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NEW APPROACH TO ENHANCE AND EVALUATE THE PERFORMANCE OF VEHICLE-INFRASTRUCTURE INTEGRATION AND ITS COMMUNICATION SYSTEMS

Final Report

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FINAL REPORT

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DISCLAIMERS

Abstract

This report describes our contribution to the Intelligent Transportation System (ITS). A summary of our work vision, objectives and approach to build and deploy the UDM test bed is presented along with recommendations to enhance system performance.

Organization of the Final Report

The UDM research program final report is organized into five sections:

Section 1: Final Report: UDM Research, Executive Summary
This section provides an overview of the UDM research as well as brief background of ITS along with goals and objectives of our research. Moreover, this section illustrates the action plan of our research. This section does not provide the detailed test results. However, it is recommended for general managers of transportation agencies who are concerned with the overall vision of ITS.

Section 2: Final Report: UDM Research, WLAN Evaluation for IVC Application
This section shows the evaluation of using WLAN protocols in Inter-Vehicle Communication (IVC) environments. Moreover, it includes all technical information. This section is recommended for researchers, research-group leaders and research assistants who are concerned with the deployment of WLAN protocols in IVC environments.

Section 3: Final Report: UDM Research, UDM Test Bed
This section provides the details and results of the two approaches investigated in our research. UDM test bed and architecture, however, were described with the test bed component. Example of how to evaluate the performance of an IVC is also provided in this section. This section is recommended for researchers, research-group leaders and research assistants who are concerned with the deployment of the test bed concept to evaluate different IEEE802.11 protocols.

Section 4: Final Report: UDM Research, Doppler Shift Investigation
This section provides information on how Doppler shift can affect the performance of WLAN protocols in IVC environments. A new method to enhance the performance of these protocols for such a dynamic environment is presented as well. This section is recommended for researchers, research-group leaders and research assistants who are concerned with Doppler shift and its impact on performance.

Section 5: Final Report: UDM Research, Traffic Light Scenario Evaluation
This section evaluates traffic flow at intersections relative to number of nodes and communication metrics. A study is conducted to compare adaptive traffic light and fixed-time traffic light controllers to the number of vehicles. This section is recommended for researchers, research-group leaders and research assistants who are concerned with traffic light control systems and their impact on traffic flow.

Table of Contents

List of Tables

List of Figures

1. UDM Research, Executive Summary

1.1. UDM Research Overview

1.1.1. Executive Summary

With the rapid advances in wireless communication and the introduction of Dedicated Short-Range Communications (DSRC) as an enhanced protocol for Vehicular Ad hoc NETwork (VANET) communications, promising opportunities for increased vehicle safety and an enhanced driving experience are available. With opportunities, however, come numerous technical challenges. In order to investigate and overcome these challenges, we started our research with studying the use of wireless local area networks (WLAN) protocols in Inter-Vehicle Communications (IVC) environments. Moreover, the protocols' performance was evaluated in terms of measuring throughput, jitter time and delay time.

In our research, we have come up with a unique setup to evaluate IEEE802.11 protocols. This setup will reduce the cost of test beds that might be deployed to evaluate the performance of new IEEE802.11 protocols. In order to validate our concept, we have implemented the test bed at University of Detroit Mercy and evaluated the performance of IEEE802.11b/g. The developed WLAN-based test bed allowed us to test different IEEE802.11 protocols and yet keep the cost at a reasonable level.

Moreover, we investigate the impact of Doppler shift on the quality of the transmitted/received signal in an Orthogonal Frequency Division Multiplexing (OFDM) communication system. The developed channel model that combines Additive White Gaussian Noise (AWGN) and Rayleigh channel representations to resemble a realistic transmission medium is presented. The model is validated by showing that the relation between Energy of Bit to Noise Ratio (E_b/N_0) and Bit Error Rate (BER) is consistent with theoretical formulas. The degradation in signal quality as a result of increased vehicle speed is presented through graphical and analytical representation of BER with respect of applied Doppler shift. Moreover, a new methodology to reduce the impact of Doppler shift is proposed and simulations are performed to confirm the reduction of Doppler shift impact on the signal quality.

1.1.2. Background

In the United States, in 2003, there were 42,643 vehicle-related fatalities. Of these, 25,136 were a result of road departure, and 9,213 were intersection-related. The problem of highway deaths is a "national epidemic" and costs society $230.6 billion a year, about $820 per person [1]. Moreover, a traveler is more likely to die in a car than on an airplane, in a train or in a terrorist attack [2]. The question is: how can we use technology to create a safe and efficient highway system? Inter-Vehicle Communications (IVC) is a system that allows vehicles to communicate their data between each other and coordinate their maneuvers safely and smoothly. IVC is an example of intelligent transportation systems (ITS), which are a combination of intelligent vehicles and intelligent transportation infrastructure.

The U.S. Department of Transportation (USDOT) proposed ITS initiative: "ITS improves transportation safety and mobility and enhances productivity through the use of advanced information and communications technologies" [9].

Vehicle-Infrastructure Integration (VII) is an emerging IVC and ITS initiative aimed at creating communication links between vehicles (V2V) and between vehicles and the infrastructure (V2I). Traditional ITS technologies rely on infrastructure-based systems to collect and process data. However, VII systems enable vehicles to collect and communicate data to the infrastructure. Moreover, VII systems will allow drivers to receive communication regarding safety hazards and relevant travel information [3].

VII has three main components, as shown in Figure 1:

- On-Board Equipment (OBE), including all components that are installed in the vehicle. This equipment includes wireless subsystems to be able to communicate with other vehicles (V2V), and with infrastructure (V2I).
- Road Side Equipment (RSE), including the wireless subsystem to allow infrastructure and the Network Subsystem to communicate with vehicles.
- Network Subsystem that enables roadside units to communicate with each other and to access the Internet.

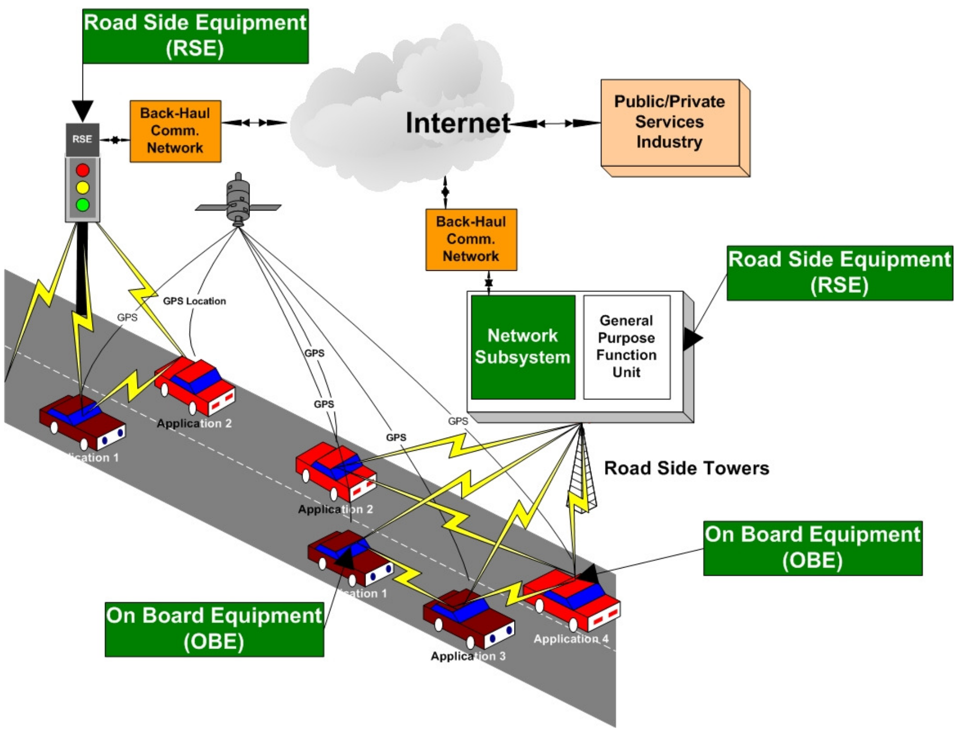


Figure 1. VII Consists of Three Interconnected Components

Graphic created by UDM Student Mahmoud Haidar

The ITS concept has received enormous attention all over the world especially in Japan, Europe, and the United States. In Japan, the ITS vision focuses on enhancing road safety, smoothing traffic, and being environmentally friendly [10]. ITS Japan deals with nine major areas in transportation including electronic toll collection, providing assistance for safe driving, improving the efficiency of the road management, supporting emergency vehicles, and supporting pedestrians. The goal is to achieve a transportation system of three traffic zones by the end of 2011. These zones are: a zero traffic fatalities zone, a zero traffic congestion zone, and a comfortable transportation experience zone [11].

In Europe, different approaches for ITS have been proposed and investigated. FleetNet and Drive-thru Internet are two of the main projects in Europe. FleetNet uses the ad-hoc concept to create a platform for IVC [12]. Its vision addresses safety and non-safety related applications and can be divided into three main categories: cooperative driver-assistance, local flouting car data, and communication and information services applications [13]. The Drive-Thru Internet project uses the infrastructure approach to provide distinct hot spots of WLAN connectivity for vehicles. However, this connectivity is planned to be a short life-time intermittent connectivity [14], which is achieved by creating so-called connectivity islands along the road. Drivers might slow down or stop by these spots to get the services they need [15].

In the process of developing an appropriate communication protocol for ITS, the DSRC was first proposed, in the unlicensed 902-928 MHz frequency range, to support electronic toll collection systems. However, in 1999, the Federal Communications Commission (FCC) assigned 75MHz bandwidth in the 5.9GHz band for DSRC to support ITS services and applications [16, 17, 18]. The ASTM group E17.51 then introduced the E2213 standard, based on the IEEE 802.11a [17, 19, 20], a standard that the FCC referenced as a base line for developing the DSRC protocol. Afterwards, IEEE initiated a new task group (TGP) and released a draft of IEEE 802.11p as their proposed standardized version of DSRC. Since all proposed solutions for DSRC are based on IEEE 802.11 standards, this paper evaluates the performance of two of the most commonly used protocols, IEEE 802.11b and g.

The IEEE 802.11 standards have two modes of operation: centralized (with infrastructure) and distributed/Ad-Hoc (without infrastructure) [17, 21, 22]. The centralized mode has two schemes with which to access the channel: a primary contention-based access scheme, called Distributed Coordination Function (DCF), and an optional contention-free scheme, called Point Coordination Function (PCF). On the other hand, the distributed mode has only one access scheme which is the DCF. DCF uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme. This means that every station (STA) has to sense the medium before transmitting any data-frame. If the channel was free for a minimum period of time, called Distributed InterFrame Space (DIFS), the STA gets access to the medium and starts sending its data. Otherwise, the STA goes through a back-off procedure. On the other hand, PCF is basically a round-robin scheduler scheme in which the PCF access point, usually called Point Coordinator (PC), polls all the stations in the network giving each one of them a contention-free time slot to send its data [23].

Two of the main challenges in DCF scheme are known as the hidden terminal and exposed terminal problems. Adding the Request-To-Send and Clear-To-Send (RTS/CTS) handshaking mechanism solves the hidden terminal problem, while adding the Data Send (DS) and Data Acknowledgment (ACK) confirmation messages solves the exposed terminal problem [21]. However, these approaches create other problems in VANET applications, such as increasing the overhead of any message, increasing the delay before transmission, and extending the range of blocked terminals [24].

Although IEEE 802.11, based standards deploy similar MAC protocols, they differ in the other physical layer's details such as operating frequencies and modulation schemes. IEEE 802.11a operates in the 5.18-5.825 GHz band, which is close to the DSRC band (5.85-5.925 GHz). Although both standards use Orthogonal Frequency Division Multiplexing (OFDM) technology, DSRC has a maximum data rate of 27 Mbps whereas IEEE 802.11a reaches a maximum bit-rate of 54Mbps. DSRC reduces the channel bandwidth to 10 MHz to reduce the impact of multipath propagation and Doppler shift effects. Moreover, DSRC adds four maximum allowable Effective Isotropic Radiated Power (EIRP) levels to extend its communication range [20]. IEEE 802.11g uses the OFDM technology with a maximum bit-rate of 54Mbps, while IEEE 802.11b uses the Direct Sequence Spread Spectrum (DSSS) technology with a maximum bit-rate of 11Mbps [25]. Both IEEE 802.11b/g operate in the 2.4 GHz ISM unlicensed band, which causes performance degradation when both co-exist.

The effects of different vehicular traffic and mobility scenarios on WLAN performance were studied in [18, 26, 27, 28, 29]. The results in [19] show that under suitable driving conditions, a 1000 m connectivity range can be achieved with IEEE 802.11b; keeping in mind that vehicles' relative speed heavily affects the connection performance. Other research groups showed that using external antennas mounted on the roof of each vehicle extends the Line of Sight (LOS) and improves signal strength [18]. Accordingly, the vehicle speed becomes less important as long as it is less than 180 Km/h and LOS is available.
The multipath propagation effect creates areas of extremely low signal strength, so-called null zones, where the signal cannot be sensed most of the time, and the network throughput suffers significant degradation [27].

Wireless channels with multipath propagation effect are usually described using the Rayleigh fading model. Although vehicular environments suffer from this effect, many other factors contribute to the channel mode. Therefore, many researchers tried to model the channel under different conditions for both V2V and V2I situations, and for single-hop and multiple-hop communication scenarios [28, 29]. The results showed that the performance of single-hop communication depends largely on the distance between vehicles. Once the single-hop communication between vehicles attains a poor connection because of large distance, multiple-hop communication becomes an alternative path that enhances connection performance.

1.1.3. The Vision

VII has many applications; however, our research focuses on those related to a traffic control system [4, 5]. It formulates some vehicle-to-vehicle and vehicle-to-infrastructure communication scenarios and develops a test bed platform to evaluate the network characteristics necessary to service such applications. We envision the project to be of two stages:

- The first stage of the project was defining the test bed requirements, capabilities and constraints, and then building the test bed and using it in the second stage of the project. IEEE 802.11p protocol is being developed for IVC networks, and is still a draft protocol [6]. Therefore, creating a generic test bed that can be used to evaluate the IVC performance for different IEEE 802.11-based protocols is an important task.

  The IEEE 802.11 protocols family uses Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) technique to access the medium [7]. In CSMA/CA, nodes within the transmission range of each other contend for the medium, and only one node wins it at a time, while others back off randomly, and contend for the medium later. In real life, we have many nodes, vehicles and infrastructure, communicating with each other using 802.11x protocols, hence, making the contention process of a serious impact on the network communications' metrics such as packet delay, throughput, network connectivity…etc. From this perspective, there is a need to develop a test bed that reflects the real life communications. However, it is impossible to bring as many nodes in the test bed as there would be in a real-life scenario, due to high cost. This research envisions a low- cost realistic test bed that allows for testing the different emerging protocols for vehicular applications. Figure 2 illustrates how dense the IVC environment could be, and thereby highlights the need for a representative test bed.

Figure 2. A Busy Highway Merge Section that Gives an Idea of How Dense an IVC Environment Could Be

- The second stage was to investigate the communication characteristics necessary to allow VII to help prevent a running a red traffic-light scenario at a traffic light intersection. Running a red traffic light is a common behavior and a major source of accidents at traffic intersections. Drivers run a red traffic-light for three reasons. First, they misjudge the vehicle's speed, i.e., the driver tries to run the yellow light, speeds up, and cannot stop when the light switches to red. Second, the driver is distracted, i.e., the driver does not pay attention to the light because he or she is distracted with a different task. Third, the driver intentionally runs the red light, i.e., violates the traffic laws on purpose. VII can be helpful in solving all three of these problems. With VII, the vehicle periodically reports its speed and position to the roadside equipment (RSE). The RSE, in turn, periodically reports the traffic-light schedule, such as current traffic light status, when the light will turn to yellow, and when the light will turn to red. The vehicle then can calculate whether it has to decelerate to stop before the light goes red, accelerate to avoid crossing the red light if a stop cannot be performed with the current speed, or warn the driver of an impending traffic-light violation. The implementation of this interaction can go further; a first stage would be an interactive warning system to alert the driver of the traffic light status and advise the proper action. A second stage would be to automate the vehicle reaction at some point and override the driver's control (i.e., prohibit the driver from running a red light). Moreover, in the case of sensing a traffic light potential violation, the RSE can adjust the other traffic-light schedules at the intersection so that it prevents other vehicles from colliding with the errant vehicle. In this case, the errant vehicle will still be violating the law by running a red light, but other vehicles will not be allowed to continue driving until the road is clear. Figure 3 shows the data flow block diagram for the traffic-light scenario.

Looking at the investigated problems as isolated scenarios simplifies them to some extent. The traffic-light scenario, however, is part of an overall system and its communication demands will be allocated from the overall system resources; therefore, challenges must be overcome for this scenario to be tenable. The next section highlights some of the challenges related to implementing VII and IVC systems and addresses those that we will explore in our research.

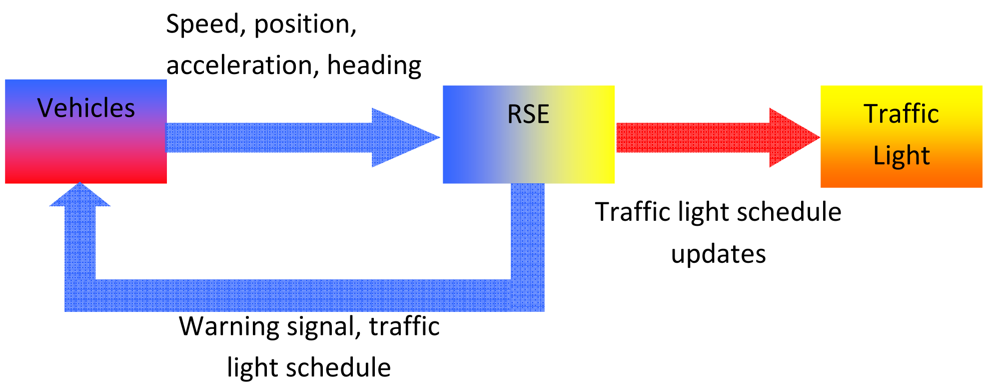


Figure 3. Data Flow Diagram for an ITS Traffic Light Scenario

1.1.4. Objectives of the Work

The purpose of this research was to develop new methodologies that would provide low delay and high throughput. The activities that will be performed as a part of the research are as follows:

1. Develop a Wi-Fi-based test bed for inter-vehicle communication
2. Evaluate the emerging wireless protocols using the developed test bed
3. Evaluate different traffic light scenarios and their impact on communication characteristics
4. Investigate Doppler shift effect on the inter-vehicle communication and possible solutions that would alleviate the problems

1.2. Support of Objectives to MDOT

Our research addresses many of the concerns and priorities of both the USDOT and the Michigan Department of Transportation (MDOT). Both agencies seek a safer road and highway environment with fewer fatal crashes and less unexpected delay due to incidents and non-recurrent congestion. The work proposed here contributes to faster and more effective VII systems that reduce the risk and occurrence of crashes, thereby saving lives and reducing delay.
An efficient VII system is expected to improve highway efficiency and reduce unexpected delay and the potential for crashes at a lower cost than is achievable by additional roadway construction. Furthermore, adding additional lanes to roadways is not always possible or feasible due to the lack of land availability, environmental concerns, citizen opposition and financial concerns. Therefore, VII promises to be a viable alternative solution to safety and travel delay problems. The success of VII in Michigan also may help build a VII industry in the state and assist other states in understanding the positive impact of the system on our congested arterial roadway network.

1.3. Action Plan for Research

Task 1: Perform a literature and technology survey to investigate what has been done in the inter-vehicle communication field.

Task 2: Develop a generic test bed that forms a foundation to evaluate wireless technologies (i.e. 802.11x) for inter-vehicle communications.

Task 3: Perform intensive measurements in the test bed to evaluate different performance metrics such as bit error rate (BER), Packet Error Rate (PER) and Packet Delay.

Task 4: Evaluate the communication metrics in our test bed when using one node to load the channel with constant bit rate packets while the others communicate useful data among themselves.

Task 5: Evaluate inter-vehicle communications performance with the help of additional Wi-Fi transceivers. The Wi-Fi nodes will emulate the contention of the medium.

Task 6: Equip the test bed with new wireless technology that has been used recently for inter-vehicle communication such as 802.11n and 802.11p (DSRC).

Task 7: Compare the recent technology performance with the Wi-Fi performance in outdoor environments.

Task 8: Simulate the traffic-light scenario using a network simulator, such as, NS-2, VIILAB …etc.

Task 9: Validate the traffic-light scenario for different number of moving vehicles.

Task 10: Study the Doppler Shift effect encountered in the outdoor high-speed vehicle environment.

2. UDM Research, WLAN Evaluation for IVC Application

2.1. Introduction

With the rapid development of the Intelligent Transportation System, Vehicular Ad-Hoc Networks (VANET) have gained significant importance in the research community. VANET deploys the concept of infrastructureless (ad-hoc) networks in the ITS environment, thereby enabling Vehicle-to-Vehicle (V2V) and Vehicle-to-Road Side Unit (V2R) communications. Still, many issues need to be studied when building VANET, such as mobility, range, bit-rate, security and Doppler shift effect. IEEE 802.11 standard protocols have the potential to serve VANET. However, they were not designed to operate in highly dynamic outdoor environments, such as ITS. Therefore, an extensive evaluation of the IEEE 802.11 family is necessary to reveal its pros and cons. This section shows the results of the tasks of the first year in our research. During the first year our research concentrated on evaluating the performance of the use of IEEE 802.11b/g protocols in Inter-Vehicle Communications (IVC). The evaluation was conducted in terms of measuring time-to-login to the network, range, throughput and jitter time.

2.2. Performance Metrics

In order to evaluate the protocol adequacy for ITS applications, we evaluate its communication range, time-to-login to a network, throughput, jitter time, delay time, and the impact of passive vehicles on the protocol performance.

We define the communication range as the maximum distance a WLAN signal can travel and still be successfully received at the destination, or the distance beyond which the connection between two communicating devices will be lost. The time-to-login is the time needed by a node to join a network, which includes the discovery time, authentication time and association time.
To avoid confusion, we define performance metrics such as data rate, throughput and goodput. The main difference among these performance metrics is that they relate to different OSI layers. The data rate represents the transmitted/received bit rate at the physical layer. The throughput represents the bit rate at the TCP layer with the IP/data link headers. Finally, the goodput measures the bit rate at the application layer. For example, if a 5 Mbyte file takes 5 seconds to be sent over the network, the goodput will be reported as 1 Mbps. Clearly, the goodput is less than the throughput, which is less than the data rate, primarily because each layer adds its own header. Telecommunication engineers usually consider average throughput value and average goodput value, whereas maximum values are considered when talking about data rate. For example, IEEE 802.11b has a data rate of 11 Mbps and the throughput is less than 11 Mbps. Throughput is not fixed in WLAN, and its value is affected by different parameters such as the number of users on the network, the propagation and latency [22]. Obviously, this creates a need for multiple data rate values, which is the case in all WiFi protocols.

To evaluate the protocol ability to serve real-time communication, we measure two timing values: the jitter time and the delay time. The jitter time is the variations in arrival times of periodically sent packets. When a transmitter sends packets periodically, the arrival time of these packets, at the receiver, is expected to follow the same period. However, the arrival time may deviate from its expected value because of channel congestion, and packets may even be received out of order. On the other hand, the delay time is the time between transmitting the packet and receiving it successfully at the destination.

The number of passive vehicles is the number of vehicles that exist in the test field, which are not sending or receiving any data on the wireless channel. The number of vehicles on roads affects the characteristics of wireless channel for vehicular environments even if they are not functioning as transceivers. The known reason for this is the multipath propagation problem that might be represented in the Rayleigh model. However, the Rayleigh model does not fully describe the behavior vehicular environments.

Throughout this task, Windows XP-based laptops and desktops were used. IEEE 802.11b/g were evaluated using both internal and external-USB wireless cards in each machine. To evaluate different protocols in ITS applications, we used the following performance metrics, communication range, time-to-login, and throughput and jitter-time measurements.

The tests were done using four laptops (nodes) running Windows XP. Three laptops were equipped with external and internal WiFi cards. The external cards have IEEE 802.11b/g/n capabilities (Linksys WUSB600N); whereas the internal cards only have IEEE 802.11b/g capabilities. One of the laptops was set up as a sniffer and/or a Signal to Noise Ratio (SNR) tester. A high accuracy DGPS receiver (Novatel ProPak-LBplus) was used to track the distance between nodes so we were able to measure the communication range. Kperf, Wireshark and NetStumbler are the software tools that were used for measuring throughput, sniffing the wireless channel and performing the SNR measurement respectively. Figure 4 depicts the basic setup of the network in both indoor and outdoor environments. The following subsections will show the setup and then will discuss the results for each measurement.

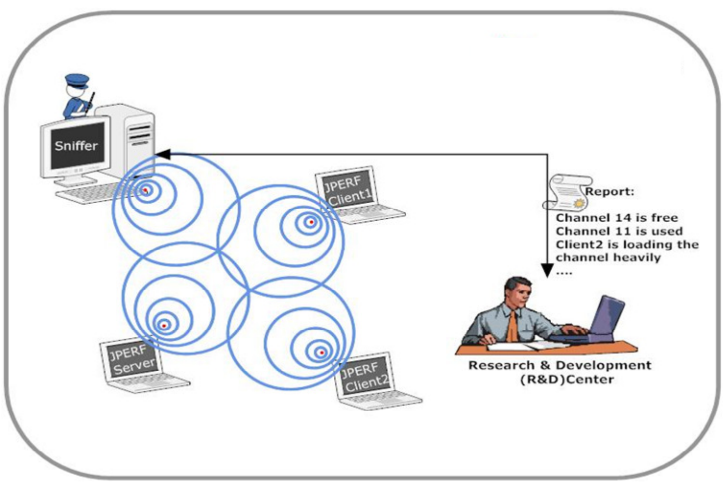


Figure 4. Basic Setup of the Network Used for Performance Evaluation

2.3. IEEE 802.11b/g Communication Range

The communication range is the maximum distance that vehicles can communicate with each other, regardless of the throughput at that distance. This experiment was conducted using two vehicles. One of the vehicles is moving and the other one is stationary. Both vehicles were equipped with laptops. The laptop in the moving vehicle was equipped with a DGPS receiver. The two laptops were communicating with each other. The connection was monitored to determine the distance between vehicles at which the connection was lost. The theoretical and measured values of the connection range of IEEE 802.11b/g standards are compared in Table 1.

For the internal network adapters, the IEEE 802.11b and IEEE 802.11g connections were lost when the communication range became more than 82.85 m and 154.06 m respectively. The communication range was considerably extended to 190.67 m and 251.3 m when using the external adapters.

The communication range plays an important role in determining the availability time and the connectivity time. The availability time is how long the vehicle is going to stay within the communication range, while the connectivity time is how long the vehicle takes to discover the network, establish connection, transfer data and finally terminate the connection. It is good to notice that the availability time changes according to the vehicle speed. As a rule of thumb, the connectivity time has to be less than the availability time. Table 1 shows the communication range values and Table 2 shows the corresponding availability time values for different vehicle speeds. 70 mph was considered as speed limit on highways, whereas 140 mph is the maximum relative speed between two vehicles driving in opposite directions on a highway.

Table 1. Expected VS Experimental Ranges of IEEE802.11b/g

Protocol	Communication Range		
	Expected (theoretical)	Experimental External WiFi adapters	Experimental Internal WiFi adapters
802.11b	~140 Meters	190.67 Meters	82.85 Meters
802.11g	~140 Meters	251.31 Meters	154.06 Meters

Table 2. Availability Time for Different Vehicle Speeds

Speed	IEEE 802.11b		IEEE 802.11g	
	External card	Internal card	External card	Internal card
45 MPH	18.96sec	8.24sec	25sec	15.32sec
65 MPH	13.12sec	5.7sec	17.3sec	10.6sec
70 MPH	12.2sec	5.3sec	16sec	9.9sec
140MPH	6.4 sec	2.65sec	8sec	4.95sec

2.4. Time-to-Login to the Network

To join a WiFi network, a vehicle has to go through an authentication process. During this process, Delay is introduced from all the network stack layers, including: the physical layer queuing, transmission and propagation times; MAC layer delays involving RTS/CTS/ACK handshake; and the network layer association and authentication handshake. After a successful association, the vehicle will be identified on the network by its IP address.

In this experiment, three laptops were used, and a peer-to-peer network was set up between two of them. The third laptop tried to join the network, and the time to join the network was measured. This scenario represents a vehicle that is trying to join other vehicles' network on the highway. WireShark, which is a network protocol analyzer developed by an international team of networking experts [31], was used to monitor the traffic on the network and to measure the third laptop's time-to-login to the network.

The effect of channel loading on both network performance and time-to-login was evaluated by increasing the traffic on the network. The software tool that was used for evaluating the network performance is Kperf. It is an open-source software developed by the University of Illinois in Champaign [32] as a modern tool to measure TCP/UDP performance. This tool is also capable of generating UDP traffic to increase the traffic on the network, and we used this feature to load the wireless channel.

The time-to-login was measured for both static and dynamic IP address allocations, In the static IP allocation method, the network administrator has to manually assign IP addresses to the PCs, while in the dynamic method, the Dynamic Host Configuration Protocol (DHCP) assigns IP addresses to devices that join the network. Figure 5 shows the average values for static and dynamic IP address allocation.

Measurements show that a vehicle took an average of 62.3 sec to join the network when DHCP was used, which is a very long time from a VANET perspective. On the other hand, it took 1.4 sec on average when static IP addresses were used.

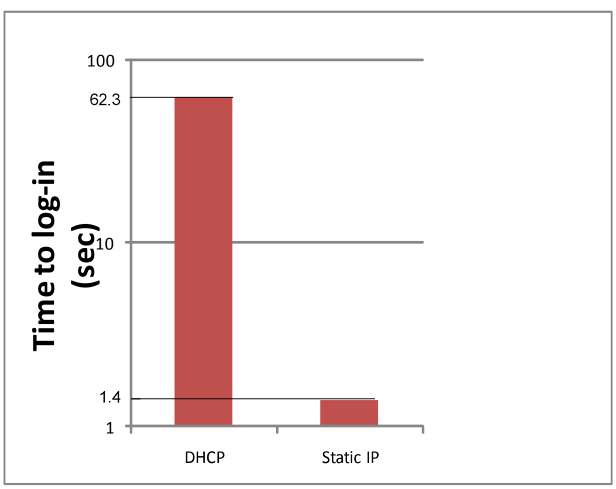


Figure 5. Shows the Time-to-Login for Static and Dynamic IP

3. UDM Research, UDM Test Bed

3.1. Introduction

IEEE802.11p amendment was only approved on Jan 17, 2010. Therefore, the cost of DSRC products available in the market is still very high. As of 2010 there were three major suppliers for DSRC terminals: DENSO, TechnoCom and Mark-IV and the access to their products is still limited. Table 3 shows the price range and availability of some DSRC products.

Table 3. DSRC Market Availability and Prices in 2008-2009

Manufacturer	Cost	Notes
TechnoCom	$28,000	Too expensive
Mark-IV	$4,500	Not for sale
DENSO	N/A	Not available

Because of the high cost and limit access to DSRC products, there has been a need for a low-cost test bed in order to evaluate the different IEEE802.11 protocols including 802.11p in vehicular and laboratory environments.

We came up with two methodologies to set up a low-cost test bed that can be used to evaluate different WLAN protocols.

3.2. Test Bed Concepts

3.2.1. First Method

In this method the network scalability test is addressed. To study the effect of having many vehicles in a road segment on the performance of different MAC/PHY protocols, a large number of nodes is needed. However, we can use fewer nodes as long as those nodes compensate for the absence of the rest of the nodes. In other words, instead of having 100 nodes - two of them are communicating useful data and the rest are loading the channel with 100kbps traffic - we can use only half of that number, i.e. 50 nodes, with double the traffic load that will be 200kbps in our example. Therefore, 50 nodes can compensate for 100 nodes if they generate double the traffic.

We can keep decreasing the number of nodes while increasing the traffic they generate until we reach a network of three (3) nodes. Two of these three nodes are communicating useful data with each other, while the third one is loading the network with different traffic data. This approach significantly cut the cost of setting up the network.

The aforementioned concept was tested and validated in the “first-method test bed”. This test bed consists of four (4) nodes running Windows XP, configured to work in Peer-to-Peer mode as well as infrastructure mode. Any node is ready to communicate with other nodes or to load the network with TCP/UDP traffic. One (1) of the nodes is capable of sniffing the traffic on wireless medium and listing the used channels. The figures 6 through 8 below show the first proposed approach.

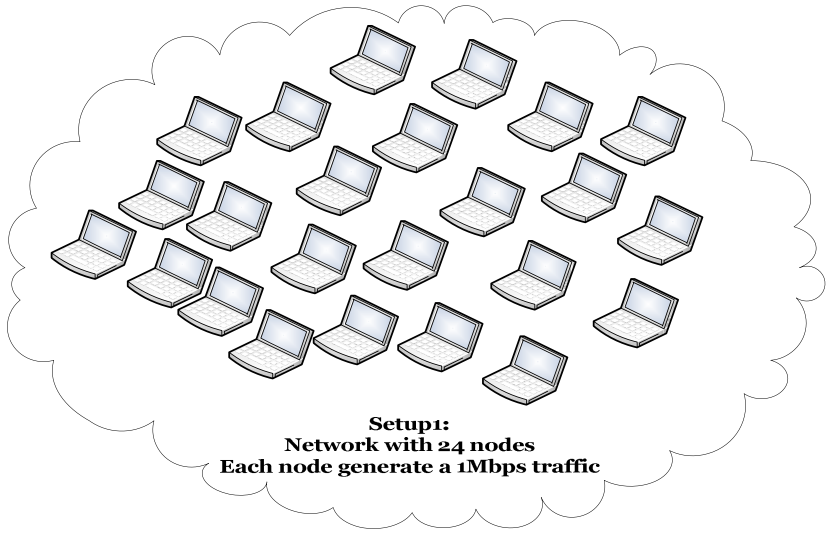


Figure 6. Network with 24 Nodes

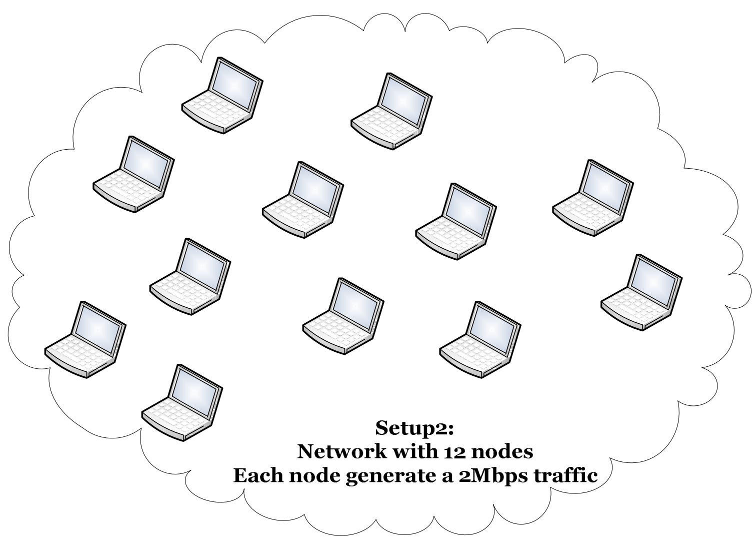


Figure 7. Network with 12 Nodes

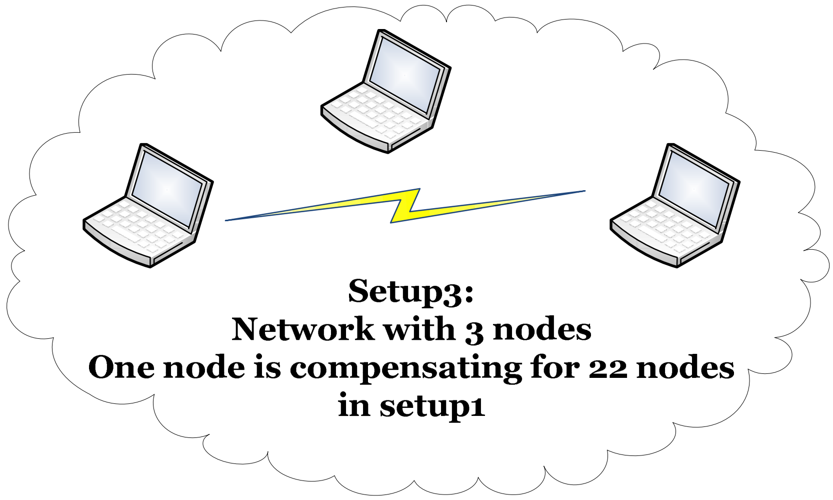


Figure 8. Network with only 3 Nodes

3.2.2. First Method Evaluation

In order to evaluate the validity of this method, we compare the performance of the network when using one node to load the channel with the performance of the network when using multiple nodes to load the channel. i.e. we compare the network throughput, jitter time, and delay time for a single loading node vs. many loading nodes and for the same loading volume.

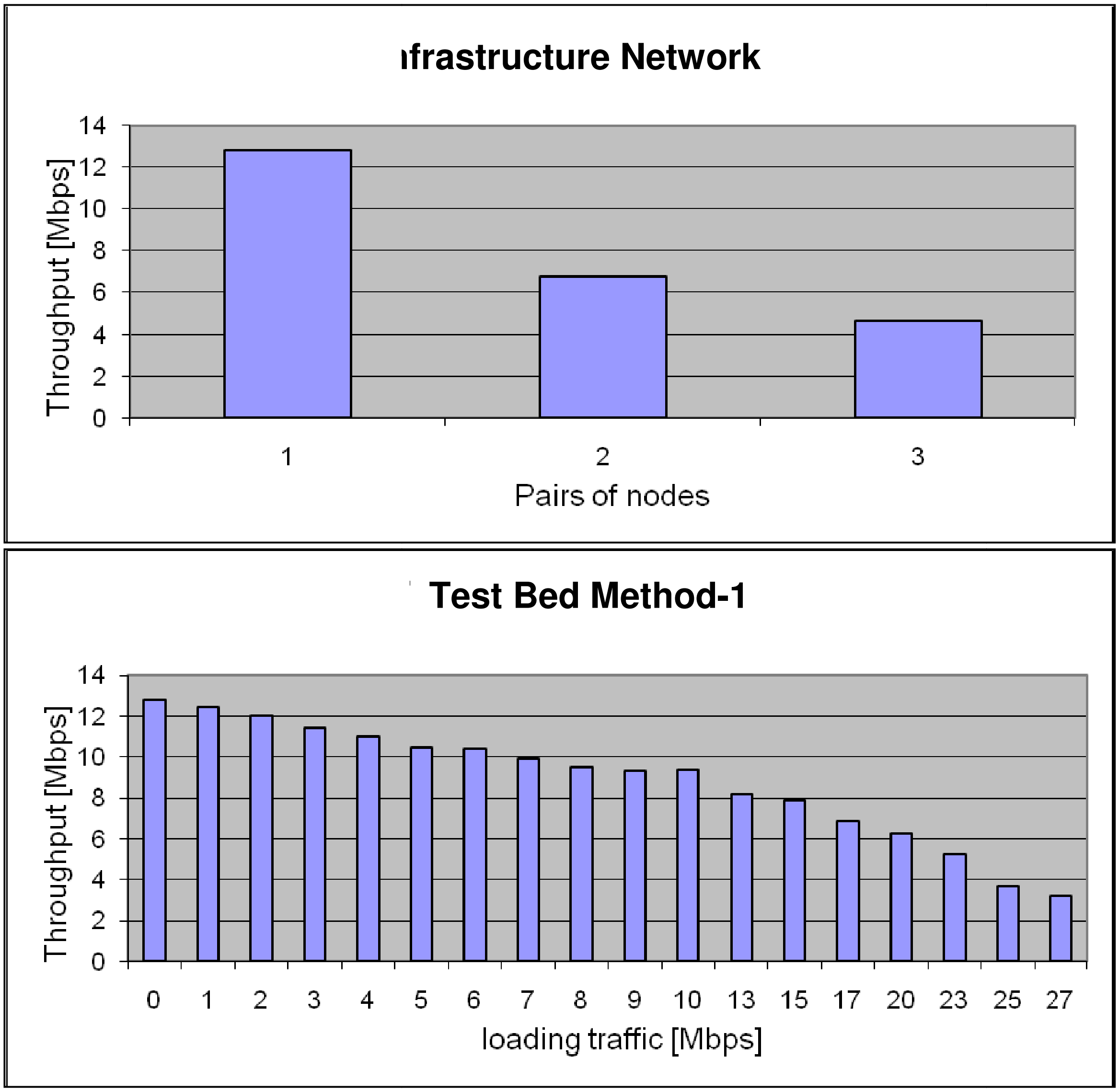


Figure 9. Throughput in a Regular Network VS. One Node Loading the Channel

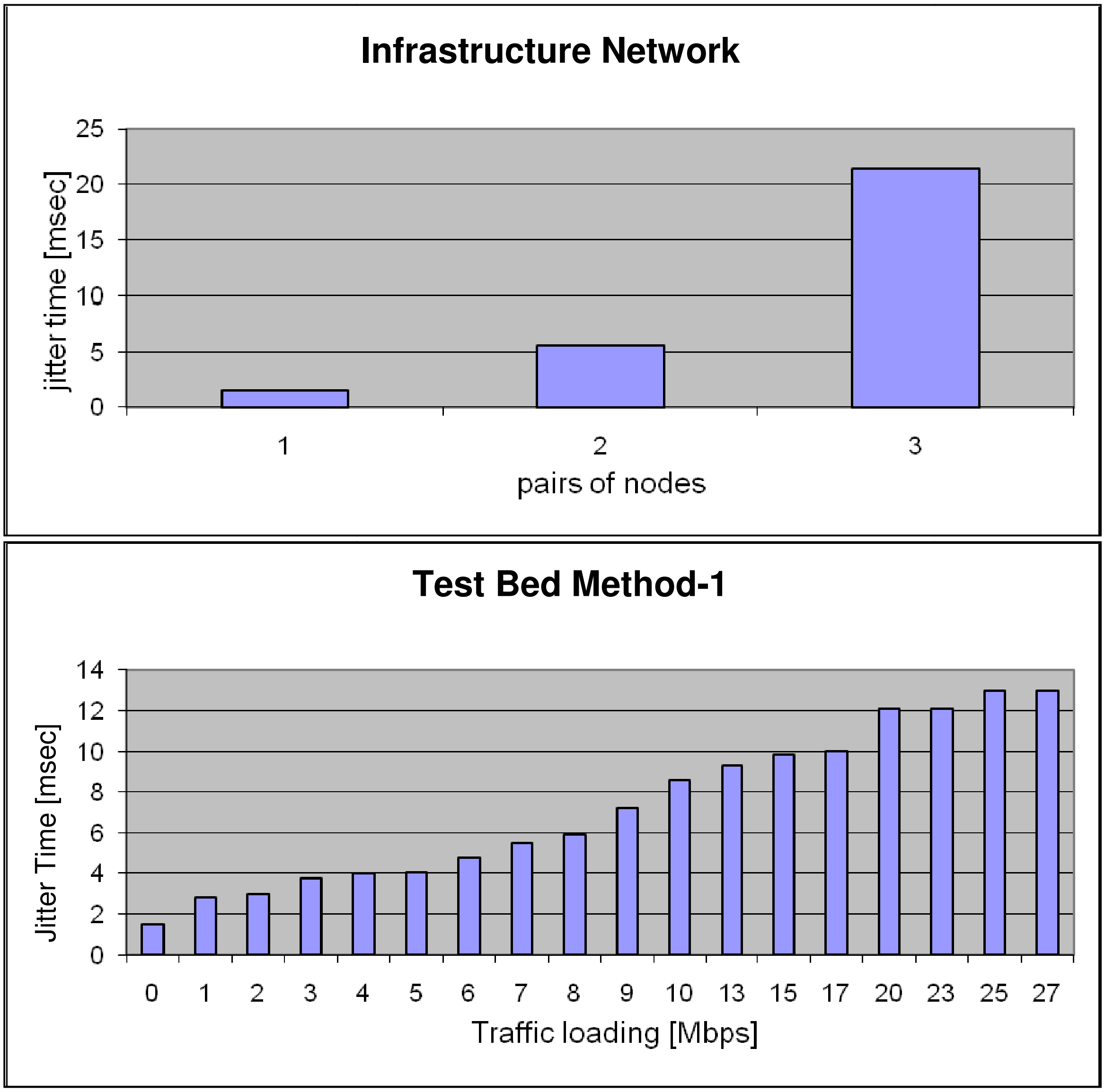


Figure 10. Jitter Time in Regular Network VS. One Node Loading the Channel

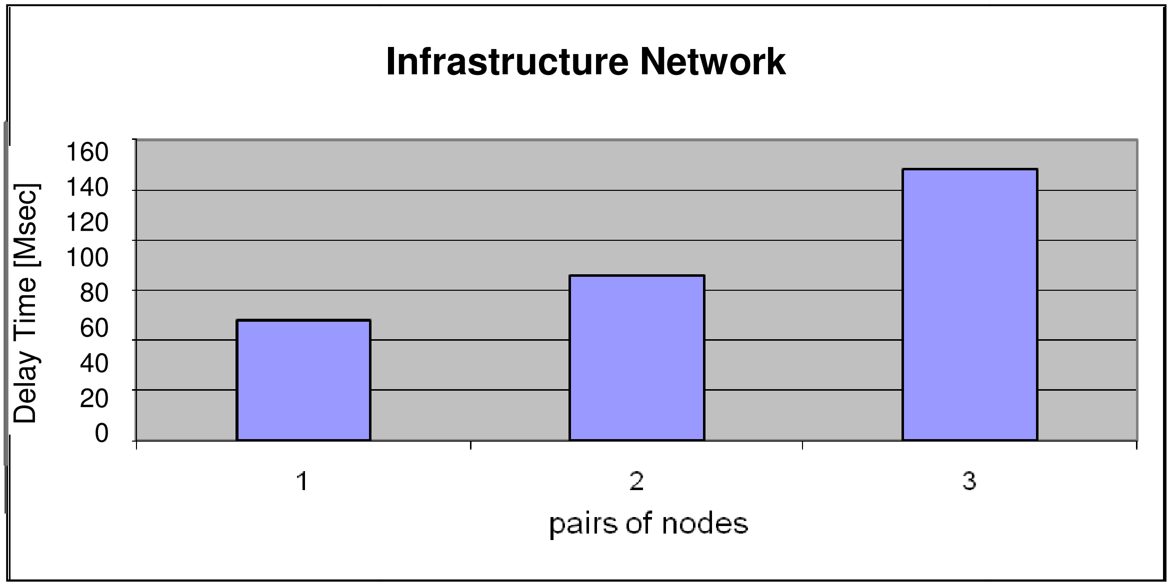


Figure 11. Delay Time in Regular Network VS. One Node Loading the Channel

The results above show that one node may not be used to compensate for the existence of other nodes in the network. That is mainly because of losing the randomness in accessing the channel when using one node for loading. When using one node for loading, it would compete to access the channel only at the beginning of its transmission and when it got access it would dominate. That is, once the node got access to the channel, no other nodes would be able to access the channel. Therefore, other methodologies are needed.

3.2.3. Second Method

In this method, the number of nodes could be kept relatively high, but instead of using high cost new technology nodes, we will use the low-cost popular Wi-Fi transceivers. The Wi-Fi network will serve as a realistic mirror network to reflect the contention process. However, a few nodes of the mirror network are wired directly to a high tech protocol transceiver (under evaluation), and we call these nodes "active nodes" versus those that only work to load the network and hence are called "passive nodes." Once an active node gets access to the channel, it forwards its message to the attached high tech transceiver, which in turn performs the communication. Hence, the new protocols will be evaluated in a more realistic environment at a low cost. Figure 12 depicts the proposed test bed layout.

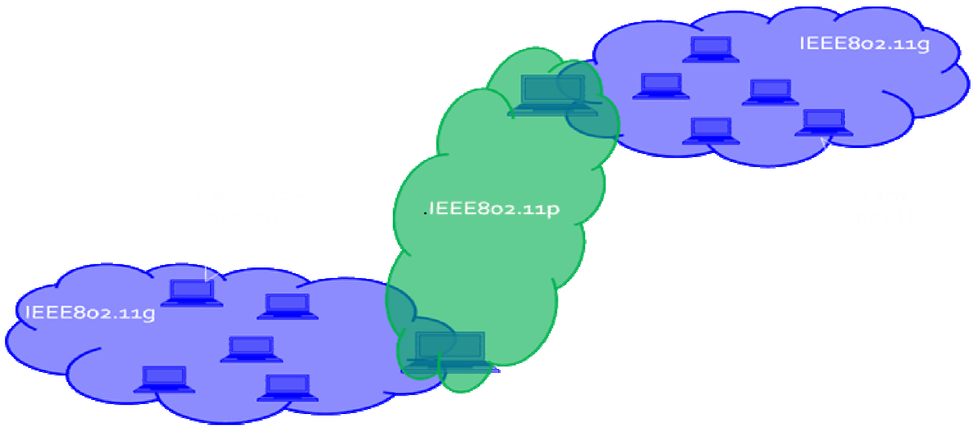


Figure 12. Test Bed Setup

In other words, the main idea behind this method is splitting the large expensive network into two low-cost subnets, which are bridged together using one expensive connection (802.11P).
We implemented this method using two access points, wireless router and three nodes running Windows XP, which is called second-method test bed. Figure 13 shows the network setup where PC_A communicates with PC_B through the access points and the router. PC_C is the one that loads the channel with traffic, thus reflecting the channel contention in the network.

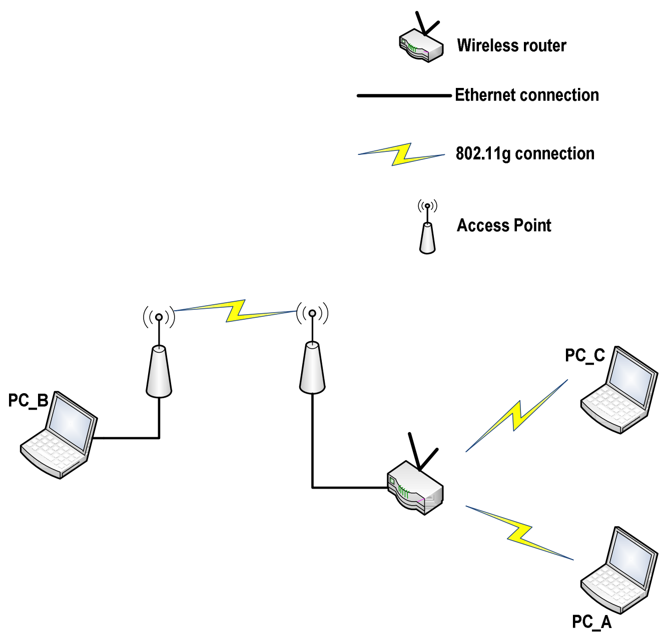
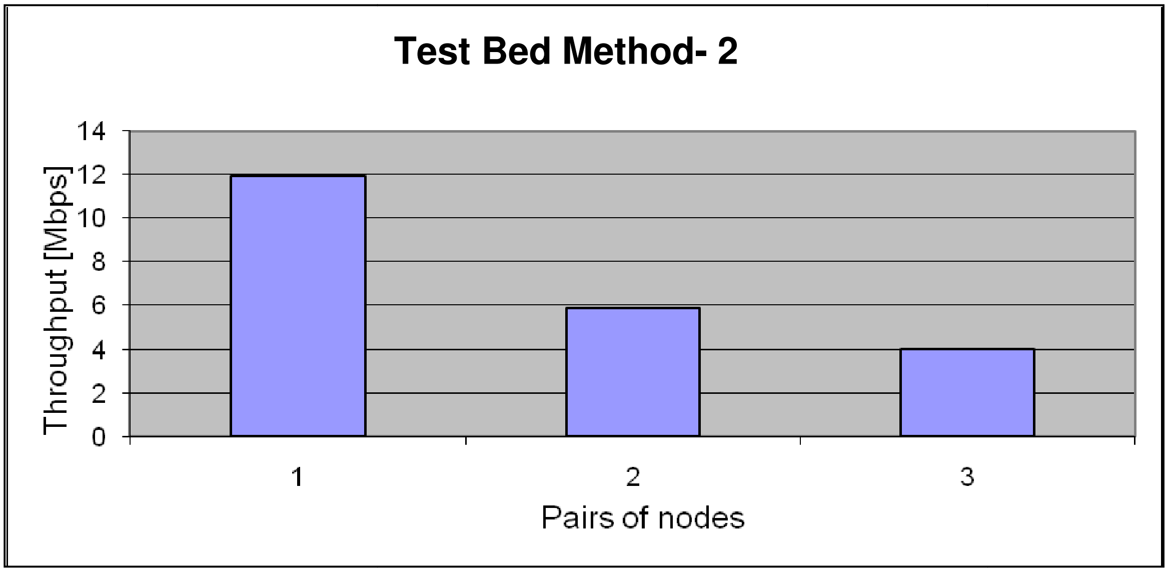


Figure 13. Test Bed Implementation

3.2.4. Second Method Validation

In our research, we have been trying to come up with a new setup to reduce the cost of the test bed needed for evaluation purposes. We have come up with two setups (mentioned in task2); the result of the first setup will be discussed in tasks4 and task5. However, here we will discuss the results of the second approach. As shown in Figures 12 and 13, we split the network into two sub-networks by using two access points, one wireless router and PCs equipped with Wi-Fi transceiver.

In order to validate the concept, we measured the throughput, jitter time and delay time of two network setups. The first setup was one large IEEE802.11g network with a different number of nodes. The second setup was two IEEE802.11g sub-networks bridged with an IEEE802.11g connection. The same two setups, with different protocol IEEE802.11b, were also built and the results ensure that the test bed concept is valid and can be used for evaluation purposes. Figures 14, 15 and 16 show the throughput, jitter time and delay time measurements for the two setups for IEEE802.11g.



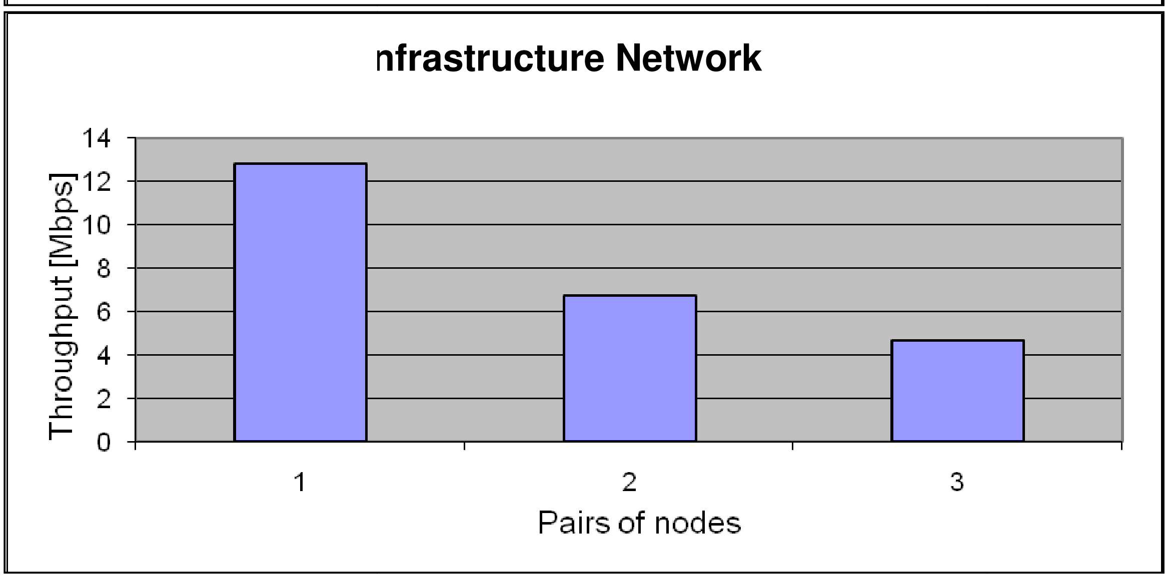


Figure 14. Throughput of IEEE802.11g in Infrastructure-Based Network VS. Test Bed

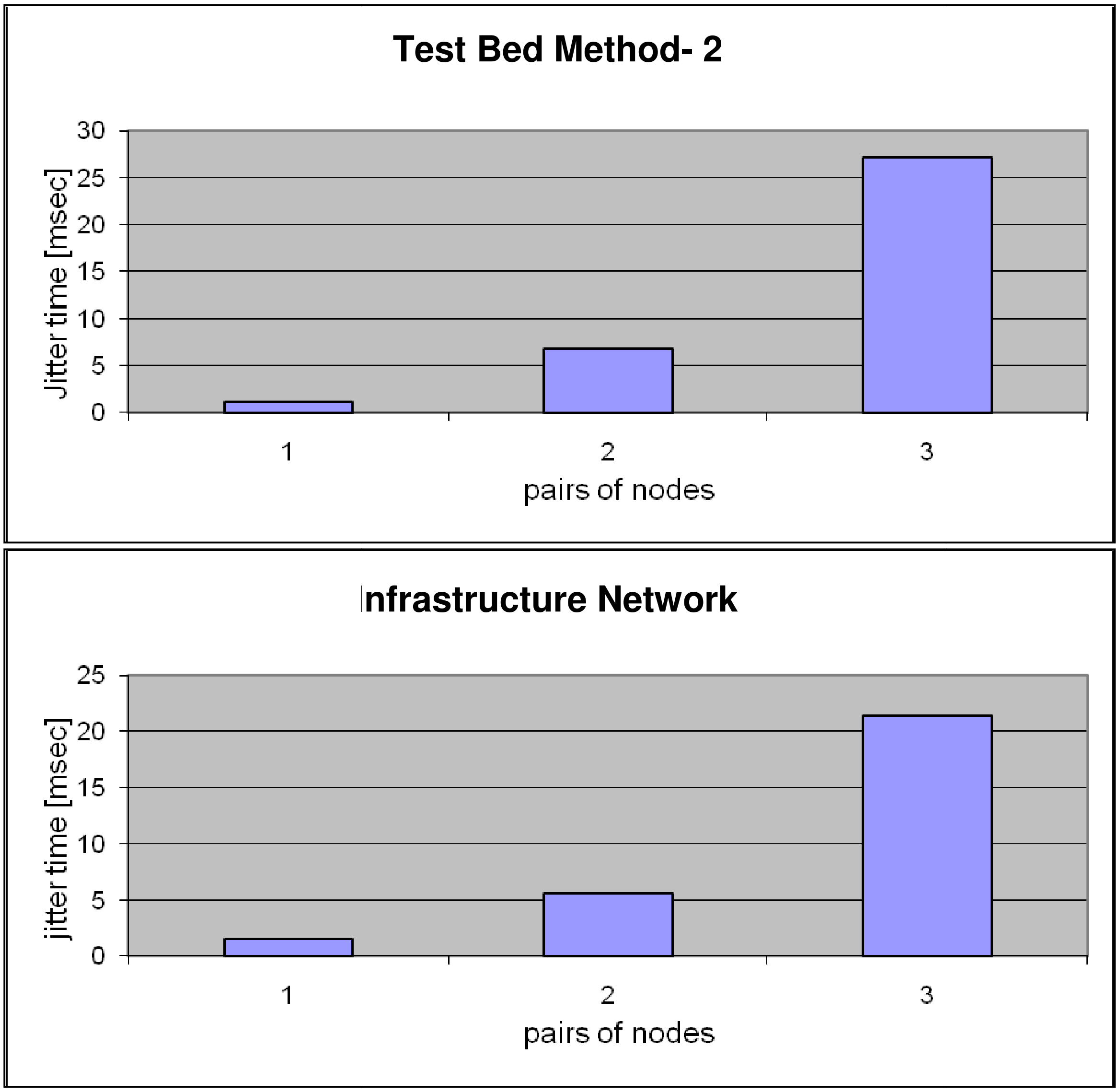


Figure 15. Jitter Time for IEEE802.11g in Infrastructure-Based Network VS. Test Bed

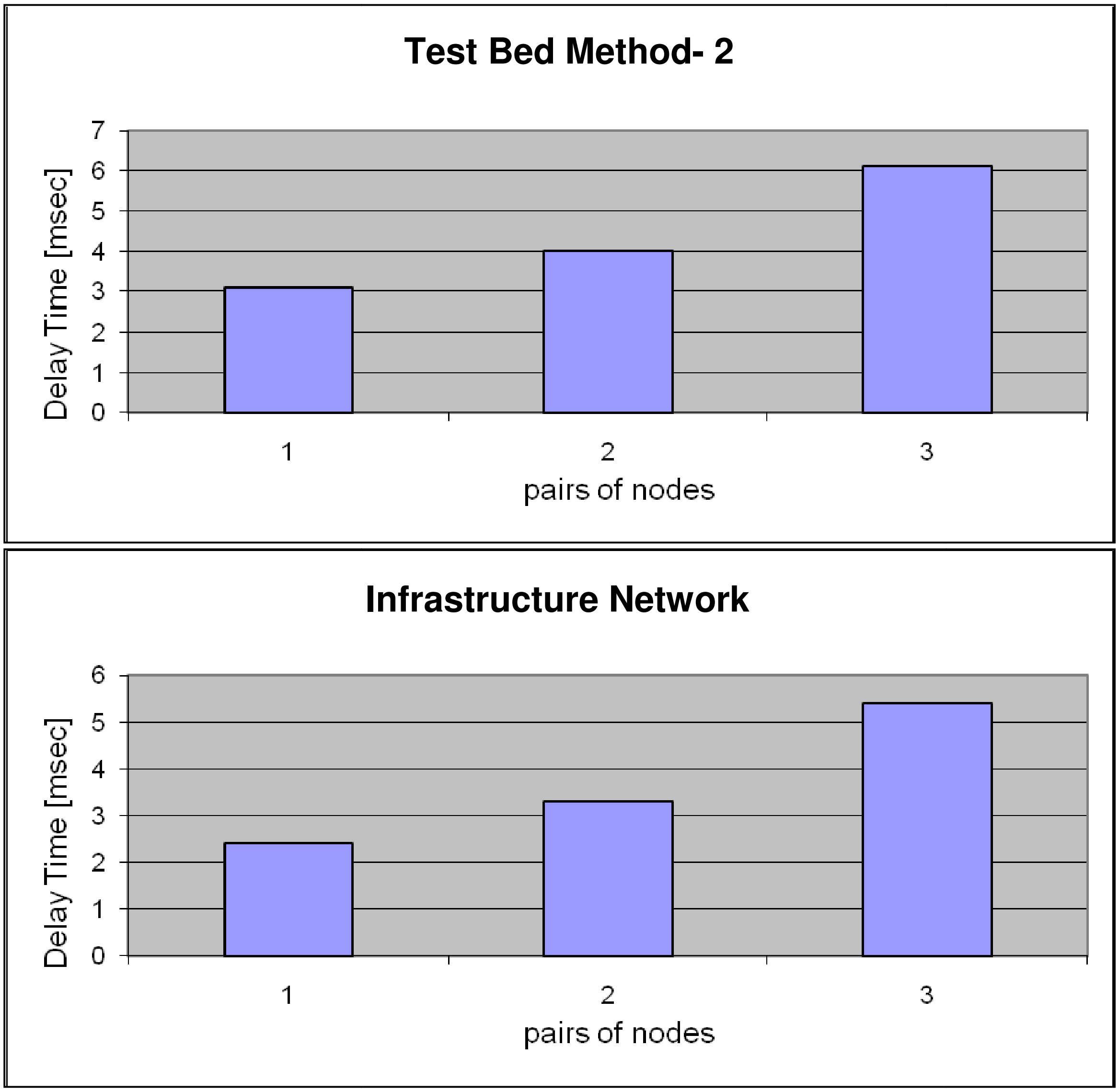


Figure 16. Delay Time in IEEE802.11g in Infrastructure-Based Network VS. Test Bed

3.2.5. Third Method

The last employed method in our test bed was developed to study the impact of distance between vehicles on channel throughput. Therefore, an experiment was designed to be able to acquire data samples from a real-world scenario.

The experiment took a place in the racing track in Michigan. It consisted of:

1. Roadside Unit: laptop running Mac OS placed at a stationary location (Unit A).
2. On-Board Unit: laptop running Windows XP placed in a mobile vehicle (Unit B).
3. Communication Links: Wireless access point to provide Wi-Fi communication and Differential Global Positioning System (DGPS) to provide position of the vehicle.

The following is a summary of the experiment:

1. RSU setup:
    - Unit A is running Jperf to generate random TCP packets
    - Unit A's GPS position is recorded and considered as a reference point
    - Unit A is connected to a wireless module via Ethernet cable which allows it to broadcast generated packets wirelessly
    - Wireless module operates on 802.11g and has large coverage

2. OBU setup:
    - Unit B is equipped with wireless network interface card to receive broadcasted TCP packets
    - Unit B is running Jperf to keep track of received packets and measure the channel throughput
    - Jperf is configured to record samples of channel throughput every time interval
    - Unit B is connected to a DGPS module via USB cable to obtain a precise position of moving vehicle
    - Unit B is running MATLAB program to record samples of vehicle position and calculate the distance from the reference point for every time interval as configured in Jperf

As a result, at each time interval we had a sample of channel throughput and a sample of the vehicle's distance from the RSU. Collected data were organized in a table format to match each throughput sample with its corresponding distance sample. The same experiment was repeated four times with the same maximum distance. Consequently, averaging of throughput samples at a specific distance was taken to obtain higher accuracy. Figure 17 shows results plot where channel throughput is a function of relative distance where the throughput is measured in Mbps and the distance is measured in meters.

A quick look at Figure 16 shows that the channel throughput has dropped from 13 Mbps at distance of 25 meter to less than 4 Mbps at distance of 350 meter. That is due to several factors such as channel delay, signal-to-noise ratio, Doppler shift effect and signal interference.

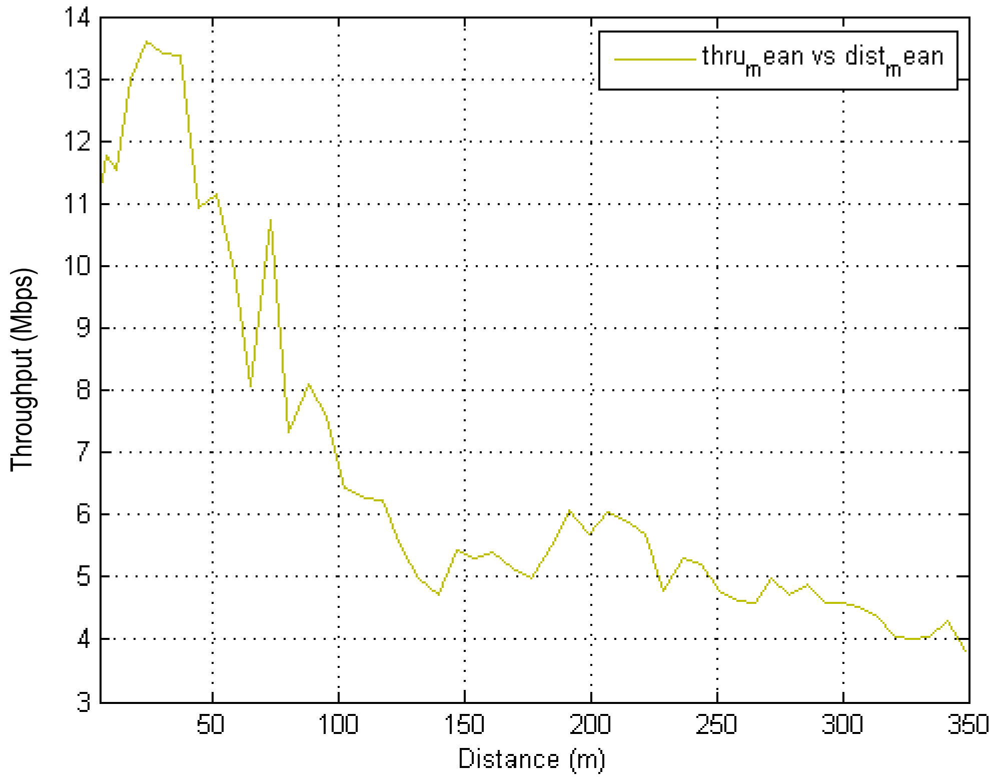


Figure 17. Throughput VS. Distance in Outdoor Environment

4. UDM Research, Doppler Shift Investigation

4.1. Introduction

With the recent trend toward transforming vehicles from simple means of transportation into a moving information platform, wireless communications have become the lifeblood of the Intelligent Transportation System (ITS) [40]. In this context, Intelli-Drive/Vehicle-Infrastructure Integration (VII) was proposed [41]. Intelli-Drive is an emerging Inter-Vehicle Communication (IVC) and ITS initiative that attempts to establish communication links between vehicles (V2V) and between vehicles and the infrastructure (V2I). Exchanging information through V2V and V2I communications aims to improve traffic safety, enhance mobility and reduce traffic jams. Therefore, several protocols of wireless communications for ITS applications have been proposed [42]. Moving vehicles impose a set of requirements on wireless communication systems. Many applications, especially safety-related, cannot tolerate long delays in connection establishment and communication. Moreover, fast moving vehicles and complex roadway environments present challenges at the PHY layer [43]. In addition, high-density roadways along with vehicle speed require a robust and high-speed communication protocol that allows sharing warning messages in real-time.

The IEEE 802.11 family of protocols [44] is a good candidate to provide Wireless Access in Vehicular Environment (WAVE) [60]. The IEEE 802.11a [45] offers a high data rate, up to 54 Mbps, at the 5 GHz band (5.15 – 5.825 GHz) allocated by the Federal Communications Commission (FCC). IEEE 802.11a uses OFDM with 52 subcarriers and a variable modulation scheme.

Although OFDM was primarily standardized for Digital Audio Broadcasting (DAB) [55] and Digital Video Broadcasting (DVB) [46], it was recently proposed for both fixed and mobile wireless applications such as Wireless Local Area Network (WLAN), Ultra WideBand (UWB), and 4th Generation (4G) cellular communication [47]. OFDM utilizes 52 spaced, orthogonal subcarriers to provide payload capabilities of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps at the 20 MHz bandwidth. Subcarriers are modulated using different modulation techniques which can be Binary Phase-Shift Keying (BPSK), Quadratic Phase-Shift Keying (QPSK), 16-Quadratic Amplitude Modulation (16-QAM), or 64-Quadratic Amplitude Modulation (64-QAM). The modulation scheme is followed by a convolutional Forward Error Correction (FEC) with 1/2, 2/3 or 3/4 coding rate. That forms a total of eight combinations, as listed in Table 4.

Table 4. OFDM Modulation/Coding Parameters

Mode	Modulation	Coding Rate	Coded bits per Subcarrier	Coded bits per OFDM Symbol	Data bits per OFDM Symbol	Data Rate [Mbps]
1	BPSK	1/2	1	48	24	6
2		3/4			36	9
3	QPSK	1/2	2	96	48	12
4		3/4			72	18
5	16-QAM	1/2	4	192	96	24
6		3/4			144	36
7	64-QAM	2/3	6	288	192	48
8		3/4			216	52

Distribution of transmitted data over multiple subcarriers increases the adaptation of OFDM to severe channel conditions as well as robustness against Inter-Symbol Interference (ISI). Moreover, the orthogonality between subcarriers, which allows an uncomplicated receiver to separate the subcarriers, eliminates the crosstalk between sub-channels, known as Inter-Carrier Interference (ICI). However, this imposes a strict demand on the accuracy of frequency synchronization between transmitter and receiver as well as sensitivity to frequency offset.

In the wireless mobile environment, Doppler shift emerges due to the motion of a transmitter relative to a receiver. When a vehicle transmits/receives a signal while moving, the transmitted/received signal is subjected to an offset in its frequency. The higher the vehicle speed, the larger the frequency distortion. As a result, frequency shifting increases and leads to a loss in orthogonally between subcarriers causing inter-carrier interference. Low ICI can be eliminated by prefixing each OFDM symbol with a repetition of its end, referred to as cyclic prefix [48]. However, higher values of ICI make signal restoration extremely difficult. Therefore, several methods have been proposed to provide an estimation of Doppler shift. In [49], two main Doppler estimators, level crossing rate-based and covariance-based estimators, were analyzed in detail to study the impact of modeling error, noise error and insufficient number of samples on estimator performance. Another estimation technique was proposed in [50] and used an auto-correlation function of two OFDM symbols in the time domain. The resulting estimator was designed for frequency-selective Rayleigh channels and evaluated at several constellation schemes. However, Doppler shift analyses based on channel estimation in frequency domain are likely to be affected by noise and ICI. Therefore, a Doppler shift analysis based on channel estimation in time domain was proposed in [51]. The auto-correlation function was used once again but this time to correlate several OFDM symbols in time domain. Simulation results showed that the proposed technique improved performance of the estimation process and reduced processing time and memory usage. A novel iterative Doppler shift estimator for low Signal-to-Noise Ratio (SNR) environments was proposed in [52]. The proposed method is based on the Logarithm Envelope (LE) of mobile propagation channel, where the Minimum Mean Square Error (MMSE) of estimation for Doppler shift is derived. Results were obtained from multiple simulation runs under heavy noise distortion, and showed advantages of the developed estimator. Experimental results on path-loss, power-delay and delay-Doppler were presented in [53]. The results were obtained from actual measurements performed at high vehicle speed on a highway in Sweden. The measurements were taken at a carrier frequency of 5.2 GHz while communicating vehicles were traveling. As a result, the delay-Doppler at a given path was investigated. An analysis of radar-based Doppler measurements for ground vehicles was proposed in [54]. Radar measurements were compiled from stationary radar observing moving ground vehicles. The recorded data was analyzed for the purpose of classifying a tracked vehicle. The results indicated that Doppler signature can be used for classification; however, further knowledge regarding the target is required to interpret Doppler signature.

4.2. System Model

In order to study the impact of Doppler shift in a wireless mobile environment, we propose a system model that simulates the PHY layer of IEEE 802.11a, represented in the OFDM. The developed model aims to form a sort of a testbed that can be used as groundwork for development, evaluation or validation of different communication protocols, methodologies and theoretical concepts. Moreover, such a testbed enables the rapid prototyping and manufacturing of wireless transceivers.

With a top-down analysis, an end-to-end baseband wireless communication system can functionally be broken down into three subsystems: IEEE 802.11a transmitter subsystem, IEEE 802.11a receiver subsystem, and wireless channel subsystem as shown in Figure 18. Transmitter and receiver subsystems are closely consistent with the IEEE 802.11a PHY layer as described in 2007-revision of IEEE 802.11a standard [45].

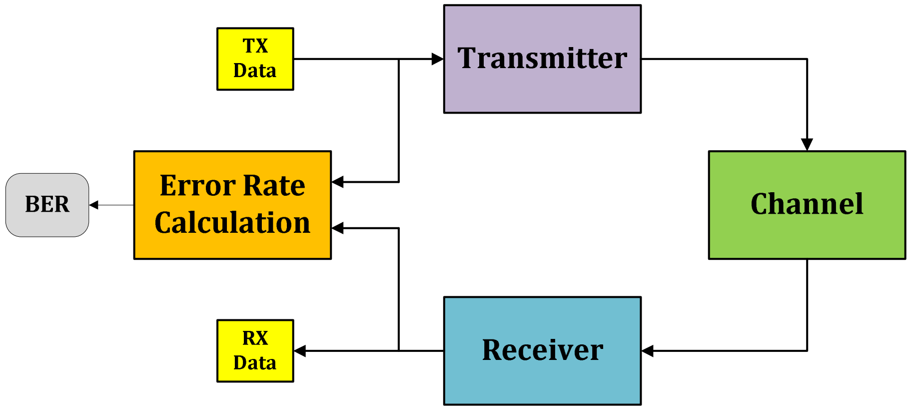


Figure 18. End-to-End System Model Block Diagram

4.2.1. IEEE 802.11a Transmitter Subsystem

Transmitter subsystem implementation can be summarized as follows. The process of transmitting a frame starts with PHY Layer Convergence Procedure (PLCP) to form a PLCP Protocol Data Unit (PPDU) out of the Medium Access Control (MAC) payload, called the PLCP Service Data Unit (PSDU). In this model, TX data was randomly generated by a variable-rate data source and assumed as PSDU. Following the PPDU frame formation, data bits are scrambled by a frame synchronous scrambler. A scrambled data string is encoded with a convolution encoder according to a coding rate (1/2, 2/3 or 3/4) defined in advance. The encoded bit string is divided into groups of coded bits per OFDM symbol, indicated previously in Table 4, to perform an interleaving based on two-step permutation. Subsequently, resulting coded and interleaved groups are modulated into a complex number using BPSK, QPSK, 16-QAM, or 64-QAM, as requested. The resulting complex number string is divided into 48 complex numbers, each of which is associated with one OFDM symbol. Four pilot signals are inserted into each OFDM symbol to create a total of 52 numbers, which is mapped into OFDM subcarriers. Conversion of 52 subcarriers into time domain is accomplished by a 64-point Inverse Fast Fourier Transform (IFFT). Cyclic prefix is pretended to the Fourier-transformed waveform to form a guard interval. Finally, time domain-OFDM symbols are appended one after another, starting after PLCP preamble and signal symbols to multiplex a complete PPDU ready for wireless channel up-conversion. Figure 19 shows a block diagram of the transmitter subsystem.

Figure 19. Transmitter Subsystem Block Diagram

4.2.2. IEEE 802.11a Receiver Subsystem

Receiver subsystem implementation is an inversion of transmitter implementation with the addition of channel estimation and equalization, as illustrated in Figure 20. Upon the detection of PLCP preamble, the receiving process starts by frame synchronization. Then, demultiplexing and cyclic prefix removal are applied on the received frame. Data carried over the 52 subcarriers is transformed back to frequency domain through 64-point Fast Fourier Transform (FFT).

Thereafter, the frame is disassembled into OFDM symbols, pilot signals are removed, and signal field is decoded to determine the desired mode and rate for the demodulation and decoding processes, respectively. Next, appropriate demodulation, which may include signal compensation based channel estimation, and de-interleaving of OFDM symbols are carried out. OFDM symbols are decoded into data bits through the use of Viterbi algorithm, as recommended by the standard. Finally, received data bits are descrambled and assembled into octets to present the RX data.

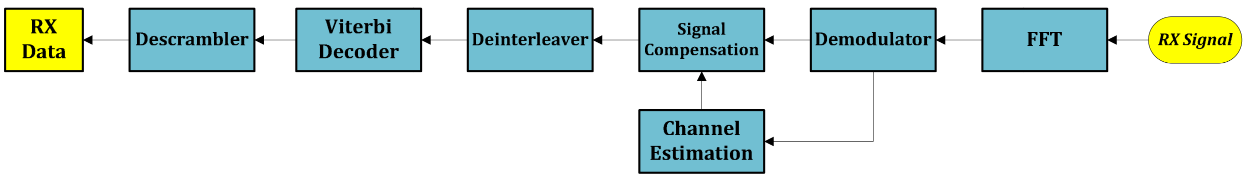


Figure 20. Receiver Subsystem Block Diagram

4.2.3. Wireless Channel Subsystem

The channel subsystem has been developed to simulate a wireless channel in a mobile environment. Therefore, the proposed model, shown in Figure 21, combines two traditional channel models, Additive White Gaussian Noise (AWGN) and Rayleigh, to imitate a real-world wireless medium. The first model is the AWGN channel, which accounts for degradation due to wideband noise. The AWGN channel model perturbs the transmitted waveform by adding a white noise that follows the Gaussian distribution. The added noise values are uncorrelated and Gaussian with zero-mean and predefined variance. Noise variance is set based on the following equations (1) and (2):

$$VAR = \frac{SignalPower\ x\ SymbolPeriod}{SampleTime\ x\ 10^{\frac{E_s/N_0}{10}}} \qquad (1)$$

$$E_s/N_0 = E_b/N_0 + 10.\log_{10}(k) \qquad (2)$$

Where: E_s/N_0 : ratio of symbol energy to noise spectral density.

E_b/N_0 : Ratio of bit energy to noise spectral density.

k : Number of bits per symbol.

The second model is the Rayleigh fading channel, which accounts for the various effects that the wireless mobile environment has on wave propagation. A transmitted signal is subject to fading, which results from multipath propagation, shadowing or motion of the transmitter and/or receiver. Rayleigh fading channel is a statistical and relatively accurate model commonly used to simulate multipath fading with no dominant line-of-sight path, based on Rayleigh distribution. Multipath fading may result from random delay, reflection, scattering and diffraction of signal components.

Moreover, the model characterizes frequency-flat or frequency nonselective fading, by which all spectral components of the transmitted signal are affected uniformly. As typically assumed, we consider that the fading amplitude is statically independent of the additive white Gaussian noise modeled in the previously discussed AWGN channel model. Furthermore, the relative motion between the transmitter and receiver is expressed by a range of frequency shifts, known as the Doppler spectrum. Doppler shift f_d is related to relative speed v_r in the following equation:

$$f_d = \frac{v_r}{c} f_0 \qquad (3)$$

Where: c : speed of light.
f_0 : transmission carrier frequency.

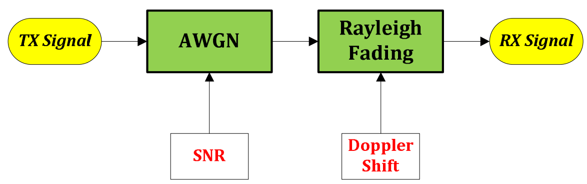


Figure 21. Channel Subsystem Block Diagram

4.3. Model Validation

The performance of wireless communication systems can be evaluated by a simulation model without the need for prototype development or field experiment design. Computer simulation has impacted research and development in the engineering industry due to its economic significance and rapid development. Our testbed has been implemented in a MATLAB/SIMULINK environment from MathWorks [61]. SIMULINK is a graphical block diagramming tool, which extends MATLAB for advanced modeling and simulation capabilities. This makes MATLAB/SIMULINK a very efficient tool to be used for developing communication systems, evaluating in real-time, and obtaining baseline performance analyses.

Our system model has been carried out as proposed in Section 2 with the addition of testbench components that provide signal flow control, data visualization and measurement, and control interface. Model control is accomplished through static and run-time parameters. Static parameters are processed at model initialization prior to execution and remain the same during simulation, while run-time parameters may be manipulated through the graphical interface during simulation. The model is driven by a MATLAB code that presets system configurations, runs the model in a finite iterative loop, and records performance measures. Each measurement is obtained through averaging samples resulting from multiple simulation runs. Moreover, different seeds have been used for data and noise sources to assure the randomness and generalization of the evaluation process.

In order to verify the performance of the proposed mode, we have simulated the proposed framework of the IEEE 802.11a communication system with the following configuration: channel bandwidth of 20 MHz, 20 OFDM symbol per transmitted block, variable modes as specified in Table 4, 64-point FFT/IFFT, and 16-sample cyclic prefix. AWGN and Rayleigh channel models have been developed to simulate the impact of additive white Gaussian noise and flat fading with the ability to specify the desired SNR as well as maximum Doppler shift.

Simulation has been performed with a setup as shown in Figure 17 to measure the BER while varying the E_b/N_0 between 0 and 30 dB. Measurements have been taken for both channel models and compared with the corresponding theoretical formulas.

4.3.1. AWGN Channel Model

The most commonly used technique for evaluating the performance of channel models is the probability of bit error rate, which is one of the most revealing criterions of system behavior. The probability of bit error depends on the constellation set of the used modulation scheme. The following analytical discussion has been concluded from [56-59]. For AWGN channel model and Phase-Shift Keying (PSK) scheme, a general formula, derived in [56], describes the probability of symbol error P_M of M-ary PSK as an integral of the probability density function $p(\theta)$ of the phase random variable θ :

$$P_M = 1 - \int_{-\pi/M}^{\pi/M} p(\theta).d\theta \qquad (4)$$

Where the equivalent bit error probability P_b can be approximated to (5) when Gray code is used in symbol mapping:

$$P_b \approx \frac{1}{k} P_M \qquad (5)$$

Generally, the integral in (4) is to be evaluated numerically; however, it reduces to a simple form when M = 2 and M = 4, which represents BPSK and QPSK, respectively. Since there is no interference between signals on the quadratic carriers, the probability of bit error of QPSK is identical to BPSK. Hence, the bit error probability is:

$$P_{b,BPSK} = P_{b,QPSK} = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \qquad (6)$$

Where Q is the tail probability of Gaussian distribution, defined as:

$$Q(x) = \frac{1}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2/2}.dt \qquad (7)$$

The Q-function can be expressed in terms of the error function as:

$$Q(x) = \frac{1}{2} - \frac{1}{2}\mathrm{erf}\left(\frac{x}{\sqrt{2}}\right) \qquad (8)$$

When Quadratic Amplitude Modulation (QAM) scheme is used over an AWGN channel model, the probability of symbol error for M-ary QAM is:

$$P_M = 2\left(1 - \frac{1}{\sqrt{M}}\right).Q\left(\sqrt{\frac{3}{M-1}\frac{E_s}{N_0}}\right) \qquad (9)$$

With Gray code mapping, the bit error for 16-QAM and 64-QAM is approximately expressed in (10) and (11), respectively:

$$P_{b,16QAM} = \frac{3}{4} Q\left(\sqrt{\frac{12}{15}\frac{E_b}{N_0}}\right) \quad (10)$$

$$P_{b,64QAM} = \frac{7}{12} Q\left(\sqrt{\frac{18}{63}\frac{E_b}{N_0}}\right) \quad (11)$$

Figure 22 shows the probability of BER in both theoretical and simulated results for BPSK, QPSK, 16-QAM, and 64-QAM, all over the AWGN channel model.

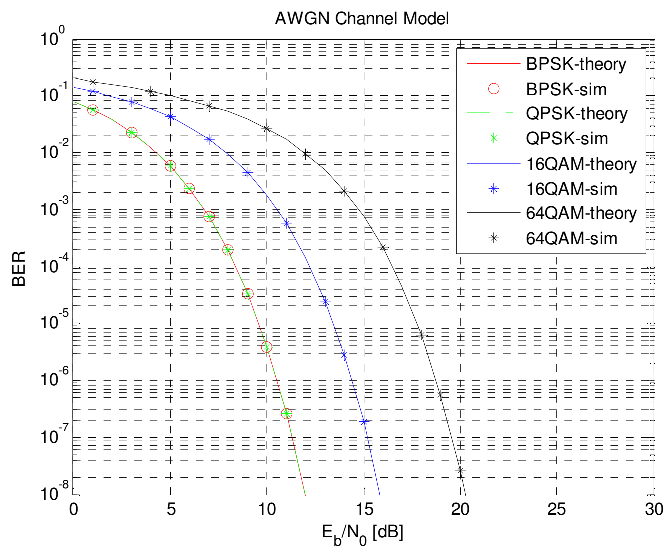


Figure 22. Theoretical and Simulated Probability of BER vs. E_b/N_o for BPSK/QPSK/16QAM/64QAM Over the AWGN Channel Model

4.3.2. Rayleigh Channel Model

Similar to the AWGN channel model, the Rayleigh channel model is to be validated in terms of the probability of BER. However, derivations of bit error probability are more complicated in the Rayleigh channels compared to the AWGN channels, due to the non-linear relation between BER and SNR. A general formula for the probability of symbol error in M-ary PSK is presented in [56]:

$$P_M = 2\int_{\pi/M}^{\pi} p(\theta).d\theta \quad (12)$$

Similar to the discussion of probability of bit error in the AWGN channel and based on the same assumptions, the probability of bit error in the presence of a fading Rayleigh channel h can be described in (13):

$$P_b = \int_0^{\infty} Q\left(\sqrt{2.\gamma}\right).p(\gamma).d\gamma \quad (13)$$

Where: $\bar{\gamma}$: ratio of bit energy to noise spectral density.

$\gamma = |h^2|.\gamma$: ratio of bit energy to noise spectral density in the presence of a channel h.

$p(\gamma) = \frac{1}{\bar{\gamma}} e^{\gamma/\bar{\gamma}}$: the probability density function of γ .

Hence, (13) can be reduced to:

$$P_b = \frac{1}{\bar{\gamma}} \int_0^\infty Q\left(\sqrt{2.\gamma}\right).e^{\gamma/\bar{\gamma}}.d\gamma \qquad (14)$$

The expression in (14) can be evaluated numerically to compute the BER for BPSK and QPSK. As for the QAM scheme, it's significantly more complicated to derive a closed-form formula that describes BER in the Rayleigh channel. However, similar to the BER derivations for the QAM under the AWGN channel, computations begin with the probability of bit error. This can be evaluated in terms of $p(D)$, the probability density function of D , where D is the decision variable of multichannel communication systems, expressed as a general quadratic form. Therefore, $p(D)$ is the Fourier transform of $\psi_D(jv)$, the characteristic function D . Thus, the probability of bit error is:

$$P_b = -\frac{1}{2\pi}\int \frac{\psi_D(jv)}{v} dv \qquad (15)$$

The probability in BER of both theoretical and simulated results for BPSK, QPSK, 16-QAM, and 64-QAM over the Rayleigh channel model is shown in Figure 23.

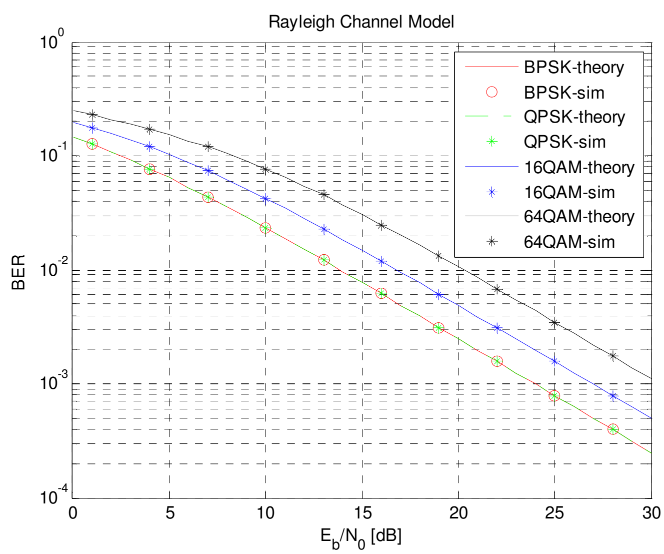


Figure 23. Theoretical and Simulated Probability of BER vs. E_b/N_o for BPSK/QPSK/16QAM/64QAM Over the Rayleigh Channel Model

As shown in Figures 21 and 23, as the energy of bit-to-noise ratio increases, the probability of bit error decreases. PSK has better BER performance than QAM. The probability of BER occurring in BPSK and QPSK is identical, as expected. Additionally, multipath fading in the Rayleigh channel increases the probability of bit error. Comparing the simulation results of BER versus E_b/N_o for the AWGN as well as the Rayleigh models, with the corresponding theoretical formulas described in equations (6, 8, 9, 14 and 15), we find that the performance of the proposed models perfectly agrees with the expected analytical performance for all four modulation schemes. Thus, the developed model is valid to be used to analyze the impact of Doppler shift.

4.4. Doppler Shift Impact Analyses

In this section we present detailed analyses regarding the impact of Doppler shift on signal quality. A systematic approach was adopted to investigate the performance of the communication system. A series of structured experiments was designed, in which changes were made to the input variables and the effects of these changes on performance measures were evaluated. We will start with the comprehensive experiment design; then, the obtained simulation results are presented and discussed, and finally we extend the analyses into mathematical and analytical modeling.

4.4.1. Design of Experiment (DoE)

DoE is widely used in engineering research and development due to its importance as a method for maximizing gathered information, minimizing the cost, and/or optimizing the number of conducted experiments. In this context, our DoE was developed by carefully choosing a number of needed experiments that provided sufficient knowledge about the measure in concern. Variables, to be controlled during the experiment, were defined to guarantee a thorough range of effect. Variables to be observed were defined to provide a meaningful, precise outcome.

The proposed framework was employed to investigate the impact of Doppler shift on signal quality. Computer simulations have been performed in MATLAB/SIMULINK to evaluate the Doppler shift impact for different modulation schemes. The same OFDM system, proposed in Section 2 and validated in Section 3, will be used with additional capabilities to manually configure multiple simulation parameters such as SNR, Doppler shift, and desired modulation scheme. Varying the SNR parameter controls the addition of the white Gaussian noise through the AWGN channel model, while varying the Doppler shift parameter changes the frequency offset of the signal passed through the Rayleigh channel model. To better explore the Doppler shift impact, SNR was set to a fixed value in order to minimize the effect of noise and highlight the effect of frequency shifting. The AWGN channel model was configured to apply an additive noise with SNR of 30 dB. On the other hand, Doppler shift was varied from 0 to 500 Hz. Choosing 500 Hz as the maximum applied frequency shift was based on the corresponding relative speed of two vehicles. According to equation (3), when the transmission carrier frequency f_0 is considered as the central frequency of the IEEE 802.11a band, the 500 Hz frequency shift results from 61.104 MPH relative speed.

Moreover, in each experiment the modulation scheme was set to one of the eight modes as described in Table 4. In each simulation run, a total of 12,500 data blocks were generated to be encoded, modulated, and transmitted over the combined channel model. The number of bits per block varies based on the preset coding rate and mapping technique from 480 bits in BPSK 1/2 to 4,320 bits in 64-QAM 3/4, which produces an approximated transmission payload of 0.57 Mb to 51.50 Mb, respectively. Subsequently, transmitted and received data were fed into an error-calculation block to evaluate the resulted BER. BER was chosen as a performance measure due to its efficiency in assessing the quality of a communication system, especially at the PHY layer. For a specific modulation scheme and Doppler shift value, each BER sample was computed by averaging the BER results obtained from 10 simulation runs with different seeds for data generation.

4.4.2. Simulation Results

The performance of BER versus Doppler shift for the PSK and QAM schemes was evaluated and is presented in Figures 24 and 25, respectively. The modulation technique used along with the associated coding rate are indicated in the figure legend.

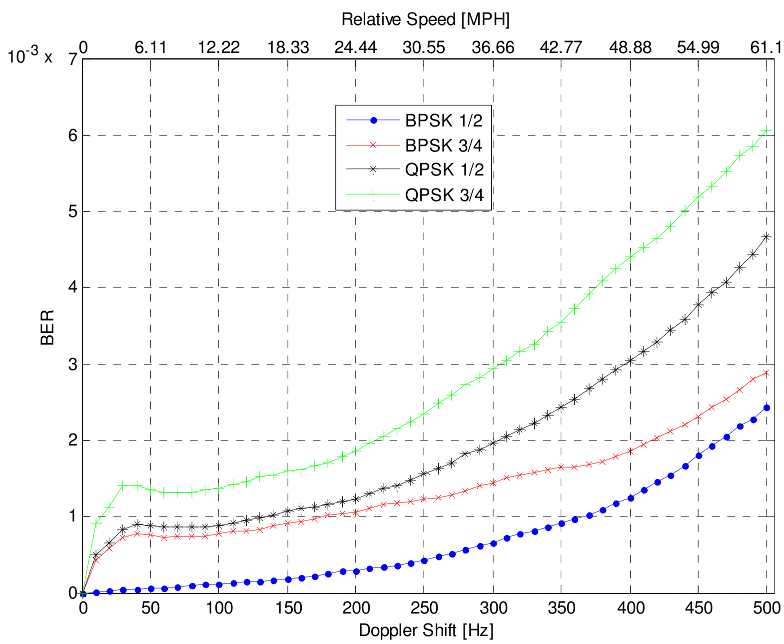


Figure 24. BER VS. Doppler Shift for BPSK and QPSK

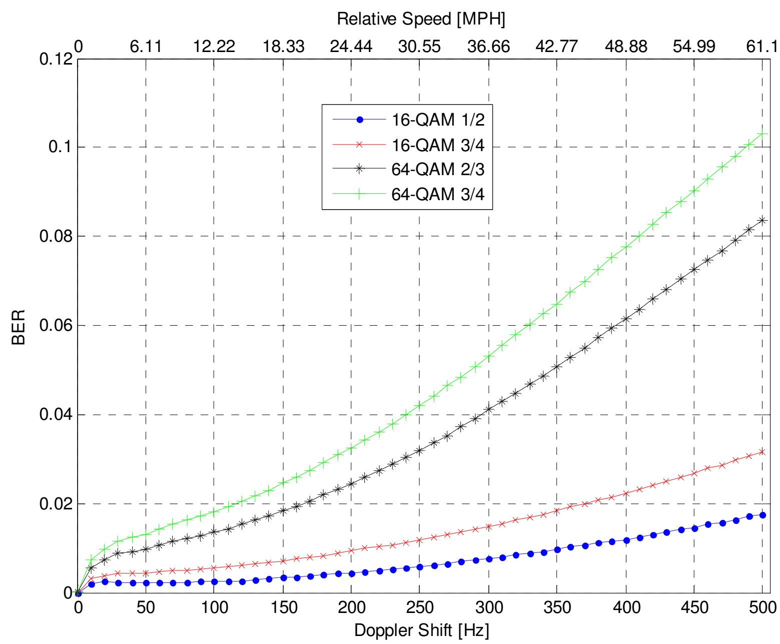


Figure 25. BER VS. Doppler Shift for 16-QAM and 64-QAM

Simulation results show that Doppler shift impact degrades signal quality. As relative speed between two vehicles increases, higher frequency shifting evolves, and as a result BER increases. In addition, the modulation scheme has a considerable impact on BER performance. The QAM scheme seems more sensitive to Doppler shift than the PSK scheme, which is evident from the BER samples, especially when evaluated for high values of Doppler shift. For instance, when Doppler shift is 300 Hz, BER in the PSK scheme is less than 3.10^{-3}, while BER in the QAM is less than 6.10^{-2}, resulting in about 20 times increased degradation. Analytically, the QAM scheme provides a higher data rate than the PSK scheme, which also corresponds with a higher BER. Furthermore, a glance at the characteristic functioning of the AWGN and the Rayleigh channel in Figures 21 and 22, respectively, confirms that the resulting BER is higher in the QAM than it is in the PSK. Moreover, since the used coding rate reflects the efficiently of the FEC, then a lower coding rate, which adds more redundant error-correction bits, should theoretically provide a lower BER. As we notice from Figures 23 and 24, we have obtained agreeable results which present a better BER performance in the case of the lower coding rate over all four modulation techniques (BPSK, QPSK, 16-QAM and 64-QAM). For example, at the 300 Hz frequency shift and QPSK, BER jumps from about 2.10^{-3} in 1/2 coding to about 3.10^{-3} in 3/4 coding. Finally, the performance of BPSK with 1/2 coding seems to be the most resistant to frequency shifting since its curve has the slowest rising of all modes. Contrarily, 64-QAM with 3/4 coding is the least resistant to frequency shifting since its curve has the fastest rising of all modes.

4.4.3. Mathematical Modeling

Data obtained through simulation can be represented mathematically. An accurate mathematical model that relates the potential Doppler shift to the corresponding BER over a particular modulation/coding mode allows for the determination of important characteristics of the given data. Curve fitting technique provides a remarkable tool to construct a function whose curve best approximates a given data set. The constructed function summarizes the relation between input and output variables, allows inferring output values based on input data, and, most importantly, makes it possible to obtain data beyond the range of the observed data, referred to as data extrapolation. To extract the mathematical models of our results, we have used curve fitting with cubic polynomial fitting. First, data resulting from using each mode has been processed to determine the best fitting method. Second, a 3rd degree polynomial equation, described in (16), has been formed for each mode by determining its coefficients (p1, p2, p3 and p4) using the non-linear least square method.

$$BER(f_d) = p1.f_d{}^3 + p2.f_d{}^2 + p3.f_d + p4 \qquad (16)$$

Then, curves of derived equations have been plotted for graphical visualization. Finally, the goodness of each fit has been computed to examine how well the model fits the actual data. The goodness of a fit is evaluated using two measures: Sum Squared Error (SSE) and R-square (R^2). SSE is a statistic that measures the total deviation of the fit from the actual data, as described in (17):

$$SSE = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \qquad (17)$$

R^2 is the square of the correlation between the actual and fitted data, and defined as the ratio of the Sum of Squares of Regression (SSR) to the Total Sum of Squares (SST):

$$SSR = \sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2 \qquad (18)$$

$$SST = \sum_{i=1}^{n}(y_i - \bar{y})^2 \qquad (19)$$

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \qquad (20)$$

Where: y_i : actual data sample.

$\hat{y}_i$: fitted data sample.

$\bar{y}$: mean value.

n : number of data samples.

The closer the SSE is to zero, the smaller the random error component in the model. On the other hand, the closer the R^2 gets to one, the better the model explains the data.

Table 5. Polynomial Coefficients and Goodness-of-Fit Parameters of Fitted Curves

Mode	Polynomial Coefficients				Goodness-of-Fit	
	p1	p2	p3	p4	SSE	R^2
1	-5.96E-11	2.49E-07	8.54E-05	6.67E-03	1.87E-08	0.9992
2	3.42E-11	-1.92E-08	6.08E-06	3.68E-04	3.15E-07	0.9851
3	3.37E-11	-9.05E-09	4.50E-06	5.01E-04	4.53E-07	0.9935
4	1.75E-11	5.02E-09	3.62E-06	9.16E-04	1.40E-06	0.9884
5	1.57E-11	4.85E-08	3.99E-06	1.65E-03	4.13E-06	0.9965
6	7.02E-11	3.22E-08	2.50E-05	2.60E-03	1.02E-05	0.9973
7	-1.54E-11	2.08E-07	5.86E-05	5.15E-03	4.50E-05	0.9984
8	-5.96E-11	2.49E-07	8.54E-05	6.67E-03	7.41E-05	0.9983

Table 5 lists polynomial coefficients of derived equations along with goodness-of-fit parameters for each mode. Figures 26(a) through 26(h) demonstrate the graphical representation of actual data (in blue) and its fitted model (in red) for all eight modes, where modulation scheme and coding rate, as well as resulting R^2, are indicated on top of each figure.

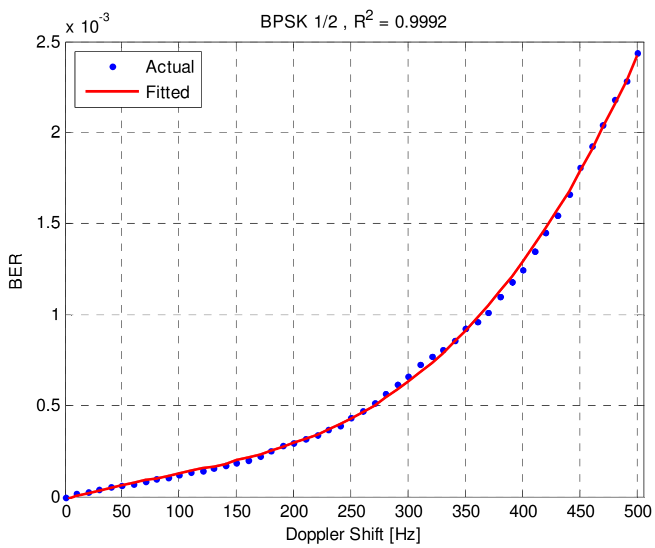


Figure 26 (a). BPSK ½

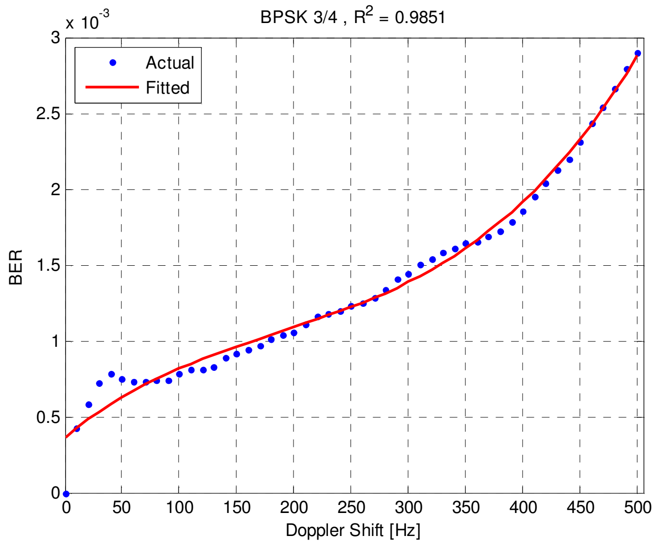


Figure 26 (b). BPSK 3/4

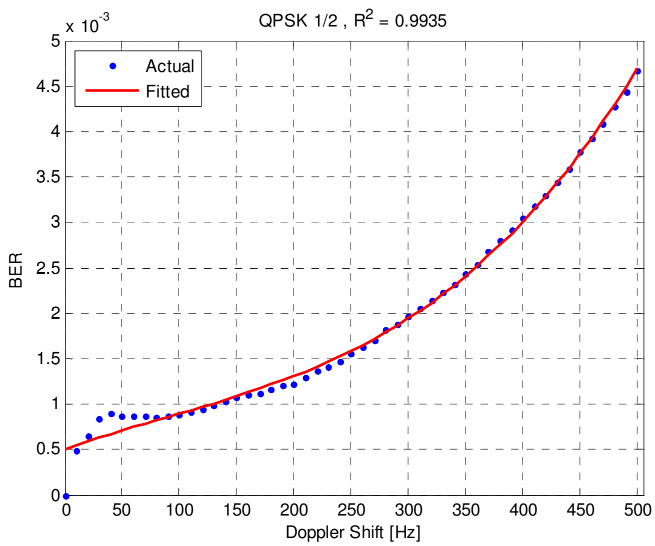


Figure 26 (c). QPSK 1/2

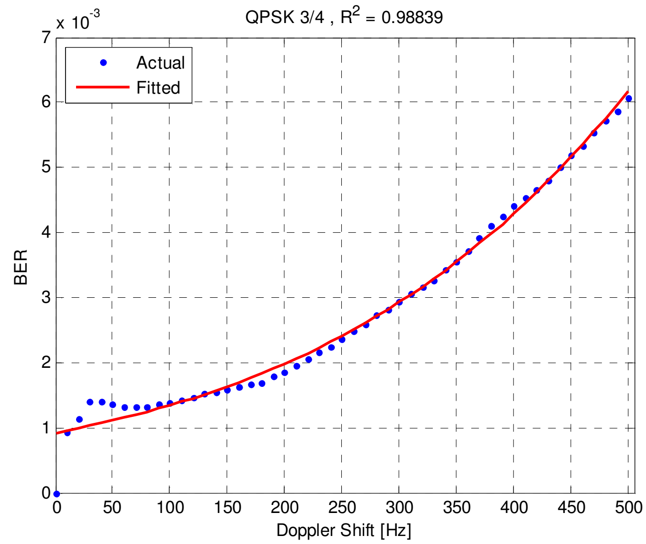


Figure 26 (d). QPSK 3/4

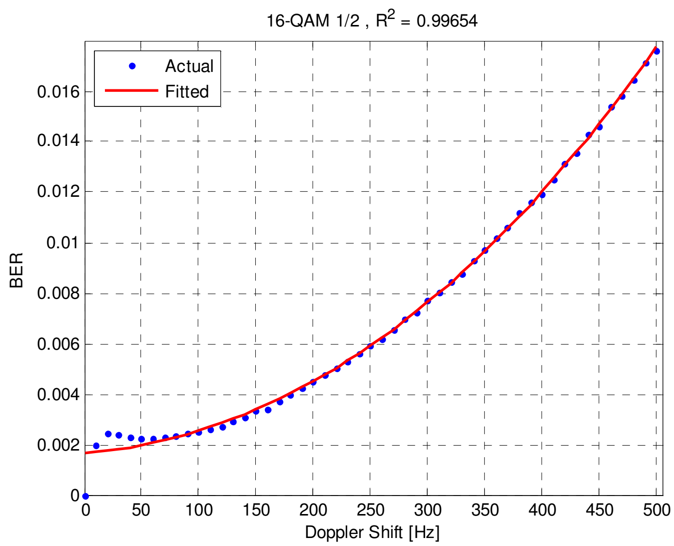


Figure 26 (e). 16-QAM ½

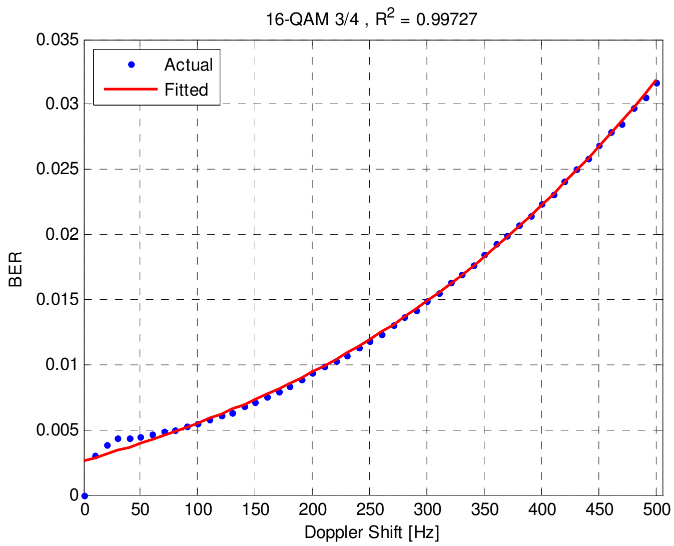


Figure 26 (f). 16-QAM 3/4

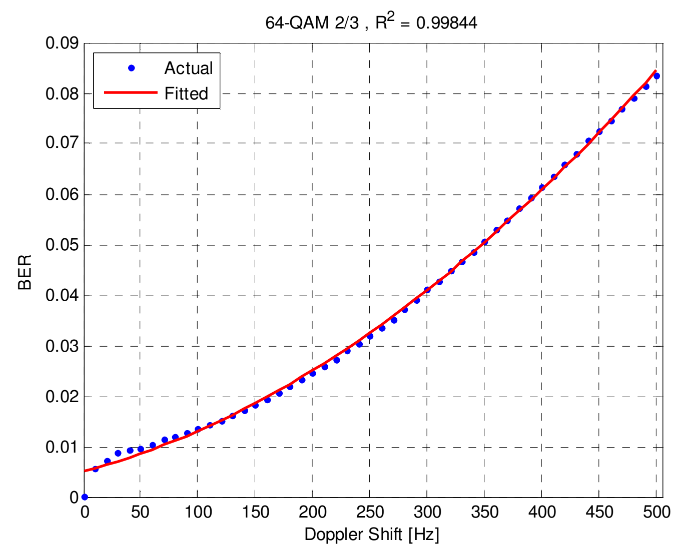


Figure 26 (g). 64-QAM 2/3

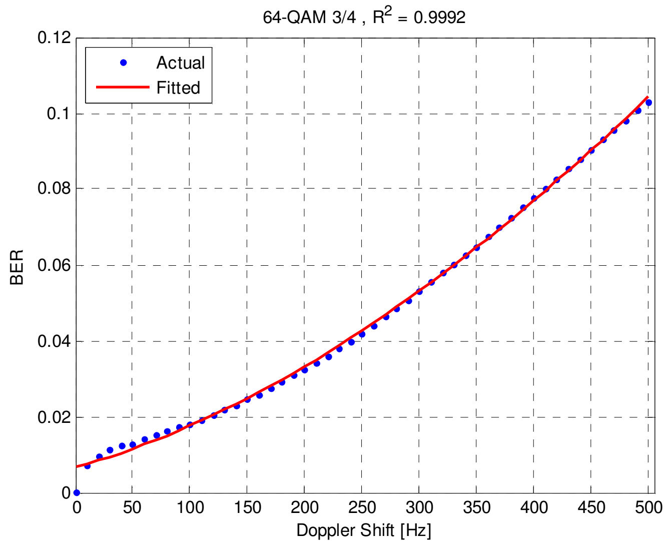


Figure 26 (h). 16-QAM 3/4

Figure 26 (a-h). Curve Fitting of BER vs. Doppler Shift

Based on R^2 values listed in Table 5, goodness-of-fit varies from 99.35% for mode 3 to 99.92% for mode 1. Hence, the derived fits are closely related to the original data. Therefore, 3rd degree equations can be used to mathematically relate the impact of Doppler shift with the resulting BER in an OFDM communication system.

4.5. Adaptive Modulation and Coding

To improve the robustness of the communication system to the encountered frequency shift, we proposed a new methodology that reduces the impact of Doppler shift on signal quality. The proposed methodology is based on an adaptive algorithm that adjusts the modulation scheme according to any Doppler shift that might occur. The developed algorithm establishes communication in the lowest data rate under Mode 1. As Doppler shift changes, the corresponding BER is computed through the appropriate equation that links the BER with the Doppler shift at a particular mode, as summarized in Table 5. These closed-form equations provide the BER for any given Doppler shift value; therefore, the BER can be found not only at the current Doppler shift value, but also at a posterior value, which produces a sort of predicted BER. Consequently, the current and subsequent BERs are compared to a predefined threshold to determine whether to switch to a higher or lower modulation mode. A flow chart of the developed algorithm is illustrated in Figure 27.

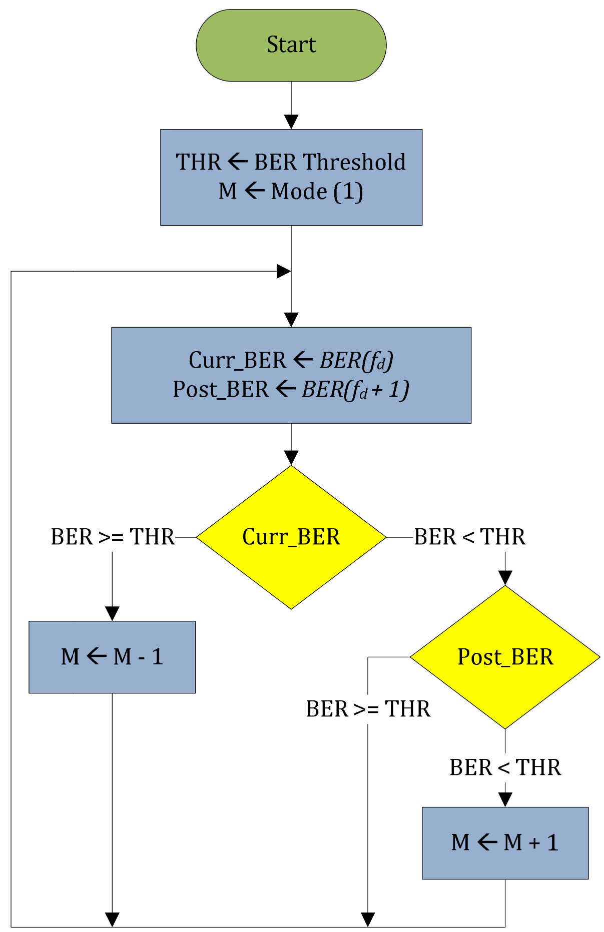


Figure 27. Adaptive Algorithm Flow Chart

The desired BER threshold is set to match the acceptable BER, defined by IEEE. According to the IEEE 802.11a standard [45], the minimum sensitivity of a receiver should fall in the range of (-82 , -65 dBm) to detect the transmitted signal and demodulate it with a Packet Error Rate (PER) of less than 10% at a PSDU length of 1000 octets. A rule of thumb to relate the PER to the BER is:

$$P_p = 1 - (1 - P_b)^N \qquad (21)$$

Where: P_p : probability of packet error.

P_b : probability of bit error.

N : number of bits per packet.

As a result, the acceptable probability of bit error in IEEE 802.11a should be less or equal to 10^{-5}, which can be expressed as a percentage BER of 10^{-3}. This agrees with the analyses and conclusions that were presented in [62].

Applying the proposed adaptive methodology while varying Doppler shift frequency from 0 to 500 Hz causes dynamic mode switching, and as a result, the corresponding BER performs in a different manner, as graphed in Figure 28. As shown, transmission initially begins with the first mode. As long as the computed BER is below the threshold, the communication mode is adjusted to the next higher mode providing a higher data rate. However, whenever the BER exceeds the desired limit, the communication mode is readjusted to the previous lower mode, providing a better robustness.

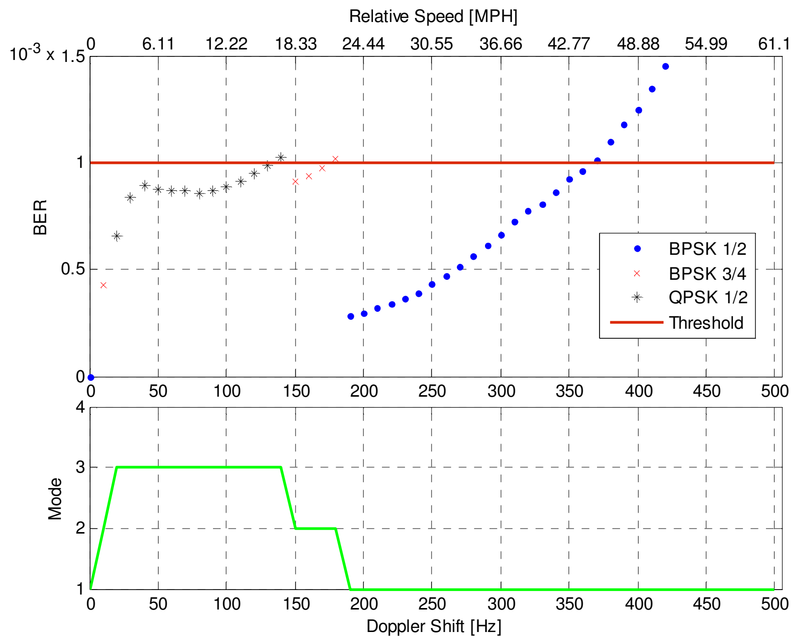


Figure 28. BER VS. Doppler Shift With Adaptive Methodology

We notice that QPSK with a 1/2 coding rate is the highest mode that is to be reached in order to keep the BER in the acceptable range. Moreover, the BER goes beyond the acceptable boundary, despite the mode of adjustment, as Doppler shift exceeds 370 Hz. Hence, we may consider that the proposed methodology is valid for up to 370 Hz of frequency shift, or in other words, up to 45.22 MPH of relative speed. In summary, mode adjustment can be divided into multiple levels based on Doppler shift or relative speed as shown in Table 6.

Table 6. Mode Adjustment Leveling

Doppler Shift f_d [Hz]	Relative Speed v_r [MPH]	Suitable Mode
$f_d <= 140$	$v_r <= 17.11$	QPSK 1/2
$140 < f_d <= 180$	$17.11 < v_r <= 22.00$	BPSK 3/4
$180 < f_d <= 370$	$22.00 < v_r <= 45.22$	BPSK 1/2
$370 < f_d$	$45.22 < v_r$	N/A

Mode adjustment in the proposed adaptive methodology has to be used in both the transmitter and receiver to allow an agreement on communication parameters. By that means, the adaptive methodology is only suitable for duplex communication between two vehicles.

5. UDM Research, Traffic Light Scenario Evaluation

5.1. Introduction

Several studies by the U.S. Department of Transportation (USDOT) have shown that traffic congestion conditions continue to deteriorate on a yearly basis, particularly in urban areas. Traffic volumes have been outgrowing road capacity in urban areas; in addition, the unconstructive financial and environmental impacts for developing additional roadway required policy makers to seek alternative solutions to further address traffic congestion. The emergence of new technologies has allowed transportation agencies to improve traffic flow and avoid roadway expansion through adaptive traffic light intersection control. Adaptive traffic light control systems such as the Sydney Coordinated Adaptive Traffic System SCATS[62]- and Split Cycle Offset Optimization Technique SCOOT [63]- have been deployed at major urban intersections. Such adaptive traffic management systems control traffic signals to increase traffic flow using road sensory networks. Recent evolution in wireless communication technologies is allowing for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, further supporting the objective of reducing traffic congestion.

The objective of this study is to evaluate the wireless communication network performance as a function of the number of nodes, the communication technologies and the message characteristics. The limited availability of wireless equipped vehicles and the complexity of empirically evaluating wireless communication technologies led us to the use of a simulator. For this evaluation, a simulation tool combining traffic and network simulation capabilities is necessary.

This study is presented in two parts:

Part I: Provides an overview of the study, the evaluation tool and the evaluation method.

Part II: Develops a simulation to simulate different scenarios and discusses simulation results.

5.2. Part I

5.2.1. Related Work

A large number of recent studies have focused on the performance evaluation of wireless communication in vehicular applications. In [64]- , research was conducted to evaluate the reliability of vehicles' ad-hoc networks using a traffic/network simulation tool (VNSim) developed by University Politehnica of Bucharest. The research results demonstrated the advantages of implementing the DSRC (Dedicated Short-Range Communications) communication protocol rather than the 802.11 communication protocol at the physical, MAC and application layers. The research limits the average number of nodes being evaluated to 90 vehicles/minute. Our simulation extends the study beyond 90 vehicles/minute to evaluate the performance of data communication in areas such as highly congested intersections, accidents or construction zones.

Other efforts have focused on developing dynamic traffic light algorithms. In [66]- , researchers developed a genetic algorithm-based traffic light controller to enhance traffic and pedestrian flow performance at traffic lights. This algorithm was based on two parameters: the queue of vehicles and pedestrians at the red light, relative to the number of vehicles and pedestrians that pass through a green light. The performance comparison revealed the proposed controller to have a performance advantage relative to other dynamic traffic light algorithms. The research does take the impact of data communication performance on the proposed traffic light algorithm.

5.2.2. Simulation Tools

In order to study the efficiency of the DSRC communication protocol, traffic and network simulators are needed. In the following section, we discuss a few simulation tools to identify a suitable tool for our simulation goals.

Simulation tools such as TSIS-CORSIM and Paramics are two of several microscopic traffic simulators. This type of simulator provides accurate traffic data; nevertheless, these simulators do not include any network simulation capabilities. Integrating a network simulator is essential to evaluate the impact of the communication network performance with high user rates.

High performance network simulators such as NS-2 are available. NS-2 is an open source simulation tool that runs on Linux. JiST/SWANS is yet another platform-independent network simulator with high performance in discrete evaluation simulation. These types of tools are good for network simulation; however, these tools do not include a traffic simulator, which is equally essential for our study.

ViiLab is a new traffic/network simulator whose development is still being enhanced. Further exploration was required to validate the capabilities of this tool, thus rendering it unqualified for this study.

The evaluation of these simulation tools led us to concentrate our efforts on utilizing VNSim. VNSim is an integrated network/traffic-simulating tool developed by University Politehnica of Bucharest [67]- . We would like to thank Professor Valentin Cristea and Professor Liviu Iftode at University Politehnica of Bucharest for their support during the use of this tool. VNSim was developed utilizing the TrafficView simulator which simulates the vehicular wireless communication network. VNSim provides traffic and vehicle information such as the maximum / average delay of vehicles, fuel consumption and emissions. Furthermore, VNSim's network simulation capabilities provide network communication data such as the number of transmitted messages, rate of received messages, cause of non-received messages, and source of messages- forward vehicle, next forward vehicle, left adjacent vehicle and right adjacent vehicle as shown in Figure 28.

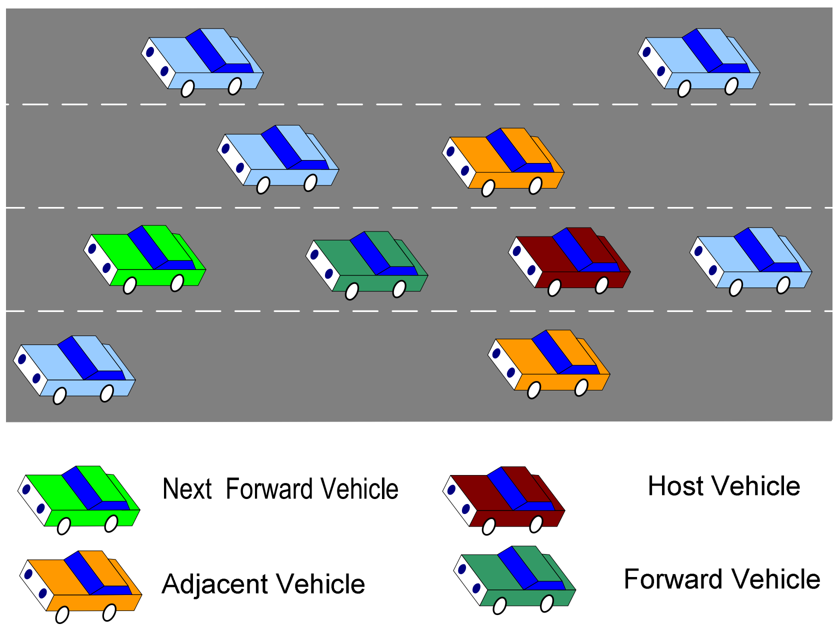


Figure 29. Communication Environment

5.2.3. VNSim: Radio Propagation Models in TrafficView

VNSim offers several radio propagation models and data dissemination models to allow studying of the impact of radio wave propagation. In an ideal communication medium, there is only one direct line of communication between the sender and the receiver units. In a real world application, there are random obstacles such as buildings and other radio wave communication that interfere with the communication path between a sender and a receiver. As a result, it is challenging to model the communication interference and analyze its characteristics. Several radio propagation models have been developed to model the different phenomena that influence the received signal such as:

- *The Shadowing Model:* This model seeks to solve the fading effects that occur on the signal, and loss of signal power that occurs on the long distance path. The model can measure the loss in received signal power using a logarithmical equation that depends on distance. In addition, the model adds a Gaussian random variable to counteract the loss caused by obstacles in the communication medium.

- *The Two Ray Ground Model:* Two paths were considered in this model: the direct line of sight, and the ground reflection path between the sender and the receiver as shown in Figure 30. Therefore, the power of the received signal is simply the sum of these two paths. It is important to note that for short distances between the sender and the receiver, such as a traffic signal, this model does not provide good-quality results.

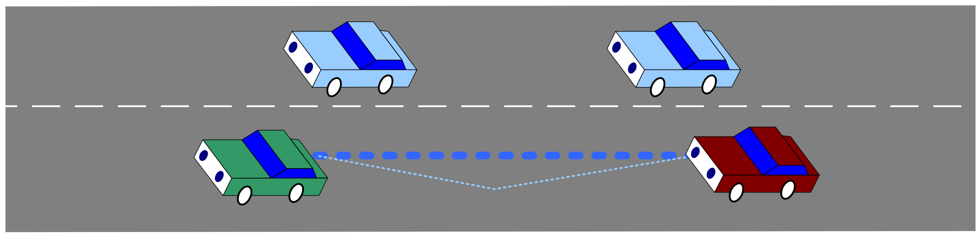


Figure 30. Two Ray Ground Model

- *The Ricean Fading Model:* The radio signal in this case tends to partially cancel itself due to the multi-path interference. This kind of fading occurs when the signal coming from generally the line of sight signal overpowers all other signals.

5.2.4. VNSim: Data Dissemination Models in TrafficView

Data dissemination models in vehicle communication networks are very important to ensure effective data sharing. TrafficView (VNSim) offers three different types of data dissemination models:

- Probabilistic Forwarding (PF)
- Complete Forwarding (CF)
- Neighbor Discovery (ND)

The communication data or packet is sent with a fixed period every 100 milliseconds, but the types of packets differ among the three data dissemination models.

1. In Probabilistic Forwarding, the vehicle can send one of two packets:
   - Packet with vehicle data, containing information about itself
   - Packet with vehicle data, containing information about itself and all other vehicles in its communication range

The application will choose which packet to send in a probabilistic way depending on the size of the platoon. Another enhancement is achieved using the following model: when a vehicle stops at a red light, the vehicle sends a message indicating that it is still in the platoon but it will not be active. This will ensure that the vehicle's information stays in the platoon packet and consequently the number of overall packets will be reduced.

2. The Complete Forwarding model does not use different types of packets. In this model, the only packet that will be sent from each vehicle is the platoon packet in which the vehicle broadcasts its database, which includes information about the other vehicles it identifies.

3. On the other hand, the Neighbor Discovery model does not deal with vehicle platoons. Each vehicle sends a static packet in a static period of time. These packets contain information about the vehicle that sends it (ID, timestamp, speed, road, point, offset, lane, direction, signal and state). The packet size is fixed to 27 bytes. The application adds two extra Bytes to this packet containing information that defines its type. Therefore, the packet size will be 29 bytes [67]-

In summary, Probabilistic and Complete Forwarding deal with large numbers of vehicles where drivers tend to travel as platoons (highway or intersection). In the Forwarding models, the packet contains general information about the road and detailed information about each vehicle in the platoon. Nevertheless, there are two constraints on the platoon packets: the information about each vehicle should not be outdated and the total size of the packet should not exceed 2300 bytes (Ethernet 802.11 frame size).

5.2.5. Performance Measures

In order to evaluate the DSRC protocol at intersections, we apply the three different data dissemination models: PF, CF and ND. In addition, we select several test cases to compare the dissemination models to communication performance in terms of the ratio of successfully received to lost packets.

For each data dissemination model, we present the ratio of successfully received/lost packets as a function of number of nodes per simulation minute. To analyze the reasons behind losing packets we evaluate each category:

- Collision: two packets arrive at the same time to the node and the ratio of the first packet to the sum of the two packets is lower than the collision threshold.
- Corrupted: the received packet does not have enough power to decode the Physical and PCLP header.
- RX (Receiving): the received packet was rejected because the node is engaged in receiving another packet (receiving mode).
- TX (Transmitting): the received packet was rejected because the node is engaged in transmitting another packet (transmitting mode).
- PER: the received packet does not have enough power to decode the data.
- Weak: the received packet does not have enough power to be detected and it is too weak to be received; it would normally be detected as noise.

5.3. Part II

5.3.1. Simulation Setup

The VNSim Simulator environment was selected to run different traffic light scenarios. These scenarios differ by number of nodes; the same simulated scenarios were repeated for the three different data dissemination models PF, CF and ND.

The simulated road is a simple cross intersection: one cross road has three lanes north/south and the other two lanes east/west as shown in Figure 31. On each side of the intersection, approximately 15 to 25 percent of all traveling vehicles will turn left; similarly the same number will turn right and the remaining will continue straight. We ran each experiment for 60 simulation minutes. The average number of nodes varied between 35 and 290 vehicles per simulation minute. Modifying the number of vehicles per lane per simulation hour generated the number of nodes used in each experiment. We divided the drivers' driving behaviors equally into very calm, regular and aggressive. We selected a pre-timed traffic light controller; the cycle's length of time was 70 seconds: green 30 seconds, yellow 3 seconds, and red on all sides of the intersection 2 seconds; hence the Red was 35 seconds long.

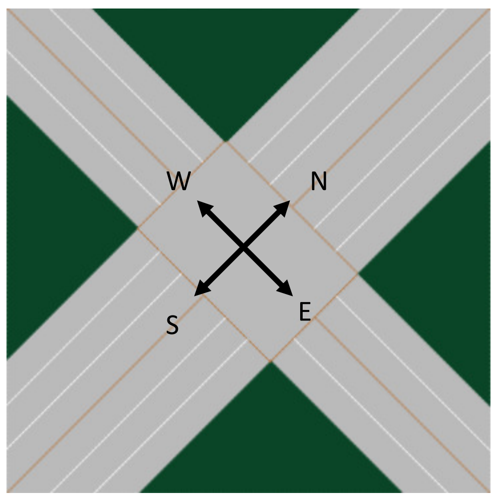


Figure 31. The Simulated Intersection

All of the simulated vehicles were equipped with a wireless device to communicate among themselves (V2V) and with the infrastructure (V2I). The communication range was set to 200 meters between the vehicles and 1,000 meters between vehicle and infrastructure. The selected radio propagation model is the shadowing model.

5.3.2. Scenarios Description

We ran seven scenarios for each different data dissemination model. The number of nodes is different for each scenario and follows the possible paths illustrated in Figure 32:

- Vehicles/Lane/Hour turning left
- Vehicles /Lane/Hour going straight
- Vehicles /Lane/Hour turning right

The selected intersection's traffic flow scenarios are as follows:

- Scenario 1: 25 (Left), 50 (Straight) and 25 (Right)
- Scenario 2: 35 (Left), 70 (Straight) and 35 (Right)
- Scenario 3: 30 (Left), 100 (Straight) and 30 (Right)
- Scenario 4: 50 (Left), 150 (Straight) and 50 (Right)
- Scenario 5: 35 (Left), 180 (Straight) and 35 (Right)
- Scenario 6: 90 (Left), 180 (Straight) and 90 (Right)
- Scenario 7: 110 (Left), 220 (Straight) and 110 (Right)

The simulation time was fixed to 60 minutes which translates into different real run time based on the selected scenario. The real run time varied between 10 and 60 minutes.

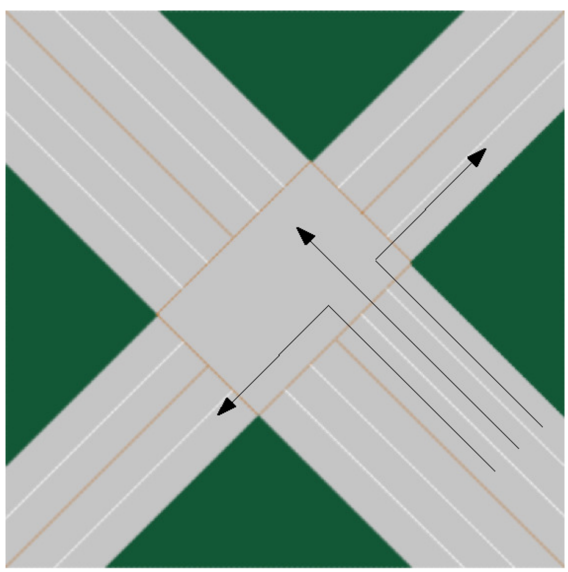


Figure 32. Traffic Direction: Vehicles Turning Left, Right and Going Straight

5.3.3. The Overall Traffic Data

We have run the simulation for all seven scenarios to study the average vehicle density of vehicles at the intersection for different data dissemination models as illustrated in Figure 33. We found that the average waiting time of the three dissemination models performs equally well for the first six scenarios. In scenario seven we can clearly identify that the CF dissemination model results in an improved performance.

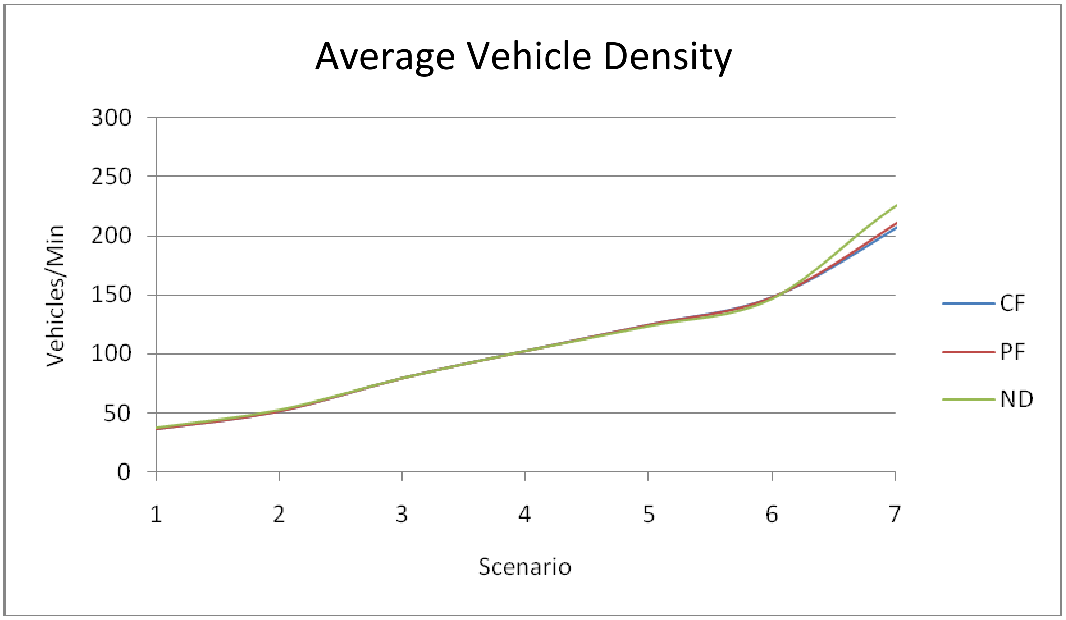


Figure 33. The Average Number of Vehicles at the Intersection for Each Scenario

Figure 34 presents the maximum waiting time of vehicles at the intersection. It can be seen that the pre-timed intersection control can no more offer an equalized control for clearing traffic with volumes identified in scenario six and beyond. The results also show that the PF and CF dissemination models perform equally and surpass the ND model performance.

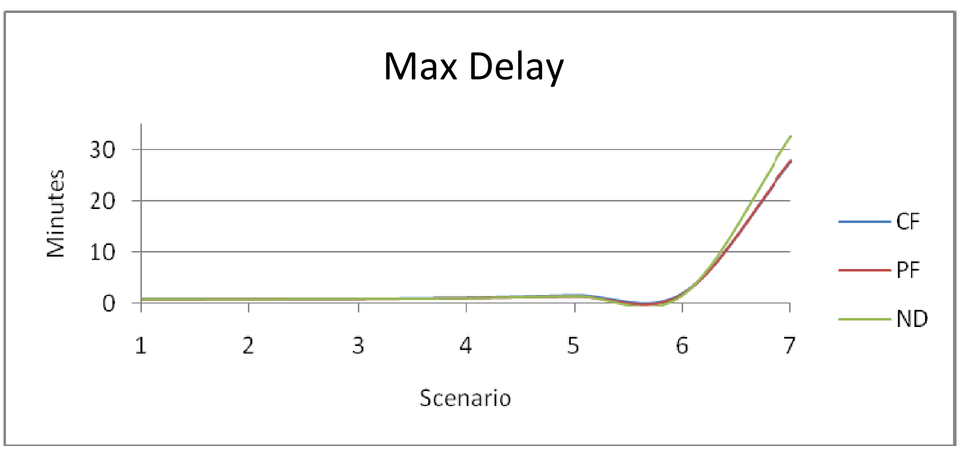


Figure 34. The Maximum Waiting Time at Intersection

An additional measure to portray the enhanced performance of the CF and PF dissemination models was “intersection average delay.” We evaluated the vehicle average delay at the intersection, and the results reflected in Figure 35 clearly show the underperformance of the ND dissemination model.

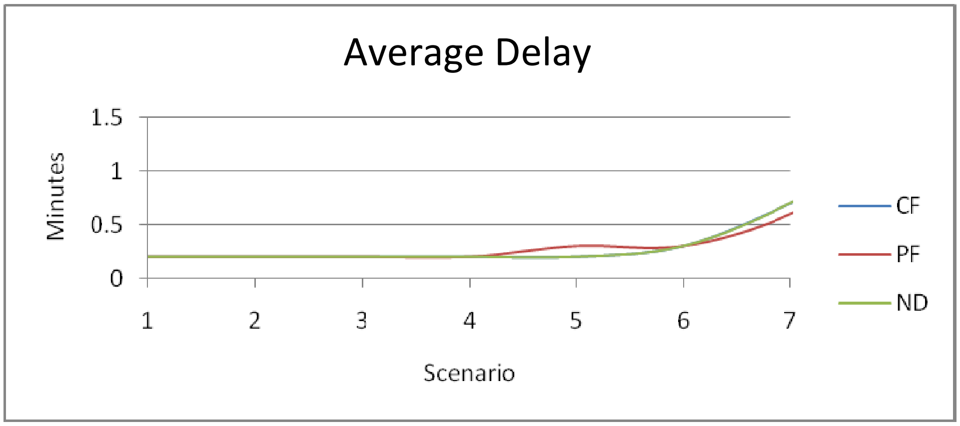


Figure 35. The Average Delay Time at Intersection

Next, the ratio of the successfully received and lost packets for each data dissemination model is discussed. This study will help identify which of the dissemination models could offer enhanced communication performance at intersections. This decision will be based on the largest number of nodes that the model can serve. The simulation results are illustrated in Figure 36. The most interesting aspect is the intersecting point of the successfully received versus lost packet curves for each of the dissemination models. The representative model’s plot intersection point identifies where half of the transmitted messages are getting lost. Half of the packets were lost at around 110 nodes when using Neighbor Discovery and Complete Forwarding, while the Probabilistic Forwarding reached approximately 130 nodes before losing half of the transmitted packets. These results lead us to conclude that the Probabilistic Forwarding model offers an improved performance compared to the Complete Forwarding and the Neighbor Discovery dissemination models.

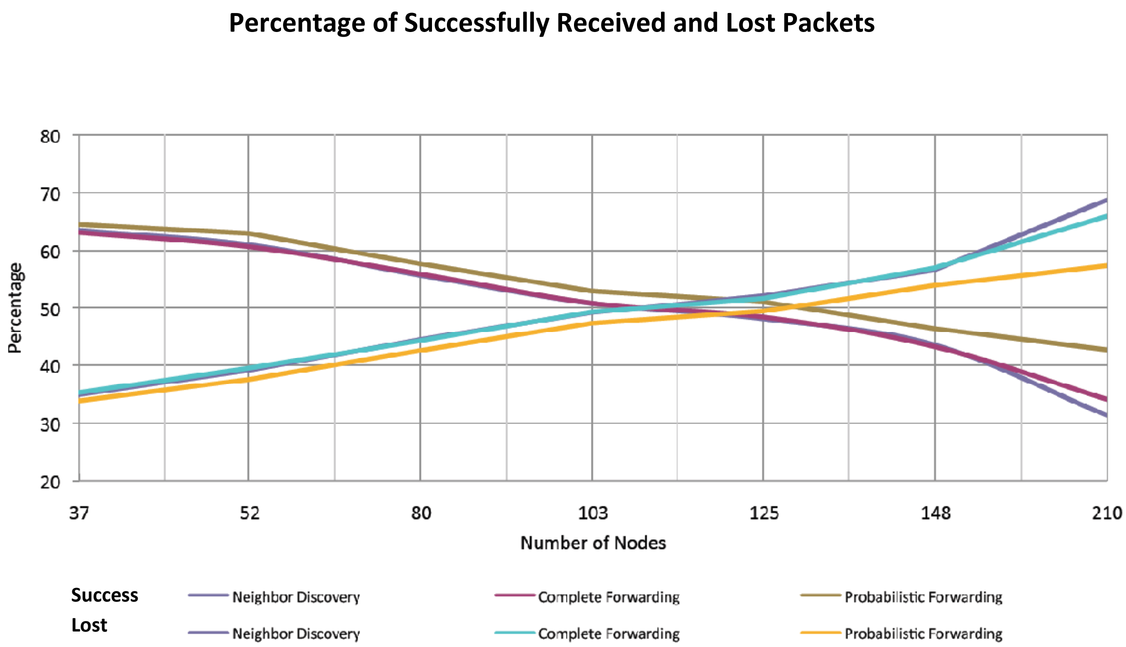


Figure 36. The Percentages of Successfully Received Packets Using the Three Data Dissemination Models

6. Conclusion

In this research, we have defined the requirements of the development of a test bed that has been used to evaluate and validate different wireless protocols. WLAN communication protocols have been evaluated for vehicular applications. Multiple performance measures, such as communication range, time-to-login, throughput and jitter time, have been used to determine the effectiveness of wireless protocols in the ITS environment. Experimental results showed that the practical communication range may vary from the theoretical value according to the type of Wi-Fi transceiver used. Another measure, time-to-login, showed the importance of having a static assignment of a unique address for network nodes, where the dynamic addressing resulted in significant delays.

Newly developed methodologies have been proposed to reduce the cost of test bed implementation. The first method aims to use a single node to generate a network load that is similar to the load of multiple nodes. As a result, it was proven that this method is not valid due to the inconsideration of the random access of the large number of nodes. The second method divides the network with costly wireless transceivers into two or more subnets with low-cost transceivers, where all subnets are bridged together using the costly link. Throughput, jitter time and delay time were used as measures to validate the proposed methodology. The last method was to evaluate the impact of the distance between vehicles on the communication throughput. Several experiments were designed and implemented at a racing track to measure the throughput while the relative distance between the transmitter and receiver varied. Results illustrated the degradation of channel throughput as the relative distance increased.

We have implemented an end-to-end OFDM communication system using MATLAB/SIMULINK with all required configuration. The consistency between simulation results and analytical solutions has validated the proposed system. A comprehensive design of the performed experiments has been presented. The main focus of this section was to analyze the impact of Doppler shift, as a function of relative speed, on the signal quality. PSK schemes have presented greater resistance for Doppler shift impact in comparison with QAM schemes; however, with a lower data rate. Moreover, an explicit, precise mathematical model has been derived for each mode to provide a close-form relation between Doppler shift and BER. An adaptive methodology has been developed to improve system robustness to Doppler shift impact. Simulation results showed the enhanced performance of the proposed methodology and indicated the possible range of operation in term of frequency shift as well as relative speed.

In Section 5, we have showed with simulation that the probabilistic forwarding dissemination model in vehicle communication is the optimal dissemination model. The probabilistic forwarding dissemination offers improved performance in achieving successful data communication between nodes in all traffic flow conditions.

7. Resulting Publications

1. Baraa Alyusuf, Rami Sabouni, Utayba Mohammad, and Nizar Al-Holou, “Performance Evaluation of IEEE 802.11b/g for Inter-Vehicle Communication (IVC),” accepted for presentation at ITS-America 2010.
2. Baraa Alyusuf, Utayba Mohammad and Nizar Al-Holou, “Performance Evaluation of IEEE802.11 Family Protocols,” poster presentation at the 2009 ITS-Michigan Annual Meeting & Exposition.
3. Khaldoun Albarazi, Fadi Saadeh, Utayba Mohammad and Nizar Al-Holou, Ghassan Shahine, “Development and Evaluation of the Next Generation Traffic Light System,” poster presentation at the 2009 ITS-Michigan Annual Meeting & Exposition.
4. “Development of Test Bed to Evaluate the Performance of Intelligent Transportation Systems (ITS),” poster, UDM Faculty and Student Research symposiums, April 15, 2008.
5. “Wireless Networks for the Next Generation Vehicles,” poster, UDM Faculty and Student Research symposiums, April 15, 2008.
6. Khaldoun Albarazi, Utayba Mohammad and Nizar Al-Holou, “Doppler Shift Impact on Vehicular Ad-hoc Network,” accepted for publication at the Canadian Journal on Multimedia and Wireless Networks.

8. Glossary of Acronyms

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
COTS	Commercial Off-the-Shelf
DSRC	Dedicated Short-Range Communications
E_b/N_0	Energy of Bit-to-Noise Ratio
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
FPGA	Field Programmable Gate Array
Gbps	Gigabit Per Second
GHz	Giga-Hertz
GPS	Global Positioning System
IP	Internet Protocol
IPv4	Internet Protocol Version 4
IPv6	Internet Protocol Version 6
ISO	International Standards Organization
IVPS	In-Vehicle Payment Service
IVTP	In-Vehicle Toll Processing
ITS	Intelligent Transportation Systems
MAC	Medium Access Control
MDOT	Michigan Department of Transportation
MHz	Mega-Hertz
MTU	Maximum Transmission Unit
OBU	On-Board Unit
OEM	Original Equipment Manufacturer
OFDM	Orthogonal Frequency Division Multiplexing
OS	Operating System
PC	Personal Computer
PER	Packer Error Rate
RF	Radio Frequency
RITA	Research and Innovative Technology Administration
RSU	Roadside Unit
SNR	Signal to Noise Ratio
TCP/IP	Transmission Control Protocol/ Internet Protocol
UDP	Universal Datagram Protocol
URL	Uniform Resource Locator
USDOT	United States Department of Transportation
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
WAVE	Wireless Access in Vehicular Environments

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