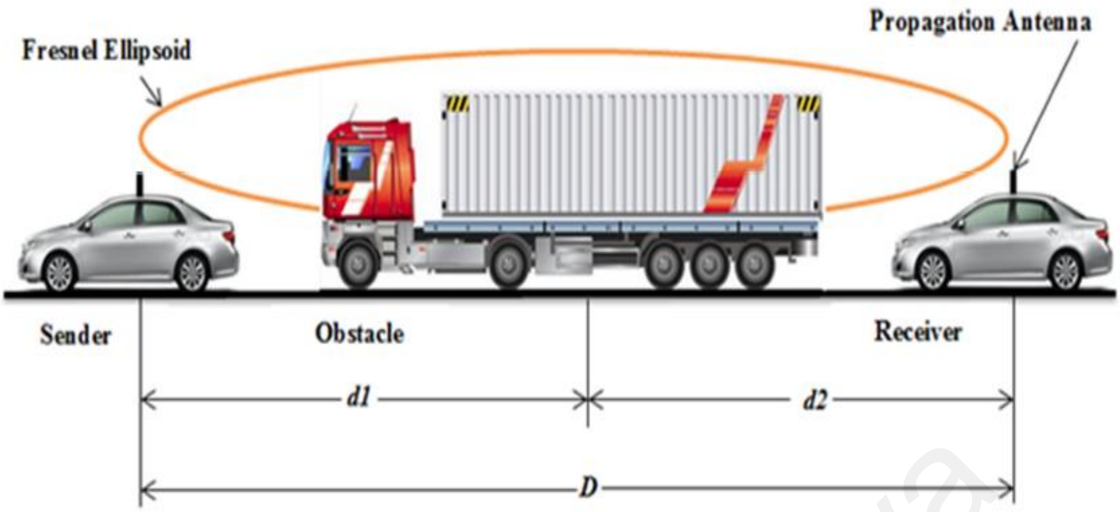

Figure 3. 4: Depicting the Impact of Large moving Obstacle using Fresnel's Ellipsoid

To understand the impact of moving radio obstacles on RSS, we simulated hypothetical scenarios. Keeping in view the recommendation from the review of existing literature on the impact of moving radio obstacles on vehicular communication, we selected the following important considerations for the simulation.

- Selection of Mobility model
- Confirmation of the presence of moving obstacles
- Calculation of the impact of moving obstacles on path loss
- Calculation of the total path loss

The detail of the simulation setup and simulation scenarios is explained in section 3.3.1. The selected mobility model for the simulation is described in section 3.3.2. Notes on checking the presence moving radio obstacles are provided in section 3.3.3 and the impact of moving radio obstacles on path loss is explained in section 3.3.4. The method of calculation of total path loss including the impact from large moving vehicles is described in section 3.3.5. A summary of the whole process for the prediction of path loss is presented in section 3.3.6 and the initial results in terms of path loss and PDR as obtained from the simulations are presented in section 3.3.7.

3.3.1 Simulation Setup

We utilize SUMO (Kenney, 2011) version 0.10.0 to generate traffic traces for various real and hypothetical traffic scenarios. The output of SUMO is given to TraNSLite (Piorkowski et al., 2008) to be converted into mobility traces which are recognized by NS-2. A separate, custom built and interactive Java program scans the output of TraNSLite and applies the formulation to calculate path loss (presented in subsequent section).

The interactive java program also computes the important metrics such as RSS and PDR. A data cube is used in the interactive Java program to store meaningful information such as position of each individual node (x,y and z coordinates) at a particular time stamp. IEEE 802.11p standard is used with 5.9 GHz frequency band in the simulation. Multiple traffic scenarios are considered that spans from a simple junction to complex real world scenarios. The considered scenarios are classified into three categories as follows.

- Simple scenario
- Urban scenario
- Highway scenario.

Different road topologies, varying traffic densities, dissimilar number of communicating vehicles, number of moving vehicles, and different simulation time is considered in each scenario. Simple scenario is a hypothetical scenario that represents the basic situation in which a total of 15 vehicles and only 2 communicating vehicles are considered. An increasing number (1-5) of large moving vehicles is used to determine the impact of large moving vehicles on path loss between vehicles. Urban scenarios and highway scenarios utilize a portion of real map acquired by SUMO (Kenney, 2011) from OpenStreetMaps (Hall, Barclay, & Hewitt, 1996). Urban scenarios consist of junctions, irregular and straight roads while highway scenarios only consider straight roads. Further, urban and highway scenarios differ from each other in terms of traffic density and individual speeds of moving vehicles. Table 3. 1 shows the detail of considered traffic scenarios.

Table 3. 1: Traffic Scenarios

Label	Total Number of Nodes	Number of Communicating Nodes	Number of Moving Obstacles	Simulation Time	Area	Shape
Simple Scenario	*15*	*2*	*5*	*100 s*	*2000 m2*	*Grid/ Junction*
Urban Scenario 1	*100*	*70*	*20*	*500 s*	*4000 m2*	*Irregular*
Urban Scenario 2	*500*	*350*	*75*	*1000 s*	*4000 m2*	*Irregular*
Highway Scenario 1	*100*	*75*	*10*	*1500 s*	*5000 m2*	*Straight Road*
Highway Scenario 2	*500*	*350*	*50*	*2000 s*	*5000 m2*	*Straight Road*

For the initial analysis, we considered the dimensions of two passenger cars of the different make and model that serve as Tx and Rx during the simulations. The dimensions of a commercial passenger vehicle are considered that served as moving radio obstacle. Table 3. 2 shows the dimensions of considered vehicles for initial analysis.

Table 3. 2: Dimensions of Considered Vehicles for Initial Analysis

Vehicle	Length (m)	Width (m)	Height (m)
Toyota Corolla 2013 (Passenger Car)	*4.54*	*1.76*	*1.48*
Honda City 2013 (Passenger Car)	*4.39*	*1.69*	*1.47*
Hino RK1SLL (Commercial Passenger Vehicle)	*11.27*	*2.43*	*3*

3.3.2 Mobility Model

The results obtained from modelling and simulation of radio signal propagation relies on the choice of mobility model. Therefore, an appropriate mobility model is essential in order to model, simulate and test a new propagation scheme. However, there is always a trade-off between the computational complexity and the degree of realism of a mobility model. Therefore, for the initial analysis, we focused on a computationally inexpensive, simple yet realistic mobility model.

The selected mobility model is based on a microscopic view of the environment in which every vehicle follows its own starting and ending point with a target time to reach the destination. Additionally predefined dimensions such as length, width and maximum height of every vehicle participating in the environment are stored to make it realistic. The dimensions of widely used vehicles are chosen for this purpose. The propagation antenna is supposed to be mounted on the highest point of a vehicle. A vehicle maintains its speed according to the relative distance to the destination. In doing so, if a vehicle comes across another vehicle on the same lane with greater speed, it changes its lane to overtake the vehicle which is having lesser speed.

We regard the urban scenario to be composed of roads having multiple lanes, in order to facilitate measurements of all possible scenarios of moving vehicles as obstacles. The usual traffic signals are considered at every junction with adjustable timings. During peak hours the vehicular density increases in urban vehicular environment. Therefore, varying vehicular density is used during different timings of the day and night to make the traffic flow more realistic. In addition to urban scenario, highway scenario is modelled using a three lane standard highway with relatively less traffic density as compared to the urban scenario.

3.3.3 Detecting the Presence of Moving Obstacles

A snapshot of the environment is taken after a pre-defined interval of time to check the presence of moving obstacles. In the first step, only the length and width of vehicles is considered to determine whether any other vehicle is obstructing the direct LOS between the sender and receiver. Only the vehicles traveling in different lanes are checked to find the presence of obstructing vehicle. Figure 3.5 represents a scenario in which LOS between communicating vehicles is disturbed by an obstructing vehicle.

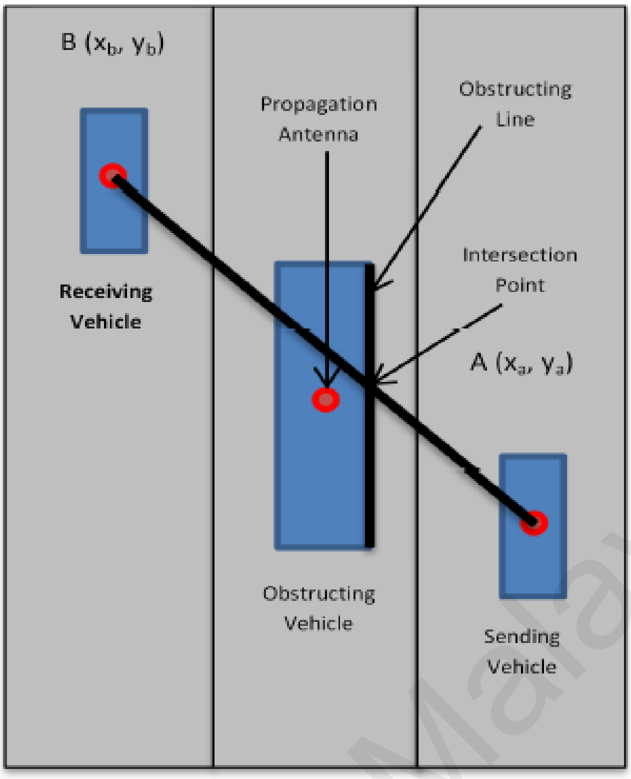

Figure 3.5: Detecting the presence of moving Obstacles in Multi Lane Straight Road

In the second step, a simple line intersection algorithm is applied to determine whether a large vehicle is obstructing the LOS of the communicating vehicles. Vehicles traveling in the same lane do not require a line intersection algorithm because they are in line with any obstructing vehicle. Consider a sender ***i*** and a receiver ***j;*** the lane difference between the two communicating vehicles be represented by ***LDij***. The value of ***LDij*** equals to zero for the vehicles traveling in the same lane and is equals to one if the communicating vehicles are traveling in two adjacent lanes. Consequently, the value of ***LDij*** is two when the vehicles are travelling on the lanes separated by another lane on a road having 3 lanes.

Figure 3.5 shows a scenario where the simple line intersection algorithm can be applied to detect an obstacle. The propagation antennas are supposed to be mounted at point

$\boldsymbol{A(x_a, y_a)}$ and point $\boldsymbol{B(x_b, y_b)}$ on the sending vehicle $\boldsymbol{i}$ and receiving vehicle $\boldsymbol{j}$ respectively. Therefore, the points $\boldsymbol{A}$ and $\boldsymbol{B}$ form a virtual line segment $\boldsymbol{L_1}$. Another line segment $\boldsymbol{L_2}$ is formed by the length of side of obstructing vehicle as shown in Figure 3.5. The side of the obstructing vehicle which is towards the sending vehicle always forms $\boldsymbol{L_2}$. It means that the side of the obstructing vehicle closer to the sending vehicle can be considered as the line segment which hinders the radio propagation. If $\boldsymbol{L_1}$ and $\boldsymbol{L_2}$ intersect, a common intersection point can be found by using simple line intersection algorithm. Common intersection point between $\boldsymbol{L_1}$ and $\boldsymbol{L_2}$ shows that a moving vehicle is obstructing the LOS between sending and receiving vehicles.

We use a different strategy to detect the presence of moving radio obstacles when the communicating vehicles and the obstructing vehicle are travelling on a single lane by considering the width of the obstructing vehicle (front width or back width whichever is facing towards the sending vehicle) as $\boldsymbol{L_2}$. In this scenario, $\boldsymbol{L_1}$ and $\boldsymbol{L_2}$ are always perpendicular to each other. Despite applying the line intersection algorithm, only the x-coordinate of $\boldsymbol{L_2}$ is taken into account. It follows that if x-coordinate of $\boldsymbol{L_2}$ satisfies $\boldsymbol{L_1}$, the large moving vehicle is in between the sending vehicle and the receiving vehicle with $\boldsymbol{LD_{ij}= 0}$. The ***LIF*** denotes a line intersection flag whose value is set to zero; if there is no common intersection point between $\boldsymbol{L_1}$ and $\boldsymbol{L_2}$. The value of ***LIF*** is set to one when there is a common intersection point between $\boldsymbol{L_1}$ and $\boldsymbol{L_2}$. The values of ***LIF*** for all communicating vehicles are summarized and sent to the next module for further processing against each time stamp. Figure 3. 6 represents a typical scenario for the detection of large moving vehicles obstructing the LOS when the communicating vehicle and the obstructing vehicle are travelling on same lane.

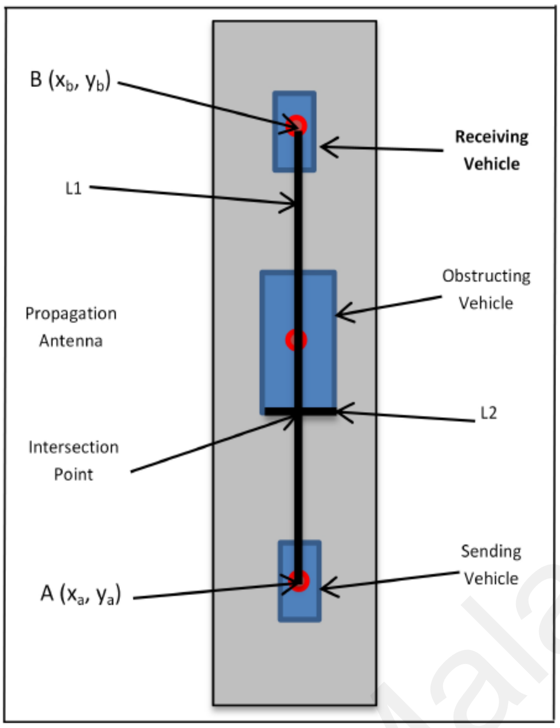

Figure 3. 6: Detecting the presence of Moving Obstacles in Single Lane Straight Road

3.3.4 Impact of Moving Obstacles

The impact of moving obstacles is calculated by using the relative heights of the communicating and obstructing vehicles after checking the presence of the obstructing vehicles. The impact of obstacles on radio communication is measured by calculating Fresnel's zones. We use the height difference ***Hd*** between sender and the moving obstacles relative to the distance between them. The ***Hd*** is compared to a threshold ***Th*** which is typically set by calculating the 40% of the radius of first Fresnel's ellipsoid between sending and receiving nodes. However, for more restrictive approach, the ***Th*** can also be set to 30% and 20% of the first Fresnel's zone. The radius of the first Fresnel's zone is inversely proportional to the frequency and depends upon the distance between the sender and the receiver. Equation 3.2 shows a simplified version for calculating the radius of first Fresnel's zone (Sheriff, 1980).

$$R = 8.657\sqrt{\frac{D}{f}} \tag{3.2}$$

Where ***R*** is the radius of the first Fresnel's zone in meters, ***D*** is the distance between sender and receiver in kilometers and ***f*** is the frequency of the radio signal in GHz. Equation 3.2 is used when the moving radio obstacle lies within the first Fresnel's zone when ***d1 = d2***. Equation 3.3 calculates the radius of the Fresnel's zone when ***d1 ≠ d2.*** Equation 3.3 is used in case of the moving vehicle obstruct the radio signals between sender and receiver at any point *p*.

$$R = 17.32\sqrt{\frac{d_1 d_2}{fD}} \tag{3.3}$$

The calculation of the radius of first Fresnel's zone allows us to infer that the radius of the Fresnel's ellipsoid is directly proportional to the distance between sender and receiver nodes. Figure 3.7 shows 60 % of first Fresnel's zone that has to be unobstructed for assuring LOS condition. We have assumed a frequency of 5.9 GHz as IEEE 802.11p DSRC standards. The height of the sender and receiver vehicles along with their respective antenna heights is compared with the heights of the obstructing vehicles using rules of permissible percentage of Fresnel's ellipsoid.

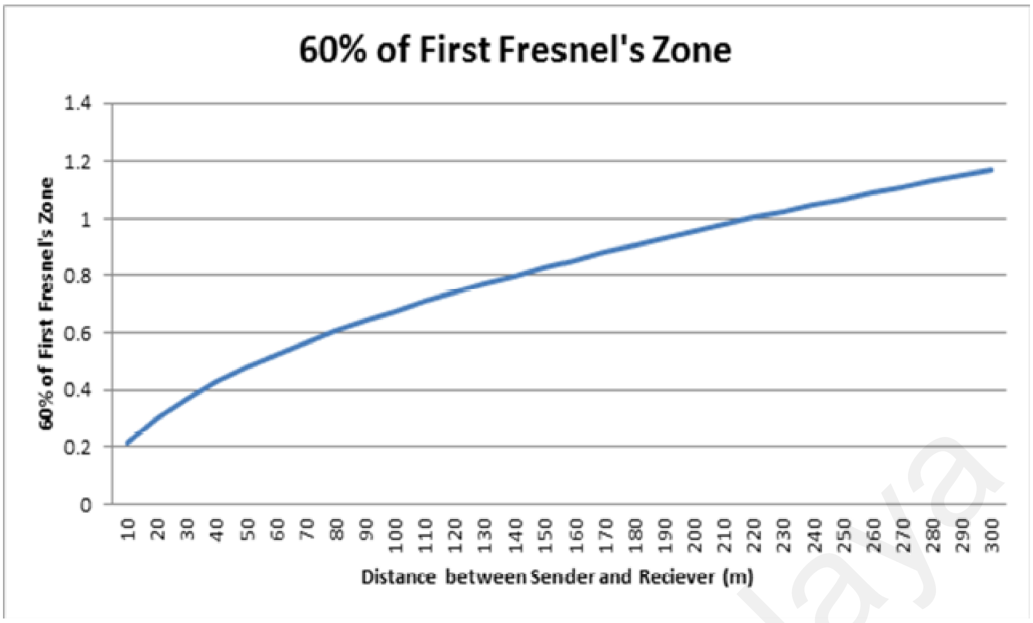

Figure 3.7: 60% of Radius of First Fresnel's Zone

Figure 3.8 shows the permissible height of moving obstacles with respect to the distance between sender and receiver vehicles. The permissible obstacle height is calculated by adding the cumulative height of the sender that includes height of vehicle and the antenna height with 40 % of the radius of first Fresnel's ellipsoid. The antenna height is considered to be 0.1 meter. The initial analysis shows that the permissible obstacle height has a direct positive relationship with distance between sender and receiver. Due to the high traffic density in urban traffic scenarios and short distances between sender and receiver, the consideration of relative height difference between sender and moving obstacles is a key aspect of ensuring LOS in vehicular communication.

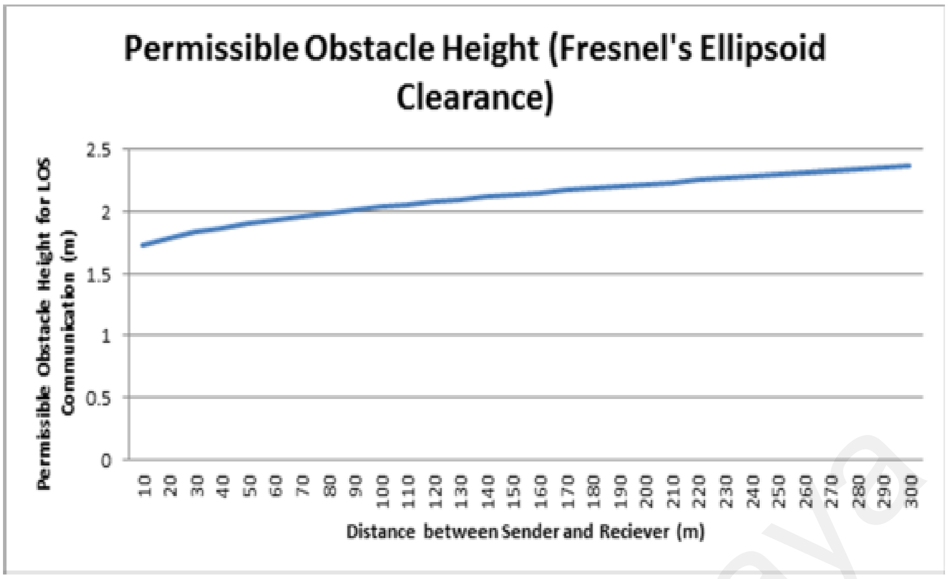

Figure 3.8: Permissible Obstacle Height w.r.t Distance between Sender and Receiver

The height difference of the sender and obstacle ***Hd*** is compared to a threshold ***Th*** which is calculated according to the relative permissible height of the obstacle. If the height difference is within the ***Th*** range, the path loss can be calculated by considering LOS scenario; otherwise it is calculated by considering NLOS scenario.

3.3.5 Calculating the Path Loss

The path loss is calculated using two different approaches based upon the impact of moving vehicles as obstacles. Using the result obtained by comparison of ***Hd*** and ***Th***, the path loss is calculated for both LOS and NLOS scenarios as follows.

3.3.5.1 LOS Scenario

Two vehicles are in LOS if they are on the same straight pathway and within the communication range of each other and no moving radio obstacles are obstructing the LOS between them. Two vehicles can also be in LOS if they are on different pathways or on a same curved highway having angular of pathways/road segments less than a threshold value (Martinez, et al., 2010). For calculating path loss in LOS scenario, free space and two ray ground models are used. A cross over distance $\boldsymbol{d_c}$ is introduced as comparison parameter for selection of the applied model. It follows that, the two ray ground model is not suitable for smaller distances between sender and receiver. When the distance $\boldsymbol{D}$ between the sender and the receiver is greater than $\boldsymbol{d_c}$, a two ray ground model is used; otherwise free space model is used to calculate path loss. The cross over parameter d_c is calculated by using Equation 3.4.

$$d_c = \frac{4\pi h_s h_r}{\lambda} \tag{3.4}$$

The value of cross over distance $\boldsymbol{d_c}$ for vehicular environment over a maximum distance of 300 meters is calculated empirically to make the simulation computationally feasible. The empirical result shows that within a range of 300 meters, the two ray ground model is not suitable for the regular small vehicles with heights (including antenna) ranging from 1.2 meters to 2.0 meters due to the oscillations caused by the two rays. Hence, in most cases, path loss is calculated using simple free space model. The Free Space Path Loss (FSPL) in decibel (dB) is already using equation 2.3. The description about free space path loss and the path loss predicted by two ray ground model are already presented in section 2.4.1.

3.3.5.2 NLOS Scenario

Two vehicles are in NLOS with each other if they are on the same or different straight pathways and one or more moving radio obstacles are obstructing the LOS between them.

In the absence of LOS between sender and receiver, the RSS for a V2Vcommunication is the result of all the radio waves that are either diffracted by the large moving vehicle or reflected by moving obstacles. The total path loss is calculated by using the sum of both the reflection and diffraction components. Therefore, the total path loss is divided into two components.

- Path loss due to reflection PL_R
- Path loss due to diffraction PL_D

We utilized the technique used in CORNER (Giordano, et al., 2011) to model NLOS scenario. However, it must be noted that CORNER utilizes reflection and diffraction components resulting from only static radio obstacles such as buildings. On the other hand, for the preliminary investigation in this thesis, the analytical formula for calculating path loss in urban scenario (Q. Sun, et al., 2005) used in CORNER is considered and amended to represent NLOS scenario for V2V communication.

Figure 3.9 represents a sample reflection path in NLOS urban scenario in a three lane road segment. An extra width of road on both sides is considered so that the distance of buildings from the roadside can be modeled. A virtual point J_m is considered which is perpendicular to both sending and receiving vehicles for the measurement of reflection pathways and NLOS path loss as shown in Figure 3.9. If r_s (the distance between the receiving vehicle and J_m) is less than r_m (the distance between sending vehicle and J_m), then path loss due to reflection PL_R is the major factor of path loss otherwise the path loss is due to PL_D.

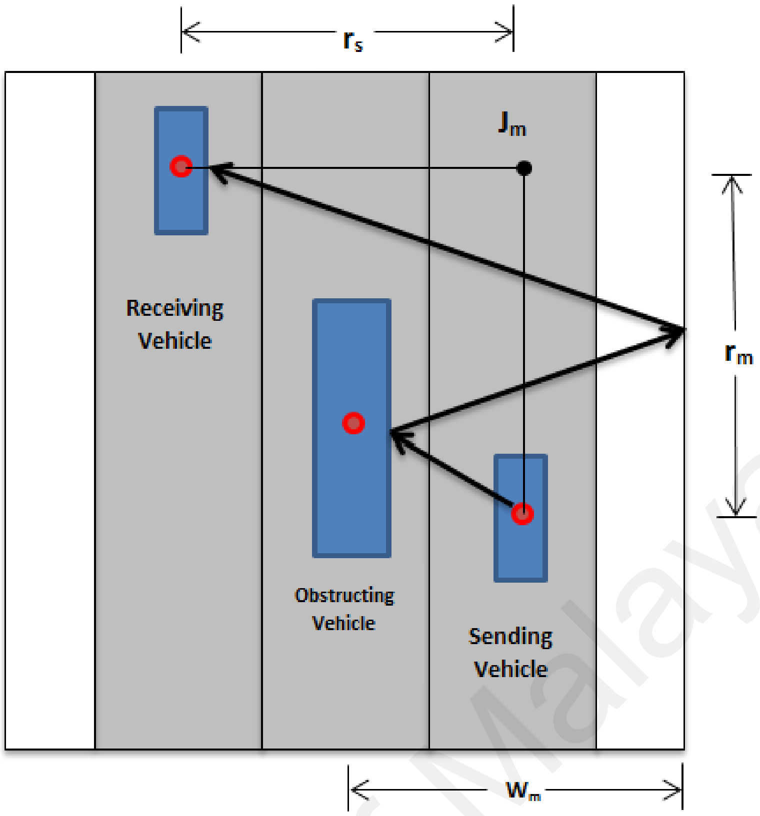

Figure 3.9: Reflection path in NLOS urban scenario

The $\boldsymbol{PL_R}$ is expressed in equation 3.5 as given in (Q. Sun, et al., 2005).

$$PL_R = 10 \log \left(\frac{\lambda}{4\pi(r_m + r_s)}\right)^2 + L_w N_{MIN} \tag{3.5}$$

Where $\boldsymbol{L_W = 20logR0}$ and $\boldsymbol{R_0}$ represents the loss per reflection. The $\boldsymbol{N_{MIN}}$ denotes minimum number of reflections. The typical value for $\boldsymbol{N_{MIN}}$ is found to be 2 based on empirical evaluations for most of the situations in V2Vcommunication in order to make the simulation computationally inexpensive.

Figure 3.10 shows the diffraction path in NLOS scenario. The edge of the obstructing vehicle that acts as a diffraction point is represented by $\boldsymbol{J_m}$. The distance between $\boldsymbol{J_m}$ and receiving vehicle is $\boldsymbol{r_{sd}}$, and $\boldsymbol{r_{md}}$ denotes the straight line vertical distance between sending vehicle and $\boldsymbol{J_m}$. Path loss due to diffraction is given by the Equation 3.6.

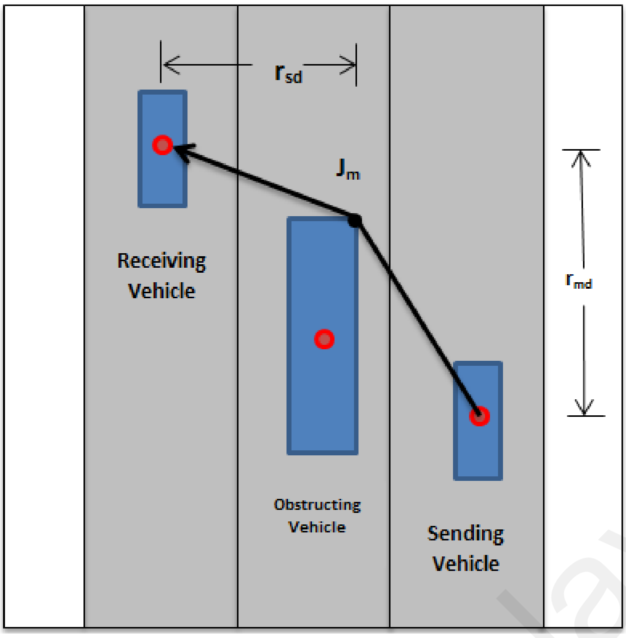

Figure 3.10: Diffraction path in NLOS urban scenario

The total path loss is given by the Equation 3.7. The details of derivation of this formula and the collection of related components can be found in (Q. Sun, et al., 2005) and (Giordano, et al., 2011).

$$PL_D = 10 \log \left(\frac{\lambda}{4\pi r_{md}}\right)^\wedge 2 + 10\, log\, \frac{\lambda r_{md}}{4 r_{sd}^2} \tag{3.6}$$

$$PL_{RD} = 10 \log \left(10^{\frac{PL_R}{10}} + 10^{\frac{PL_D}{10}}\right) \tag{3.7}$$

3.3.6 Process for the Prediction of Path Loss

Algorithm 3.1 shows the process to predict path loss in different propagation environments. The algorithm utilizes the mobility pattern of vehicles by taking a snapshot of individual vehicles mobility along with the road topology at the specified time stamps. The snapshot of mobility of vehicles consists of position, size and dimensions of the vehicle at a particular time stamp. The number of senders, receivers and potential radio obstacles (large vehicles) are initialized using separate functions designed for this purpose. To determine whether a large moving vehicle disturbs the LOS between sender and receiver, a simple line intersection algorithm is used (explained in section 3.3.3). Two different strategies are adopted for checking the presence of radio obstacles traveling in unidirectional and bidirectional lanes. Subsequently, the impact of large moving vehicles on the radio propagation among communicating vehicles is considered. Finally, the attenuation is calculated either for LOS or Non-LOS scenarios. The calculated signal attenuation for LOS scenario is the PLA component and the signal attenuation for Non-LOS scenario is the NPLA component. If NPLA component is greater than a predefined fixed value, ***FV***; it is assumed that the packet at the particular time stamp between two communicating vehicles is not delivered. Further, the time stamp increments and the whole process stops if the number of time stamps exceeds the desired Maximum Epochs (ME).

Algorithm 3.1: ARPM Process

```
Define Mobility Pattern
t ← 0 Set Time Stamp
for t = 1 to ME do
    Take Snapshot of Mobility
    n1 ← getNumberOfSenders()
    n2 ← getNumberOfReceivers()
    Obs[] ← populateObstacleList()
    for i = 1 to n1 do
        for j = 1 to n2 do
            if LDij >= 1 then
                LIF ← lineIntersection(i; j;Obs[]) // Apply Simple Line Intersection
                Algorithm considering length and  width of i,j and the length of Obs
                yielding LIF=0 if no obstacle and LIF=1  otherwise.
                if LIF = 1 then
                    Hd = calHeightDiff(i; j;Obs[k]) // Calculate Height Difference Hd of
                    specific Obs[k] with respect to i,j  using Fresnel's Ellipsoid
                    if Hd >= Th then
                        NPLA ( calNAtten(i; j;Obs[k]) // Calculate NLOS Attenuation
                        and Path Loss (NPLA  component)
                    else
                        PLA ( calLAtten(i; j) // Calculate LOS Attenuation and Path
                        Loss (PLA component)
                    end if
                else
                    PLA ← calLAtten(i; j)
                end if
            else
                Hd = calHeightDiff(i; j;Obs[k])
                if Hd >= Th then
                    NPLA ← calNAtten(i; j;Obs[k])
                else
                    PLA ← calLAtten(i; j)
                end if
            end if
            if NPLA < FV OR PLA < FV then
                << Packet Not Delivered >>
            else
                << Packet Delivered >>
            end if
        end for
    end for
end for
<<Prepare Report >>
```

The choice of an appropriate propagation formula for path loss depends upon the traffic environment. Deterministic path loss formula such as free space path loss and ray tracing models are applied in the scenarios where large moving vehicles seldom disturb the LOS among communicating vehicles. However, the path loss due to reflection and diffraction becomes a major factor in a scenario where large moving vehicles frequently obstruct the LOS among communicating vehicles. Hence, a propagation model must be able to select and switch between appropriate formula to predict the actual path loss and depending upon the current traffic environment. However, it is difficult for an radio propagation model to consider every aspect of traffic environment such as relative position of vehicles, size of vehicles, relative speed of vehicles, height of vehicles and the properties of underlying road network at every time stamp because the task of predicting accurate path loss becomes computationally complex. Thus, probabilistic RPMs provide a workable solution to predict approximate path loss which is close to the realistic modelling of radio wave propagation. The probability of moving radio obstacles to obstruct LOS between any two communicating vehicles plays a vital role in predicting accurate path loss and in a particular traffic environment. Assume that *P(A)* denotes the probability of moving radio obstacles to disturb LOS between any two communicating vehicles then the path loss is given by Equation 3.8.

$$PL = P(A)(PL_{RD}) + \big(1 - P(A)\big)(PL_{DET}) \text{ ------------------- } (3.8)$$

Where, PL_{RD} is the path loss due to reflection and diffraction previously computed by Equation 3.7. The PL_{DET} is path loss computed by any appropriate deterministic radio propagation model such as free space and two ray ground model. The probability of a moving vehicle to obstruct LOS between two communicating vehicles determines the weight of reflection/diffraction component relative to overall path loss. The value of *P(A)* is heavily dependent upon the ratio of moving radio obstacle to the total number of communicating vehicles, the density of large moving vehicles, the relative difference in speed of the vehicles and the route followed by the individual vehicles. The calculation of *P(A)* is simplified by constructing a tree diagram for conditional probability and then navigating through the path with negative occurrences. The tree diagram used to calculate *P(A)* is shown in Figure 3. 11.

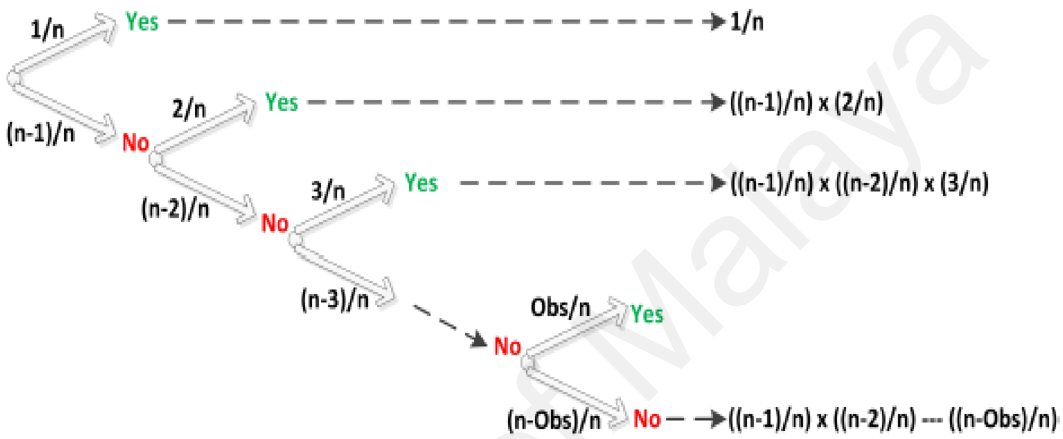

Figure 3. 11: Tree diagram to calculate P(A)

For simplicity, it is assumed that if only one moving obstacle is present, the probability of obstructing LOS is 1/n where n is the number of communicating vehicle pairs at a particular time stamp. By following the negative path (the "No" path) in the tree diagram, and multiplying individual probabilities with each other, the probability that no moving vehicle obstruct the LOS is calculated as shown in Equation 3.9.

$$P(N) = \left(\frac{n-1}{n}\right)\left(\frac{n-2}{n}\right)\left(\frac{n-3}{n}\right) \dots \dots \dots . . \left(\frac{n-Obs}{n}\right) \text{----------------- } (3.9)$$

Where, *Obs* denotes the number of large moving vehicles that can impede the radio signals of the vehicles that are following the same route and having different speeds as compared to the communicating vehicles. The calculated probability through negative path in tree diagram is subtracted from the maximum probability to yield the value of *P(A)*. Hence the probability *P(A)* is given by:

$$P(A) = 1 - P(N) \text{ --------------------------- } (3.10)$$

$$P(A) = 1 - \left(\frac{(n-1)(n-2)(n-3)....(n-Obs)}{n^{Obs}}\right) \text{ -------------- } (3.11)$$

Equation 3.8 is further simplified as follows.

$$PL = PL_{DET+} + P(A)(PL_{RD} - PL_{DET}) \text{ -------------------- } (3.12)$$

Equation 3.12 predicts the path loss due to large moving vehicles however, to constitute the effect of other environmental obstructions, additional fading components might also be considered.

3.3.7 Initial Results

Radio signals are supposed to travel in a straight line from sender to receiver in the absence of obstacles. However, radio signals have a tendency to reflect/diffract in the presence of obstacles. Consequently, a radio signal may reach the destination out of phase causing the degradation of the RSS. Therefore, the degradation of RSS up to a certain extent has a negative effect on PDR because the data carried by the radio wave is not delivered as expected.

Signal Attenuation between two vehicles in simple scenario is represented in Figure 3.12. Abrupt change in attenuation is observed at time 20 and 85 denoted by red circles. This abrupt change in attenuation is caused by large moving vehicles that block the line of sight and hence; serve as radio obstacles. Figure 3.13 explains the simulation scenario as visualized in SUMO in which a large moving vehicle disturbs the line-of-sight and causes an abrupt change in the signal attenuation.

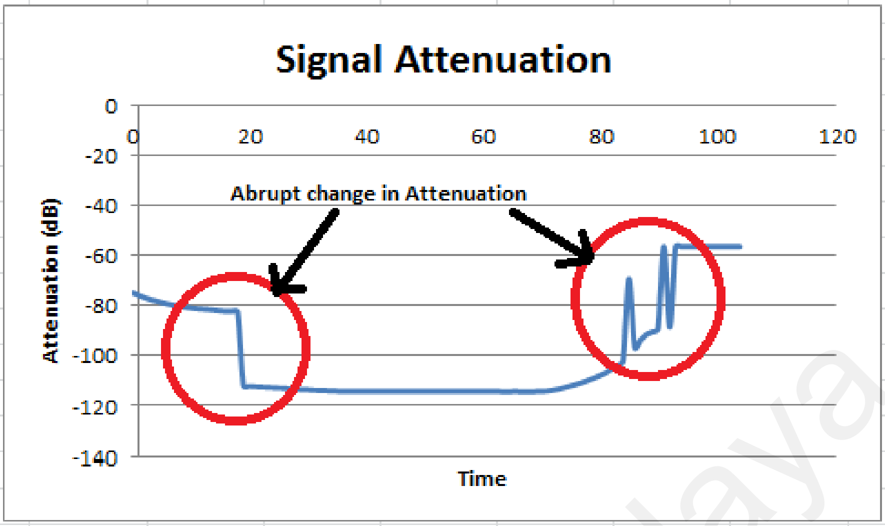

Figure 3.12: Signal attenuation while crossing a junction in simple scenario

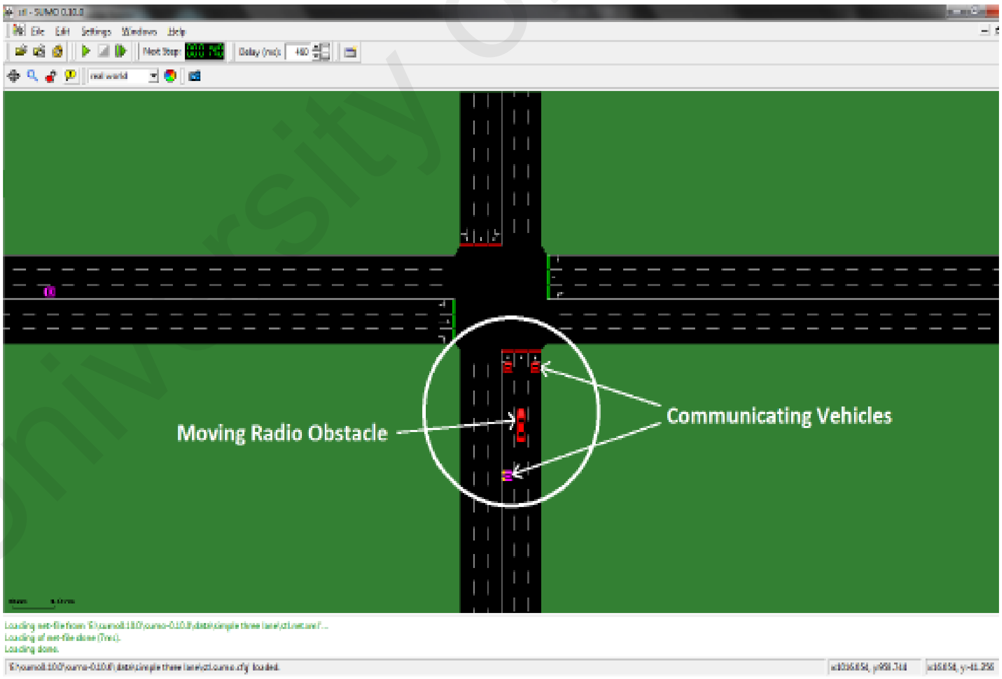

Figure 3.13: Visualization in SUMO (crossing a junction in urban scenario 1)

The results of applying the above mentioned process to predict path loss showed degradation in PDR when the number of moving radio obstacles is increased. This clearly indicates the fact that the presence of large moving vehicles negatively affects the radio propagation. Figure 3.14 represents PDR in all the considered scenarios showing a relative decrease in PDR as the number of large vehicles is increased. However, a relatively gradual decrease in PDR in highway scenarios is observed as compared to the urban scenarios. This change in PDR is due to the varying traffic densities, low traffic congestion and different type of traffic flow in highway and urban scenarios.

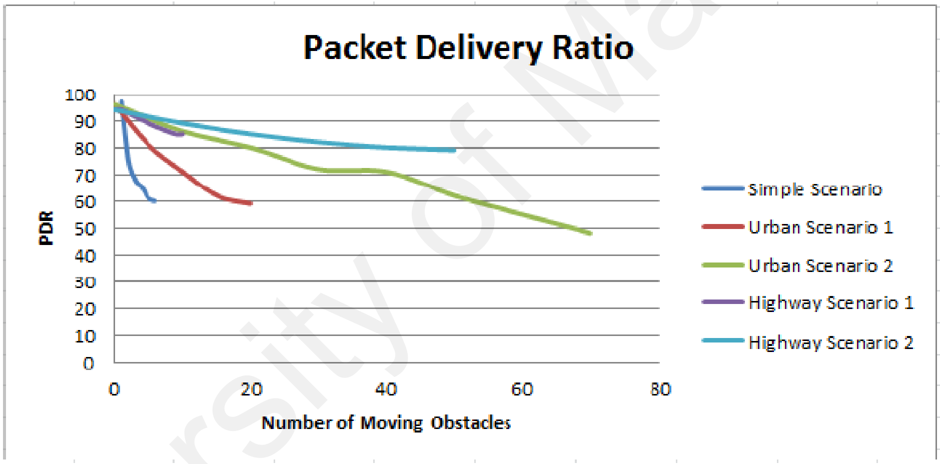

Figure 3.14: Packet Delivery Ratio

The abrupt change in signal attenuation is also observed in highway scenarios because of the presence of large moving vehicles. However, the abrupt changes in highway scenarios are not so frequent as compared to urban scenarios due to the different traffic density and higher speeds of vehicles in highway scenarios. Moreover, the large moving vehicles follow a specific lane (extreme left) on the highway and they change the lane only while overtaking another vehicle. The light transport vehicles and passenger cars usually follow the middle and extreme right lane. Therefore, the phenomenon of abrupt change in the single attenuation is not frequently observed in highway scenarios.

3.4 Impact of Modern Road Infrastructure on Vehicular Communication

Radio waves with greater wavelength have tendency to pass through non-conducting materials such as wood, glass, bricks and concrete; however, they cannot penetrate solid conducting materials. This is why; a GSM and a Wi-Fi device have a better reception inside the premises with bricked walls and concrete ceilings as compared to inside an elevator. This is because of the fact that metal body of elevator forms a faradays cage (Svein Sigmond, 2000) and hinders the radio wave propagation. A GSM device has a wavelength around 17cm if the frequency of 1800 MHz is considered. A Wi-Fi device operates on 2.4 GHz having wavelength around 12.5 cm.

However in VANETs, OBUs and RSUs utilize IEEE 802.11p standard that operate on 5.9 GHz frequency band and the radio waves propagated by these devices have wavelengths approximately equal to 5 cm. The radio waves having shorter wavelengths have less penetrating power even in the non-conducting materials. Hence, it is inferred that static objects in vehicular environment such as buildings, advertisement boards and dense vegetation and most importantly, the modern road infrastructure unit such as flyovers obstruct the radio signals. Study of impact of reinforced concrete on reflection of radio signals showed that radio signals are obstructed by concrete in 3.5 GHz band(Chiba & Miyazaki, 1999).

If vehicles are in LOS with each other then they can better communicate. Hence, maintaining LOS among sender and receiver improves throughput in VANETs. Consequently, it is obvious that modern road infrastructures units (such as flyovers, underpasses and road tunnels etc.) have a high impact on vehicular communication because the communicating vehicles might lose LOS among themselves while travelling on these modern infrastructure units. The modern road infrastructure units in terms of radio propagation and the challenges in maintaining LOS conditions among sender and receiver travelling on modern road infrastructure units are already discussed in section 2.2.5. For instance, it was stated that flyover may serve as a potential static radio obstacle for the vehicular communication. Moreover, radio propagation characteristics inside a road tunnel and underpass are different from free space. Therefore, it is deduced that the modern road infrastructure unis effect the radio propagation in vehicular communication.

3.5 Conclusion

The existing radio propagation models for VANETs are the analogous extensions of earlier radio propagation models that were primarily designed for MANETs. Existing radio propagation models for VANETs are deficient in terms of the limitation imposed by the underlying road infrastructure, vehicular speed, network topology and different types of obstacles that impede radio signals in VANETs.

We examined by extensive experimentation and simulation that static and moving obstacles have high impact on radio propagation in VANTs. A gradual decrease in RSS of approximately 70 dB is observed when the radio transmission is affected by the presence of multiple buildings in the real scenario. Similarly, the presence of moving radio obstacles also causes sudden change in the signal attenuation. An abrupt decrease in RSS of approximately 20 dB is observed when the radio transmission is affected by large moving vehicles. This abrupt change in signal attenuation sometimes results in packet loss. The overall decrease in PDR is observed in all the simulated scenarios when number of moving obstacles is increased. Moreover, the modern road infrastructure units have high impact on radio transmission due to the formation of varying LOS conditions.

Therefore, the radio transmission in VANETs is highly affected due to the presence of static and moving obstacles. Moreover, the modern road infrastructure also influences the radio transmission in VANETs.

CHAPTER 4: ADAPTIVE RADIO PROPAGATION MODEL FOR MODERN ROAD INFRASTRUCTURE UNITS IN VANETS

4.1 Introduction

This chapter reports on methods and procedures for solving the problems found in existing radio propagation models employed for VANETs for the effective communication among vehicles. It introduces the proposed adaptive radio propagation model for modern road infrastructure in VANETs. The chapter is organized into four sections. Section 4.2 explains the proposed framework for the development of adaptive radio propagation model for VANETs and explains the standard operating procedure of the proposed framework. The interconnected modules defined in the framework are also explained along with the propagation formulas separately designed for each road infrastructure unit. Section 4.3 explains the optimal positioning of RSUs by utilizing the geometric techniques in modern road infrastructure units. Section 4.4 draws conclusive remarks by emphasizing the usefulness and applicability of the proposed adaptive radio propagation model.

4.2 Proposed Adaptive Radio Propagation Model for VANETs

As stated earlier, the existing radio propagation models lack in addressing physical factors that affect radio propagation in VANETs environment. The realistic impact of static and moving obstacles is also ignored in existing radio propagation models. Moreover, the modern road infrastructure units and their effect on radio propagation in assigned frequency band for VANETs along with the realistic traffic detail found in actual traffic environment is not considered in traditional radio propagation model. The incorporation of physical factors, consideration of radio obstacles and modeling of the impact of modern road infrastructure units collectively make the radio propagation models computationally expensive in VANETs. Therefore, a computationally inexpensive and adaptive radio propagation model is proposed that is capable of (a) addressing physical aspects of radio propagation, (b) modelling both static and moving obstacles, and (c) considering the modern road infrastructure unit and their effects on radio transmission in VANETs. The adaptability in prediction of path loss is introduced in the proposed radio propagation model by considering specialized input which is required in the modern road infrastructure units. The development of adaptive radio propagation model for VANETs results in the accurate prediction of path loss and effective coverage area of communication. Moreover, the optimal positioning of RSUs that result in effective V2X communication is introduced to facilitate reliable communication infrastructure in VNAETs.

We propose a realistic adaptive radio propagation model (ARPM) for VANETs. ARPM addresses the issues related to the drawbacks of existing radio propagation models. ARPM removes the drawbacks of current radio propagation models by incorporating the effects of modern road infrastructure units on radio propagation. ARPM adds the adaptability in the prediction of path loss by utilizing separate schemes for the calculation of signal attenuation in different scenarios using the adaptive selector. The adaptive selector provides intelligent ratings for every individual component that has an impact on radio propagation in VANETs to calculate total attenuation caused by multitude of factors in different real world scenarios. ARPM utilize real world data in terms of maps in the calculation of path loss to make accurate prediction while remain computationally inexpensive. Further, we perform optimal positioning of RSUs on modern road infrastructure units and the positive effect of optimal RSU positioning is observed using the proposed ARPM. Section 4.2.1 explains the interconnected modules that systematically used to develop the framework presented in section 4.2.2. Section 4.2.3 explains the propagation formulas utilized to predict path loss for the communicating vehicles travelling in individual modern road infrastructure units.

4.2.1 The Interconnected Modules

The adaptive radio propagation suitable for all types of modern traffic situations in VANETs is developed using a modular approach that consists of five major modules.

a) Traffic information processing

b) Signal attenuation calculation

c) Adaptive selection

d) Optimal positioning of RSUs

e) Evaluation and comparison

Figure 4. 1 provides a schematic flow of the interconnected modules. The following subsections provide brief description about each of the major modules.

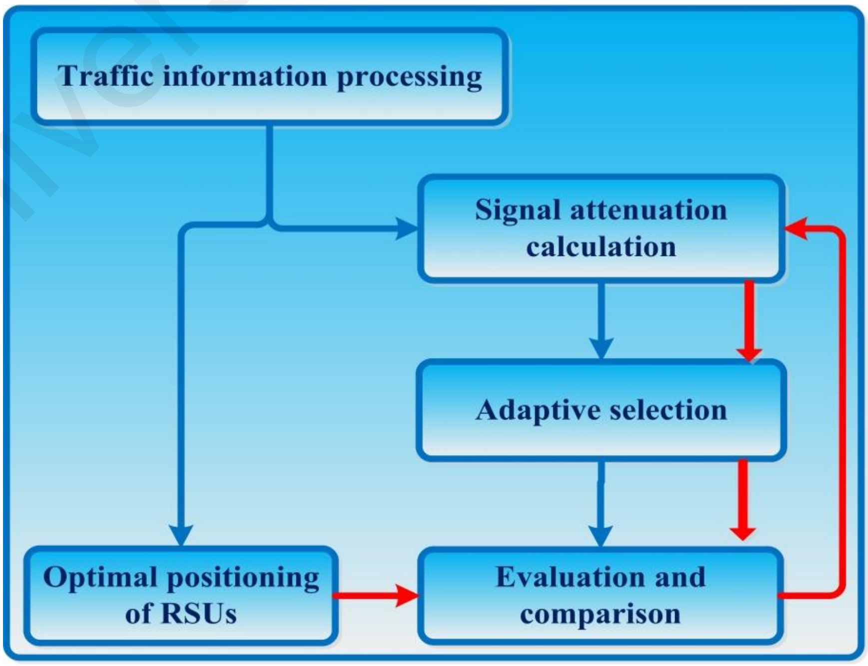

Figure 4. 1: Schematic flow of interconnected modules

4.2.1.1 Traffic Information Processing

The traffic information processing module is responsible for collection of traffic detail, transformation of information into usable format for the calculation of signal attenuation and extraction of geometrical data as needed by other modules in the framework. The OpenStreetMap (Hall, et al., 1996) is a community driven, freely available and editable map of the world that contains information about the roads, trails and buildings with sufficient amount of detail. These maps contain information that also serves as a platform for modelling the behavior of radio signals. However, accurate modelling of radio signals in VANETs requires traffic detail in addition to the basic topological characteristics of a typical modern VANET environment. Therefore, the map data obtained from OpenStreetMap needs to be transformed in such a format that incorporates traffic and modern road infrastructure detail. Further, different type of information is needed by other modules in the framework such as geometrical data is needed for the optimal positioning of the RSUs along the road sides on modern road infrastructure units. Hence, Traffic information processing module process the data obtained from OpenStreetMap, incorporates traffic detail and provides the relevant data to other module as needed for further processing.

4.2.1.2 Signal Attenuation Calculation

This module is responsible for calculating the signal attenuation caused by multiple factors present in the VANETs environment. The factors consist of path loss itself along with the attenuation caused by different types of radio obstacles, shadowing and fading effects. The signal attenuation caused by factors such as reflection and diffraction from different static and moving radio obstacles is also calculated individually in this module. Moreover, the impact of modern road infrastructure units in terms of signal attenuation is also incorporated to generate the value of total path loss for a particular situation along with the other factors.

Obstacle handling is one of the most important issue relating to the development of realistic radio propagation models. The proposed ARPM emphasize on accurate yet computationally inexpensive calculation of signal attenuation in modern day traffic environments considering both static and moving obstacles. The average optimal distance (AOD) between two RSUs at the road side is calculated where RSS is suitable for V2I and I2V communication and to assist in determining optimal position of RSUs in modern road infrastructure units. Including AOD in the radio propagation model makes the model (a) accurate, (b) simplistic, and (c) computationally less complex, because the physical area under consideration for radio propagation is reduced.

Figure 4. 2 shows a three-step process that is useful in developing a realistic and computationally inexpensive radio propagation model with the ability to cope with the challenges of modern road traffic environments. It is now been cleared that the modern road infrastructure units affects the radio propagation; therefore, different input parameters for different modern road infrastructure units are required to predict the path loss. For instance, road tunnel dimensions are needed to predict path loss for the communicating vehicles travelling inside a road tunnel.

Hence, the first step in the calculation of path loss is the selection of the input parameters for each of the modern road infrastructure units in order to predict the path loss with acceptable accuracy involving relatively less number of computations. The second step is to calculate the free space path loss using the distance $\boldsymbol{d}$ between the communicating vehicles and the wavelength $\boldsymbol{\lambda}$ of the radio signals. However, to improve the prediction quality, at least three major types of impacts must be added to the free space path loss. The following major effects are added to the free space path loss in order to complete the third step in the three-step process.

- Effect of static radio obstacles
- Effect of moving radio obstacles
- Impact of modern road infrastructure unit on signal attenuation.

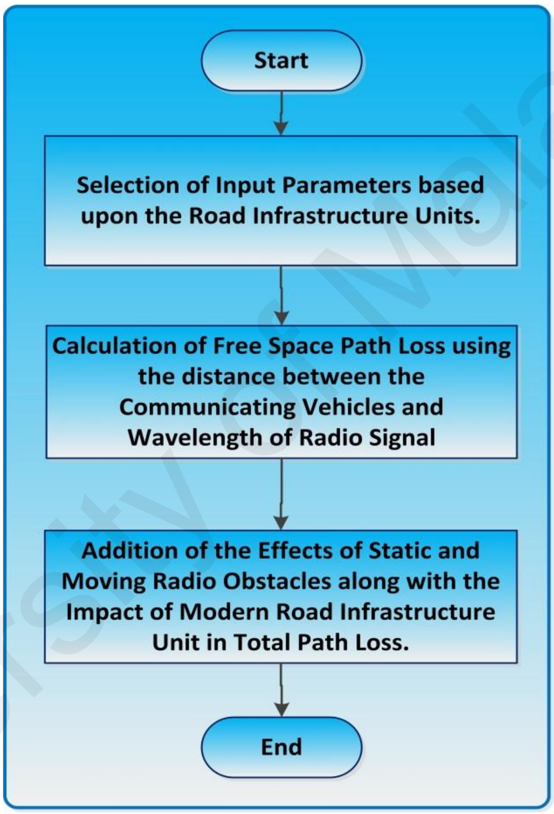

Figure 4. 2: Proposed Three-Step Process for the calculation of signal attenuation

The geometric characteristics that need to be considered for accurate modelling of static obstacles are the dimensions and position of the static radio obstacles while the speed of the moving radio obstacle has to be considered in addition to the geometric characteristics in case of handling moving radio obstacles. The frequency of moving obstacles relative to the number of communicating vehicles plays an important part in the prediction of the total path loss. The impact of modern road infrastructure units on signal attenuation is modeled by utilizing individual properties of the infrastructure units; for instance, height of the flyover and cross sectional area of an underpass. Therefore, in the third step, both static and moving obstacles are modelled along with the impact of modern road infrastructure units using geometric techniques and algorithms that may treat an obstacle as a three-dimensional object.

The prediction of path loss, in vehicular environments is mainly dependent upon the road infrastructure type (*RIT*) on which the communicating vehicles are travelling. A threshold value TRSS that represents the minimum value of *RSS* suitable for vehicular communication is set for every *RIT*. *TRSS* is a value of RSS that guarantees optimal communication in a vehicular environment with minimum packet loss. The optimal distance between two RSUs deployed on a particular *RIT* is determined using the *TRSS* value and the geometric properties for maintaining LOS among the communicating vehicles. The value of optimal distance is mathematically formulated to yield the *AOD* for each *RIT*.

The free space path loss is calculated using the *AOD* for a particular *RIT*. The transmission range strictly within *AOD* is considered to determine the values of path loss. The value of total path loss is further updated by calculating the impact of modern road infrastructure unit and optionally in case of a detection of a radio obstacle within the environment.

A separate strategy is adopted for measurements in cases of static and moving obstacles. Real-world maps are used and static topology is extracted to model static obstacles. However, dynamic topology is used to model moving obstacles for V2V communication. The effect of static and dynamic obstacles on radio propagation is measured and hence, the NLOS path loss component is calculated.

The value of the total path loss is updated for the modelling of obstacles in a vehicular environment. Total path loss is formulated to yield a message predictor *MP*. A threshold value *Th* for *MP* is determined through real-world measurement in various *RITs* to ensure message delivery. If the value of *MP* in a particular scenario is greater than or equal to the predefined threshold *Th*, the message is believed to be delivered. However, if the value of *MP* is less than *Th*, an in-range RSU which is in LOS with the communicating vehicles is utilized to deliver the message. The use of RSU to maintain LOS among communicating vehicles is possible if the RSUs are deployed in the vehicular environment by calculating *AOD* and positioning RSUs at optimal distances in each of the modern road infrastructure unit. Figure 4. 3 elaborates the proposed three-step process for the calculation of signal attenuation in modern road infrastructure units with acceptable accuracy while keeping the computational complexity as low as possible.

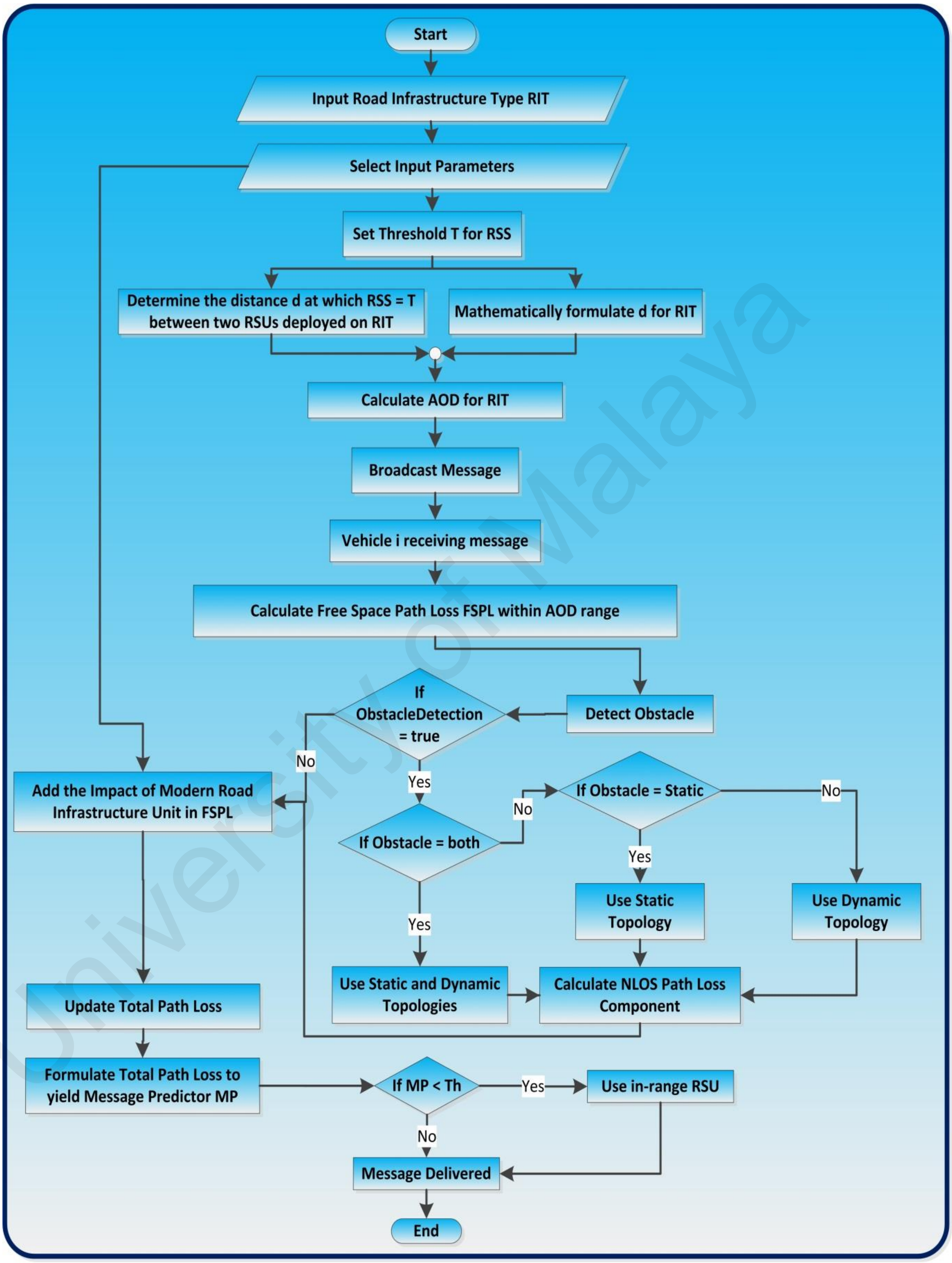

Figure 4. 3: Elaboration of Proposed Three-Step Process

4.2.1.3 Adaptive Selection

Adaptive selection module is responsible for the accurate estimation of total signal attenuation as a result of weighted collection of signal attenuation from all related components caused by diverse factors in the modern VANETs environment. Adaptive selector operates on statistical data obtained from the signal attenuation calculator and it rates each component individually according to the underlying road infrastructure unit and prepares an estimation of the total signal attenuation.

To account for free space path loss and environmental obstructions due to radio obstacles, every component is rated using relative weight for each type of component (under the specific road infrastructure unit / traffic environment) especially in case of moving radio obstacles as explained in section 3.3.6. Equation 4.1 represents a general formula for the weighted average attenuation (PL_{AVG}) while utilizing a total of ***n*** components.

$$PL_{AVG} = \frac{1}{n}\sum_{i=1}^{n} W_i PL_i \text{ ------------------------ } (4.1)$$

In Equation 4.1, W_i represents the calculated weight of *ith PL* component.

Different set of parameters are required in different road infrastructure units to accurately calculate the path loss. This research work adds adaptability in the accurate prediction of path loss by selecting specialized input parameters for each road infrastructure unit. The input parameters are categorized into four groups; (a) Infrastructural input parameters, (b) Basic / LOS inputs, (c) NLOS for static obstacle inputs and (d) NLOS for moving obstacles inputs. Table 4.1 represents the input parameters for every road infrastructure unit.

Table 4.1: Input Parameters

Road Infrastructure Unit	Input Parameters			
	Infrastructural	Basic /LOS	NLOS (Static Obstacles)	NLOS (Moving Obstacles)
Straight Road	-------	d, λ	-------	F, υ, H, r_f, d_{obs}
Curved Road	R_1, R_2, W	d, λ	β, γ, n, d_m	F, υ, H, r_f, d_{obs}
Road Tunnel	k, r, w, h	d, λ	-------	F, υ, H, r_f, d_{obs}
Flyover	h	d, λ	β_f, ρ_f, n_f, m_f	F, υ, H, r_f, d_{obs}
Underpass	k, r, w, h, l_{eu}, A_{cu}	d, d_{eu}, λ	-------	F, υ, H, r_f, d_{obs}

Legend:

d: Distance between the communicating vehicles
λ: Wavelength of radio signal
F: The probability of moving obstacles to disturb the LOS among the communicating vehicles.
H: Height difference of moving radio obstacle and the communicating vehicles
rf: Radius of the first Fresnel's zone ellipsoid
υ: Ratio of ***H*** and $\mathbf{r_f}$.
d_{obs}**:** Distance between the radio obstacle and the transmitting vehicle.
R_1**:** Radius of curvature of outer curve in the curved road.
R_2**:** Radius of curvature of inner curve in the curved road.
W: Width of curved road
r: Absolute value of the difference of height and width of the road tunnel / underpass
w: Width of the road tunnel / underpass
h: Height of the road tunnel / underpass / flyover
k: Constant of proportionality using ***r, w*** and ***h.***
l_{eu}**:** Effective length of the underpass
A_{cu}**:** Area of cross-section of underpass
d_{eu}**:** Effective distance (underpass)

4.2.1.4 Optimal positioning of RSUs

The extraction of geometrical data from the OpenStreetMap is carried out by traffic information processing module and is utilized for the optimal positioning of RSUs on modern road infrastructure unit. RSUs are placed optimally depending upon the road topology and dimensions by considering modern road infrastructure units. The detail description of optimal positioning of RSUs is discussed in section 4.3.

4.2.1.5 Evaluation and Comparison

The evaluation and comparison is carried out in two different formats;

- Before the optimal positioning of RSUs
- After the optimal positioning of RSUs.

At first, evaluation of proposed ARPM is performed by comparing it with the existing state-of-the-art radio propagation models including free space model, two ray ground model and CORNER, using RSS and PDR in the absence of optimal positioning of RSUs. Secondly, the proposed ARPM is again applied after the optimal positioning of RSUS to collect the data in terms of RSS and PDR. The comparison is again made, but this time the effects of optimal positioning of RSUs are compared using the proposed ARPM.

4.2.2 The Proposed Framework

Figure 4.4 present the proposed framework for the development of ARPM. The information from OpenStreetMap is sent to the information generator which is a part of traffic information processing module. The information generator parses the related information along with the detail of modern road infrastructure units and sends the parsed information to signal attenuation calculator. The signal attenuation calculator computes the following;

- Free space path loss
- NLOS path loss component due to static obstacles
- NLOS path loss component due to moving obstacles
- Impact of modern road infrastructure unit on path loss

After the calculation of all components of path loss, the data is then sent to adaptive selector that rates individual component and then calculates the total signal attenuation by applying appropriate weights to each individual components that participates in the calculation of signal attenuation in a particular scenario.

The ARPM is evaluated using empirical data obtained from the real-world measurement of signal attenuation in prescribed frequency band for VANETs. The results obtained by incorporating ARPM are also compared with state-of-the-art radio propagation models (free space, two-ray ground, CORNER). The information generator also produces geometrical information that is used to perform optimal positioning of RSUs along the road side. A comparison is made between the signal attenuation values before and after applying the optimal positioning of RSUs using the proposed ARPM.

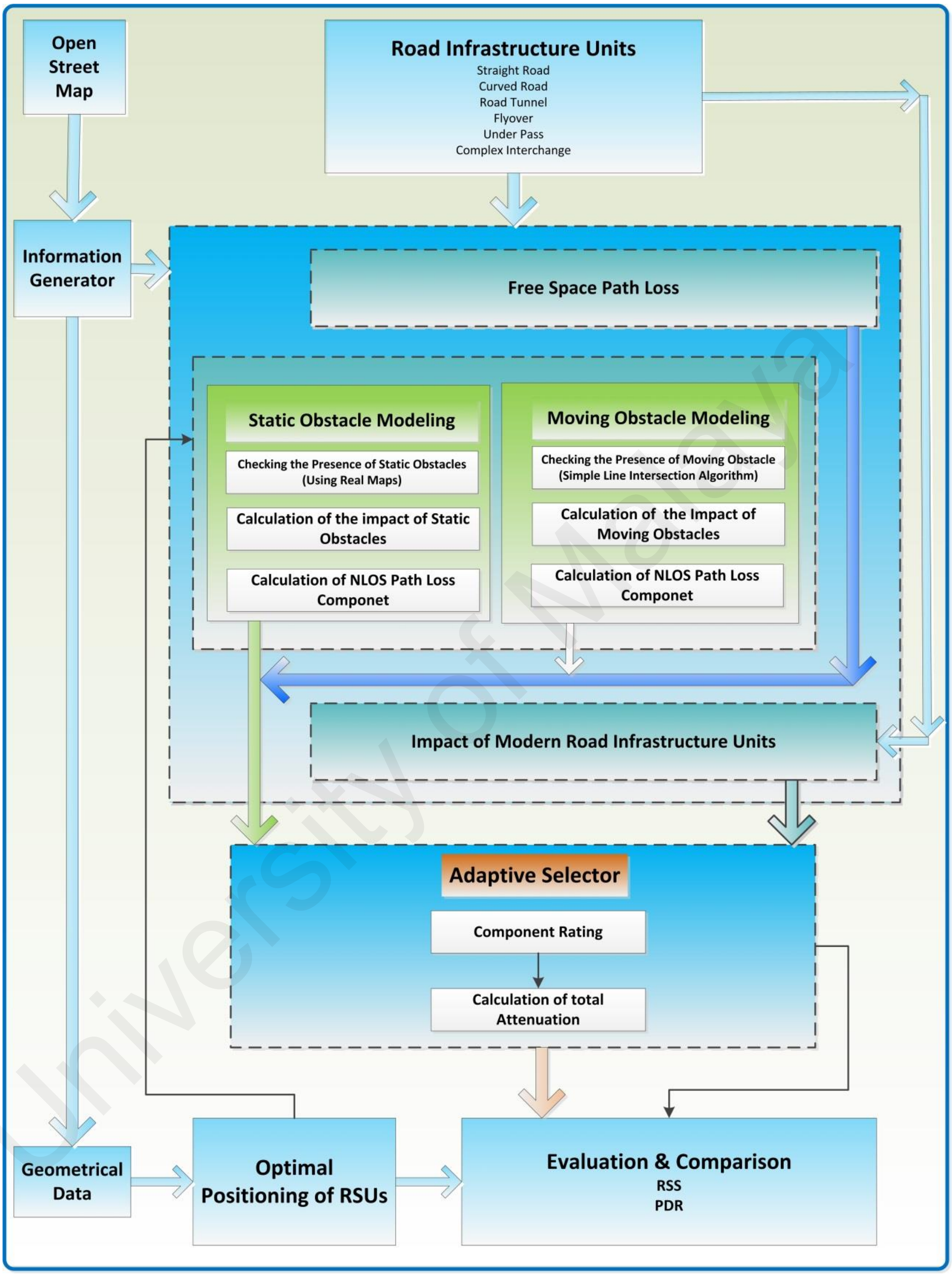

Figure 4.4: Proposed Framework

4.2.3 The Propagation Formulas

This subsection presents various propagation formulas for the calculation of path loss in multiple modern road infrastructure units. The propagation formulas for (a) straight and confined curved road, (b) road tunnel (c) flyover, and (d) underpass are presented here. The propagation formulas presented in this section also consider the impact of different types of radio obstacles on signal propagation along with the impact of modern road infrastructure units.

4.2.3.1 Radio Propagation Formula for Straight and Curved Roads

It is clear from the literature review (chapter 2) that the existing radio propagation models in VANETs lack in one or more of the critical aspects regarding the accurate prediction of the behavior of radio signals. A computationally inexpensive radio propagation model is needed that is capable of accurately predicting the path loss in straight and curved roads because these types of roads are integral part of modern road infrastructure. Further, the path loss prediction formula for straight and curved roads must account for the critical features which include (a) path loss in free space due to multiple factors, (b) additional attenuation caused by the static radio obstacles and (c) additional attenuation due to the moving radio obstacles. Moreover, the proposed ARPM containing the path loss prediction formula for straight and curved roads must be validated in the widely used frequency band for VANETs.

The objective here is to propose a computationally inexpensive propagation formula for straight and curved roads that considers the above mentioned critical features. In the proposed path loss formula for the straight roads, the total path loss in straight roads ($\boldsymbol{PL_{TS}}$) is considered to be a combination of two participating factors namely,

(a) LOS path loss ($\boldsymbol{PL_{freespace}}$)

(b) Path loss due to moving obstacle ($\boldsymbol{PL_{AM}}$).

The additional attenuation due to static obstacles such as advertising boards has no effect on vehicular communication because the communicating vehicles essentially maintain LOS among them on straight roads.

However, the propagation formula for the curved roads consists of the three participating factors. The additional attenuation is caused by NLOS condition resulting from the road curvature and presence of large buildings in most of the urban environments. The three factors participating in the total path loss for curved roads ($\boldsymbol{PL_{TC}}$) are as under.

(a) LOS path loss ($\boldsymbol{PL_{freespace}}$)

(b) Path loss resulting from static radio obstacles including buildings and concrete structure in case of confined curved road ($\boldsymbol{PL_{AS}}$)

(b) Path loss due to moving obstacle ($\boldsymbol{PL_{AM}}$).

The formula for the calculation of total path loss $\boldsymbol{PL_{TS}}$ ***[dB]*** for the vehicular communication while the communicating nodes are travelling on a straight road includes the LOS path loss along with the additional attenuation caused by the occasional moving radio obstacles. $\boldsymbol{PL_{TS}}$ ***[dB]*** is given by equation 4.2.

$$PL_{TS}\,[dB] = PL_{freespace}\,[dB] + F(PL_{AM}[dB]) \tag{4.2}$$

$\boldsymbol{PL_{freespace}}$ ***[dB]*** represents the LOS path loss in dB as expressed in equation 2.3. In equation 4.2, ***F*** represents the probability of the large moving obstacles to disturb the line-of-sight (LOS) among the communicating vehicles. The value of ***F*** is dependent upon the ratio of moving radio obstacles to the total number of communicating vehicles as utilized in adaptive selection.

$PL_{AM}[dB]$ represents the additional attenuation caused by the moving radio obstacles. The impact of moving radio obstacles on the radio propagation can be estimated in the simplest of ways by using single knife-edge model. The single knife-edge model is applied in the situations where the wavelength of the radio signal is significantly smaller than the size of the radio obstacle (Boban, et al., 2011). Therefore, the single knife-edge model is well suited for the vehicular communication. An approximation of the maximum additional path loss in dB caused by the moving radio obstacles in vehicular communication can be represented using equation 4.3.

$$PL_{AM}[dB] = 6.9 + 20log_{10}\left[\sqrt{(v-0.1)^2+1}+v-0.1\right] \tag{4.3}$$

where

$$v = \sqrt{2}\,\frac{H}{r_f} \tag{4.4}$$

H denotes the height difference of the radio obstacle and the height of the straight line connecting the communicating vehicles. The presence of the of the radio obstacle within 60% of the first Fresnel's zone ellipsoid is the cause of the additional signal attenuation. Therefore, equation 4.4 includes a parameter r_f which is the radius of the first Fresnel's zone ellipsoid and is obtained by the following equation (Boban, et al., 2011).

$$r_f = \sqrt{\frac{\lambda d_{obs}(d - d_{obs})}{d}} \tag{4.5}$$

In equation 4.5, d_{obs} denotes the distance between the radio obstacle and the transmitting vehicle.

The formula for the calculation of total path loss PL_{TC} ***[dB]*** for the vehicular communication while the communicating nodes are travelling on a curved road includes the LOS path loss along with the additional attenuation caused by the static obstacles (buildings) and occasional moving radio obstacles. $\boldsymbol{PL_{TC}}$ ***[dB]*** is given by equation 4.6.

$$PL_{TS}\,[dB] = PL_{freespace}\,[dB] + PL_{AS}\,[dB] + F(PL_{AM}[dB]) \qquad (4.6)$$

Using the existing work on the impact of static radio obstacles on the radio propagation (Sommer, Eckhoff, et al., 2011), $\boldsymbol{PL_{AS}}$ is expressed in dB in equation 4.7 by using two calibration factors $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$. In equation 4.6, β is the signal attenuation in dB experienced by the radio signal due to exterior wall of the building and $\boldsymbol{\gamma}$ is an estimation of the additional signal attenuation caused by internal structure of the building given in dB/meter. Moreover, $\boldsymbol{n}$ denotes the number of times LOS between the communicating vehicles is obstructed by the border of the obstacle and $\boldsymbol{d_m}$ represents the total effective length of the obstacle's intersection.

$$PL_{AS}[dB] = \beta n + \gamma d_m \qquad (4.7)$$

4.2.3.2 Radio Propagation Formula for Road tunnels

From the existing work on radio propagation models for road tunnels (discussed in chapter 2), it is identified that some of the existing radio propagation models are computationally complex as they are based on deterministic approach. Most of the existing radio propagation models for tunnels are not validated for the widely utilized frequency band for VANETs. Further, many of the existing models do not consider additional attenuation from the large moving objects in road tunnels. Therefore, a computationally inexpensive radio propagation model with minimal number of parameters for vehicular communication in road tunnels that provides accuracy in an acceptable range is required that is validated in the allowed frequency band for VANETs and accounts for the additional signal attenuation

Our goal is to propose a propagation formula for vehicular communication inside road tunnels which utilizes a minimal set of parameters to estimate path loss in an acceptable range. It is obvious from existing literature (discussed in chapter 2, section 2.2.5.2) on signal propagation in road tunnels that initially there is a steep decrease in the RSS values and as the distance between the communicating vehicles increases, the deterioration of RSS becomes gradual. The sudden decrease of the RSS value near to the transmitter and then gradual deterioration of the signal power as the distance between the communicating vehicles increased showed that the path loss in tunnel is logarithmically proportional to the distance between the communicating nodes as shown in equation 4.8.

$$PL_M[dB] = k\ log_{10}(d) \tag{4.8}$$

In equation 4.8, PL_M denotes the major component of path loss, d is the distance between communicating vehicles. The constant of proportionality is k, determined by using the dimensions of the road tunnel. The value of k also depends upon the radio signal characteristics such as wavelength of the transmitted signal. The formula for the calculation of k is shown in Equation 4.9.

$$k = r + \frac{w}{h\lambda} \tag{4.9}$$

In equation 4.9, r represents the absolute value of the difference of height and width of the road tunnel ($|w\text{-}h|$); where w and h are width and height of the road tunnel respectively. The equation 4.2 can be used to calculate k if $w > h$. However, if the height of the tunnel is greater than the width, then the value of k is calculated as (r + h/wλ).

The impact of moving radio obstacles on the radio propagation is already formulated in section 4.2.3.1. The approximation for the total path loss in road tunnel PL_{TT} is the combination of PL_M and PL_A as given in equation 4.10.

$$PL_{TT}\ [dB] = PL_M[dB] + F(PL_{AM}[dB]) \tag{4.10}$$

In equation 4.10, $\boldsymbol{PL_M}$ denotes the major component of path loss in road tunnel; $\boldsymbol{F}$ represents the probability of the large moving obstacles to disturb the line-of-sight (LOS) among the communicating vehicles. Moreover, $\boldsymbol{PL_{AM}}$ represents the maximum signal attenuation caused by a large moving radio obstacle given by equation 4.3.

4.2.3.3 Propagation formula for Flyovers

The architecture of a flyover makes it a potential static radio obstacle for the communicating vehicles. Two sorts of communication occur among the vehicles while driving on the flyover; (a) LOS communication and (b) NLOS communication. The communicating vehicles are in LOS with each other when at least one the vehicle (transmitter/receiver) is either travelling on the highest point along the flyover or it is currently at a relatively higher position on the flyover as compared to the other communicating vehicle. However, the LOS between two communicating vehicles may be disturbed by large moving radio obstacles that happen to appear between the communicating vehicles. The vehicles travelling on the opposite ends of the flyover loose LOS among them due to the height of the structure. The structure of the flyover is the cause of NLOS condition among the communicating vehicles in this scenario. This phenomenon is explained in Figure 4. 5. Here, the green straight line represents LOS communication and red line shows the NLOS scenario. The pillars of the flyover and the concrete base at the ends of the flyover are potential static radio obstacles for the vehicular communication.

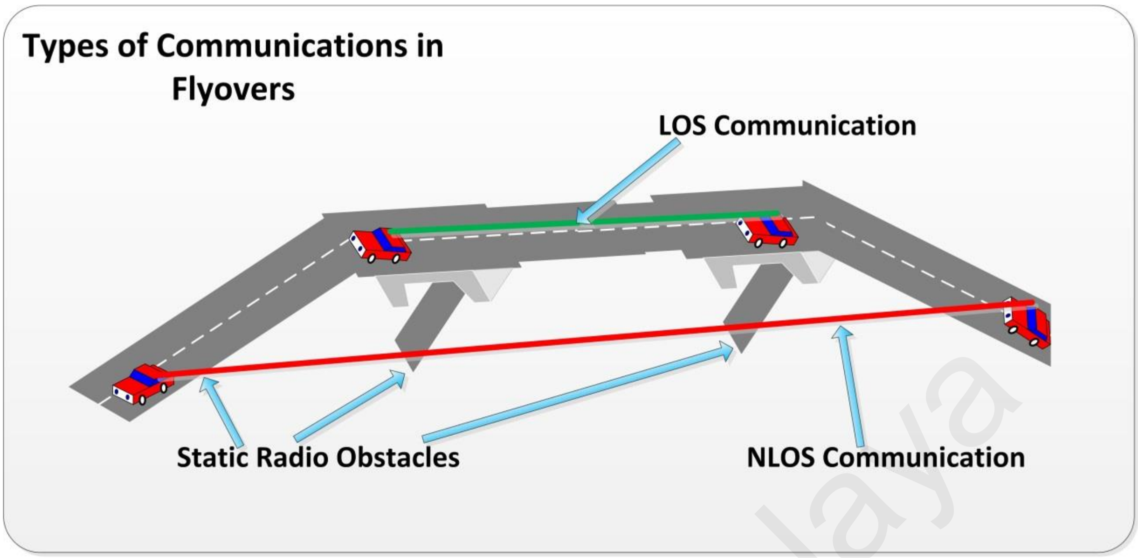

Figure 4. 5: Types of Communication in Flyovers

In case of LOS communication among the vehicles on the flyover, the same radio propagation model that is used for the straight road can be applied. The free-space model can be utilized for the prediction of path loss in LOS scenario if the additional attenuation due to large moving radio obstacle on the flyover is also considered. Therefore, the total path loss in LOS scenario on the flyover is dependent upon two factors;

- Free space path loss ($PL_{freespace}$)
- Additional attenuation due to the presence of the large moving radio obstacle (PL_{AM}).

The maximum path loss due to the presence of large moving radio obstacles is already estimated using single knife edge effect as explained in section 4.2.3.1. However, the additional attenuation due to moving radio obstacles depends upon the frequency F of the large radio obstacles in the overall traffic. The formula for the calculation of total

LOS path loss for the vehicular communication while the nodes are travelling on the flyover is given by the equation 4.11.

$$PL_{LOS}\,[dB] = PL_{TS}\,[dB] = PL_{freespace}\,[dB] + F(PL_{AM}[dB]) \tag{4.11}$$

Where PL_{AM} *[dB]* is described in equation 4.2 and $\boldsymbol{PL_{freespace}}$ is previously explained in equation 2.3.

The general model for path loss prediction is to be extended to contemplate the impact of flyover structure on the vehicular communication. Therefore, the NLOS scenario for the vehicular communication that arises due to the architecture of the flyover is modelled by capturing additional attenuation caused by the structure of the flyover. A calibration factor $\boldsymbol{\beta_f}$ is introduced to represent the additional signal attenuation in dB caused by one of the two inclined concrete structures on the edges of the flyover. Another calibration factor $\boldsymbol{\rho_f}$ is considered that represents the additional signal attenuation in dB caused by the pillars of the flyover. The additional attenuation is modelled by calculating $\boldsymbol{n_f}$ and $\boldsymbol{m_f}$**;** the number of times the LOS is obstructed by the static radio obstacles (pillars and flyover edges). The number of times LOS of communicating vehicles is disturbed by the flyover edges is represented by *n* (maximum value of n is 2) and ***m*** represents the number of times LOS of communicating vehicles is obstructed by the pillars of the flyover. The additional attenuation due to the structure of the flyover $\boldsymbol{PL_{AF}[dB]}$ is given in equation 4.12.

$$PL_{AF}\,[dB] = n_f\,\beta_f + m_f\,\rho_f \tag{4.12}$$

The additional attenuation PL_{AF} is combined with the free-space model to elucidate the total path loss $\boldsymbol{PL_{NLOS}}$ in NLOS scenario for the flyover. The $\boldsymbol{PL_{NLOS}}$ is calculated as shown in equation 4.13.

$$PL_{NLOS}[dB] = PL_{freespace}[dB] + PL_{AF}[dB] \tag{4.13}$$

The total path loss in flyover $\boldsymbol{PL_{TF}}$ is either represented by equation 4.11 for LOS scenario or it is represented by equation 4.13 for NLOS scenario.

$$PL_{TF} = \begin{cases} PL_{LOS} & If\ communicating\ vehicles\ are\ in\ LOS \\ PL_{NLOS} & If\ communicating\ vehicles\ are\ in\ NLOS \end{cases} \tag{4.14}$$

The LOS scenario represents a situation where the structure of the flyover has no effect on the LOS of the communicating vehicles. However, the LOS among the communicating vehicles may be disturbed occasionally by the presence of moving radio obstacles in the LOS scenario. Therefore, $\boldsymbol{PL_{LOS}}$ represents the total path loss in the scenario where the structure of flyover has no effect on radio signals of communicating vehicles. Further, $\boldsymbol{PL_{NLOS}}$ represents the total path loss in the scenario where the LOS among communicating vehicles is disturbed by the structure of the flyover.

4.2.3.4 Propagation formula for Underpasses

A computationally inexpensive radio propagation model is already proposed for road tunnels in subsection 4.2.3.2 which is applicable on the vehicular communication inside the underpass as well. However, due to relatively short length of underpass as compared to road tunnel, it is likely that only one of the transmitting or receiving vehicles is inside the underpass at the time of the communication while the other vehicle may be travelling outside the underpass. Moreover, a scenario might exist where both the communicating vehicles are present outside; on two different ends of the underpass. Therefore, a computationally inexpensive radio propagation model is needed to predict signal attenuation for underpass that caters not only for the communication inside the underpass but also accommodate the scenarios where only one or both of the communicating vehicles are outside the underpass.

Hence, three possible scenarios are to be considered when proposing the propagation formula to predict path loss for the underpasses. The three possible scenarios are;

a. Both the communicating vehicles are inside the underpass
b. Only one of the communicating vehicles is inside the underpass
c. Both the communicating vehicles are outside on two different ends of the underpass.

The approximation for the total path loss when the communicating vehicles are inside the underpass (scenario a) can be given by equation 4.9. However, equation 4.9 cannot be used to predict path loss in the situation wherein only one of the communicating vehicles is inside the underpass or wherein the communicating vehicles are communicating on the two different ends of the underpass such that the structure of the underpass resides between them.

A novel approach of calculating the effective distance $\boldsymbol{d_{eu}}$ between communicating vehicles to predict path loss for the vehicular communication in and outside the underpass is adopted in this research. The advantage in the strength of the received signal gained as a result of waveguide effect due to the structure of the underpass can be modeled by calculating the effective distance $\boldsymbol{d_{eu}}$ between the communicating vehicles. The effective distance $\boldsymbol{d_{eu}}$ is the calculated distance between the sender and receiver such that a portion of the distance travelled by the radio signal inside the underpass is subtracted from actual straight line distance $\boldsymbol{d}$ between the communicating vehicles. Therefore, the effective distance $\boldsymbol{d_{eu}}$ is always less than the actual straight line distance $\boldsymbol{d}$ between the sender and the receiver ($\boldsymbol{d_{eu} < d}$). The portion of the distance which is subtracted from $\boldsymbol{d}$ to yield $\boldsymbol{d_{eu}}$ is proportional to the area of cross-section of the underpass because the waveguide effect is phenomenal only in those tunnels/underpasses whose transverse dimensions are several times greater than the wavelength of the radio signal (Klemenschits & Bonek, 1994), (Y. P. Zhang, 2003), (Deryck, 1978). The effective distance $\boldsymbol{d_{eu}}$ is expressed in equation 4.15.

$$d_{eu} = d - l_{eu}\left(1 - \frac{\sqrt{w^2 + h^2}}{A_{cu}}\right) \qquad (4.15)$$

In equation 4.15, $\boldsymbol{l_{eu}}$ is the effective length of the underpass starting from the point where one of the communicating vehicles is present and ends at the outer edge of the underpass towards the other communicating vehicle in case when one of the communicating vehicles is inside the underpass (scenario b). However, $\boldsymbol{l_{eu}}$ equals to the exact length of the underpass in case wherein both the communicating vehicles are outside the underpass on different ends (scenario c). In equation 4.15, $\boldsymbol{w}$ and $\boldsymbol{h}$ represents the width and height of the underpass respectively and $\boldsymbol{A_{cu}}$ represents the area of cross-section of the underpass.

The total path loss $\boldsymbol{PL_{TU}}$ in scenarios b and c for the underpass can be represented by equation 4.16.

$$PL_{TU}[dB] = PL_{fs(d_{eu})}[dB] + \ F(PL_{AM}[dB]) \qquad (4.16)$$

In equation 4.16, $\boldsymbol{PL_{fs(deu)}}$ represents the free space path loss by considering $\boldsymbol{d_{eu}}$ as the distance between the sender and the receiver. Therefore $\boldsymbol{PL_{fs(deu)}}$ is expressed as under.

$$PL_{fs(d_{eu})}[dB] = 20\log_{10}(d_{eu}) + 20\log_{10}(f) + 32.44 - G_t - G_r \qquad (4.17)$$

The vehicular communication is not substantially affected by the static radio obstacles in the underpass simply because of the inexistence of static obstacle that can cause severe change in the signal attenuation. Therefore, in equation 4.16, $\boldsymbol{PL_{AM}}$ ***[dB]*** is the only additional signal attenuation components caused by the moving radio obstacles. As previously explained, $\boldsymbol{F}$ is the probability of the large moving obstacles to disturb the line-of-sight (LOS) among the communicating vehicles.

4.2.4 Computational Complexity

The calculation of additional attenuation caused by the moving radio obstacles in simulation is the most expensive step if the microscopic view of the environment is considered because it involves at least an $O(m \log m + k)$ line intersection algorithm (Chazelle & Edelsbrunner, 1992) for computing k intersections among m lines. However, in this work, the maximum signal attenuation caused by moving radio obstacles is calculated only once. The probability ***F*** of the moving obstacles to disturb LOS among communicating vehicles is multiplied with the maximum signal attenuation caused by moving obstacles in order to reasonably estimate the additional path loss. The calculation of additional attenuation due to moving radio obstacles becomes an algorithm with a constant running time. Therefore, the proposed path loss formulas for the modern road infrastructure units are light-weight in terms of computational complexity.

4.3 Optimal Positioning of RSUs/ Signal Reflectors/ Signal Repeaters on Modern Road Infrastructure Units

Maintaining LOS condition among communicating vehicles not only improves packet delivery ratio (PDR) but also adds reliability to the overall communication system. Therefore, in this subsection, optimal positioning of RSUs, signal reflectors and signal repeaters is calculated using geometrical concepts.

OBUs and RSUs in VANETs are IEEE 802.11p transceivers capable of transmitting data and control information through separate channels within the allowed frequency range. RSUs are deployed at those physical locations where the communication between vehicles to infrastructure is inevitable for specific applications or to make V2V communication more reliable by maintaining the indirect LOS conditions. Therefore, optimal positioning of RSUs in vehicular environment is a challenging task.

Metals such as silver, aluminum and stainless steel reflect radio signals. Ideally, the perfect conductors reflect radio waves incident on them without absorbing any radio power exactly like a mirror that perfectly reflects light (Stein, 1998). Simple radio signal reflectors can replace RSUs in some situations where the information exchanged between two communicating vehicles need not to be stored in intermediate nodes. Therefore, simple signal reflectors made up of nearly perfect conducting materials are useful in providing cost effective and efficient solution to maintain LOS condition among communicating vehicle’s in modern vehicular environment especially when considering modern road infrastructure units like curvatures and flyovers.

In situations where the signals from transmitting vehicle (Tx) can reach the receiving vehicle (Rx) using only reflection phenomenon, simple signal reflectors provides cost effective way of maintain LOS between Tx and Rx. Signal repeaters are used in the situations where the signal power deteriorates due to distance between Tx and Rx.

RSUs are fully functional static (stationary) transceivers that receive packets from Tx and send packet to Rx. The choice of selection of device (signal reflectors, signal repeaters, RSUs) to maintain LOS between Tx and Rx depends upon the road infrastructure unit that is currently used by the communicating vehicles. For instance, simple signal reflectors are helpful for maintaining LOS on curved roads because signals just need to be reflected in a particular direction to reach Rx. Simple signal reflectors are also useful in irregular roads. However, a flyover demands that either multiple reflectors are deployed or a signal repeater is used in order to maintain LOS between Rx and Tx which are travelling at opposite ends of the flyover. Using multiple signal reflectors reduces the signal power due to the absorption. The optimal positioning of RSUs/ signal reflectors / signal repeaters for multiple road infrastructure units are explained in the following subsections individually.

4.3.1 Optimal Positioning of Reflectors on Curved Roads

Using a simple geometrical technique, the optimal distance between the reflectors is calculated on a curve road as shown in Figure 4.6. Every curve is a part of a big circle and hence the center of the circle is easily identified. The radius of the curvature is the distance between the center of the circle and any point on the curve. A curve road contains two curves geometrically with the same center ***C***. Let $\boldsymbol{R_1}$ represents radius of curvature of outer curve and $\boldsymbol{R_2}$ represents radius of curvature of inner curve. The difference between $\boldsymbol{R_1}$ and $\boldsymbol{R_2}$ represents width ***W*** of the road segment.

$$W = R_1 - R_2 \tag{4.18}$$

Radius of the curvature for any curve can be determined using equation 4.19.

$$R = \frac{\left(1+\left(\frac{dy}{dx}\right)^2\right)^{3/2}}{\frac{d^2y}{dx^2}} \tag{4.19}$$

D represents the optimal distance between the two reflectors *A* and *B* on the curve road. It is clear from Figure 4.6 that $\boldsymbol{R_2}$ is perpendicular to line ***D***, therefore two right angled triangles are formed. Using the simple Pythagorean Theorem, the distance ***x*** between *A* and *E* is calculated. The optimal distance ***D*** is 2 times x because $\boldsymbol{R_2}$ meets line *D* at the middle point of *D*. Equation 4.20 represents the optimal distance using Pythagorean Theorem. It is noted that a quantity $\mathcal{E}$ is subtracted from the calculated distance because Line D is not tangent to inner curve of the road with radius of curvature $\boldsymbol{R_2}$. The value of $\boldsymbol{\mathcal{E}}$ depends upon the radius of width ***W*** of the curved road.

$$D = 2\sqrt{R_1^2 - R_2^2} - \mathcal{E} \tag{4.20}$$

If the angle A or angle C is known, equations 4.21 and 4.22 give the optimal distance ***D*** between two reflectors at point A and B respectively.

$$D = R_1\sqrt{2(1 - \cos C)} - \mathcal{E} \tag{4.21}$$

$$D = 2\,R_1 \cos A - \mathcal{E} \tag{4.22}$$

The three variants (equations 4.20, 4.21 and 4.22) use different information to calculate the optimal distance between reflectors but produce the same result for a specific scenario.

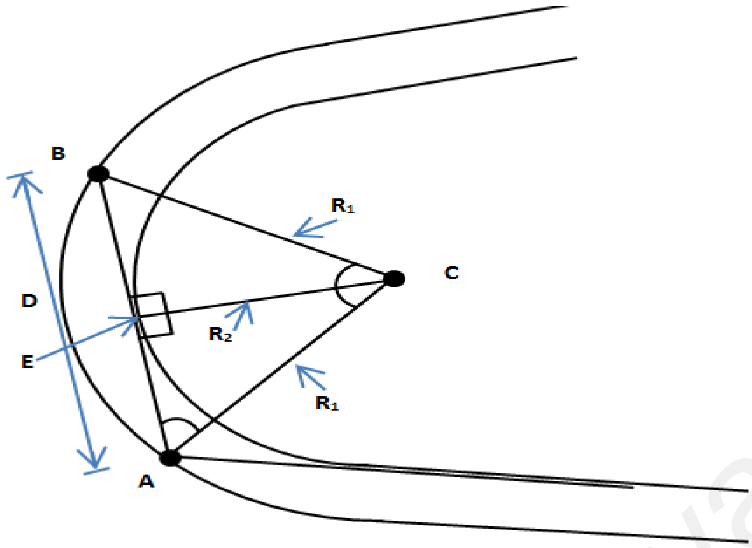

Figure 4.6: Optimal Positioning of Signal Reflectors on Curved Road

4.3.2 Optimal Positioning of Signal Repeaters / RSUs on Flyover

Any radio obstacle that lies within 60% of the first Fresnel's zone has the tendency to obstruct radio signals (Boban, et al., 2011). Flyover itself behaves like a radio obstacle for the vehicles that are travelling on opposite ends of it. A vehicle attains height gradually as it starts using flyover and keeps on doing so until the highest point on the flyover is reached. On the other hand a vehicle after attaining the maximum height on the flyover, start descending and gradually reaches the ground level. So a simple signal reflector is not appropriate in the case of flyover. A signal repeater mounted at the highest point which is in LOS with the vehicles at both ends of flyover is needed to repeat the radio signals. The height of the signal repeater is determined so that the two vehicles at the opposite ends of the flyover are in LOS with each other as shown in Figure 4.7.

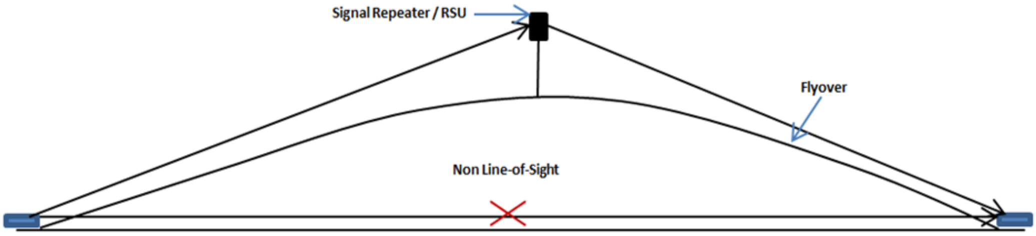

Figure 4.7: Optimal Positioning of Repeater/ RSU on Flyover

4.3.3 Optimal Positioning of Reflectors / Signal Repeaters / RSUs in Road Tunnels

The path loss in the straight tunnels is relatively less than the path loss in free space probably due to waveguide effect inside the tunnel. Therefore, the optimal distance between the reflectors / signal repeaters / RSUs is relatively large in tunnels as compared to the straight roads and is dependent upon AOD. However, the signal strength abruptly decreases in case of a curve inside a tunnel. The simple signal reflectors are recommended to be used inside the curved tunnels. Hence the optimal positioning of reflectors for the curved roads inside the tunnels is calculated in the same way as in case of curved road except the value of Ɛ. The value of Ɛ is kept relatively larger in tunnels as compared to open curved roads. The larger the value of $\mathcal{E}$, the smaller is the distance between two reflectors. So the distance between the reflectors to maintain LOS inside a curved tunnel is relatively less as compared to open curved roads.

4.3.4 Optimal Positioning of Reflectors / Signal Repeater / RSUs in Underpasses

An underpass is a type of small road tunnel to provide signal free junctions in modern urban and highway environments. Therefore, the same concept of signal propagation in road tunnels can be applied on underpasses. The length of the underpass depends upon the width of the road segment under which an underpass is built. Hence, due to very small length of underpass (20 meters to 60 meters) signal reflectors / signal repeaters /RSUs are not required inside an underpass. However a gain in RSS is expected for the vehicles communicating inside an underpass.

4.3.5 Optimal Positioning of Reflectors / Signal Repeater /RSUs on Irregular Roads

The optimal positioning of reflectors, signal repeater and RSUs on irregular roads depends upon the angular difference between the two streets. If the angular difference between two adjacent streets is less than a predefined threshold value (typically set to 45 degrees), a simple signal reflector positioned at the meeting point of two road segments is recommended. However, if angular difference exceeds the threshold value, a signal repeater is utilized to maintain LOS between the vehicles travelling on different streets. In case of an irregular junction, an RSU is recommended to be deployed at the entry point on the junction in order to maintain LOS among communicating vehicles. Figure 4. 8 and Figure 4. 9 explain the conditions of positioning of simple signal reflector, signal repeater respectively.

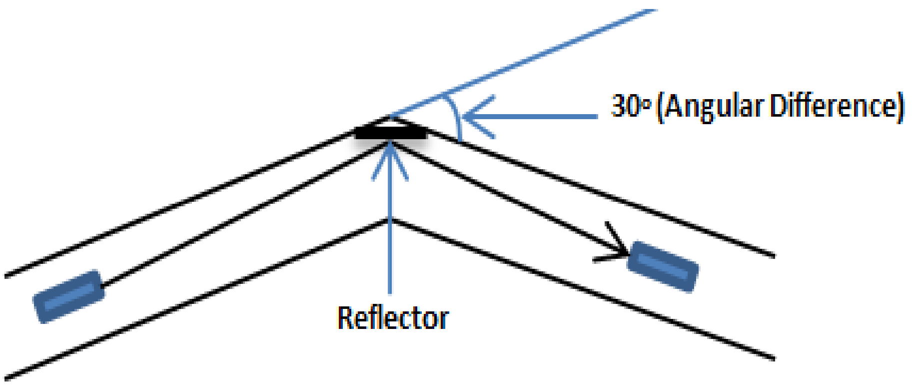

Figure 4. 8: Angular difference less than threshold

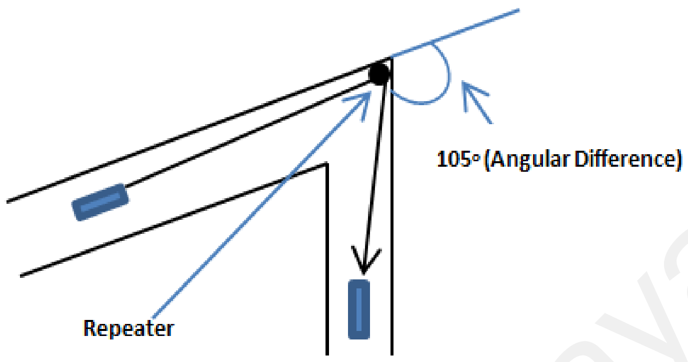

Figure 4. 9: Angular difference greater than threshold

4.4 Conclusion

In this chapter, an adaptive radio propagation model for VANETs is proposed. Existing radio propagation models in VANETs do not contemplate modern road infrastructure units and lack in considering all type of radio obstacles. The distinctive features of ARPM are the adaptability in consideration of modern road infrastructure units in the prediction of signal attenuation along with the static and moving radio obstacles and the component rating of each individual component that affects the radio propagation. Multiple propagation formulas are proposed for individual road infrastructure units in order to accurately predict the path loss using minimum possible number of computations. The modular architecture of ARPM allows an application to efficiently select an appropriate scenario (components that affect signal propagation in a particular traffic environment) among multiple scenarios to predict signal attenuation. The incorporation of static and moving obstacle modeling with the adaptive selector allows an accurate prediction of path loss estimation. Therefore, it is concluded that ARPM provides realistic solution for the prediction of signal attenuation in modern VANETs.

Moreover, the guidelines for deployment RSUs, signal reflectors and signal repeaters using simple geometric properties of modern road infrastructure units are also provided in order to provide a reliable communication infrastructure for VANETs.

CHAPTER 5: EVALUATION AND COMPARISON

5.1 Introduction

This chapter reports on the data collection method for the evaluation of proposed ARPM along with the discussion about the results. The comparison of ARPM in terms of RSS, path loss and PDR is also presented in this chapter. It explains the tools used for testing the proposed solution, data collection technique and the statistical method used. The chapter is organized into six sections. Section 5.2 explains the evaluation model used for assessment of the proposed ARPM. Section 5.3 explains the experimental setup and programming tools used for the implementation and testing of the proposed ARPM and presents the evaluation of the proposed ARPM in multiple road infrastructure units. Section 5.4 summarizes the comparison of ARPM with state-of-the-art widely used radio propagation models in VANETs. Section 5.5 presents the evaluation of optimal positioning of RSUs in modern road infrastructure units. Finally, section 5.6 extracts the conclusive remarks.

5.2 Evaluation Model

The proposed ARPM provides a realistic and computationally inexpensive solution for the prediction of signal attenuation in VANETs for underlying modern road infrastructure units. The significance of proposed ARPM is evaluated by using real-world data gathered on multiple physical sites and elaborated using the simulations. Experimental results are validated by utilizing real-world data for each individual modern road infrastructure unit. A custom-built application is developed which is used to simulate multiple real world scenarios on larger scale (having large number of communicating nodes). Optimal positioning of RSUs in multiple real-world scenarios is tested and the impact of optimal positioning of RSUs on signal attenuation is figured out. The predicted signal attenuation by using ARPM is analyzed from the perspective of RSS and PDR. Empirical results of Applying ARPM are compared with existing radio propagation models to validate the significance of the proposed solution. Figure 5. 1 represents the evaluation model used in this research work. The evaluation is divided into three categories;

- Small scale evaluation
- Large scale evaluation
- Evaluation of the optimal positioning of RSUs

The following subsection explains the above mentioned evaluations.

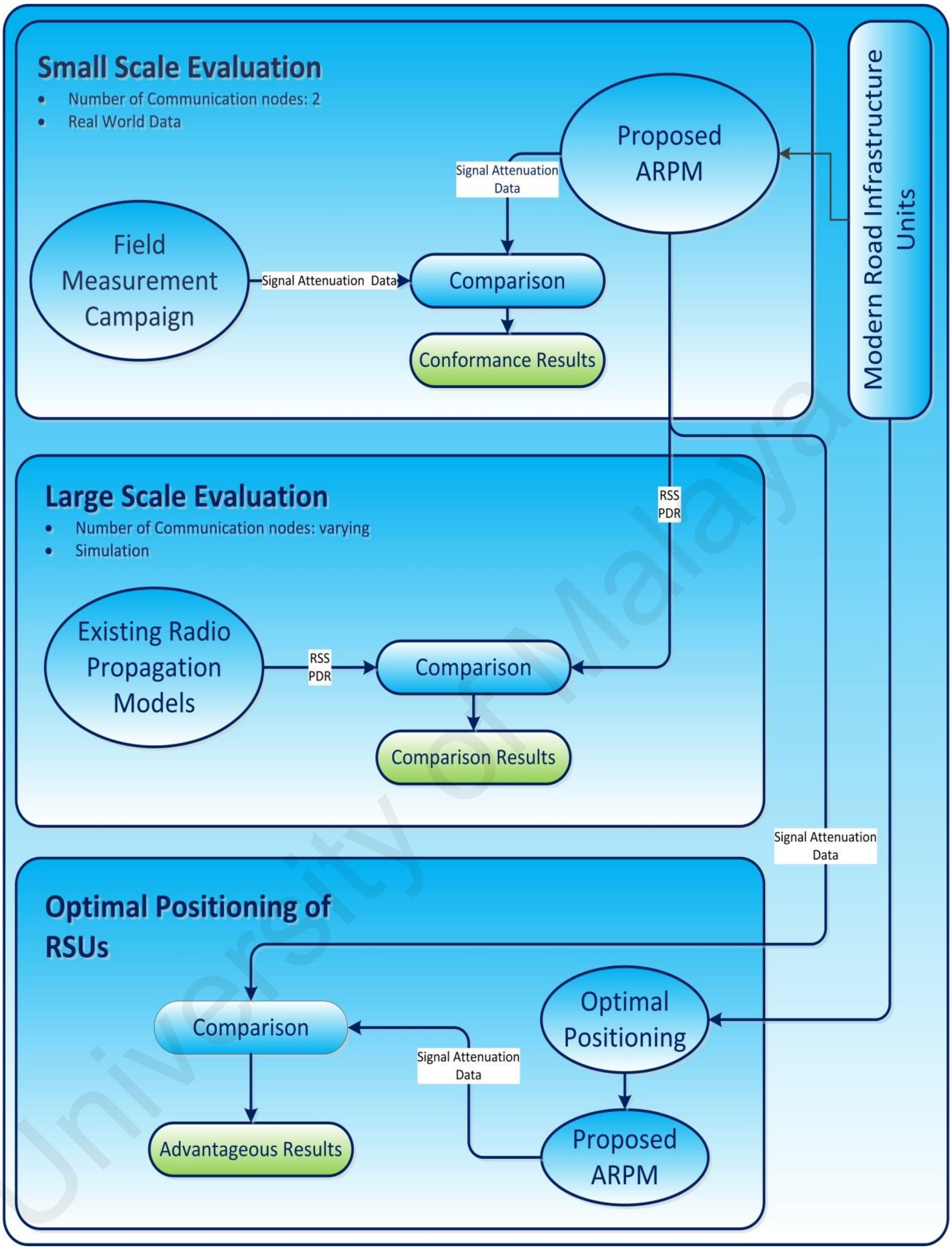

Figure 5. 1: Evaluation Model

5.2.1 Small Scale Evaluation

The evaluation of the proposed ARPM is accomplished in a small scale by using the RSS data obtained from field measurement campaigns at different physical locations. Two communicating vehicles equipped with transceivers (suitable for vehicular communication) were driven in multiple sites containing modern road infrastructure units during the field measurement campaigns. All the selected physical sites for the field measurements were busy roads having varying traffic densities during different timings throughout the day. Although, the number of communicating vehicles were limited in the field experiments but the data collected from these campaign carry significant importance in the evaluation of the proposed ARPM. The data obtained from the field experiments are compared with the results of the proposed ARPM in order to evaluate the level of conformance between the actual data (signal attenuation) and the proposed model.

In the data gathering campaigns, the communicating nodes consist of Intel Dual Band Wireless-N 7265 wireless adapter connected to a D-Link ANT70-0800 antenna that provided a gain of 10dBi at 5Ghz. The antenna was connected with the wireless device using a cable of length 3 m and approximately 3 dB loss. We utilize Garmin GPS 18x USB receiver for locating the position of nodes. The vehicles used in the experiments were Honda city 2007 (height: 1495 mm) and Suzuki Mehran (height: 1410 mm). The antenna and the GPS receiver were mounted on the roof of the vehicles.

For the validation of the proposed ARPM, we utilized an evaluation metric called average accuracy of prediction. The average accuracy of prediction expresses the degree of correctness of the proposed model by comparing a predicted value with a measured value. Equation 5.1 represents the average accuracy of prediction where n denotes the total number of data values compared.

$$Average\ Accuracy = \frac{1}{n}\sum_{i=1}^{n}\frac{Predicted\ value_i}{Measured\ value_i}\ x\ 100 \tag{5.1}$$

Further, the coefficient of determination ($\boldsymbol{R^2}$) is used as another evaluation tool to determine the proportion of variability in some of the data sets that is accounted for by the proposed model.

5.2.2 Large Scale Evaluation

Simulation provides a cost effective way to evaluate a proposed model on large scale. To evaluate the proposed ARPM, multiple simulators were used to accommodate for the real road traffic environment within the simulation. Multiple traffic densities and varying number of communicating nodes are considered in the simulation environment. The total number of communicating vehicles ranging from 100 vehicles to 150 vehicles is simulated for each road infrastructure unit along with the varying number of moving radio obstacles.

Simulation of Urban Mobility (SUMO) was used as traffic simulator that facilitates the modelling of intermodal traffic systems. The physical sites selected for field measurements are reproduced in simulation environment by importing the road topologies from the web-based OpenStreetMap utility into the traffic simulator SUMO. We utilized TraNSLite to convert the output of SUMO into mobility traces which are further fed to the custom-built Java Discrete Event Simulator (JaDES). JaDES is developed to scans the output from SUMO/TraNSLite and applies the formulations proposed in ARPM for various road infrastructure units. We utilized JaDES as a network simulation platform to simulate radio propagation in physical layer and the results are produced based in terms of RSS, path loss and PDR.

Widely used radio propagation models (free space path loss model, two ray ground model and CORNER) and proposed ARPM were implemented in the simulation environment. A comparison is made among the existing RPMs and the proposed ARPM on the basis of RSS, path loss and PDR. Therefore, large scale evaluation in this work is used mainly for the comparison of the proposed ARPM with the existing radio propagation models in VANETs

5.2.3 Evaluation of the Optimal Positioning of RSUs

The evaluation of the optimal positioning of RSUs in multiple modern road infrastructure units is also performed. The impact of optimal positioning of RSUs in terms of signal attenuation is determined using the proposed ARPM. The amount of gain in RSS due to the optimal positioning of RSUs in different road infrastructure units is compared with the RSS values in the absence of RSUs. We utilized PDR as another performance metric in order to observe the impact of optimal positioning of RSUs on modern road infrastructure units. Hence, the positive effects of optimal positioning of RSUs are evaluated.

5.3 Evaluation of the Proposed ARPM

This section elaborates the evaluation of the proposed ARPM in multiple road infrastructure units, namely;

- Straight Road
- Confined Curved Road
- Road Tunnel
- Flyover

- Underpasses.

For the small scale evaluation, the field measurements of signal attenuation in road tunnel are taken at 5 GHz, therefore, the results are equally applicable to predict the radio propagation properties at 5.9 GHz which is widely adapted frequency band in VANETs.

5.3.1 Evaluation of proposed ARPM in Straight Road

This subsection elaborates the evaluation of the path loss formula as a part of proposed ARPM in straight road. An extensive data gathering campaign was carried out at Islamabad Highway (Capital territory, Pakistan, latitude: 33.6779224, longitude: 73.0769473) using 802.11 n WiFi devices configured at 5 GHz. The Islamabad Highway is a 28 km straight road having multiple sections that can be categorized on the basis of type of vehicles, width of the road and magnitude of traffic load during different timings around the clock. For instance, one section of the road (Section B) is expanded into a 10-lanes signal free expressway with two lanes dedicated to heavy traffic on each side of the road. Another section of the road (Section A) is a 6-lane highway which mostly used by urban vehicles (passenger cars and SUVs) as the heavy traffic (delivery trucks) is banned to enter during the day time. We utilized both sections of the highway for the data gathering campaign.

5.3.1.1 Measurement Scenarios

Multiple tests were conducted using different arrangements of the communicating vehicles while driving on multiple sections of the highway. In the simplest arrangement, one vehicle (Tx) was parked beside the left lane and the RSS was measured using the other vehicle which is driven at very low speed on the left lane. In another scenario, the

RSS is measured while Tx was stationary and vehicle (Tr) was driven at 40 km/hr. Both vehicles were driven at same speed (30 km/hr on section A) while maintaining a distance of 150 meters from each other. The same test is repeated by driving both the vehicles on section B of the highway to observe the impact of moving radio obstacles on the RSS as the section B has a large frequency of heavy traffic (delivery trucks and large buses) during the day time as compared to the section A of the highway. In one of the arrangements, both vehicles were driven at variable speeds is such a manner that one vehicle approaches the other vehicle with greater speed and then overtakes it for the rest of measurement.

Table **5. 1** shows the multiple scenarios used for the measurement of RSS on straight road.

Table 5. 1: Measurement Scenarios in straight road experiment

Scenario	Tx Speed	Tr Speed	Updation	Inter-vehicular Distance	Road Section	Orientation
SSC_1	Stationary	5 km/hr	1 meter	Variable	A	Tr going away from Tx
SSC_2	Stationary	40 km/hr	5 meters	Variable	A	Tr going away from Tx
SSC_3	30 km/hr	30 km/hr	~8 meters	150 meters	A	A constant distance is maintained
SSC_4	30 km/hr	30 km/hr	~8 meters	150 meters	B	A constant distance is maintained
SSC_5	30 km/hr	60 km/hr	~8 meters	variable	B	Tr approaching Tx and then going away

5.3.1.2 Experimental Results (Straight Road)

This subsection presents and discusses the experimental results obtain from field measurement campaign on straight road. The communication performance was measured and analyzed under different measurement scenarios in order to ascertain the effects that cause major change in the signal attenuation. The communication performance was analyzed using the measured RSS as a function of distance between the communicating nodes.

Figure 5. 2 shows the RSS in dBm as measured in SSC_1. A clear deterioration in RSS is observed as the distance between the communicating vehicles increased. A gradual degradation in RSS is observed as the Tr moved further away from Tx. As the measurement in SSC_1 is carried out in section A of the highway where the propagation is least affected by the large moving vehicles, therefore, no abrupt change in RSS due to the presence of moving radio obstacles is observed in SSC_1.

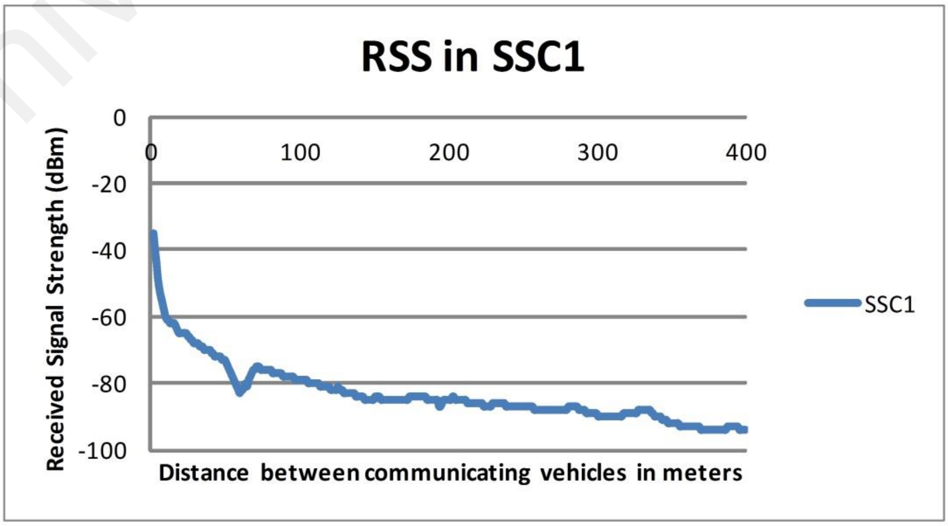

Figure 5. 2: RSS in SSC_1

In another arrangement (SSC2), the RSS values are recorded by driving the Tr with slightly high speed (40 km/hr) as compared to SSC1. The degradation in RSS in SSC_2 is shown in Figure 5. 3. No major change in RSS in SSC2 is observed as compared to SSC1 except a slightly abrupt deterioration probably caused by a high-roof SUV close to the Tx at one occasion during the test. The deterioration in RSS due to the moving radio obstacle can be seen in Figure 5. 3 when the distance between the communicating vehicles is approximately 250 meter.

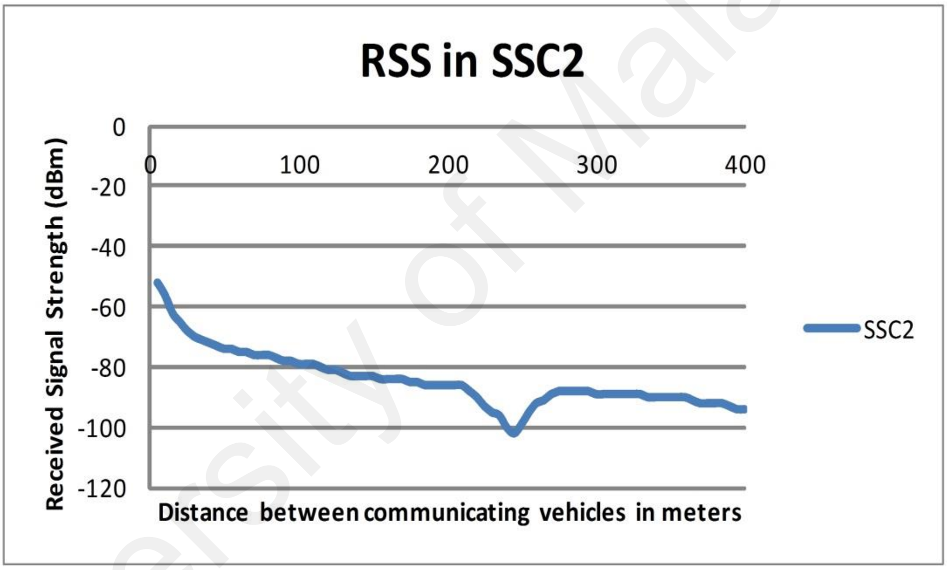

Figure 5. 3: RSS in SSC_2

In another measurement scenario (SSC3), Tx and Tr were driven on section A of the straight highway while maintaining a constant distance of 150 meters between them. The major portion of the traffic in section A of road comprises of passenger cars, so, the Tr and Tx maintained the LOS with each other for the entire 800 meters during the drive. Therefore, no notable change in the RSS is observed in SSC3 as shown in Figure 5. 4.

The same test (in SSC_3) is repeated for the section B of the highway to check the impact of large moving vehicles on the communication between Tx and Tr. As, the section B of the highway has a relatively very high frequency of large moving vehicles (delivery trucks and busses) as compared to section A, so, the LOS between the communicating vehicles is bound to be disturbed due to the presence of moving radio obstacles. Hence, for SSC_4, an abrupt deterioration in the RSS due to the NLOS scenario is observed more than once, during the 800 meters journey of Tx and Tr as show in Figure 5. 4.

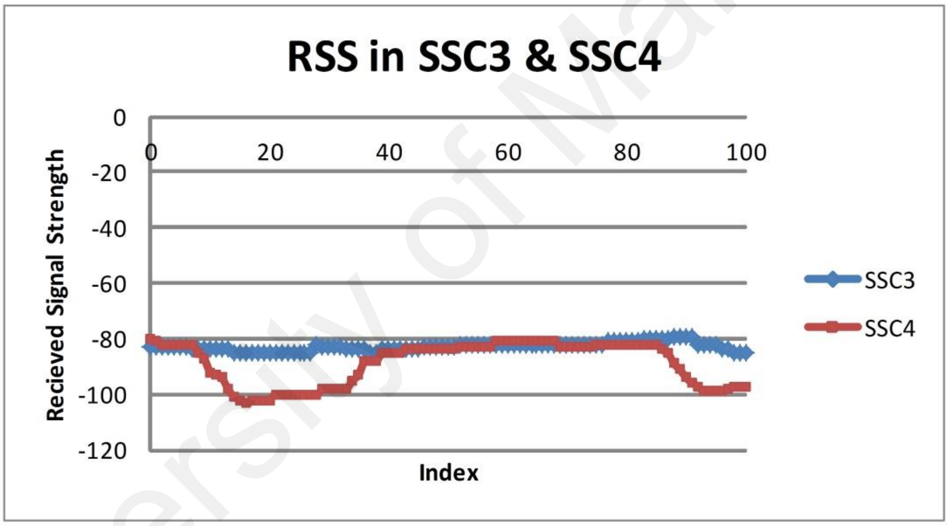

Figure 5. 4: RSS in SSC_3 and SSC_4

In another arrangement (SSC_5), both the communicating vehicles were driven at variable speeds in such a manner that initially Tx was 150 meters ahead of Tr. The inter-vehicular distance began to reduce as Tr (with greater speed: 60 km/hr) started to approach Tx (with lesser speed: 30km/hr). Tr approximately covered 16 meters every second while Tx only covered 8 meters in each second. The communicating vehicles were in LOS with each other during the whole test. Due to the reduction in inter-vehicular distance with the passage of time, the RSS started to increase as Tr approached Tx. The RSS increased to a maximum level and then started to deteriorate as the Tr passed Tx and inter vehicular distance again increased. The change in RSS in SSC_5 is shown in Figure 5. 5.

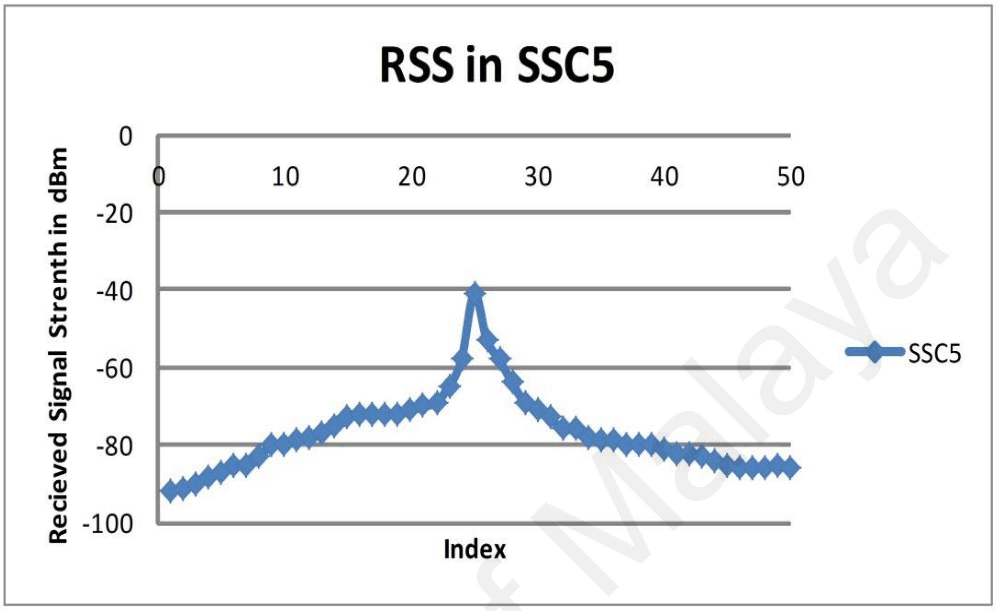

Figure 5. 5: RSS in SSC_5

5.3.1.3 Validation (Straight Road)

This subsection explains the effectiveness of the portion of proposed ARPM for straight road in the prediction of the path loss.

The proposed RPM for straight road is validated by comparing the predicted path loss with the data obtained from the field measurement campaign on highway (straight road). The RSS values from the real-world testing in multiple scenarios are converted to the path loss and compared with the predicted path loss using the formulas given in section 4.2.3.1 as a part of the proposed ARPM. The predicted path loss values for the straight road are compared with the measured results in multiple scenarios to validate the proposed formulas designed specifically for the straight road.

The increase in the predicted path loss with the increase in inter-vehicular distance is monitored and compared with measurement values of the path loss on straight road. A comparison among the measured results obtained from the field measurement campaign in one of the scenarios and the predicted path loss using the formulas given in section 4.2.3.1 is shown in Figure 5. 6.

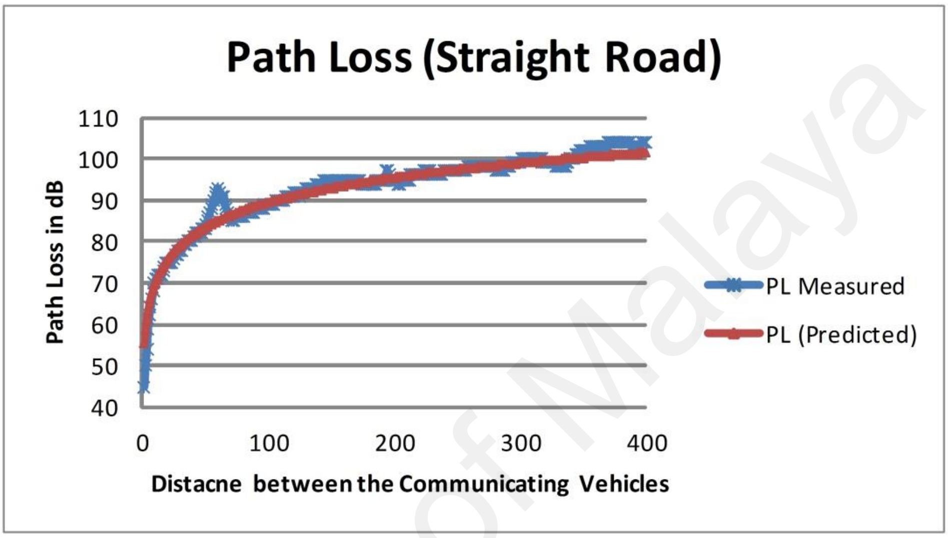

Figure 5. 6: Path Loss (Straight Road)

A close agreement exists among the measured and predicted values of path loss on straight road as shown in Figure 5. 6. The R^2 value as obtained by the statistical analysis yield **0.96**; hence, confirming the applicability of the proposed ARPM to predict path loss in straight road for vehicular communication. A residual analysis on the path loss data was also performed and no clear pattern was observed. Furthermore, a phenomenal average accuracy of **98%** was observed when the predicted path loss values were compared with the measured path loss values. The R^2 value, the residual analysis and the average accuracy reaffirmed the suitability of the proposed ARPM to predict path loss on flyovers for the frequency band suitable for VANET environment.

5.3.2 Evaluation of proposed ARPM in Curved Roads

This subsection presents the evaluation of the path loss formula as a part of proposed ARPM in curved road. A considerable data gathering campaign was carried out at Peshawar Road (Rawalpindi, Pakistan, latitude: 33.615728, longitude: 72.9949632) using 802.11 n WiFi devices configured at 5 GHz. The selected curved road is a part of a busy interchange that connects the twin cities (Rawalpindi and Islamabad) with each other. The above mentioned curved road is confined with concrete walls on both sides which serve as potential static radio obstacles. Therefore, this curved road is selected for the RSS measurement campaign to observe the amount of path loss that prevails due to the emergence of NLOS scenario. The selected curved road is 120 meters long and approximately 8 meters wide that connects two straight roads

5.3.2.1 Measurement Scenarios (Curved Roads)

Like the measurement scenarios for other road infrastructure units, multiple tests were conducted using different arrangements of the communicating vehicles while driving on selected curved road as well. In the first arrangement, the vehicle (Tx) was parked beside the left lane just before the curve and the RSS was measured using the other vehicle (Tr) which is driven at very low speed (5 km/hr) along the curve to carefully record the RSS values. In the next scenario, the same test is repeated while Tx was stationary and vehicle (Tr) was driven at 40 km/hr. In the 3rd scenario (CSC_3), both the vehicles were driven at same speed (20 km/hr) while maintaining a distance of 30 meters from each other such that the vehicles remain in LOS with each other during the test. The arrangement of CSC_3 is repeated in CSC_4 by driving both the vehicles with the same speed while maintaining a distance of 60 meters between them such that an NLOS condition may arise between the communicating vehicles. In one of the arrangements, both vehicles were driven at variable speeds in such a manner that Tr approaches Tx with greater speed and then overtakes it for the rest of test. Specific markers at road side were utilized to calculated road distance between communicating vehicles as opposed to straight line distance obtained from GPS device. Table 5. 2 shows the multiple scenarios used for the measurement of RSS on curved road.

Table 5. 2: Measurement Scenarios in Curved road experiment

Scenario	Tx Speed	Tr Speed	Updation	Inter-vehicular Distance	Orientation
CSC_1	Stationary	5 km/hr	1 meter	Variable	Tr going away from Tx
CSC_2	Stationary	30 km/hr	5 meters	Variable	Tr going away from Tx
SSC_3	20 km/hr	20 km/hr	~5 meters	40 meters	A constant distance is maintained
SSC_4	20 km/hr	20 km/hr	~5meters	60 meters	A constant distance is maintained
SSC_5	15 km/hr	30 km/hr	~5 meters	variable	Tr approaching Tx and then going away

5.3.2.2 Experimental Results (Curved Road)

This subsection presents and discusses the experimental results obtain from field measurement campaign on the curved road. Communication performance was analyzed using the measured RSS as a function of distance between the communicating nodes. Due to the curved nature of the road, the straight line distance between the communicating vehicles is less than the road distance travelled by the vehicles. Like other road infrastructure units, multiple arrangements of vehicles were considered in the data gathering campaign in order to identify and analyze the factors that cause the change in RSS.

Figure 5. 7 shows the RSS in dBm as measured in the scenario SSC_1. A sudden deterioration in RSS (15 dBm to 20 dBm) is observed as the distance between the communicating vehicles reached approximately 55 meters. The abrupt decrease in RSS is due to the introduction of NLOS condition after Tr travelled 55 meters along the curved path. A gradual degradation in RSS is observed as the Tr moved further away from Tx. As, the measurement in CSC_1 is carried out in a sharp bend confined with concrete structures at both sides of the road, therefore, the structure of the road itself acted as a potential static radio obstacle. Hence, a large degradation in RSS is observed in the specific curved road as compared to the signal deterioration in other road infrastructure units. It is obvious from Figure 5. 7, that after travelling a merely 90 meters from the source, the connection is lost between the communicating vehicles because the deterioration in RSS is immense resulting from NLOS condition.

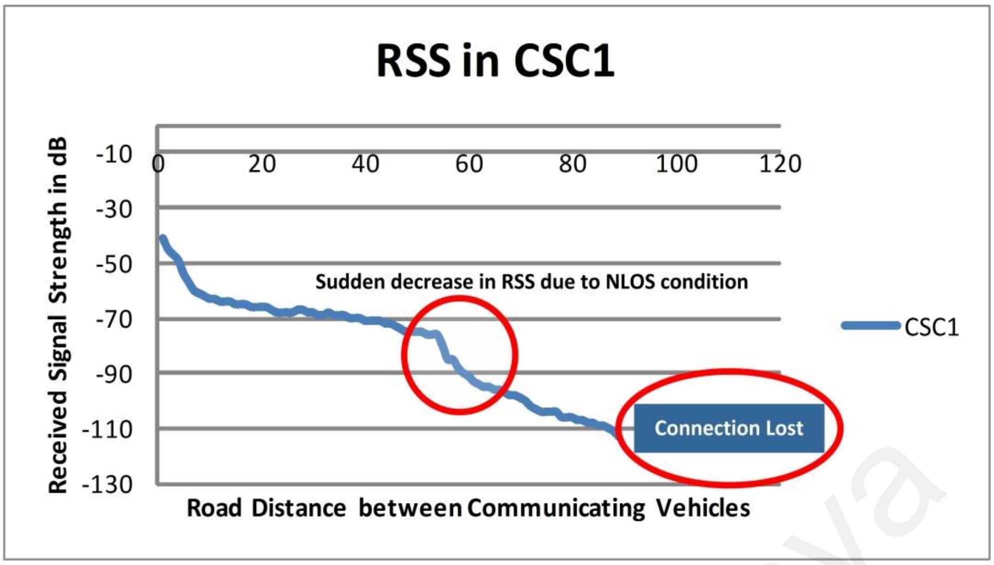

Figure 5. 7: RSS in CSC_1

The arrangement of vehicles in CSC_1 is repeated in CSC_2 with the exception of Tr speed. The node Tr is driven with relatively high speed in CSC_2 as compared to CSC_1. The speed of the vehicles in the legitimate range (street legal) seems to have no effect on the signal attenuation in prescribed frequency band for VANETs. Therefore, the results obtained in CSC_2 are conformed to the measurement results in CSC_1. The measurement results in CSC_2 show a steep deterioration in RSS when the communicating vehicles are no longer in LOS with each other complementing the measurements in CSC_1. The connection between Tx and Tr is also lost in CSC_2 as the radio signals are obstructed by the concrete structure that surrounds the curved road. Figure 5. 8 presents the RSS in dBm as measured in CSC_2.

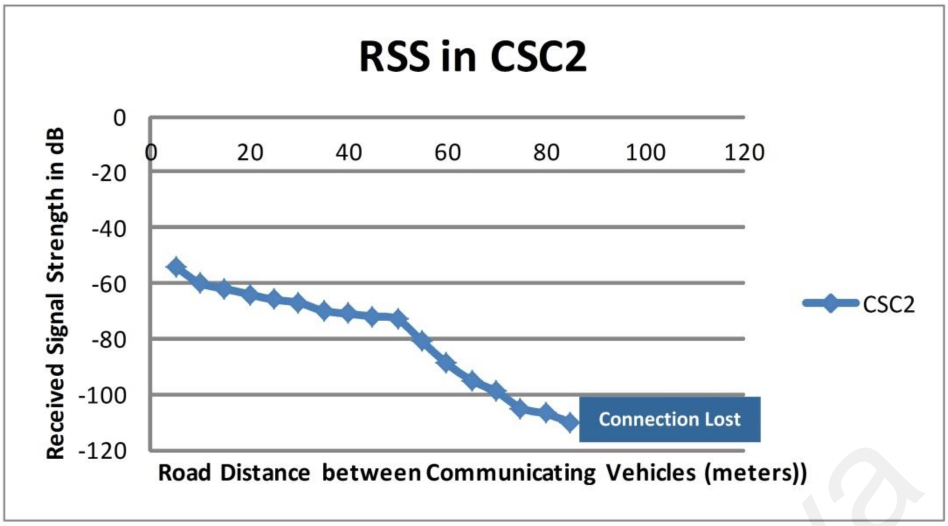

Figure 5. 8: RSS in CSC_2

In order to develop a deep understanding about the effect of NLOS condition on the signal attenuation, the next two arrangements of communicating vehicles were planned and executed. The vehicles Tx and Tr were driven by maintaining an inter-vehicular distance of 40 meters in CSC3. However, the inter-vehicular distance between Tx and Tr was increased to 60 meters in CSC4. In CSC3, both the communicating vehicles maintained LOS with each other throughout a total travel distance of 200 meters along the curved path. Therefore, no sudden deterioration in RSS is observed in CSC3. The change in RSS as the vehicles move along the curved road maintaining a constant distance between them is shown in Figure 5.9.

However, totally different results are obtained in the scenario CSC_4 due to the introduction of NLOS condition. The measurement started in CSC_4 when Tx was on the edge of the curved road while Tr was 60 meters behind Tx on the connecting straight road. Therefore, the communicating vehicles were in LOS with each other at the start of the test. However, the vehicles lost the LOS as Tx committed to take the sharp curve along the curved road. A steep degradation (15 dBm to 20 dBm) was observed due to

NLOS condition along the curved path as shown in Figure 5.9. The communicating vehicles again came in LOS with each other after completing the curve.

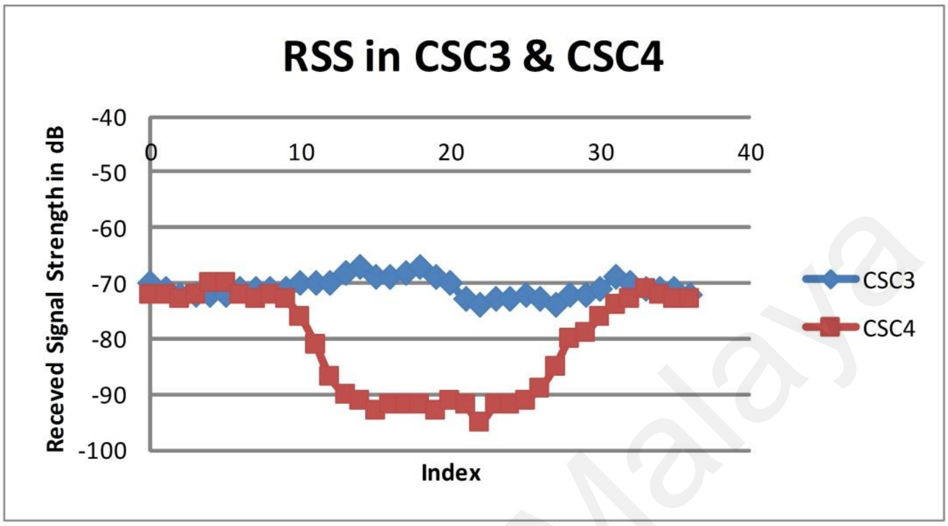

Figure 5.9: RSS in CSC_3 and CSC_4

In another arrangement of communicating vehicles (CSC_5), both Tr and Tx were driven at variable speeds in such a manner that initially Tx was 60 meters ahead of Tr just before the edge of the curved road. The inter-vehicular distance began to reduce as Tr (with greater speed: 30 km/hr) started to approach Tx (with lesser speed: 15km/hr). Tr approximately covered 8 meters every second while Tx only covered 4 meters in each second. It is interesting to note that the communicating vehicles maintained LOS with each other during the whole test in which they cover 220 meters. Due to the reduction in inter-vehicular distance with the passage of time, the RSS started to increase as Tr approached Tx along the curved road. The RSS increased to a maximum level and then started to decline as the Tr passed Tx and inter vehicular distance again increased. The change in RSS as both the vehicles having different speeds moved along the curved road observed in CSC_5 is shown in Figure 5.10.

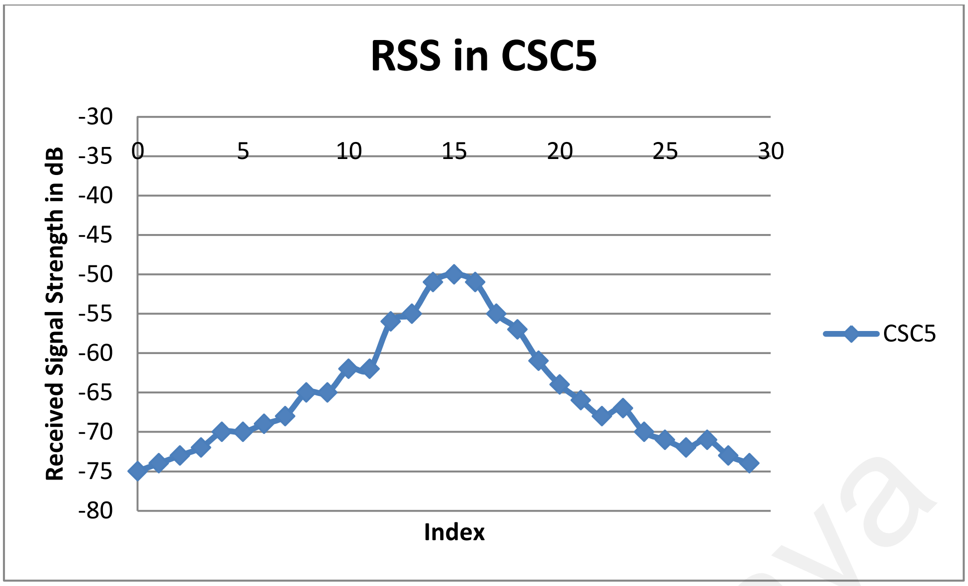

Figure 5.10: RSS in CSC_5

5.3.2.3 Validation (Curved Road)

This subsection explains the effectiveness of the portion of proposed ARPM for curved road in the prediction of the path loss.

The proposed RPM for curved road is validated by comparing the predicted path loss with the data obtained from the field measurement campaign on the selected curved road. Like the validation for other road infrastructure units, the RSS values from the real-world testing in multiple scenarios are converted to the path loss and compared with the predicted path loss using the formulas given in section 4.2.3.1 as a part of the proposed ARPM for curved roads. The predicted path loss values for the straight road are compared with the measured results in multiple scenarios to validate the proposed formulas designed specifically for the curved road.

The increase in the predicted path loss with the increase in inter-vehicular distance is observed and compared with measurement values of the path loss on curved road. Both LOS and NLOS conditions resulting in different path loss values are considered. A comparison among the measured results obtained from the field measurement campaign in one of the scenarios for curved road and the predicted path loss using the formulas given in section 4.2.3.1 is shown in Figure 5. 11.

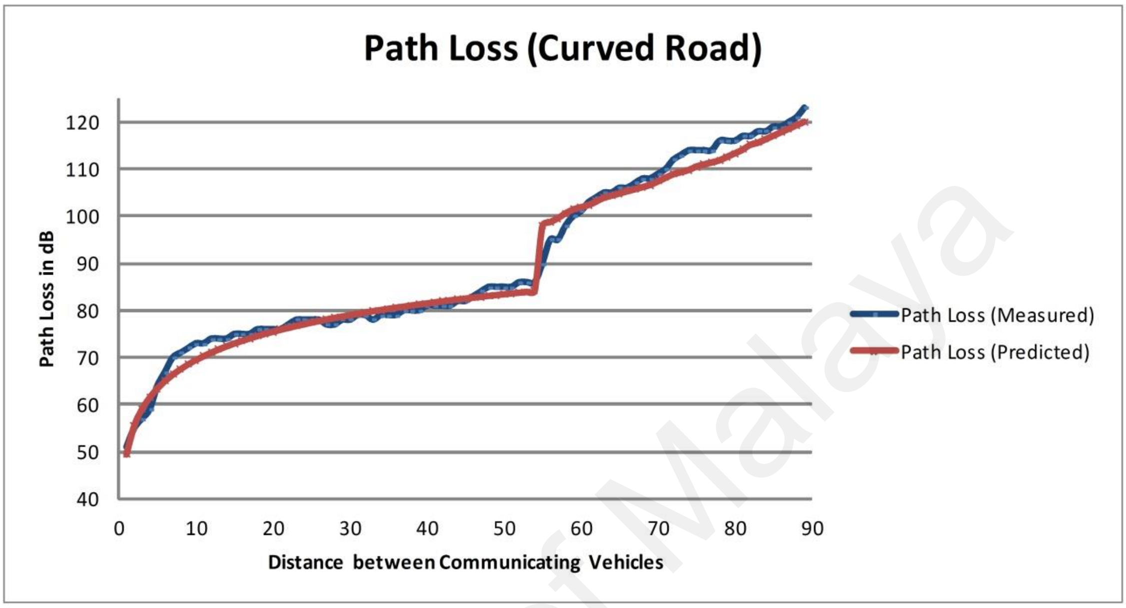

Figure 5. 11: Path Loss in Curved Road (Measured vs Predicted)

A close agreement exists among the measured and predicted values of path loss on selected curved road as shown in Figure 5. 11. The R^2 value as obtained by the statistical analysis yield **0.98**; hence, confirming the applicability of the proposed ARPM to predict path loss in straight road for vehicular communication. A residual analysis on the path loss data was also performed and no clear pattern was observed. Furthermore, a phenomenal average accuracy of **98%** is calculated by comparing predicted path loss values with the measured path loss values. The R^2 value, the residual analysis and the average accuracy reaffirmed the suitability of the proposed ARPM to predict path loss on curved road for the frequency band suitable for vehicular communication.

5.3.3 Evaluation of proposed ARPM in Road Tunnels

This subsection elaborates the evaluation of the proposed ARPM in road tunnels. An extensive data gathering campaign was carried out in Kohat tunnel (Khyber Pakhtunkhawa, Pakistan, latitude:33.6570 longitude:71.5420) using 802.11 n WiFi devices configured at 5 GHz. The Kohat tunnel is nearly a straight tunnel having length: 1.9 Km, width: 10.3 m, and height: 6 m. The Kohat tunnel is a part of national highway that connects the Khyber Pakhtunkhawa province with rest of the country.

5.3.2.1 Measurement Scenarios (Road Tunnel)

Multiple tests were conducted using different arrangements of the communicating vehicles. In the simplest arrangement, one vehicle (Tx) was parked inside the tunnel and the RSS was measured using the other vehicle at every 50 meters distance. At certain points during the field testing campaign, GPS signals were lost due to lack of inter-visibility with GPS satellite. Therefore, the vehicle tachometer was used manually to measure the distance among the communicating nodes on the points where no valid GPS signal was detected. In another scenario, the RSS is measured while Tx was stationary and vehicle (Tr) was driven at 40 km/hr and the test is repeated at 60 km/hr. In one of the arrangements, both vehicles were driven at variable speeds is such a manner that one vehicle approaches the other vehicle with greater speed and then leaves it behind for the rest of test. Table 5. 3 shows multiple scenarios used for the measurement of RSS inside the tunnel.

Table 5. 3: Measurement Scenarios in Road Tunnel Experiment

Scenario	Tx Speed	Tr Speed	Updation	Orientation
$RTSC_1$	Stationary	Stationary	50 meters	Tr going away from Tx
$RTSC_2$	Stationary	40 km/hr	1 meter	Tr going away from Tx
$RTSC_3$	Stationary	70 km/hr	1 meter	Tr going away from Tx
$RTSC_4$	Stationary	54 km/hr	15 meters	Tr going away from Tx
$RTSC_5$	Stationary	72 km/hr	20 meters	Tr going away from Tx
$RTSC_6$	30 km/hr	60 km/hr	10 meters	Tr approaching Tx and then going away

5.3.2.2 Experimental Results

This subsection presents and discusses the experimental results obtain from field measurement campaign in road tunnel. The communication performance was measured and analyzed under different measurement scenarios is order to identify the effects that cause major change in the signal attenuation. Another reason of analyzing communication performance was to neglect the effects that do not have significant impact on the path loss. The communication performance was analyzed using the measured received signal strength (RSS) as a function of distance between the communicating nodes. In order to summarize the results, we utilized path loss in dB as another performance indicator.

Figure 5. 12 shows the RSS in dBm as measured in $RTSC_1$. Due to lack of valid GPS signals in one of the measurements, we manually calculated the distance between the communicating nodes (measurement 1). However, the same test was repeated close to the entrance of the tunnel using GPS signals and no significant difference was found between the two measurements. Both the measurements are shown in Figure 5. 12. It is clearly visible that the radio signal quickly deteriorates when Tx is close to Tr. However, the decrease in the RSS is gradual when the Tr is more than 100 meters away from Tx.

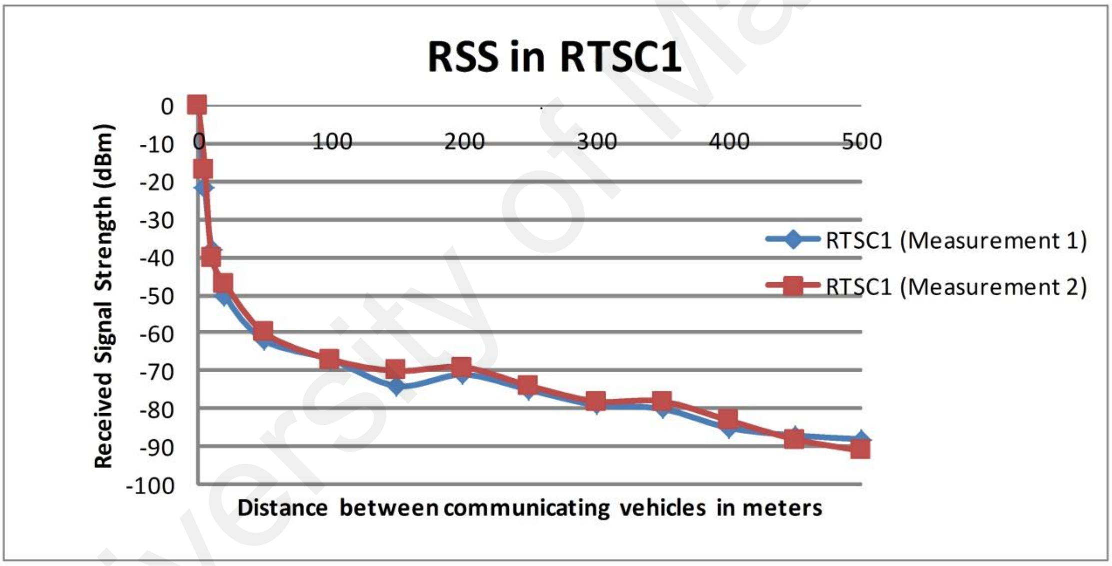

Figure 5. 12: RSS in $RTSC_1$

Figure 5. 13 presents the RSS in dBm as measured in the scenarios $RTSC_1$ and $RTSC_2$. A sudden decrease in RSS is observed when the Tr moved away from Tx initially for the first few meters. This decrease in RSS becomes gradual after about 50 meters. As the distance between the communicating nodes exceed, the change in the signal strength became steady probably due to the waveguide effect. This steady signal strength can be observed till the distance among communicating nodes reach almost 350 meter. When

the distance between the communicating vehicles exceed 350 meters, a relatively more deterioration in the signal strength is observed. It is worth noting that there is no major difference in the signal attenuation in $RTSC_1$ and $RTSC_2$ which implies that the speed of the vehicle has very little or no effect on the signal attenuation in allowed speed range of vehicles.

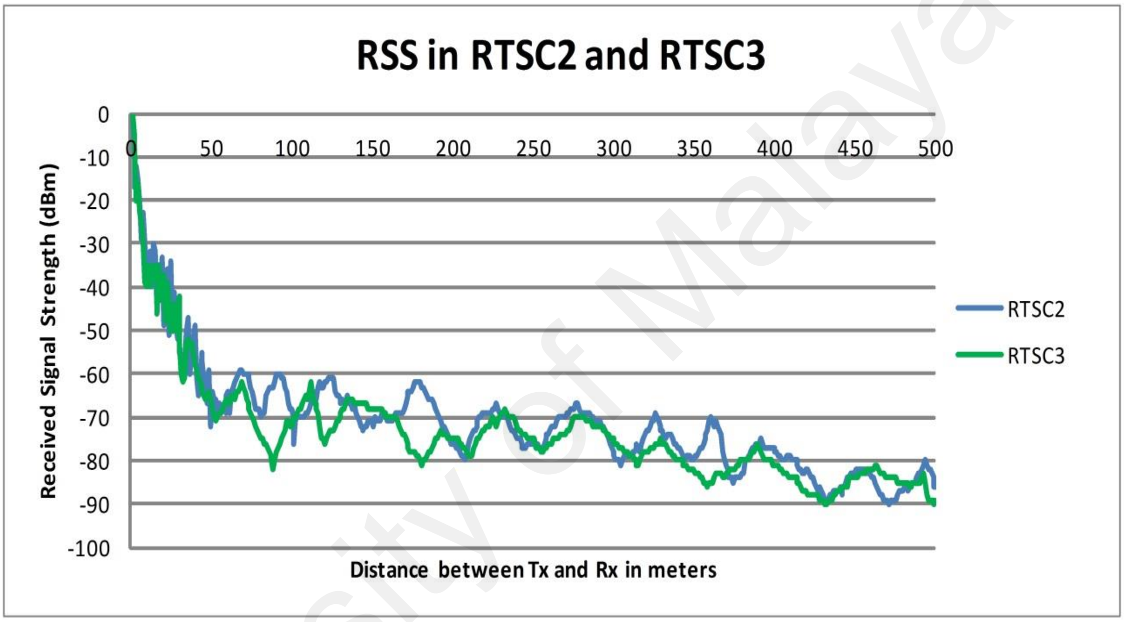

Figure 5. 13: RSS in $RTSC_2$ and $RTSC_3$

Figure 5. 14 and Figure 5. 15 show the degradation in RSS for the scenarios RTSC4 and RTSC5 respectively. Tx was again parked and Tr was driven at 54 km/hr and 72 km/hr for the tests $RTSC_4$ and $RTSC_5$ respectively. The measured RSS values in $RTSC_4$ and $RTSC_5$ complement the results obtained in RTSC2 and RTSC3 because a sudden deterioration in RSS was observed in the first few meters and then a gradual decline in RSS was monitored. Although, Tr was driven at different speeds in RTSC4 and RTSC5, yet again, there was no significant difference in the RSS values observed in the above said tests.

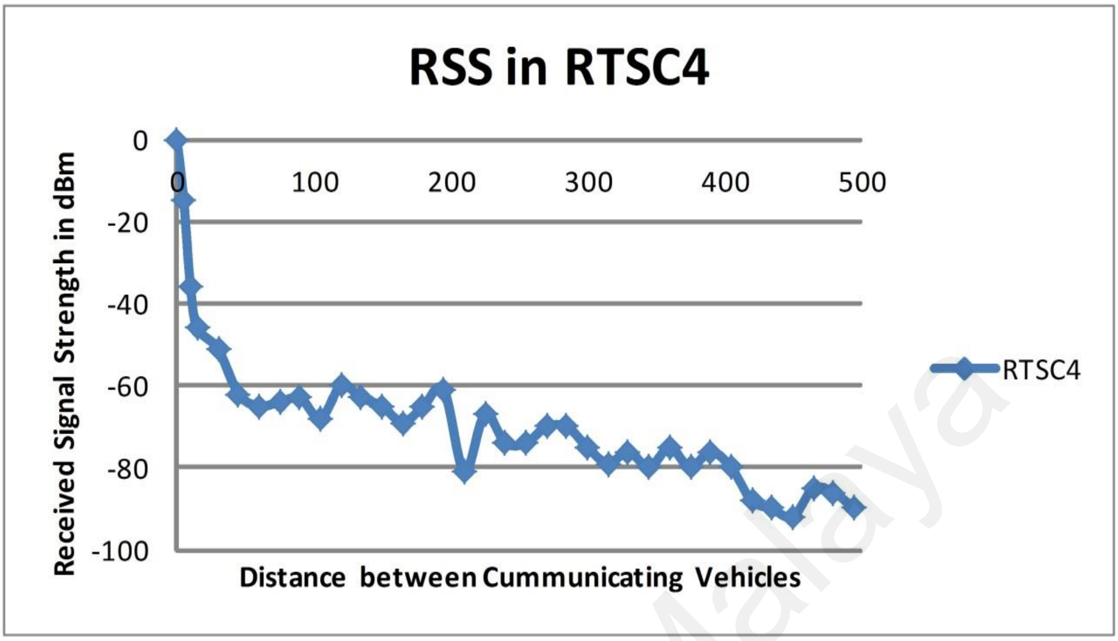

Figure 5. 14: RSS in $RTSC_4$

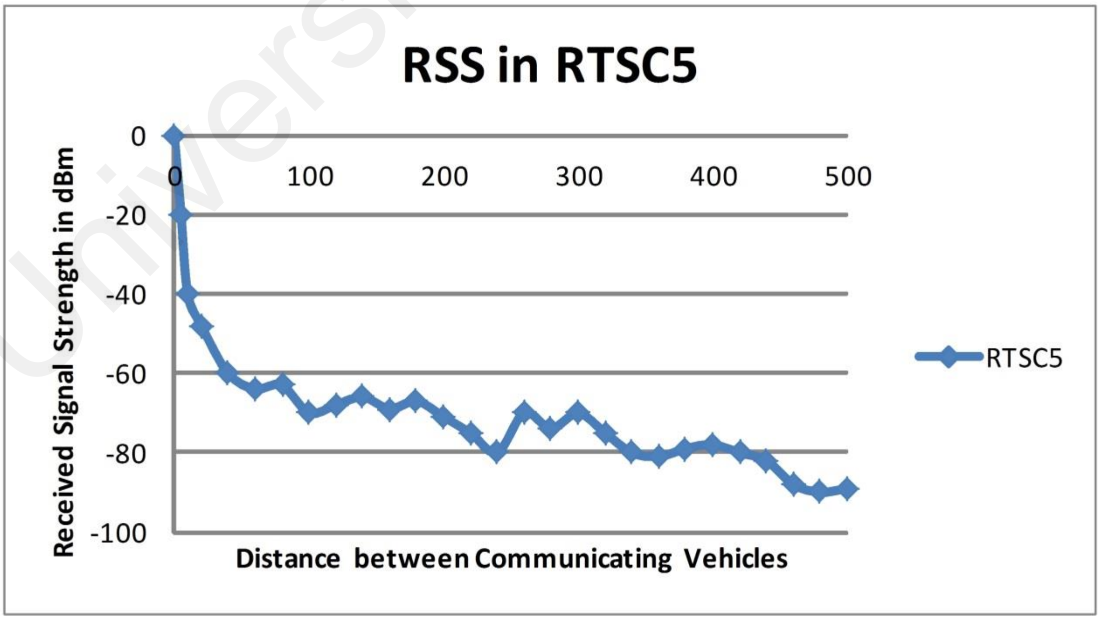

Figure 5. 15: RSS in $RTSC_5$

In another scenario namely $RTSC_6$, both Tx and Tr were driven at variable speeds such that Tr was behind Tx at the start. Having greater speed as compared to Tx, Tr approaches Tx in approximately 30 seconds at first and then it passes by Tx with the same speed. Figure 5. 16 represents the measured RSS values in the scenario $RTSC_6$. The RSS started to increase slowly as the distance between Tr and Tx decreases. The RSS suddenly increased as the Tr approached Tx. However, the RSS decreased as the distance between the communicating vehicles increased again due to the higher speed of Tr. The results obtained from $RTSC_6$ also conform to the other results where one vehicle was stationary.

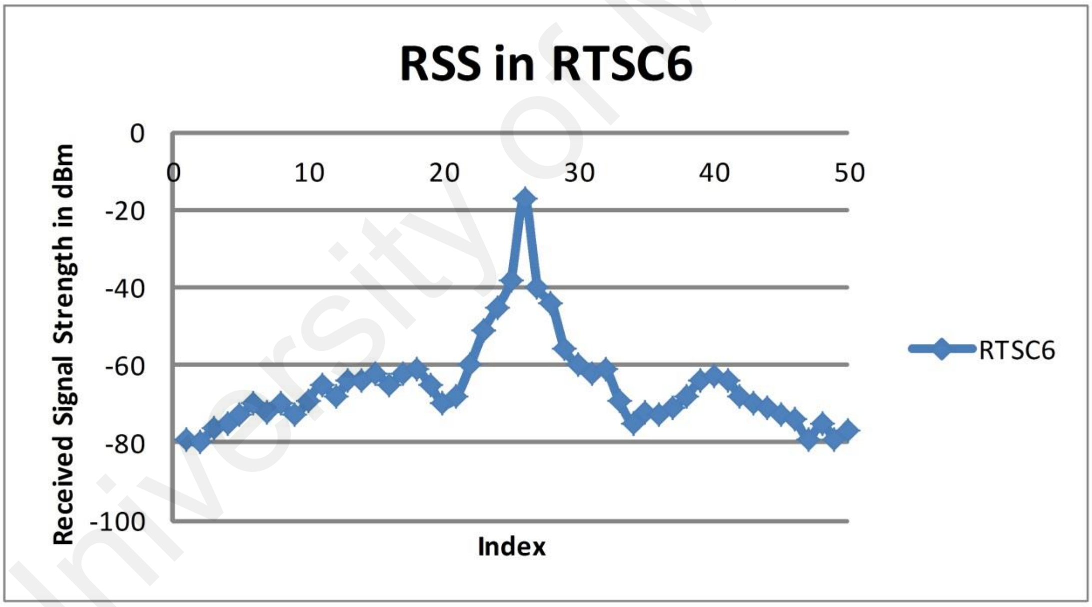

Figure 5. 16: RSS in $RTSC_6$

It is observed from the measurement campaign that moving radio obstacles have a significant impact on the radio propagation in road tunnels. By carefully examining the results and considering the actual situation of road traffic, it is clear that the large moving vehicles (delivery trucks) cause an additional decrease in RSS of about 20dB to

30dB. This fact about additional signal attenuation due to moving radio obstacles is evident from different scenarios, for instance, a decrease of about 20dB was observed in $RTSC_3$ as opposed to $RTSC_2$ when the vehicles were about 170 meters apart. Therefore, it is clear from the measurement results that moving radio obstacle cause additional attenuation in road tunnels.

5.3.2.3 Validation (Road Tunnel)

This subsection explains the effectiveness of the portion of proposed ARPM for road tunnels to predict the path loss in vehicular communication.

The proposed RPM for road tunnels is validated by comparing the predicted path loss with the data acquired during the field measurement campaign. The RSS values obtained from the field measurement campaign in multiple scenarios is converted to the path loss. The additional path loss $\boldsymbol{PL_A}$ caused by the moving radio obstacle was calculated as described in section 4.2.3.2. We obtained a maximum value of path loss for the most common case where the Tx is close to the moving obstacle and more than 60% of the first Fresnel's zone ellipsoid is obstructed by the moving obstacle.

The maximum value of the additional path loss PLA is found to be approximately 30 dB using equation described in section 4.2.3.2 for the most commonly occurring case. To obtain the frequency of large moving vehicles (F) that disturb the LOS among communicating vehicles, we carefully examined the frequency of heavy traffic in the tunnel. As, the measurement site was a part of a busy national highway, therefore, the frequency of heavy traffic was relatively high. The value of F is considered to be 0.2 to compare the predicted value of path loss with the actual measurement results. Figure 5. 17 shows a comparison of predicted path loss with the measured results.

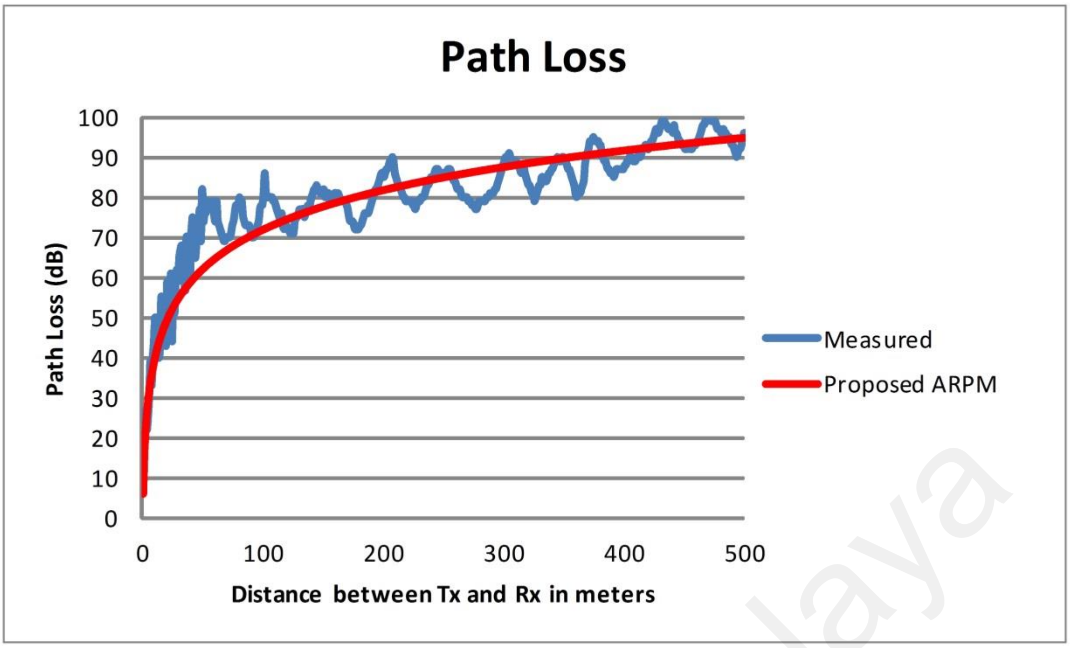

Figure 5. 17: Path Loss in Tunnels (Measured vs Predicted)

Figure 5. 17 shows a close agreement between the measured and predicted values of path loss. The R^2 value obtained by the statistical analysis yield 0.85 that confirms the applicability of the proposed RPM to predict path loss in road tunnels for vehicular communication. A residual analysis on the data was also performed and no clear pattern was observed. Furthermore, an average accuracy of **94%** is found between the measured and predicted values of path loss. The R^2 value, the residual analysis, and the average accuracy of the predicted path loss reaffirmed the suitability of the proposed model to predict path loss in road tunnels for the frequency band suitable for VANET environment.

5.3.4 Evaluation of proposed ARPM in Flyovers

This subsection explains the evaluation of the proposed ARPM for the flyovers. The small scale evaluation is completed using the field measurements of signal attenuation in flyover taken at 5 GHz; therefore, the results are equally applicable to predict the radio propagation properties at 5.9 GHz. An extensive data gathering campaign was carried out at sixth road flyover (Rawalpindi, Punjab, Pakistan, latitude: 33.6424722 longitude: 73.0714255) using 802.11 n WiFi devices configured at 5 GHz. The length of the sixth road flyover is a 462 meters with 3 lanes on each side of the road. It is part of a very busy urban road in a densely populated city situated in north of Pakistan.

5.3.3.1 Measurement Scenarios

Multiple tests were conducted using different arrangements of the communicating vehicles while driving on the flyover. In the simplest arrangement, one vehicle (Tx) was parked on the left lane at the start of the flyover and the RSS was measured using the other vehicle driven at very low speed. In another scenario, the RSS is measured while Tx was stationary and vehicle (Tr) was driven at 40 km/hr and the test is repeated at 60 km/hr. Both vehicles were driven at same speed (30 km/hr) while maintaining a distance of 150 meters, 200 meters and 250 meters respectively from each other in three of the subsequent arrangements. In one of the arrangements, both vehicles were driven at variable speeds is such a manner that one vehicle approaches the other vehicle with greater speed and then leaves it behind for the rest of measurement. Table 5. 4 shows the table multiple scenarios used for the measurement of RSS on the flyover.

Table 5. 4: Measurement Scenarios in Flyover Experiment

Scenario	Tx Speed	Tr Speed	Updation	Inter-vehicular Distance	Orientation
FSC_1	Stationary	5 km/hr	1 meters	Variable	Tr going away from Tx
FSC_2	Stationary	40 km/hr	5 meter	Variable	Tr going away from Tx
FSC_3	Stationary	60 km/hr	5 meter	Variable	Tr going away from Tx
FSC_4	30 km/hr	30 km/hr	5 meters	150 meters	A constant distance is maintained
FSC_5	30 km/hr	30 km/hr	5 meters	200 meters	A constant distance is maintained
FSC_6	30 km/hr	30 km/hr	5 meters	250 meters	A constant distance is maintained
FSC_7	30 km/hr	60 km/hr	~8 meters	variable	Tr approaching Tx and then going away

5.3.3.2 Experimental Results

This subsection presents and discusses the experimental results obtain from field measurement campaign at flyover. Different arrangements of communicating vehicles were considered to measure the communication performance in order to identify the effects that cause major change in the signal attenuation. The communication performance at flyover was analyzed using the measured received signal strength (RSS) and its dependency on the distance between the communicating nodes in multiple arrangements. We utilized path loss in dB as another performance indicator to summarize the results.

Figure 5. 18 shows the RSS in dBm as measured in FSC_1 where Tx was kept stationary at the start of the flyover and Tr was driven at a very low speed to acquire RSS value after each meter along the flyover. A sudden decrease in RSS (15dBm to 20dBm) was observed when the vehicles were no longer in LOS with each other. The decrease in RSS in NLOS scenario is due to the additional attenuation caused by the concrete structure of the flyover as Tx was parked at the start of the flyover and Tr was present at a certain height where there was no LOS between the two communicating vehicles. This decrease in RSS was observed when the distance between the communicating vehicles exceeded 150 meters and is shown by the red circle in Figure 5. 18.

Due to the extreme load of traffic on the flyover, the measurement in FSC_1 was taken using the left lane of the flyover. The pillars of the flyover have minimal effect on LOS on communicating vehicles in the left lane due to the structure of the flyover. The underneath structure of the flyover is shown in Figure 5. 19. It is clearly visible that the radio signals quickly deteriorate when NLOS scenario arises. However, the decrease in the RSS was gradual up till the Tr was driven along the highest part of the flyover. When the distance between the communicating vehicles exceeds approximately 310 meters, the connection between Tx and Rx was lost. This is due to the fact that Rx start to descend and the LOS is now disturbed once again due the concrete structure causing a further attenuation of RSS that result in the perishing of the connection.

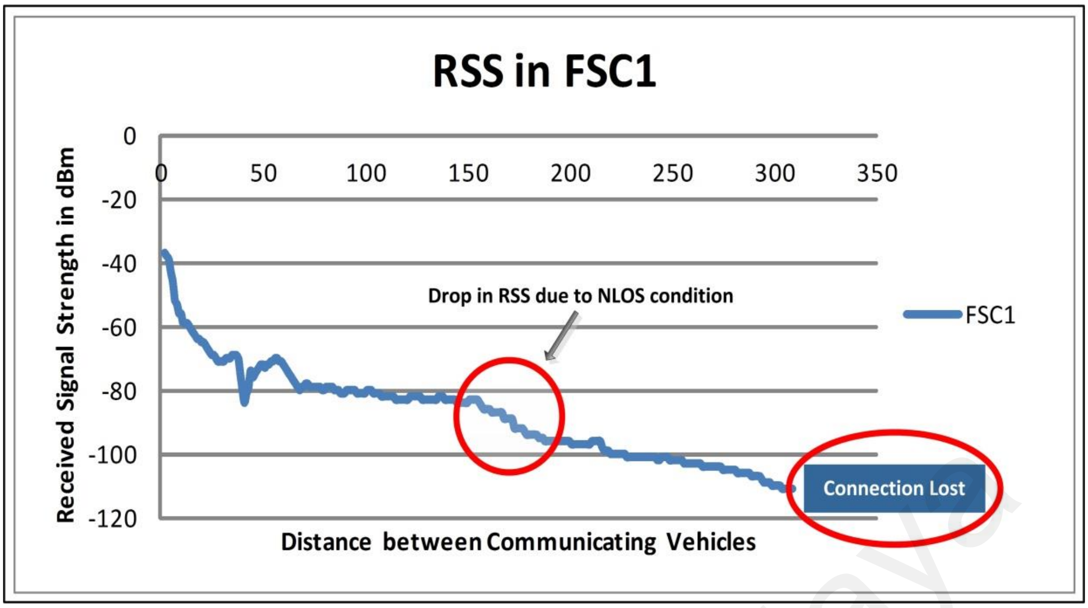

Figure 5. 18: RSS in FSC_1

Figure 5. 19: Underneath Structure of Flyover

In the next two scenarios (FSC2 and FSC3), the vehicle Tx was parked again at the start of the flyover and Tr was driven at legal speed limits (30 km/hr and 60 km/hr). These tests were conducted to observe the impact of variable speeds of Tr on signal attenuation. However, the RSS values in FSC_2 and FSC_3 are no different than the values observed in FSC_1. Therefore, the variable speeds of Tr have no significant effect on the signal attenuation. The results of FSC_2 and FSC3 (Figure 5. 20) also endorsed the results obtained in FSC_1 that maintaining the LOS between the communicating vehicles on the flyover ensures reliable connection because the strength of radio signals quickly deteriorates in case of NLOS scenario.

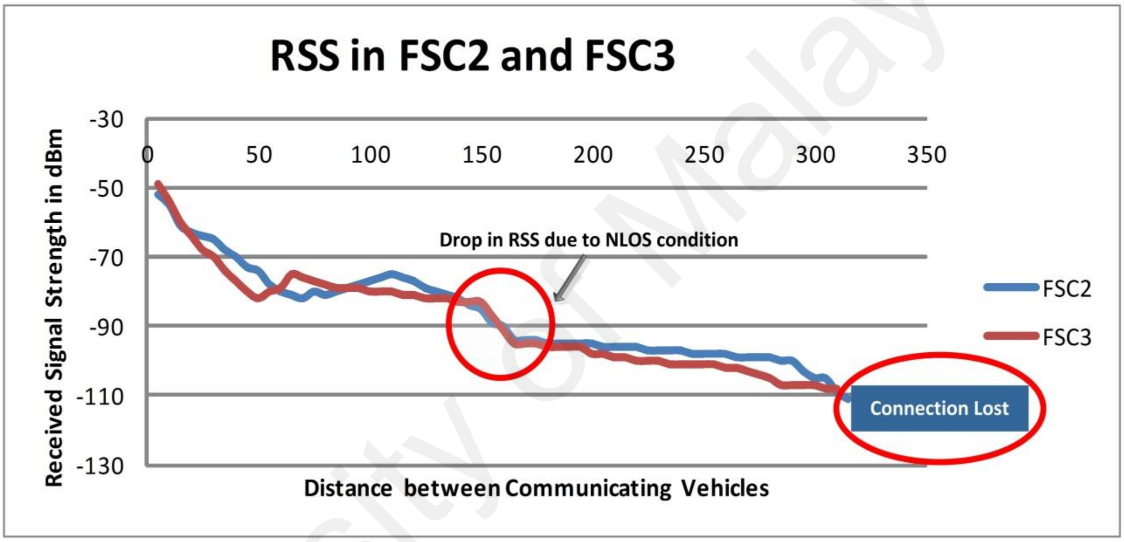

Figure 5. 20: RSS in FSC_2 and FSC_3

In the next three scenarios (FSC_4, FSC_5 and FSC_6), both Tx and Tr were driven at 30km/hr maintaining a distance of 150 meters, 200 meters, and 250 meters respectively. The RSS measurements in these scenarios were taken to observe the impact of flyover's structure on the signal attenuation by maintaining a constant distance between the communicating vehicles and driving both vehicles at with the same speed. In this manner, a deep apprehension of decline in the signal strength due to the flyover's structure is cognizance.

In $FSC_{4,}$ the RSS values were recorded when the Tx and Tr were in LOS at the beginning of test because a distance of 150 meters was maintained between them. Tx was at lower point on the flyover as compared to Tr in the beginning of the test. As the vehicles were driven along the flyover, they started to lose the LOS. Therefore a steady decline in the RSS values was observed. However, the radio signals became stronger when Tx and Tr again came in LOS with each other while driving at the highest points over the flyover. The rise in the signal strength can be observed when both the vehicles have travelled about 150 meters as shown in Figure 5. 22. The decline in RSS was again observed when the vehicles lose LOS but this time Tx was at a higher point as compared to Tr.

The arrangement of vehicles in FSC_4 was again repeated in FSC_5, however, the distance maintained between Tx and Tr was 200 meters in FCS5. At the start of the test, the vehicles (Tx and Tr) were not in LOS with each other. Therefore, an RSS of approximately -100dBm was observed at the start of the test. As the vehicles move on, they gradually begin to come within the LOS with each other, hence, resulting in a steady increase at the start of the test. The increase in the RSS in FSC5 was persistent up to the point where both the vehicles were at the highest points on the flyover. However, a decrease in RSS was observed when Tr started to descend and the vehicles were no longer in LOS with other as shown in Figure 5. 22.

In order to analyze the change in RSS, another scenario FSC_6 was arranged where the inter-vehicular distance of 250 meters was maintained while driving both vehicles at 30 km/hr. Both the vehicles (Tx and Tr) were not in LOS with each other at the start of the test as Tx was at the lowest point on the flyover. After the vehicles travelled approximately 80 meters along the flyover, the connection was lost between the communicating vehicles. This is due to the fact that both the vehicles were on lower points on opposite ends of the flyover. Therefore, the LOS between Tx and Tr was disturbed more than once due to the structure of the flyover that results in the connection lost. This phenomenon is shown in Figure 5. 21.

The communicating vehicles were again connected after travelling approximately 150 meters along the flyover because the LOS was disturbed only one due to the underneath structure of the flyover. A gradual increase in RSS was observed as the communicating vehicles begin to come in LOS with each other. At the end of the test, Tx was at the highest point on the flyover and Tr was at a lower point on a straight road after the flyover. Therefore, the communicating vehicles were in LOS with each other at the end of the test. Hence, an increased RSS value of approximately -88 dBm was observed when the two vehicles have covered about 250 meter distance.

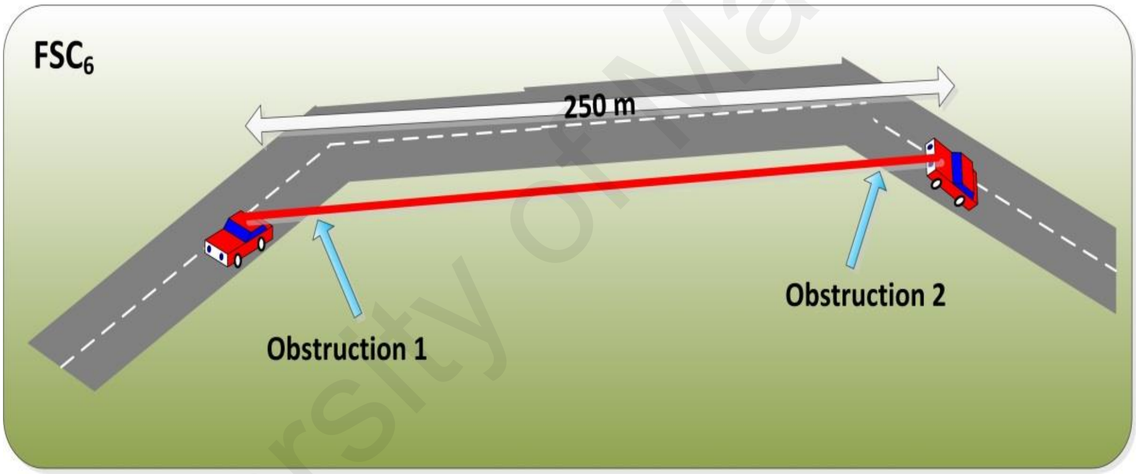

Figure 5. 21: Connection Lost in FSC_6

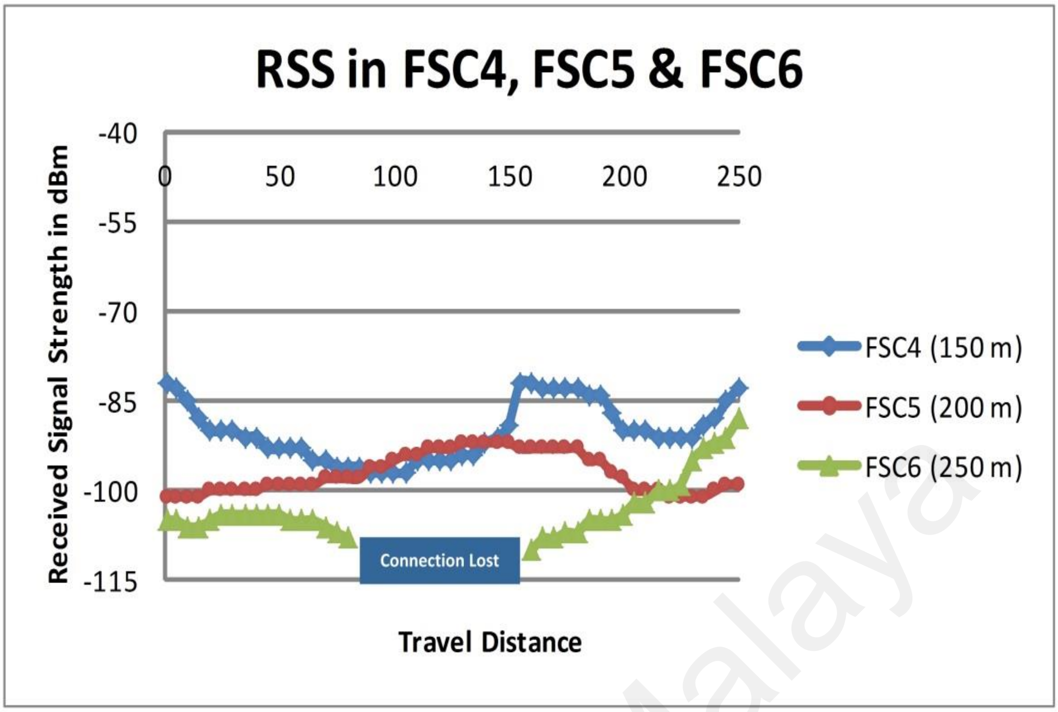

Figure 5. 22: RSS in FSC_4, FSC_5 and FSC_6

In another arrangement, both the communicating vehicles were driven at variable speeds in such a manner that Tx was 150 meters ahead of Tr at the start of the test. The inter-vehicular distance began to shrink as Tr (with greater speed) started to approach Tx. Tr approximately covered 16 meters every second while Tx only covered 8 meters in each second. The communicating vehicles lose the LOS with each other in the beginning of the test. However, due to the greater speed of Tr, the two vehicles came in LOS with each other afterwards. Therefore, the RSS started to increase as Tr approached Tx. The RSS increased to a maximum level and then started to decline as the Tr passed Tx. The change in RSS in FSC7 is shown in Figure 5. 23.

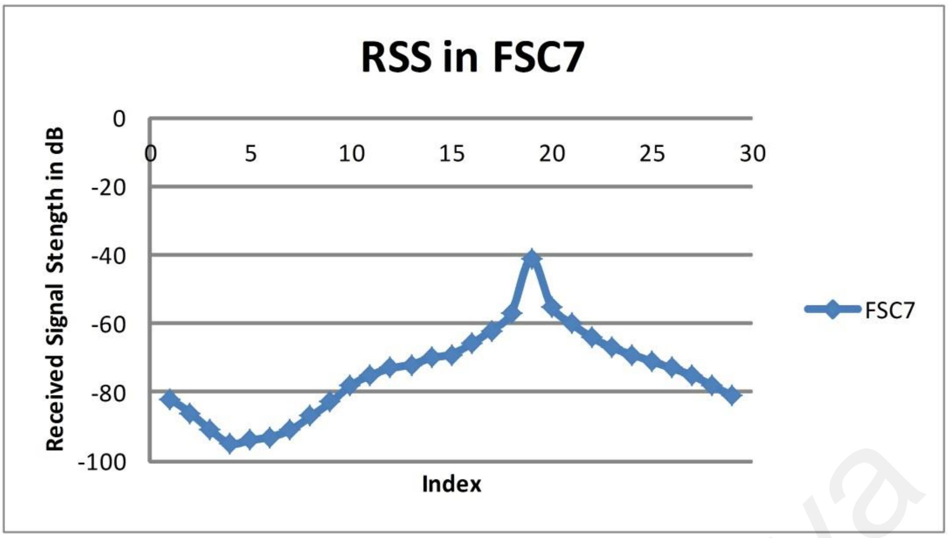

Figure 5. 23: RSS in FSC_7

5.3.3.3 Validation (Flyover)

This subsection explains the efficacy of the portion of proposed ARPM for flyovers to predict the path loss in vehicular communication.

The proposed RPM for flyovers is validated by comparing the predicted path loss with the real-world data obtained from the field measurement campaign on flyover. The RSS values from the real-world testing in multiple scenarios is converted to the path loss and compared with the predicted path loss using the formulas given in section 4.2.3.3 as a part of the proposed ARPM. To apply the proposed formulas for the flyover, we divided the path loss values in to two groups; LOS path loss and NLOS path loss.

In LOS path loss, two components participating in total path loss were considered namely, (a) free space path loss, (b) additional attenuation caused by the moving radio obstacles. There was low frequency of moving radio obstacles because the actual site of the measurement campaign was a part of busy urban roadway and the mass transportation system (Metro Bus) has its own elevated track. Therefore, the additional attenuation caused by moving radio obstacle had a little impact on the total LOS path loss on the particular selected site for field measurement. Hence, the value of *F* (Equation 4.7) is considered to be 0.1 to compare the predicted value of path loss with the actual measurement results for LOS scenario.

A relatively high additional signal attenuation (β = ~ 14dB) was observed due to the heavy and wide concrete material used on the two outer edges of the flyover, Therefore, the edges of the flyover acted as static radio obstacles with a higher impact on signal attenuation in NLOS path loss. The pillars of the flyover did not obstruct the LOS between the communicating vehicles because the measurements were performed on the extreme left lane. Therefore, the impact of pillars on the signal attenuation in NLOS scenario was neglected in this particular situation.

The predicted path loss values for the flyover are compared with the measured results in multiple scenarios to validate the proposed formulas designed specifically for the flyovers. The increase in the predicted path loss with the increase in inter-vehicular distance is monitored and compared with measurement values of the path loss on flyover. A comparison among predicted path loss values using the formulas given in section 4.2.3.3 and measured results obtained from the field measurement campaign is shown in Figure 5. 24.

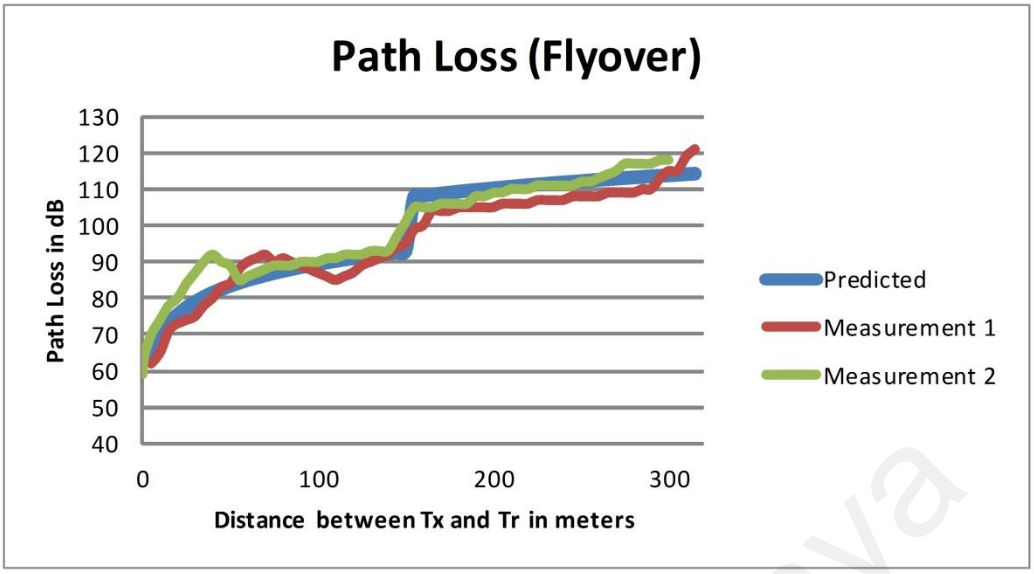

Figure 5. 24: Path Loss on Flyovers (Measured vs Predicted)

Figure 5. 24 shows a close agreement between the measured and predicted values of path loss for flyover. The R^2 value as obtained by the statistical analysis yield **0.94** that confirms the applicability of the proposed ARPM to predict path loss in flyover for vehicular communication. A residual analysis on the path loss data was also performed and no clear pattern was observed. The R^2 value and the residual analysis reaffirmed the suitability of the proposed ARPM to predict path loss on flyovers for the frequency band suitable for VANET environment. Furthermore, a remarkable average accuracy of **97%** was observed when the predicted path loss values were compared with the measured path loss values.

5.3.5 Evaluation of proposed ARPM in Underpass

This subsection expresses the evaluation of the proposed ARPM for the underpass which is a vital infrastructure unit of modern complex interchanges. The small scale evaluation is completed using the field measurements of signal attenuation inside and underpass taken at 5 GHz, therefore, the results are equally applicable to predict the radio propagation properties at 5.9 GHz. An extensive data gathering campaign was carried out at committee chowk underpass (Rawalpindi, Punjab, Pakistan, latitude: 33.6108749 longitude: 73.0651639) using 802.11 n WiFi devices configured at 5 GHz. The length of the underpass is approximately 27 meters with two lanes on each side of the road. The width of the under pass on one side of the road is 9 and height is approximately 6 meters separated by a concrete wall in between the two roads. It is part of a very busy urban road (Murree road) in a densely populated city situated in north of Pakistan.

5.3.5.1 Measurement Scenarios (Underpass)

Different tests were conducted for the measurement of RSS inside the selected underpass using multiple arrangements of the communicating vehicles. In the first arrangement (USC_1), the vehicle (Tx) was parked just before the start of the underpass in the left lane. To measure RSS, the other vehicle (Tr) is driven at very low speed (5 km/hr) inside the underpass to carefully monitor the fluctuation in the RSS values. In order to check the impact of vehicle's speed variation on the RSS values, the same test is repeated in the next scenario (USC_2) while Tx was stationary and Tr was driven at 30 km/hr. In another scenario (USC_3), both the vehicles were driven at same speed (20 km/hr) while maintaining a distance of 15 meters. The arrangement of USC_3 is repeated in USC_4 by driving both the vehicles with the same speed while maintaining a distance of 25 meters between them. In both the scenarios (USC_3 and USC_4), the vehicles maintained the LOS between them while driving inside the underpass because the selected underpass consisted of a street road. In the last of the measurement scenarios, vehicles were driven at different speeds in such a manner that Tx is ahead of Tr at the beginning of the test on the straight road. Tx enters the underpass and continue its journey with relatively low speed as compared to Tr. Therefore, Tr approaches Tx with greater speed and then overtakes it inside the underpass. Tr continue to move further away from Tx for the rest of the test as both the vehicles leave the underpass behind. Table 5. 5 shows the multiple scenarios used for the measurement of RSS inside the underpass.

Table 5. 5: Measurement Scenarios in Underpass Experiment

Scenario	Tx Speed	Tr Speed	Updation	Inter-vehicular Distance	Orientation
USC_1	Stationary	5 km/hr	1 meter	Variable	Tr going away from Tx
USC_2	Stationary	20 km/hr	1 meters	Variable	Tr going away from Tx
USC_3	10 km/hr	10 km/hr	~2 meters	15 meters	A constant distance is maintained
USC_4	20 km/hr	20 km/hr	~2 meters	25 meters	A constant distance is maintained
USC_5	15 km/hr	30 km/hr	~4 meters	variable	Tr approaching Tx and then going away

5.3.5.2 Experimental Results (Underpass)

This subsection presents and discusses the experimental results obtain from field measurement campaign carried out in selected underpass. Communication performance was measured using different arrangements of communicating vehicles to determine the major causes of change in attenuation inside an underpass. The communication performance in underpass was analyzed using the measured received signal strength (RSS) and its dependency on the distance between the communicating nodes in different pre-planned scenarios. We utilized path loss in dB as another performance metric to summarize the results.

Figure 5. 25 shows the RSS in dBm as measured in USC_1 and USC2. In both the scenarios (USC_1 and USC_2), Tx was kept stationary at the start of the underpass and Tr was driven at a very low speeds (5 km/hr in USC_1 and 20 km/hr in USC_2) in order to carefully obtained the RSS values after each meter along the flyover. Furthermore, these tests were carried out also to observe the impact variable Tr speed inside the underpass and on the straight road just after the underpass. As, the selected underpass was a part of very busy and major urban road in a metropolitan city, therefore, the speed of Tr was kept in a range which is followed by the usual traffic on which use the selected underpass.

Random fluctuations in RSS values were monitored inside the underpass in resemblance to the RSS measurements which were taken previously inside the road tunnel. A steep decline in RSS is monitored inside the tunnel in spite of random fluctuation of RSS at the start of the measurement. A decrease in RSS up to approximately 40 dBm is observed with in the first 20 meters of the measurement inside the underpass. However, when the Tr moved a few meters outside the underpass, the fluctuation in RSS became stable and a gradual decrease in RSS was observed. The phenomenon of gradual decrease and relatively stable RSS values can be seen in Figure 5. 25 when the distance between communicating vehicles exceed 30 meters in both USC_1 and USC_2. However, the different speeds of Tr in USC_1 and USC_2 seems to have no major effect on the RSS values.

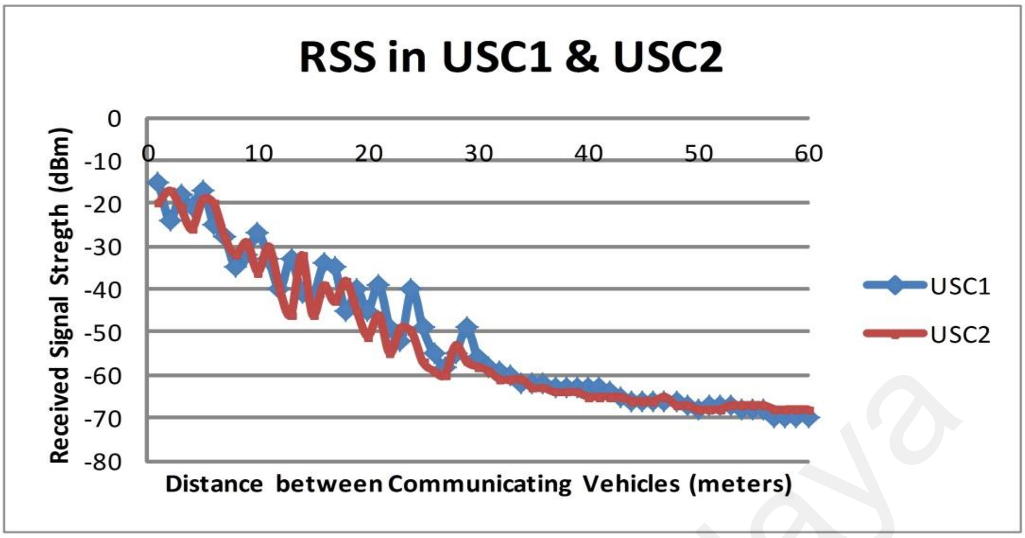

Figure 5. 25: RSS in USC_1 and USC_2

In the next scenario, USC_3, the communicating vehicles are driven with the same speed maintaining a distance of 15 meters between them. This test is carried out to observe the change in attenuation as the one or both of the vehicles enter in the underpass. Both the vehicles start their journey on the straight road 15 meters away from the underpass and then enter into the underpass one after another. As, the two vehicles are separated by a predefined distance throughout the journey in USC_3, so, no dramatic change in the RSS is expected under normal circumstances. However, due to the waveguide-effect resulting from the structure of the underpass, diverse change in the RSS with the overall increase in the RSS is observed as the vehicles enter into the underpass one after the other. The fluctuation in the RSS values was soon balanced as the vehicles left the underpass at the end of the test. The same arrangement of USC_3 is repeated in USC_4 by maintaining a larger distance (25 meters) between the communicating vehicles. One of the vehicles was kept 25 meters away from the entrance of the underpass maintaining a further distance of 25 meters with the other vehicle. An increase in RSS is observed as the vehicles enter the underpass one after the other. This increase in RSS was at the highest level when both the vehicles were inside the underpass. However, a decrease in

RSS was monitored at the two vehicles left the underpass at the end of the test. The change in RSS in USC_3 and USC_4 is shown in Figure 5. 26.

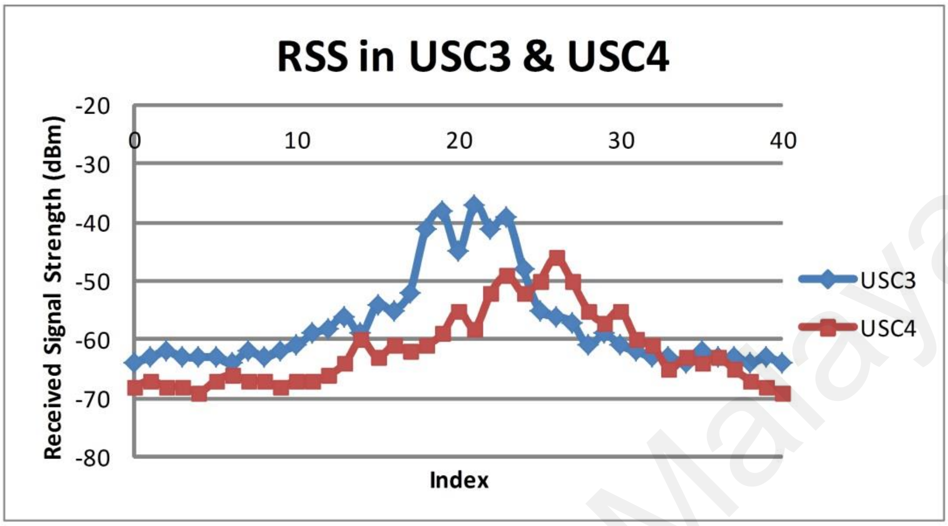

Figure 5. 26: RSS in USC_3 and USC_4

In another scenario (USC_5), both the communicating vehicles were driven at variable speeds (Tx with 15 km/hr and Tr with 30 km/hr) in such a manner that Tx was 30 meters ahead of Tr initially. The inter-vehicular distance began to reduce as Tr (with greater speed) started to approach Tx. Both the vehicles were inside the tunnel after approximately 8 seconds from the start of the test. Therefore, a sharp increase in the RSS is observed as both the communicating vehicles were not only inside the underpass but were also very close to each other as Tr overtakes Tx. However, the RSS increased to a maximum level and then started to decline as the Tr passed Tx and continually went further away from Tx. In the process, both Tx and Tr left the underpass on to the straight road ahead. The change in RSS in USC5 is shown in Figure 5. 27.

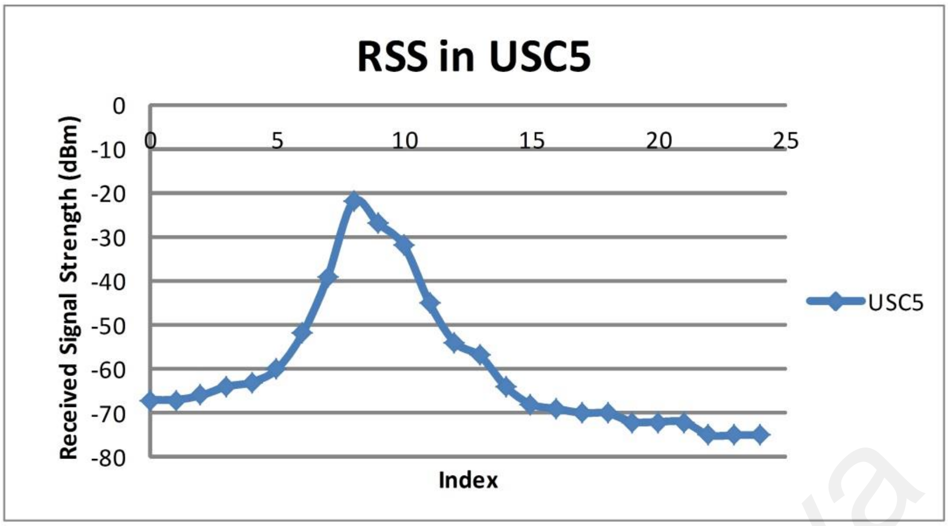

Figure 5. 27: RSS in USC_5

5.3.5.3 Validation (Underpass)

This subsection explains the effectiveness of the portion of proposed ARPM for underpass to predict the path loss in vehicular communication.

The proposed RPM for underpass is validated by comparing the predicted path loss with the real-world data obtained from the field measurement campaign inside the underpass. The RSS values from the real-world testing in multiple scenarios are converted to the path loss values and are compared with the predicted path loss using the formulas given in section 4.2.3.4 as a part of the proposed ARPM. To apply the proposed formulas for the underpass, we divided the path loss values in to three groups; group A (when both the communicating vehicles driven inside the underpass), group B (when only one of the communicating vehicles is been inside and the other vehicle is outside the underpass) and group C (when both the communicating vehicles are outside on two different ends with the architecture of the underpass between them).

In the group A, the major participating path loss factors were the dimension of the underpass and the distance between the communicating vehicles inside the underpass. The communication inside the underpass was merely disturbed by the moving radio obstacles because of the low frequency of the large moving vehicles in the selected underpass. Likewise, the communicating vehicles were in LOS with each other in group B as well, therefore, the major factors participating in the total path loss were; (a) free space path loss utilizing the effective distance d_{eu} between the communicating vehicles (as discussed in section 4.2.3.4) and (b) additional attenuation caused by the moving radio obstacles. However, due to the low frequency of large moving vehicles, additional attenuation due to other vehicles was not on a large scale in group B as well. Moreover, in group C, the whole length of the underpass is considered to obtain the effective distance d_{eu} between the communicating vehicles.

The predicted path loss values for the underpass are compared with the measured RSS values resulting from the underpass experiment in multiple scenarios to validate the proposed formulas designed specifically for the under. The increase in the predicted path loss with the increase in inter-vehicular distance is monitored and compared with measurement values of the path loss in underpass. A comparison among predicted path loss values using the formulas given in section 4.2.3.4 and measured results obtained from the field measurement campaign is shown in Figure 5. 28.

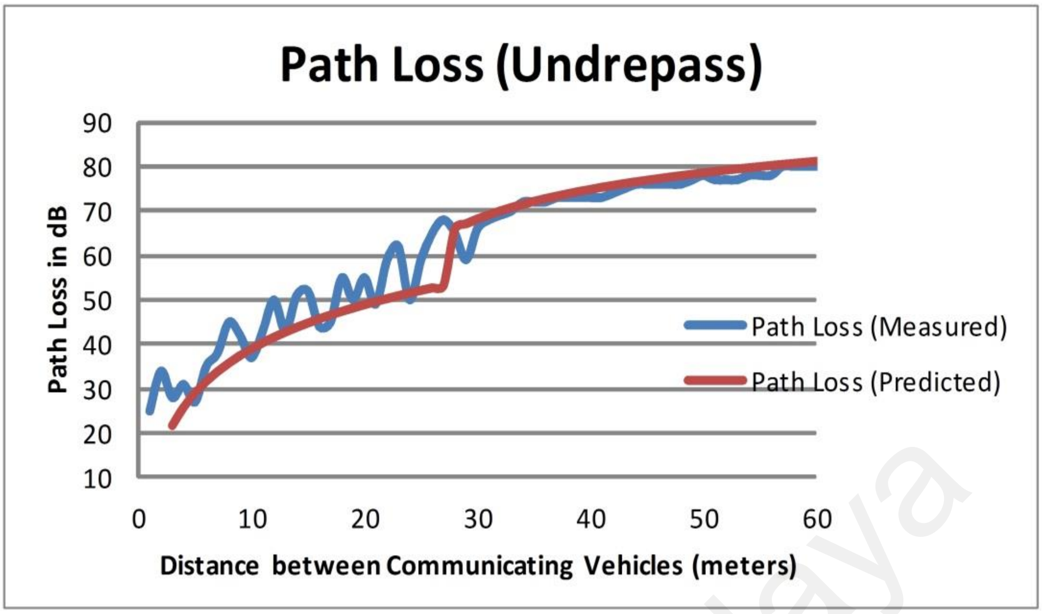

Figure 5. 28: Path Loss in Underpass (Measured vs Predicted)

Figure 5. 28 shows a close agreement between the measured and predicted values of path loss for underpass. The R^2 value as obtained by the statistical analysis yield **0.94** that affirms the suitability of the proposed ARPM in the estimation of the path loss in underpasses for effective vehicular communication. A residual analysis on the path loss data was also performed and no clear pattern was observed. Furthermore, an average accuracy of **91%** was calculated when the predicted path loss values were compared with the measured path loss values. The R^2 value, the residual analysis and the average accuracy reaffirmed the suitability of the proposed ARPM to predict path loss in underpasses for the frequency band suitable for VANET environment.

5.4 Comparison of ARPM with State-of-the-Art Radio Propagation Models in VANETs

In this section, we present a comparison of the proposed ARPM with the existing state-of-the-art widely used radio propagation models to predict path loss in VANETs. We selected existing radio propagation models to compare based upon two important characteristics; (a) usage in existing simulations and (b) innovation. According to this criterion, we selected three existing radio propagation models which are

- Free Space Radio Propagation Model
- Two Ray ground Radio Propagation Model
- CORNER

The first two radio propagation models namely free space and two-ray ground are widely used in different popular network simulators (for example NS2, NS3, Omnet++) and the CORNER is one of the innovative radio propagation model used in VANETs simulations which is rapidly gaining popularity. The following subsections present the comparison among RPMs in different road infrastructure units namely; (a) road tunnel, (b) confined curved road, (c) flyover and (d) underpass. The selected physical sites for the field measurement campaign on various road infrastructure units are reproduced in simulation environment to compare the proposed ARPM with existing radio propagation models in VANETs.

5.4.1 Comparison of Radio Propagation Models in Road Tunnel

The path loss in road tunnels is relatively low as compared to other road infrastructure units probably due to waveguide effect as explained in section 4.2.3.2. Therefore, the free space model over-estimates the path loss in a road tunnel. Same is the case with CORNER; as it considers an LOS scenario to be modeled as free space propagation. Hence, employment of both free space model and CORNER yield the same values of path loss which are not suitable for predicting path loss in road tunnels. However, the two-ray ground model does not over-estimate the path loss when the transmitter and the receiver are close to each other (approximately within 60 meters). The prediction of path loss from the two-ray ground model gradually starts to exaggerate with the increasing distance between the communicating vehicles till it coincides with the free-space model and CONER. Therefore, all the three models namely; free-space model, two-ray ground model and CORNER are not suitable to predict path loss in a road tunnel.

The formulas used in ARPM for road tunnels are specifically designed by utilizing the tunnel's dimensions and incorporating the additional attenuation caused by the moving radio obstacles to predict path loss. Therefore, ARPM does not over-estimate the path loss in road tunnel as opposed to existing RPMs. A comparison between the predicted path loss values from ARPM and the exiting radio propagation models is presented in Figure 5. 29. It is clear that the path loss curve resulting from application of ARPM in road tunnels is below all other curves; depicting the fact that ARPM better predicts the path loss as compared to existing radio propagation models.

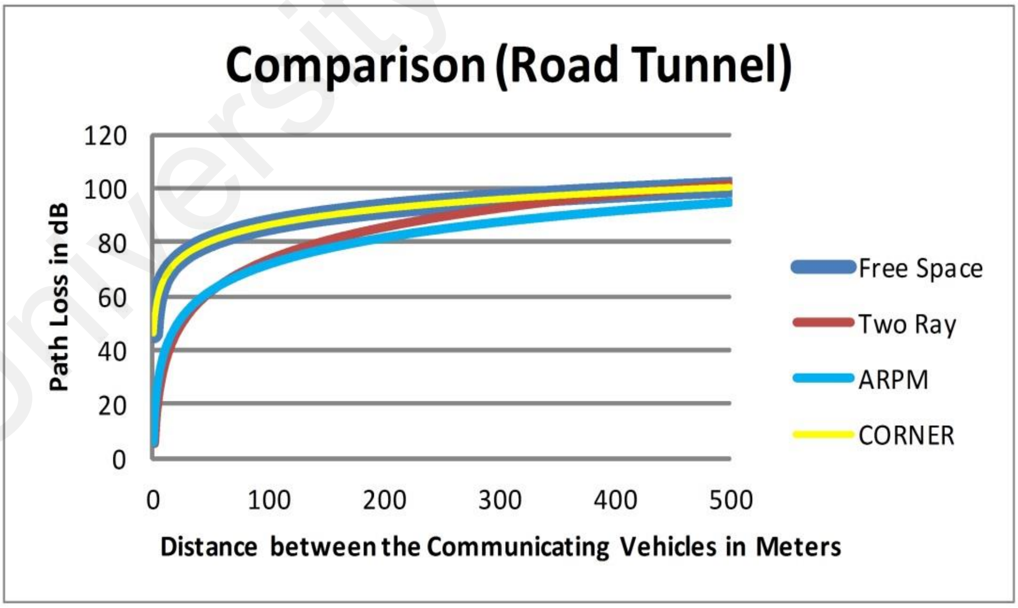

Figure 5. 29: Comparison of predicted path loss (Road Tunnel)

A comparison among the PDR predicted by the existing radio propagation models and the proposed ARPM in road tunnel is performed using the simulation at large scale. The comparison results for the road tunnel in terms of PDR as predicted by various radio propagation models are shown in Figure 5. 30. The application of free-space model and two-ray ground model to predict the path loss in road tunnel yield PDR in a range of **85%** to **87%**. CORNER also models the LOS scenario as free-space model; hence, the PDR predicted by CORNER in our simulation setup is also approximately 85%. The three existing radio propagation models consider LOS communication with no effect of any type of radio obstacles on radio propagation. However, they ignore the positive effect of the road tunnel's geometry on the signal propagation. The PDR predicted by free space model, two-ray ground model and CORNER are towards a slightly low threshold; therefore, the PDR prediction by the existing radio propagation is not realistic for road tunnels.

On the other hand, the proposed ARPM considers the positive effects of road tunnel geometry on radio propagation. Therefore, the PDR values predicted by using the proposed ARPM are in a relatively high threshold (approximately **85%**) as compared to exiting radio propagation model in spite of the additional signal attenuation due to the large moving obstacles inside the road tunnel.

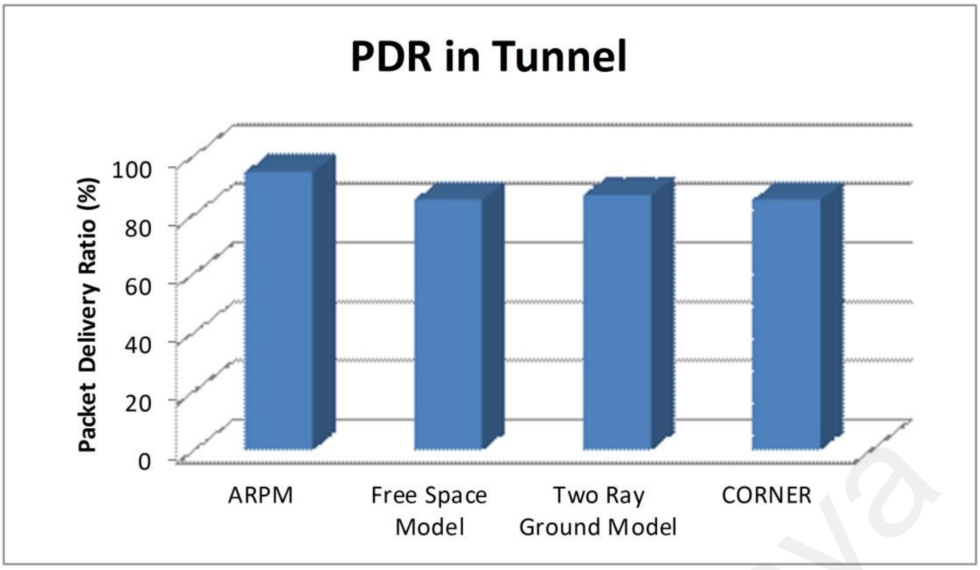

Figure 5. 30: Comparison of PDR in Road Tunnel

5.4.2 Comparison of RPMs in Confined Curved Road

The driving of vehicles along a confined curved road (or a curved road having buildings on its sides) creates an NLOS condition. Free-space model does not consider NLOS scenario, therefore, it under-estimates the path loss in confined curved road. Two-ray ground model is not suitable to predict path loss in VANETs when the communicating vehicles are near each other as it tends to under-estimate the path loss even in LOS scenario. Although, CORNER is applicable only on urban grid environment, but still the prediction of path loss is relatively accurate in confined curved roads as compared to free-space model and two-ray ground model if NLOS scenario is carefully simulated. CORNER can be used in confined curved roads by considering the starting point of NLOS conditions as a junction. However, CORNER tends to under-estimate as the distance between the communicating vehicles in NLOS scenario increases.

The ARPM specifically calculates the path loss for a confined curved road by considering the NLOS scenarios that are generated due to the driving of vehicles along the confined curved road. It also considers the additional attenuation as resulted by moving radio obstacles. Therefore, ARPM accurately predicts the path loss in confined curved road as compared to existing radio propagation models. A comparison between the predicted path loss values from ARPM and the exiting radio propagation models in confined curved road is presented in Figure 5. 31. It is clear that the path loss curve resulting from application of ARPM in confined curved road is above all other curves; representing the NLOS scenario and depicting the fact that ARPM better predicts the path loss as compared to existing radio propagation models.

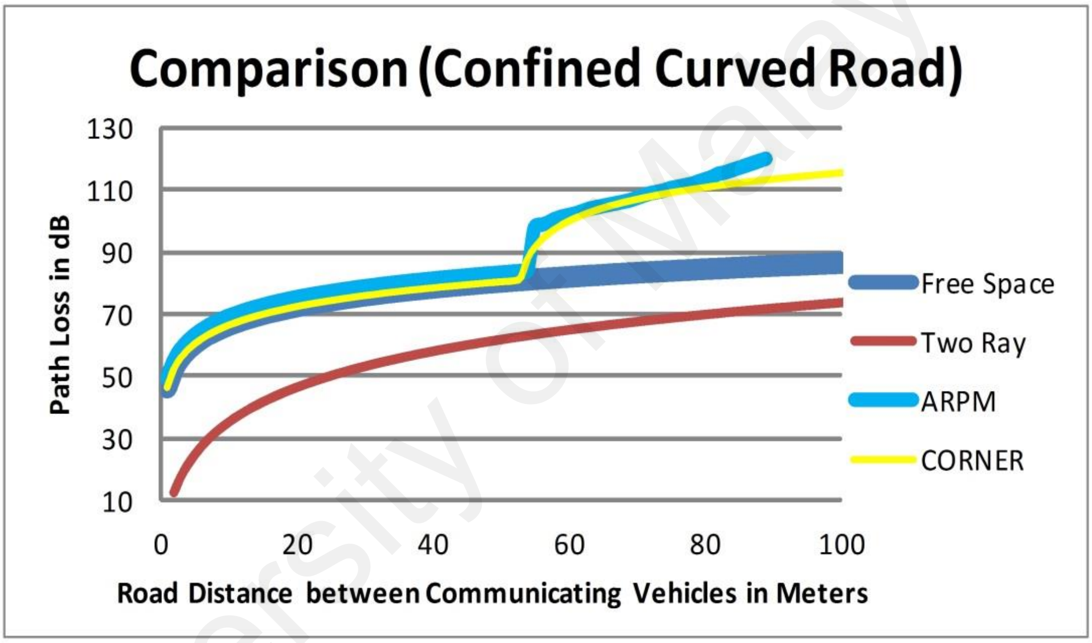

Figure 5. 31: Comparison (Confined Curved Road)

A comparison among the PDR predicted by the existing radio propagation models and the proposed ARPM in confined curved road is also performed using the simulation at large scale. The comparison results for the confined curved road in terms of PDR as predicted by various radio propagation models are shown in Figure 5. 32. It can be seen that the application of free-space model and two-ray ground model to predict the path loss in confined curved road yield maximum PDR (approximately 100%) with not a single packet loss. Both the free-space model and two-ray ground model only consider LOS communication with no effect of any type of radio obstacles on radio propagation.

Therefore, the PDR predicted by free-space model and two-ray ground model is not at all realistic.

However, if CORNER is applied carefully (by considering NLOS scenario in the confined curved road as a potential corner in the grid) to predict the path loss, it calculates the PDR of approximately 49% for the selected confined curved road. The PDR calculated by the CORNER is very close to the value of PDR (approximately 47.5%) calculated by the proposed ARPM. Both the proposed ARPM and CORNER consider the NLOS scenarios, therefore, the PDR calculated by them is towards a relatively low threshold. The PDR calculated by proposed ARPM is even less than the PDR calculated by CORNER because the proposed ARPM also considers the attenuation from the moving radio obstacles in addition to the path loss in NLOS scenario. The analysis of proposed ARPM for the confined curved road support the inclusion of RSUs placed at the optimal positions in order to improve the PDR for the vehicles communicating and driving in a confined curved road.

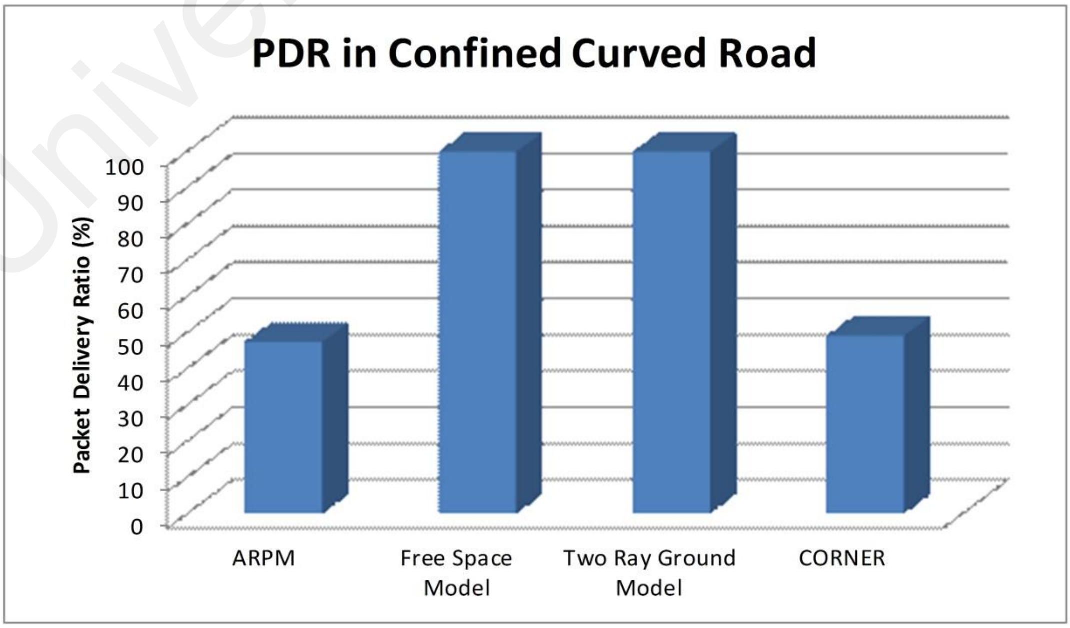

Figure 5. 32: Comparison of PDR in Confined Curved Road

5.4.3 Comparison of RPMs on Flyover

The existing radio propagation models do not consider the structure of the flyover as a potential radio obstacle. Therefore, they lack in predicting path loss accurately for the communicating vehicles that are travelling on the flyover. The free space model only predicts the path loss when the communicating vehicles are in LOS with each other. However, due to relative height of the flyover at different locations, the communicating vehicles even travelling on a straight line have a tendency to lose LOS among them. The existing radio propagation models consider a two dimensional plane and do not contemplate height of the flyover in estimating path loss. CORNER uses free space model in estimating the path loss in LOS scenario and two-ray ground model underestimates the path loss for the shorter distances. Therefore, all three of the existing radio propagation models are unable to predict the accurate path loss for the vehicular communication on flyovers.

A comparison among the path loss predicted by ARPM and existing radio propagation model is shown in Figure 5. 33. The ARPM accounts for the additional attenuation caused by multiple NLOS conditions for the communicating vehicles travelling on the flyover. The communicating vehicles in NLOS scenarios on opposite sides of the flyover may lose effective communication due to repeated obstructions resulting from the edges and pillars of the flyover. This phenomenon is only modeled in ARPM as opposed to existing radio propagation models. Abrupt increase in path loss predicted by ARPM can be seen in Figure 5. 33. No existing radio propagation model considers the abrupt change in path loss because of the NLOS condition between the communicating vehicles travelling on the flyover.

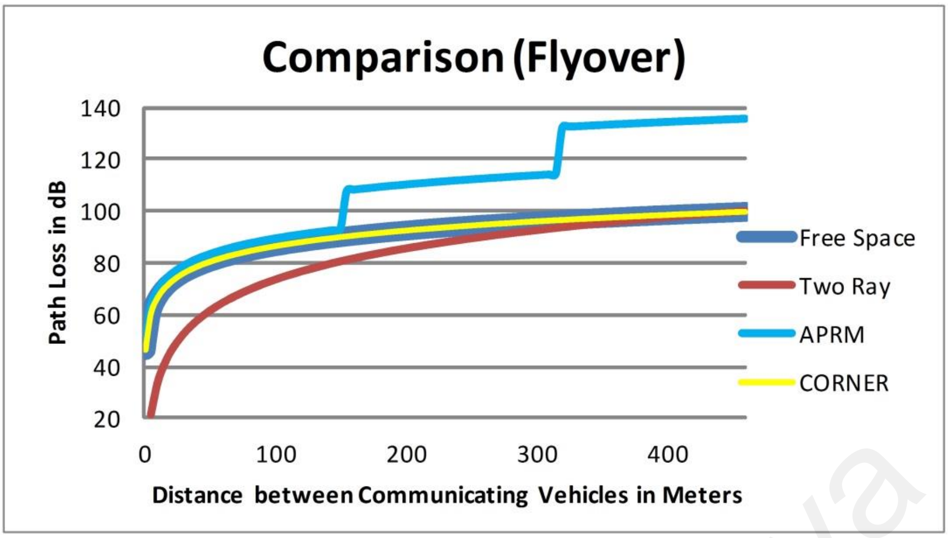

Figure 5. 33: Comparison (Flyover)

A comparison among the PDR predicted by the applying existing radio propagation models and the proposed ARPM in flyover is also performed using the large scale simulation. The comparison results for the flyover in terms of PDR as predicted by using various radio propagation models including the proposed ARPM are shown in Figure 5.34. Unrealistic values of PDR in a high range (greater than 90%) are predicted for the flyover using the three existing radio propagation models namely free-space, two-ray ground and CORNER. The three existing radio propagation models consider only LOS scenario among the communicating vehicles. The signal attenuation caused by the structure of the flyover and the additional attenuation due to large moving vehicles is not contemplated by the exiting radio propagation models. Therefore, such unrealistic values of PDR are predicting using the existing radio propagation models.

On the other hand, the proposed ARPM not only considers the structure of a flyover as a potential radio obstacle but also takes into account the additional signal attenuation due to the large moving obstacles. Therefore, the PDR values predicted by using the proposed ARPM are in a relatively very low threshold (less than 40%). Hence, the analysis of proposed ARPM advocates the inclusion of an RSU placed at the optimal position on the flyover in order to provide a reliable communication infrastructure for the vehicles communicating and driving along a flyover. The placement of RSU at optimal position on the flyover will surely improve the PDR for the vehicles communicating and driving along the flyover.

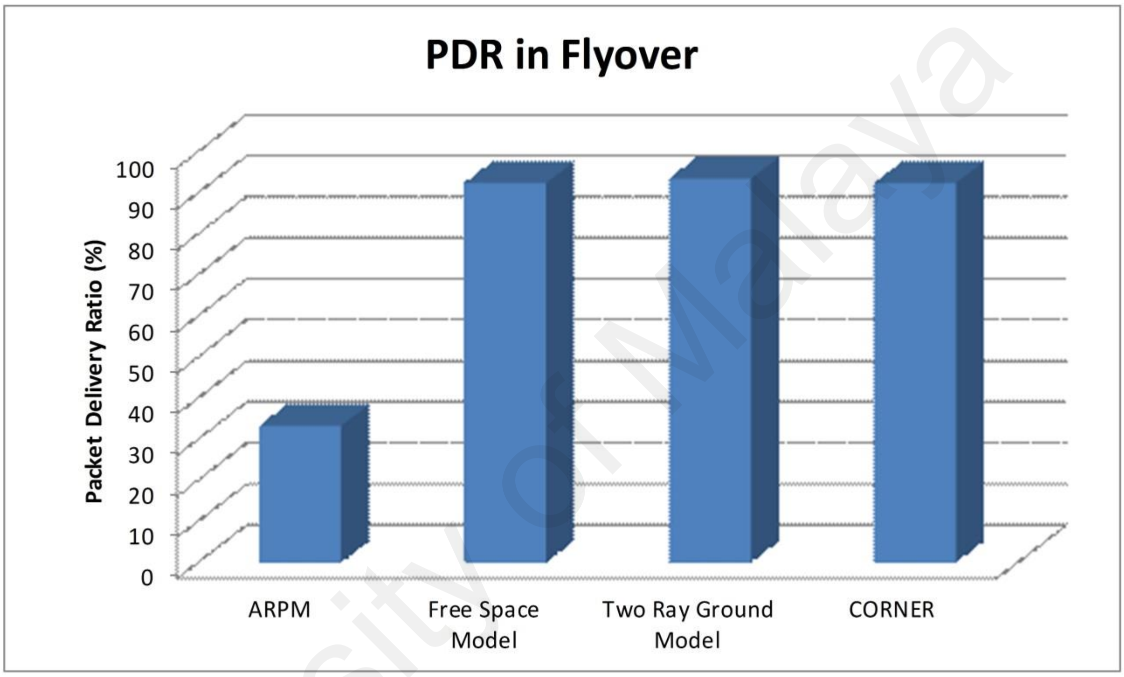

Figure 5.34: Comparison of PDR in Flyover

5.4.4 Comparison of RPMs in Underpass

The positive effects of an underpass on the signal propagation in vehicular environment have never been considered by the existing radio propagation models employed in VANETs. Therefore, existing radio propagation models presents an unrealistic view of radio propagation and path loss while at least one of the communicating vehicles are inside the underpass or both the communicating vehicles are present outside on the opposite sides of the underpass. The free-space model over-estimates the path loss in underpass because the underpass geometry is not considered. Same is the case with

CORNER as it utilizes free-space model to predict path loss in LOS scenario. However, two-ray ground model slightly under-estimates the path loss when the vehicles are communicating inside the underpass but this path loss estimation becomes unrealistic when only one of the communicating vehicle is inside the underpass.

The proposed ARPM specifically calculates the path loss for the communicating vehicles which are inside or near to an underpass and it also accounts for the additional signal attenuation caused by the large moving obstacles. Therefore ARPM predicts the path loss accurately for the situations where at least one of the vehicles is inside the underpass or both the vehicles are outside the underpass on its opposite sides. A comparison among the path loss predicted by ARPM and existing radio propagation models is shown in Figure 5. 35. The comparison results showed that the existing radio propagation models (free space, CORNER) either over-estimate the path loss or under-estimate (two-ray) it. Unlike, the existing radio propagation models, the proposed ARPM keeps track of the positive effects of the underpass dimensions on the signal propagation and calculates effective distance to predict path loss. Therefore, the proposed ARPM is more suitable to predict path loss for underpass environment as compared to existing radio propagation models in VANETs.

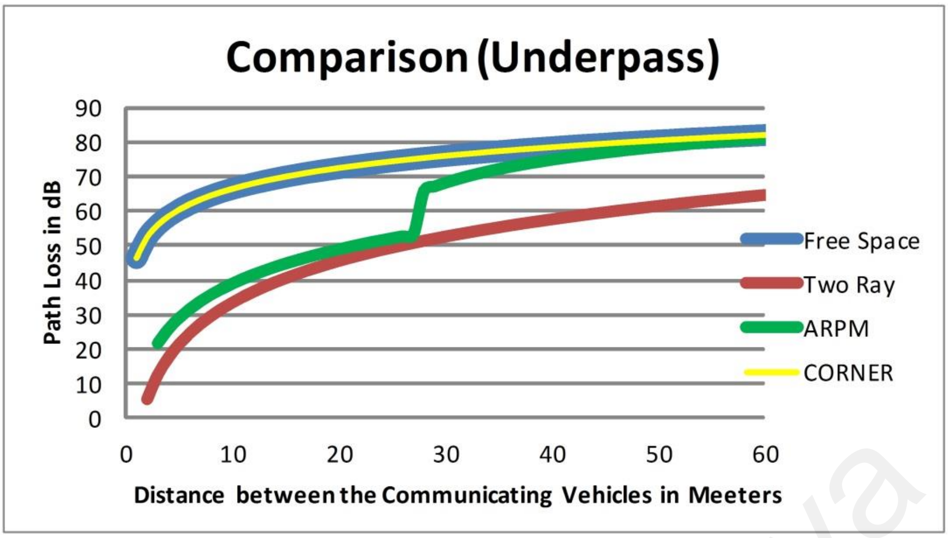

Figure 5. 35: Comparison (Underpass)

A comparison among the PDR predicted by the applying existing radio propagation models and the proposed ARPM in underpass is also performed using the large scale simulation. However, due to the very small length of the underpass and the positive effects of underpass dimensions on radio propagation, the exiting radio propagation models as well as the proposed ARPM predict the maximum PDR for underpass. Therefore its plot is not shown.

5.5 Evaluation for Optimal Positioning of RSUs in Modern Road Infrastructure Units

This section presents the impact of optimal positioning of RSUs on radio propagation in various modern road infrastructure units that includes (a) road tunnel, (b) curved road, (c) flyover, (d) underpass, and (e) irregular road. The positive effects of optimal positioning of RSUs are evaluated by determining the gain in RSS and the increase in PDR resulting from the deployment of RSUs on pre-defined locations. The calculation of exact deployment of RSUs on various modern road infrastructure units using geometrical concepts is already explained in section 4.3. However, the experimental scenarios of the field measurement campaign on various road infrastructure units are reproduced in simulation environment and the advantages of optimal positioning of RSUs in terms of RSS and PDR are monitored using the proposed ARPM. The discussion about the reproduced scenarios and the advantages gained by the optimal positioning of RSUs in various modern road infrastructure units are explained in the following respective subsections.

5.5.1 Evaluation of Optimal Positioning of RSUs in Road Tunnel

This subsection elaborates the evaluation of optimal positioning of RSUs in road tunnels. The existing research on the issues related to radio propagation in tunnels explained the phenomenon that the RSS in free space deteriorate quicker than in tunnels. This phenomenon was reaffirmed by our field measurement campaign as well. Therefore, signal repeaters that receives and then transmits the radio signal with the same strength as the original signal is deployed separated by a distance of 300 meters from each other beginning from the start of the tunnel in the simulation. The difference among the RSS values in the absences and presence of the signal repeater are monitored and compared.

Figure 5. 36 represents a graph depicting the difference in path loss; when RSU/signal repeater is optimally placed (blue curve) and in the absence of RSU/signal repeater deployment (red curve). The two curves follow a same path initially (up to a distance of 150 meters between the communicating vehicles), as the communicating vehicles were in LOS with each other. However, the difference between curves started to extend as one of the communicating vehicle begins to approach towards RSU / signal repeater. The path loss came to a minimum level when one of the communicating vehicles reached the RSU / signal repeater and then the path loss again started to enhance as the

vehicle moved away from the RSU / signal repeater. The path loss again begins to decrease as the vehicle started to approach the second RSU / signal repeater. However, it is worth noticing that the path loss when the RSUs are optimally positioned remains low as compared to the situation when RSUs / signal repeaters are not deployed inside the tunnel.

The positive effects of optimal RSU positioning in terms of path loss are clearly visible even within a relatively small distance of 500 meters inside the tunnel as shown in Figure 5. 36. An average gain of 15.7 dB is observed in RSS within a short distance of 500 meters inside the tunnel due to the optimal position of RSU / signal repeater. The average gain in dB translates to an average gain of **24.15 %** in case of optimal deployment of RSU / signal repeater inside the road tunnel.

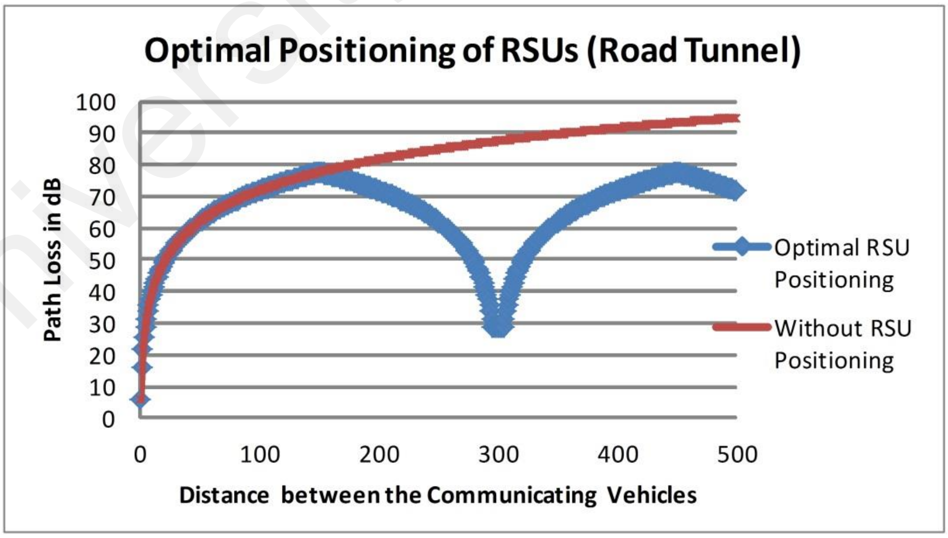

Figure 5. 36: Evaluation of Optimal Positioning of RSUs in Road Tunnel in terms of path loss

5.5.2 Evaluation of Optimal Positioning of RSUs in Curved Road

This subsection describes the evaluation of optimal positioning of RSUs in confined curved roads. The geometry of optimal positioning of RSUs/ signal repeaters / signal reflectors is already explained in subsection 4.3.1. We utilized the formulas in presented in the above said subsection and determined the optimal positioning of RSUs / signal repeater / signal reflectors on the curved road location which was selected for the field measurement campaign. The whole scenario along with the optimal positioning of RSUs / signal repeaters / signal reflectors is reproduced in a simulation environment. Signal repeaters that receive and then transmit the radio signals with the same strength as the original signal are deployed, separated by a distance of approximately 52 meters (as calculated by the formulas given in subsection 4.3.1) from each other beginning from the start of the curve. Likewise, the difference among the RSS values in the absence and presence of the signal repeater are monitored and compared.

Figure 5. 37 shows a graph describing the difference in path loss wherein the RSUs / signal repeaters / signal reflectors are optimally positioned (blue curve) along the curved road and in the absence of RSU/signal repeater deployment (red curve). As in case of road tunnel, the two curves follow a same path initially (up to a distance of 50 meters between the communicating vehicles), as the communicating vehicles do not lose LOS between them and were relatively close to each other as compared to RSU / signal repeater / signal reflector. However, the difference between curves started to extend as one of the communicating vehicle begins to approach towards the first deployed RSU / signal repeater. The path loss came to a minimum level when one of the communicating vehicles reached the first deployed RSU / signal repeater and then the path loss again began to enhance as the vehicle moved away from this RSU / signal repeater. The path loss decreased as the vehicle started to approach the second RSU / signal repeater making an arch like structure. It is interesting to note that in the presence of optimal

deployment of RSUs / signal repeaters, the path loss remains low as compared to the situation when RSUs / signal repeaters are not deployed at optimal distances along the confined curve road.

The advantage of optimal RSU positioning in terms of path loss are clearly visible throughout the complete 122 meters of the curved road that allows the LOS communication among the nodes along the curved road as shown in Figure 5. 37. It is worthwhile to observe that an average gain of 18.56 dB is monitored in RSS within a short distance of 122 meters along the curved road due to the optimal position of RSUs / signal repeaters. This average gain in dB translates to a remarkable average gain of **26.5 %** in case of optimal deployment of RSU / signal repeater along the curved road. The vehicles were able to communicate in case of accurate deployment of RSUs / signal repeaters / signal reflectors as opposed to the scenario wherein the connection among the communicating vehicles was lost in the absence of optimal deployment of RSUs / signal repeater / signal reflectors along the curved road.

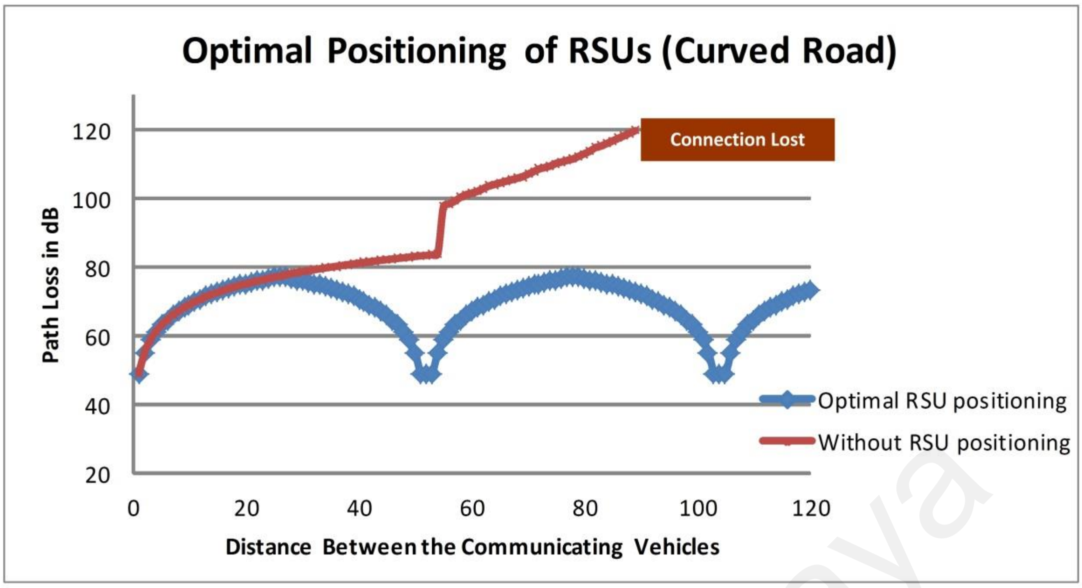

Figure 5. 37: Evaluation of Optimal Positioning of RSUs in Curved Road in terms of path loss

5.5.3 Evaluation of Optimal Positioning of RSUs on Flyovers

This subsection describes the evaluation of optimal positioning of RSUs on flyovers. The geometry of optimal positioning of RSUs/ signal repeaters is already explained in subsection 4.2.3.3. We utilized the directions as presented in the above said subsection and determined the optimal positioning of RSUs / signal repeater / signal reflectors on the flyover location which was selected for the field measurement campaign. The whole scenario along with the optimal positioning of RSUs / signal repeaters / signal reflectors is reproduced in a simulation environment. RSUs / Signal repeaters that receive and then transmit the radio signals with the same strength as the original signals are deployed, in the middle of the flyover at a height of 10 meters measured from the highest point on the flyover. The difference among the RSS values with the optimal positioning of RSU and without the RSU deployment are monitored and compared.

Figure 5.38 shows a graph describing the variation in path loss in the presence of optimal positioning of RSUs / signal repeaters (blue curve) along the flyover and in the absence of RSU/signal repeater deployment (red curve). As in case of other road infrastructure units, the both the curves follow a same path initially (up to a distance of 115 meters between the communicating vehicles), as the communicating vehicles maintained LOS between them and were relatively close to each other as compared to RSU / signal repeater. However, the difference between path loss curves started to increase as one of the communicating vehicles begins to approach towards the first deployed RSU / signal repeater, thus maintaining the LOS between indirectly with the assistance of deployed RSU / signal repeater. The path loss came to a minimum level when one of the communicating vehicles reached under the first deployed RSU / signal repeater on the highest point along the flyover and then the path loss again started to increase as the vehicle moved away from this RSU / signal repeater and started to descend. The path loss remains low in the case of optimal positioning of RSU / signal repeater as compared to the situation when RSUs / signal repeaters are not deployed at optimal distances along the flyover

The benefit of optimal RSU deployment in terms of path loss is evident throughout the complete 462 meters of the flyover because it allows the communicating vehicles to remain in LOS indirectly as shown in Figure 5.38. An average gain of 18.3 dB is observed in RSS within the 462 meters of flyover resulting from the optimal positioning of RSU / signal repeater. This average gain in dB translates to a remarkable average gain of **23%** in case of optimal deployment of RSU / signal repeater on the optimal location on flyover.

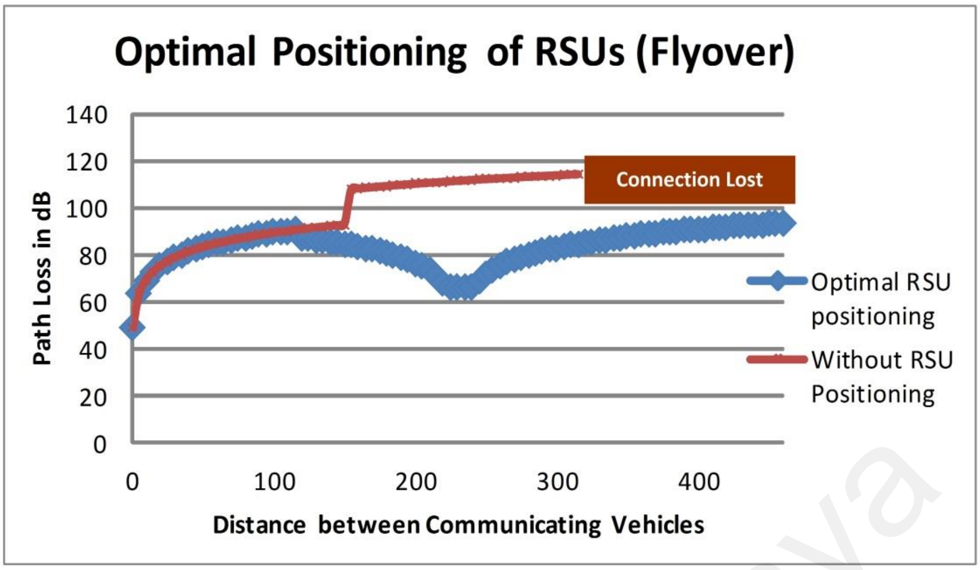

Figure 5.38: Evaluation of Optimal Positioning of RSUs on Flyover in terms of path loss

5.5.4 Evaluation of Optimal Positioning of RSUs in underpass

A relative gain in RSS is expected when the communicating vehicles utilize a road segment which has an underpass as compared to a straight road segment. The gain in RSS is due to the waveguide effect inside an underpass because the wavelength of radio signals is very small as compared to the transverse dimensions of the underpass. To confirm this phenomenon, a comparison is made among the RSS values on a straight road and on a road segment having a 27 meters long underpass using the proposed ARPM. The comparison between the path loss values on the straight road segment and the road segment having an underpass is shown in Figure 5. 39. An average decrease of approximately 16 dB in path loss is observed on a 60 meter road segment having an underpass in comparison with a 60 meter straight road. However, average decrease in the path loss becomes negligible as the distance between the communicating vehicles increased. Therefore, the deployment of RSU / signal repeater / signal reflector is not needed for the reliable communication in underpass as directed in section 4.3.3.

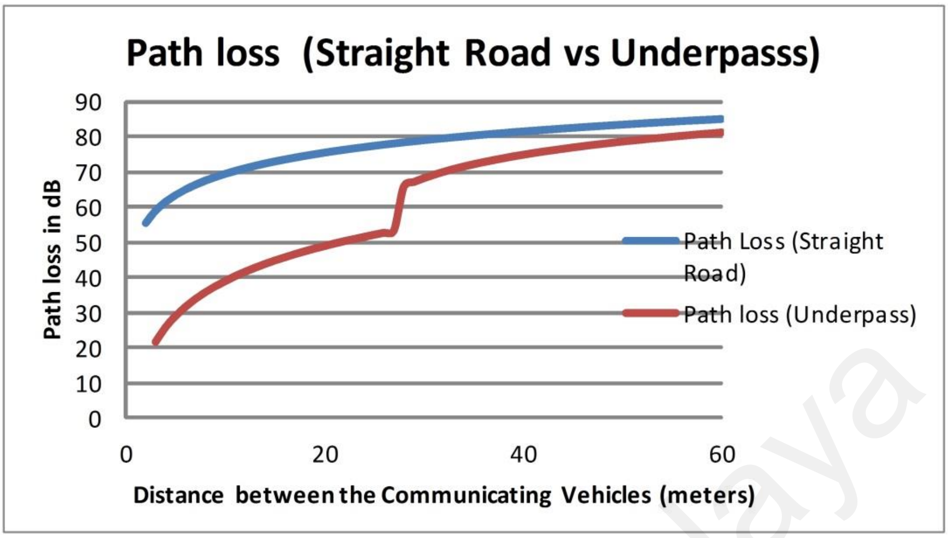

Figure 5. 39: Path loss (Straight road vs Underpass)

5.5.5 Evaluation of Optimal Positioning of RSUs in Irregular Roads

This subsection evaluates the optimal RSU positioning designed for the irregular roads. The geometry of optimal positioning of RSUs/ signal repeaters is already discussed in subsection 4.3.5. The directions presented in the above said subsection are used to determine the optimal positioning of RSUs / signal repeater on irregular roads. We considered two road segments of length 100 meters separated with each other at different angles ranging from 30^o to 105^o in simulation. The space between the road segments is supposed to be filled with static radio obstacles. The RSU / signal repeater is deployed at the intersection of two road segments as explained in subsection 4.3.5. The difference among the path loss values with the optimal positioning of RSU and without the RSU deployment is compared. To make the analysis easily understandable, the angular difference between the road segments is converted into separation angle between using the following equation.

$$SeparationAngle = 180 - AngularDifference \tag{5.1}$$

Figure 5. 40 represents the variation in path loss for the scenarios wherein the two 100 meter road segments are separated by multiple angles; 30^o, 45^o, 60^o and 105^o respectively using the proposed ARPM. The path loss without the optimal positioning of RSU / signal repeater are represented by relatively thin curves while the path loss with the RSU / signal repeater deployed at the intersection is shown using a relatively thick curve (blue curve) in Figure 5. 40. There is no difference among the RSS values for different separation angles in the presence of RSU / signal repeater because the radio signal is retransmitted / repeated by the RSU / signal repeater arbitrarily in irregular roads. Therefore, a single curve is used to represent the path loss in the presence of RSU / signal repeater in all the selected scenarios as shown in Figure 5. 40.

As in case of other road infrastructure units, the path loss curves follow a same path initially (up to a distance of 50 meters between the communicating vehicles on one of the road segments), as the communicating vehicles maintained LOS between them and were relatively close to each other as compared to RSU / signal repeater. However, the difference among the path loss curves started to increase as one of the communicating vehicles begins to approach towards the deployed RSU / signal repeater, thus maintaining the LOS indirectly with the assistance of deployed RSU / signal repeater. The path loss reduced to a minimum value wherein one of the communicating vehicles was near to the deployed RSU / signal repeater. However, the path loss again started to increase as the vehicle moved away from this RSU / signal repeater on the other road segment. The path loss remains low in all the selected scenarios when RSU / signal repeater was optimally positioned as compared to the situation when RSUs / signal repeaters are not deployed in the irregular roads.

The benefit of optimal RSU deployment in terms of path loss is evident in all scenarios with different separation angles. However, the average gain in path loss is increased as the separation angle between the road segments is increased. This phenomenon is clearly evident from Figure 5. 40. An average gain of 27.79 dB is observed within the 200 meters of irregular road resulting from the optimal positioning of RSU / signal repeater. This average gain in dB translates to a remarkable average gain of approximately 35% in case of optimal deployment of RSU / signal repeater on the optimal location in irregular roads.

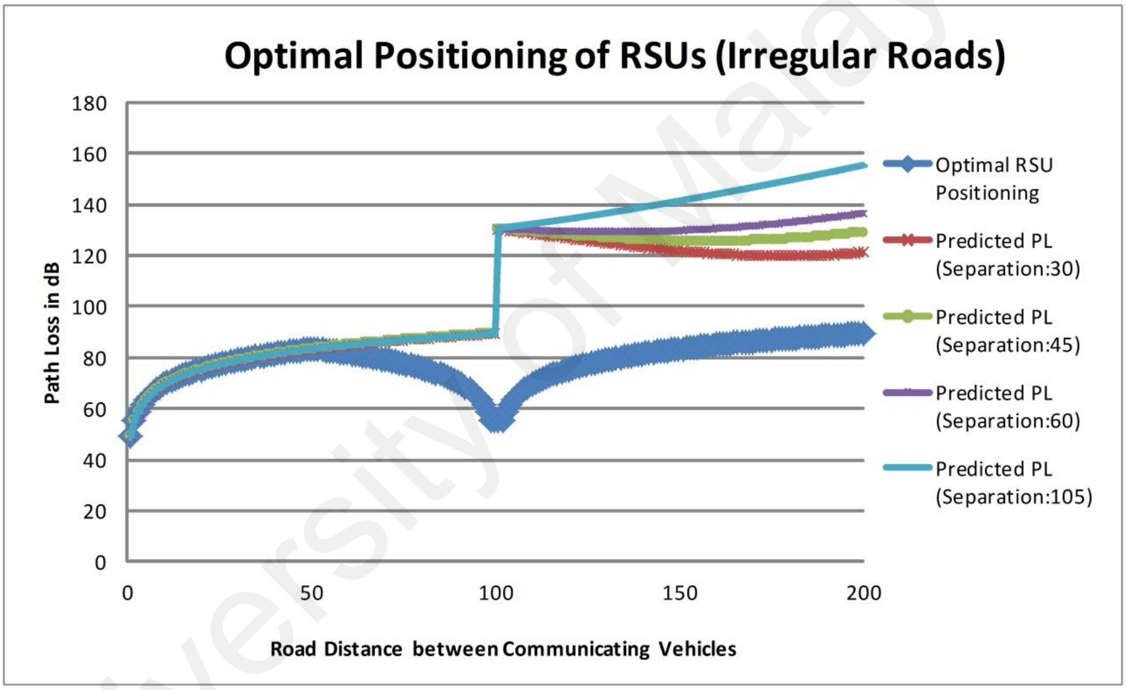

Figure 5. 40: Evaluation of Optimal Positioning of RSUs on Irregular road in terms of RSS

5.5.6 Effect of Optimal Positioning of RSUs

The effects of optimal positing of RSUs in modern road infrastructure units were studies in simulation environment by reproducing the physical sites that were selected for field measurements using web-based OpenStreetMap utility into the traffic simulator SUMO. The output of SUMO is converted into mobility trances using TraNSLite which is further scanned by JaDES to simulate radio propagation characteristics in physical layer. A module of JaDES named Optimal RSU Positioning (ORP) was developed specifically to evaluate the effects of optimal positioning of RSUs on modern road infrastructure units.

A simple unicast protocol was utilized to evaluate the effect of optimal positioning of RSUs in terms of PDR. A packet consisting of 256 bytes is sent after each millisecond by every Tx; which was intended to be received by a particular Tr in the simulation environment. The simulation time was different for each infrastructure unit depending upon the road length and the total number of vehicles. We considered a total of 100 communicating vehicles (excluding the large moving vehicles that served as moving radio obstacles) on each of the road infrastructure unit. The vehicles randomly appeared in the simulation and were having different speeds. The proposed ARPM was applied to predict path loss in confined curved road, flyover, tunnel and irregular roads prior to the calculation of PDR.

A comparison between the presence and absence of optimal positioning of RSUs in terms PDR was performed for each road infrastructure unit. An increase in PDR due to optimal positioning of RSUs was observed in all of the road infrastructure units as shown in Figure 5.41. A remarkable increase of approximately 66%, 52%, and 50% due to the optimal positioning of RSUs was observed in flyover, confined curved road and irregular road respectively. However, a nominal gain of approximately 6% was observed in road tunnel probably due to LOS condition of the vehicles throughout the whole simulation. The research on optimal positioning of RSUs on road side units suggested that the underpass does not require an RSU. Therefore, the underpass is not included in this comparison.

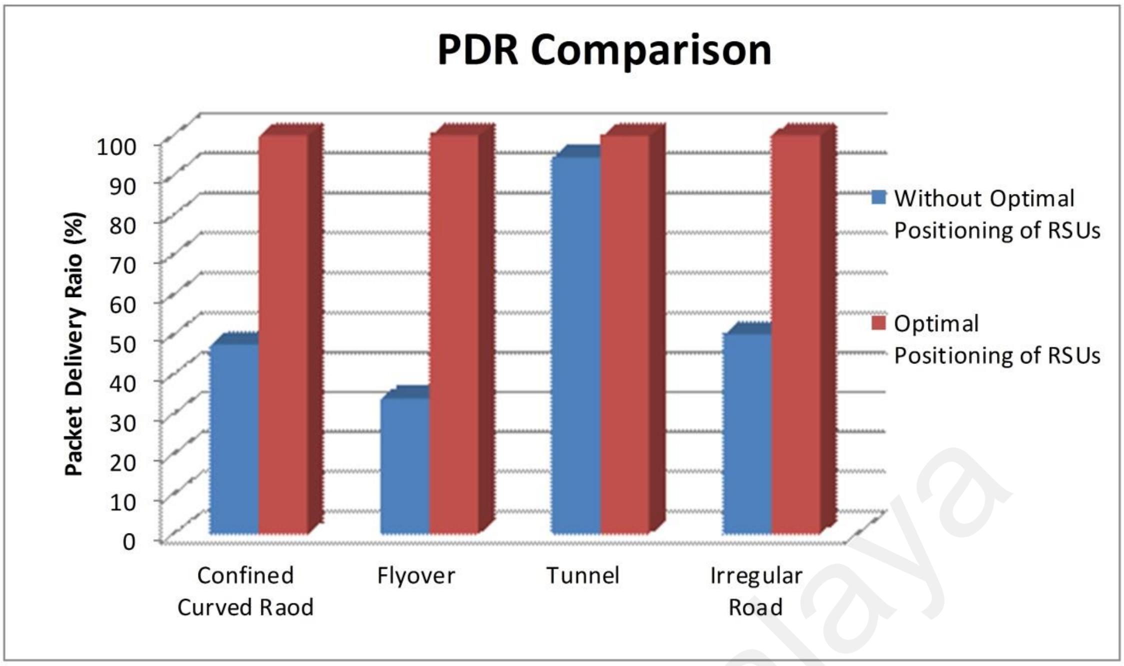

Figure 5.41: Effect of Optimal Positioning of RSUs on PDR

5.6 Conclusion

The proposed ARPM is evaluated on small as well as large scale using the real world data gathering campaign in multiple road infrastructure units and reproducing the scenarios for large scale evaluation in simulation environment respectively. For the small scale evaluation, multiple sites comprising of modern road infrastructure units were selected and extensive data gathering campaigns in terms of RSS are carried out using specialized equipment suitable for vehicular communication. RSS values are monitored using multiple arrangements of communicating vehicles. Afterwards, the proposed ARPM is applied to predict the path loss in the selected environment. The measured path loss values are compared with the predicted path loss values to confirm the suitability of application of proposed ARPM to predict the path loss in an acceptable range for the modern road infrastructure units. The accuracy of prediction of path loss using proposed ARPM is calculated for each road infrastructure unit along with the R-square test and residual analysis. Remarkable accuracy ranging from 91% to 98% between the predicted and measured path loss was found confirming the applicability of the proposed ARPM in the prediction of path loss in modern road infrastructure units. For large scale evaluation of the proposed ARPM, the real-world road scenarios were reproduced in the simulation environment with relatively high number of communicating vehicles and random movements of the road traffic. The proposed ARPM along with the existing widely used RPM (CORNER, free-space RPM and two-ray ground RPM) are applied on the simulated scenarios to compare the predict path loss values again endorsing the applicability of the proposed ARPM. The optimal positioning of RSUs is also evaluated and its advantages in terms of reduction in path loss are discussed. The path loss values in the absence as well as in the presence of RSUs were monitored and compared in modern road infrastructure units. A phenomenal decrease in path loss ranging from 23% to 35% is observed in different road infrastructure units. Therefore, the proposed ARPM is validated on the basis field measurement campaign in small scale evaluation, its applicability to predict the path loss in modern road infrastructure unit is further supported by comparing it with some of the existing RPMs in large scale evaluation, and the benefits of optimal RSU positioning in terms of reduction in path loss are evaluated.

CHAPTER 6: CONCLUSION

6.1 Introduction

This conclusive chapter re-evaluates the objectives of this research, summarizes the major contributions of the research work, re-discusses the scope and limitation of the work, and presents the future research directions in this area. The chapter is organized into five sections. Section 6.2 discusses the reappraisal of the objectives of the research. Section 6.3 provides a summary of the contributions of the research work. Section 6.4 discusses the scope of the research work. Section 6.5 proposes future directions of the research work and concludes the discussion.

6.2 Reappraisal of Objectives Achievement

This research investigates the problem of developing a light-weight and realistic radio propagation model suitable of predicting path loss with acceptable accuracy by considering both static and moving radio obstacles in modern road infrastructure units to facilitate reliable communication infrastructure in VANETs. Section 1.5 highlighted four major objectives of this research, which are achieved as follows:

To achieve the objective of literature review, a thematic taxonomy of existing radio propagation in VANETs is developed. The state-of-the-art is studied from web databases and online digital libraries (ACM, IEEE and ISI Web of Knowledge). Existing research papers in the broader domain of radio propagation, radio propagation in VANETs and obstacle modeling in VANETs are selected. We reviewed the latest literature for widely used and innovative radio propagation models employed to predict path loss in VANETs. Existing radio propagation models in VANETs are categorized using thematic taxonomy and further classified into three major groups on the basis of obstacle handling (Section 2.5). We reviewed and highlighted the critical aspects of existing radio propagation model using the qualitative analysis (Section 2.6). Existing radio propagation models in VANETs are compared with each other (Section 2.7) and are analyzed on the basis of thematic taxonomy (Section 2.8). The open issues and challenges for radio propagation in VANETs are highlighted (Section 2.10).

The impact of modern road infrastructure units on radio propagation is investigated by (a) considering the structure of modern road infrastructure units; (b) investigating the possibility of LOS communication among the vehicles and inferring the impact of NLOS scenario that may arise due to the road infrastructure unit; and (c) measuring the RSS in multiple road infrastructure unit to establish factual radio propagation detail that serves as a guideline to develop radio propagation formula to predict path loss in modern road infrastructure units. The structure of modern road infrastructure unit and their effect on LOS among the communicating vehicles are discussed in subsection 2.2.5 and section 2.9. Measurement scenarios at multiple road infrastructure units namely, (a) straight road, (b) curved road, (c) road tunnel, (d) flyover, and (e) underpass are described in subsections 5.3.1.1, 5.3.2.1, 5.3.3.1, 5.3.4.1 and 5.3.5.1 respectively and their respective measurement results in terms of RSS are explained in subsections 5.3.1.2, 5.3.2.2, 5.3.3.2, 5.3.4.2 and 5.3.5.2.

To achieve the third major objective, we designed and developed an adaptive radio propagation model that considers both static and moving radio obstacles in modern road infrastructure units. The proposed adaptive radio propagation model is elaborated in section 4.2. The radio propagation formulas proposed for modern road infrastructure units which consider all types of radio obstacles are explained in section 4.2.3. Furthermore, the proposed adaptive radio propagation model is evaluated in small scale using real-world data which was collected during the extensive field measurement campaign. The real-world RSS data confirmed the applicability of the proposed adaptive radio propagation model to predict the path loss in modern road infrastructure units because of the level of accuracy achieved when predicted path loss values are compared with the measured results. The evaluation of the proposed adaptive radio propagation model is discussed in section 5.3. The proposed adaptive radio propagation model was further evaluated on large scale using simulation and analysed by comparing it with some of the existing radio propagation models widely used in VANETs simulation.

The fourth major objective of optimal positioning of RSUs on modern road infrastructure units is achieved by utilizing geometrical concepts to identify the most advantageous position of RSUs in terms of RSS. Optimal positioning of RSU on multiple road infrastructure units is explained in section 4.3. The positive effects of optimal positioning of RSUs on radio propagation are observed using proposed adaptive radio propagation model. A comparison is made among the path loss values in the presence and absence of optimal RSUs positioning on modern road infrastructure units (Section 5.4).

6.3 Contribution of the Research Work

This research has redirected the existing efforts in the design of radio propagation models for VANETs towards a novel perception by which to incorporate adaptability in radio propagation models for modern road infrastructure units as a benchmark towards realistic and reliable performance evaluation of new applications and protocols. This research produced a number of contributions to the body of knowledge which are summarized as follows:

- ***Thematic Taxonomy***:

  The thematic taxonomy in this research is used to analyse the implications and critical aspects of existing radio propagation models. With the help of thematic taxonomy, a comparison among the existing state-of-the-art propagation models is performed on the basis of significant parameters that are identified to analyse the radio propagation models. Literature review contributed to identify issues and challenges for the development of a realistic radio propagation model in VANETs. Existing radio propagation models in VANETs tend to abstract away from the real urban road architecture of modern cities because they focused mainly on grid architecture. Furthermore, the existing radio propagation models do not consider all types of radio obstacles in the movement restricted environment of urban roads are some of the identified issues resulting from the analysis and comparison of existing radio propagation models based on the thematic taxonomy. Therefore, the analysis and comparison of radio propagation models based on the thematic taxonomy necessitated the study of modern urban traffic environment and scenarios with regard to radio propagation in VANETs.

- ***Investigation of the Impact of Modern Road Infrastructure Units on radio propagation in VANETs:***

  We investigated the impact of modern road infrastructure units on the RSS. We identified that the structure of different road infrastructure units such as flyover and confined curved roads may serve as potential static radio obstacles for vehicular communication that may negatively affect the vehicular communication. Conversely, the positive effect of underpass on the path loss as compared to free space radio propagation is also recognized in this research. We also identified that the speeds of the communicating vehicles in the legitimate speed range (street legal) has a minimal effect on radio propagation in modern road infrastructure units. Therefore, the research on the impact of modern road infrastructure unit on radio propagation in VANETs is another major contribution to the body of knowledge.

- ***Development of an Adaptive Radio Propagation Model:***

  The major contribution of this research to the body of knowledge is the proposition, design and development of an adaptive radio propagation model that considers both static and moving radio obstacles in modern road infrastructure units. Computationally feasible radio propagation formulas (simple yet realistic) were proposed for each of the road infrastructure units to facilitate the prediction of path loss with acceptable accuracy. The proposed propagation formulas for each of the modern road infrastructure units (curved roads, road tunnels, flyover and underpasses) contains three major factors namely (a) LOS path loss covering the signal attenuation resulting from distance between the communicating vehicles, wavelength of the radio signal and other physical factors that cause signal attenuation, (b) path loss due to static radio obstacles including buildings and the structure of road infrastructure units, and (c) path loss resulting from knife edge effect from various moving radio obstacles that obstruct the 60% of first Fresnel's zone due to the difference of height between the communicating vehicles and moving radio obstacles.

  The proposed adaptive radio propagation model is evaluated on small scale using the data gathered from real-world field measurement campaign. The proposed adaptive radio propagation model is also evaluated on large scale using simulation in which real scenarios are reproduced in the simulation environment to check the validity of the proposed solution. The proposed adaptive radio propagation model is also compared with other widely used state-of-the-art radio propagation models such as Free Space Model, Two Ray Ground Model and CORNER using simulation. The evaluation of the proposed adaptive radio propagation model confirms its suitability to accurately predict the path loss in modern road infrastructure units.

- ***Optimization of RSU positioning in modern road infrastructure units :***

  Another contribution of this research to the body of knowledge is the optimal positioning of RSUs in modern road infrastructure units. The optimal positioning of RSUs is determined using simple geometrical concepts by considering the dimensions and restricted movement of the communicating vehicles for the individual road infrastructure units. Guidelines are provided for the optimal positioning of RSUs based on the idea of maintaining LOS among the communicating vehicles while travelling on confined curved roads, flyovers and irregular roads. The optimal positioning of RSUs in tunnels having straight road inside tem is based on the RSS values because the path loss in tunnels is relatively less as compared to free space. However, from the field measurement results for underpasses, it is inferred that the RSU / signal repeater / signal reflectors are not required due to the reduction of path loss resulting from a waveguide effect inside an underpass. The effects of maintaining LOS among communicating vehicles by using RSUs / signal repeater / signal reflectors positioned at optimal distances are monitored by reproducing the real-world scenarios in simulation environment.

  Furthermore, a comparison between the absence and presence of RSUs at optimal positons is made to evaluate the positive effects of optimal positioning of RSUs on

RSS, path loss and PDR using the proposed adaptive radio propagation model. A remarkable decrease in path loss in presence of RSUs at optimal positions for modern road infrastructure units is observed; thus stamping the high impact of optimal positioning of RSUs on radio propagation to facilitate reliable communication infrastructure in VANETs.

6.4 Research Scope and Limitation

The scope of this research work is limited to analysing the problem of identification of critical issues in existing radio propagation models in VANETs, proposing an adaptive solution for the prediction of path loss in modern urban traffic environment and providing a reliable communication infrastructure by optimal positioning of RSUs in modern road infrastructure units. This research only covers the physical layer and MAC sublayer of the protocol stack. Therefore, this research lacks in the consideration of the supplementary issues related to the higher layers in protocol stack. The supplementary issues include performance evaluation of particular routing algorithms using the proposed adaptive radio propagation model and the effect of the accurate prediction of path loss on the evaluation metrics such as delivery latency and average path length. Furthermore, the field measurements used in this research are taken by utilizing the equipment configured at 5 GHz. Furthermore,

6.5 Future Work

This research is focused on the design and development of an adaptive radio propagation model that accurately predicts the path loss in various modern road infrastructure units; each of the road infrastructure unit has its own challenges and inputs when it comes to the prediction of the path loss which is realistic yet simple in terms of computational complexity. Hence, this research emphasizes on the computationally feasible yet accurate prediction of path loss in VANETs generally and in the modern urban road infrastructure units specifically.

However, this research lacks in considering supplementary issues associated with higher layers of the protocol stack. Therefore, the future research work includes;

- Extending the scope this research to address the issues of performance evaluation of particular routing protocol using our proposed adaptive radio propagation model.
- The inclusion of performance metrics such as delivery latency and average path length for further cementing the applicability of the proposed solution.
- Although, the results obtained using the equipment configured at 5 GHz are equally applicable on the frequency of 5.9 GHZ, but still, the measurement of RSS and hence the path loss using the specialized transceivers used in modern vehicles that are configured at 5.9 GHz can be performed in future. This new measurement campaign using the equipment configured at 5.9 GHz will not only further confirm the applicability of the proposed solution to accurately predict the path loss in VANET environment but will also identify the minute differences (if any) in the results of this research.

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Article Under Review

Muhammad Ahsan Qureshi and Rafidah Md. Noor, “A Computationally Inexpensive Radio Propagation Model for Vehicular Communication on Flyovers and Inside Underpasses.” *KSII Transactions on Internet and Information Systems*. (*ISI/SCOPUS Cited Publication*)