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Tarig M. Osman

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USING LARGE-SCALE FIELD TEST DATA FOR HIGH FIDELITY MODELING OF DSRC RECEIVER IN NS-3

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Thesis submitted to the
Benjamin M. Statler College of Engineering and Mineral Resources
at West Virginia University

in partial fulfillment of the requirements for the degree of

Master of Science in
Computer Science

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Morgantown, West Virginia
2015

Keywords: DSRC; VANET; V2V; capture effect; receiver model; BSM broadcast

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ABSTRACT

USING LARGE-SCALE FIELD TEST DATA FOR HIGH FIDELITY MODELING OF DSRC RECEIVER IN NS-3

S M Osman Gani

Vehicle-to-vehicle communications (V2V) has attracted the interest of research community in recent years because of its potential to increase safety and efficiency of roads and make connected-vehicles a reality. DSRC-based vehicular networks are already standardized by IEEE 802.11 which supports communication among vehicles and road-side infrastructures. However, before deployment, different safety applications need to be tested and validated for numerous road scenarios to show the benefit of DSRC-based networks. Since large-scale field tests are expensive to conduct for vehicular networks, researchers mostly depend on simulation tools that come in handy where a sizable number of tests are required to substantiate the performance of safety applications. ns-3 is such a network simulation tool that offers a rich set of libraries for modeling mobility, communication channel, and many other network components. Although ns-3 is specially designed for simulating Wi-Fi networks, some enhancements are still required to make the simulations more realistic for vehicular networks. Large-scale field tests reveal that some of the substantial details are missing in existing ns-3 implementation of physical (PHY) and medium access control (MAC) layers that play a major role in defining the network behavior. Since safety applications are implemented at the top layer of the DSRC protocol stack, reliability of their performance largely depends on how well the lower layers are simulated.

This research work is a step toward an exhaustive and higher fidelity simulation of IEEE 802.11. In this work, existing implementation of ns-3 physical and medium access layers are thoroughly studied, and compared with modern transceiver behavior to identify if they work the same way. It is observed that receiver functionalities such as preamble detection, PLCP header decoding, and frame capture are not considered in ns-3 receiver model. We reviewed IEEE 802.11 specifications for receiver requirements, and developed a new receiver model for ns-3 to align it with IEEE 802.11. Though frame capture is not explicitly outlined in the standard, it has been reported to be prevalent in wireless networks, especially in vehicular networks. We have integrated all these functionalities into our enhanced receiver model, and validated the model by comparing simulation results with large-scale field test data.
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<td>Access Category</td>
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<tr>
<td>AIFS</td>
<td>Arbitration Inter-Frame Space</td>
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<tr>
<td>BSM</td>
<td>Basic Safety Message</td>
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<td>CSMA/CA</td>
<td>Carrier Sense Multiple Access/ Collision Avoidance</td>
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<td>Federal Communications Commission</td>
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<td>Preamble Successful Capture Threshold</td>
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<tr>
<td>PSDT</td>
<td>Preamble Successful Decoding Threshold</td>
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<td>Service Channel</td>
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<td>SIFS</td>
<td>Short Inter-Frame Space</td>
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<td>V2I</td>
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</tr>
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<td>Vehicle-to-Vehicle</td>
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<td>Vehicular Ad hoc Network</td>
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<tr>
<td>WAVE</td>
<td>Wireless Access in Vehicular Environments</td>
</tr>
</tbody>
</table>
Chapter 1: Introduction

Dedicated Short-Range Communications (DSRC) based safety applications have the potential to make driving safer [1]–[3], [25]–[30] by broadcasting periodic safety messages (Figure 1-1). However, extensive research and tests are required before we put vehicle safety applications in action. Due to the dynamic nature of vehicular networks and various factors that affect such networks, it is often challenging and expensive to conduct field tests for all possible traffic scenarios. Thus, researchers resort to simulation tools to verify the performance of different safety applications. While these simulation tools come in handy to provide an inexpensive means to testing, credibility of the results is a must. High accuracy simulation of lower layer network components is required for performance analysis of any safety applications as they are implemented at the top of the protocol stack. In recent years, ns-3 has become popular among communities that are active in wireless communication research because of its rich set of libraries for various networking components [13]. ns-3 is an open source discrete-event network simulator targeted primarily for research and educational purposes. Though ns-3 is currently in an active development phase and various modules of ns-3 are being upgraded regularly, it still lacks a full-fledged implementation of IEEE 802.11[14], and requires enhancements to meet DSRC research demands.

Figure 1-1: Broadcasting safety messages to local neighborhood
1.1 Literature Survey

In recent years, there has been considerable interest in DSRC research, and several research attempts have been made to integrate simulation of DSRC-based communication into existing popular network simulators. Chen et al. [4] have addressed the shortcomings of simplistic physical layer (PHY) and medium access control (MAC) implementation of ns-2 that cannot accommodate the research demands of DSRC. In their work, they have separated PHY and MAC layers in a proper way so that functionalities of the network components are placed in their respective layers. Also, they improved the simplistic carrier sensing approach of ns-2 by integrating a “NoiseMonitor” to keep track of all interferences at a transceiver, and proposed a SINR based reception criteria that should mark whether a frame is successfully received or not. In [5], a new architecture has been proposed for PHY and MAC layers with an aim to increase the accuracy of ns-2 simulation by addressing transceiver functionality for preamble and PLCP header decoding, and preamble and frame capture. Also, the functionalities of PHY and MAC are described systematically such that this model can be used as a core for other simulation platforms. Lee et al. [6] has extensively investigated, using their 802.11 test bed, the details of physical layer capture effect by explaining various capture scenarios, and based on that study [7], [8] proposed some modifications of the 802.11 PHY in QualNet [19].

Papanastasiou, Mittag et al. [9], [10] developed a detailed PHY model (PhySim-Wifi) based on ns-3 in an effort to incorporate DSRC based vehicular communication. The main objective of their work is to increase accuracy in physical layer simulation. As ns-3 works in packet level and does not consider the details of frame construction, they argued that this abstraction practically hinders the proper analysis of channel effects on physical layer. Their proposed PhySim-Wifi follows the IEEE 802.11 standard for OFDM based communication, and considers the details of signal processing.
Thus, this simulator models a very realistic Wi-Fi physical layer and can be used as drop-in PHY module in default ns-3. While PhySim-Wifi promises a higher accuracy in physical layer simulation, it trades off additional memory requirements and extra processing time for the additional signal processing computations. Though the memory requirements are not that much, the additional computational effort leads to a great slow down when simulating a fast fading channel as illustrated in Figure 1-2(from [9]).

![Figure 1-2: Slow-down of a simulation when using the PhySim-Wifi with a data rate of 6 Mbps and with/without Rayleigh fading. The simulation time is compared to default ns-3 in which only a static path loss is considered.](image)

In the above experiment, authors used one sender and one receiver that are operating at 6 Mbps and transmitting frames of different sizes. Based on the channel model, i.e., whether simple path-loss or slow/fast fading are used, the simulation time varies by a factor between 330 and 159275. The authors attributed this slow-down to the number of operations required for considering complex time samples instead of whole frame. As higher PHY simulation accuracy was the main objective of their work they have validated the model against CMU Wireless Network Emulator testbed. Error rate model is another important component which plays a large part in receiver modeling as it models the reception probability of a frame, and has been studied by various research groups. In [11]
authors suspected that in the simulation results of [9], default ns-3 differed (7-8 dB better) from the CMU testbed results because of the optimistic error rate model (YansErrorRateModel) used in ns-3. They developed a new ns-3 error rate model, namely NistErrorRateModel based on [12], and compared it with YansErrorRateModel. Also, they conducted independent experiments on CMU testbed to confirm the observations of [9], and recommended NistErrorRateModel for default OFDM frame error rate model in ns-3.

1.2 Contributions

The contributions of this work are mainly as follows:

1. Studying the existing ns-3 receiver model and finding out the functionality that are not accounted for in the receiver model design but are inherent parts of real-world network chipsets.

2. Developing higher fidelity ns-3 receiver model to align it with the specifications outlined in the IEEE 802.11, by adding the functionality of capture effect, preamble detection, PLCP header decoding.

3. Also, validating the resulting receiver model by comparing simulation results with large-scale field test data collected by the Crash Avoidance Metrics Partnership (CAMP) Vehicle Safety Communications 3 (VSC-3) Consortium, in partnership with the United States Department of Transportation (USDOT), as part of the V2V safety communications scalability activity of the Interoperability Issues of Vehicle-to-Vehicle Based Safety Systems (V2V-Interoperability) Project [20], [24].
1.3 Organization of the Thesis

The main focus of this work is to develop a high accuracy DSRC receiver model, and keeping that in mind, we present a brief overview of the DSRC and IEEE 802.11 in Chapter 2. We cover two coordination functions, namely DCF and EDCA that are used by wireless stations for coordinated access. Also, a brief overview of the OFDM technology is given. In Chapter 3, we first discuss channel modeling since an accurate model is required to substantiate the reliability of receiver model. Model derivation process is described for both the deterministic and stochastic components of the channel. Next, receiver model enhancements are discussed by exploring the missing functionality in ns-3 receiver model. Preamble detection, PLCP header decoding, and frame capture features are explained and their implementation details are provided. We also provide necessary details of some MAC issues that we fixed during implementation of the new receiver model. In Chapter 4 we present simulation results which are compared with field test data to validate our proposed receiver model. And finally, we conclude in Chapter 5.
Chapter 2: DSRC and IEEE 802.11

2.1 Dedicated Short Range Communication (DSRC)

Federal Communications Commission (FCC) has allocated 75 MHz of spectrum at 5.9 GHz band for Dedicated Short-Range Communications (DSRC) which provides a means for low latency communication link. The main goals of DSRC-based safety communication are to ensure safe, interoperable connectivity to help prevent vehicle crashes, and to enable other non-safety services. To make this happen, Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications require a safe and secure wireless interface that can work in harsh environments, and can do communication within a short delay. DSRC is specifically designed to facilitate all these requirements of time-critical safety applications. Technically, DSRC is similar to Wi-Fi technology; however, DSRC is preferred over Wi-Fi because the number of devices that use the unlicensed Wi-Fi channels would make significant interferences that could hamper the safety concerns of vehicular applications.

Safety applications utilizing DSRC have the potential to reduce fatal accidents by alerting drivers about imminent crashes. DSRC can be used in a variety of applications that can benefit us:

- Emergency warning systems for vehicles
- Cooperative cruise control
- Cooperative Forward collision warning
- Intersection Collision warning
- Electronic parking payments
- Electronic toll collection, and many more
The DSRC spectrum is divided into seven non-overlapping 10 MHz wide channels (see Figure 2-1). Channel 178 is used as the control channel (CCH), which is reserved for broadcasting periodic safety messages. Channel 172 and 184 are reserved for special uses, while the other channels are service channels (SCHs) that are available for both safety and non-safety services.

Initially, the IEEE 802.11p draft was considered for DSRC which is now added to the IEEE 802.11 standard to enable wireless access in vehicular environment (WAVE) [21]. This amendment enhances the existing 802.11 standard to accommodate interoperable low-latency communications between vehicles by adapting it to the highly dynamic vehicular environments. Orthogonal frequency division multiplexing (OFDM) scheme is used in WAVE physical layer because of its interference resilient modulation technique, and ability to cope with severe environment. Furthermore, Quality-of-Service extension of 802.11e is defined for WAVE medium access (MAC) layer along with default Distributed Coordination Function (DCF). To provide faster access to channel, WAVE MAC enables participants of vehicular network to establish a network or join a pre-existing network by discarding the association and authentication of BSS setup.

In the upper protocol layers, DSRC utilizes a suite of IEEE 1609 standards that provide a set of specifications regarding the organization of management functions and modes of operation of system devices to make devices from different manufacturers interoperable [22]. Basically, the family of IEEE 1609 standards is meant to be used in conjunction with the IEEE 802.11p to accomplish...
homogenous communications interfaces between different automotive manufacturers. These standards collectively define the architecture, communications model, security mechanisms, network services, multichannel operation, and the functionality to work with the PHY and MAC of DSRC communications link in a vehicular environment.

DSRC also supports existing Internet Protocols (IP) for the network and transport layer, such as Internet Protocol version 6 (IPv6), User Datagram Protocol (UDP), and Transmission Control Protocol (TCP). Figure 2-2 illustrates the protocol stack for DSRC-based vehicular networks.

To summarize, we can list the following features of DSRC:

- DSRC enables secure communication by allocating a specified spectrum dedicated for vehicular safety applications.
- It allows vehicle to establish communication in a very short time.
- DSRC is designed for high speed communication (up to 27 Mbps).
• It employs a robust OFDM modulation scheme to cope with severe environments.

• DSRC provides interoperability between different automotive manufacturers through the use of standardized protocols at different layer.

2.2 IEEE 802.11

As discussed in the previous subsection, DSRC has been integrated in 802.11 through the 802.11p amendment. In this chapter we discuss about IEEE 802.11 which is a set of standards for media access control (MAC) and physical layer (PHY) of wireless local area networks (WLANs).

2.2.1 Medium Access Control (MAC)

The IEEE 802.11 uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme to coordinate access to the wireless medium. To avoid collision, CSMA/CA employs clear channel assessment (CCA) which serves two main purposes:

• Carrier sense (CS): If a transceiver can decode the physical layer convergence protocol (PLCP) header of an incoming frame, it can get the information about that frame’s intended recipient, and its length. The transceiver can then use this knowledge to update the MAC about the time duration the medium will be occupied and thus, held the CCA flag busy until the ongoing transmission is finished.

• Energy detection (ED): If a transceiver detects the total energy in the channel surpassed a specified threshold referred to as energy detection threshold (EDT), the CCA flag is held busy until the medium energy goes below the threshold. Any transmission attempt is prevented if CCA flag is busy.

CCA is the least possible collision avoidance scheme undertaken by the MAC layer which can avoid most of the collision scenarios, but frame collision is still possible because of the presence of hidden
terminals/nodes in the network. The hidden terminal refers to a network topology where two sender nodes, which are physically apart more than the communication range of each other, attempt to transmit to a receiver node that is within the communication range of both the senders. Figure 2.3 illustrates a network topology where hidden terminal problem can arise.

![Diagram of hidden terminal problem]

**Figure 2-3: Hidden Terminal Problem**

In the above example, both node A and C can communicate with node B, but are hidden from each other. Now, if node A begins to transmit to B, determining the channel idle, there is no way for node C to know about A’s transmission because it is hidden from node A. Unaware of the ongoing transmission, node C may start a transmission assuming the channel is idle, and end up colliding with the other signal which could result both the signals be discarded at the receiver.

To counter this problem, nodes in a WLAN typically employ a mechanism that use two additional frames, namely Ready-to-Send (RTS) and Clear-to-Send (CTS) frames. With this mechanism, potential sender first requests permission from the receiver by sending a RTS frame. Upon receiving RTS, the receiver will issue a CTS frame, which will eventually tell the sender to start transmission. All nodes within receiver’s carrier sense (CS) range can hear this CTS frame and keep themselves from any transmission attempts until the receiver finishes its current reception. Though RTS/CTS
mechanism helps to resolve most of the hidden node collision scenarios, it incurs some overhead because of the transmission of these two extra frames. Therefore, it is used only when data frames exceed a predefined size.

There is another possible collision scenario which can occur when two nodes, even if they are within communication range of each other, wish to transmit at the same time and sense the channel idle. To reduce frame collisions, coordination among nodes is also required to prioritize access, which we discuss in subsections 2.2.1.1 and 2.2.1.2.

2.2.1.1 Distributed Coordination Function (DCF)

Distributed coordination function (DCF) is the fundamental medium access technique employed by the IEEE 802.11 which works along with CSMA/CA to coordinate access. DCF allows a station access to the medium using the following rules:

- For a station to transmit a frame, medium status is first checked by performing a physical carrier sense. If the medium is sensed idle for a period of time referred as distributed inter-frame space (DIFS), station can immediately transmit. If channel is not idle, the station must defer its transmission and wait a random time before accessing the channel. This random waiting time referred to as backoff counter is basically an integer which is uniformly distributed in the contention window \([0, CW]\). For the first transmission, \(CW\) is set to \(CW_{\min}\).

- The backoff counter is decremented after each idle slot followed by the DIFS. Decrement procedure is suspended if the medium is seized by another station. When the medium becomes idle again, and DIFS elapsed, decrement procedure starts again. Medium is granted to the station once the backoff counter reaches zero. If the transmission is unsuccessful, meaning that the sender station does not get an ACK within short interframe space (SIFS), the frame is retransmitted with an extended contention window by doubling the previous \(CW\). After each
failed retransmission attempt, the CW is doubled until it reaches the $CW_{max}$. A threshold is employed to discard the frame after the number of attempted retransmission reaches that threshold. After each successful transmission or frame discard, the CW is reset to $CW_{min}$.

- For a fragmented frame, if the first frame is successfully received and acknowledged by the receiver, successive frames can be transmitted after waiting SIFS. This is to ensure that channel is not seized by other stations before the entire frame is completely transmitted.
- A station must start a new backoff after a transmission when ACK was not required and frame was not fragmented.

Figure 2-4 illustrates an example of DCF coordination. In this example, three nodes coordinate to get access to the network. Node C has a packet to send, and finds the channel idle. It starts transmitting immediately after an idle DIFS period. When node A wants to send its frame, B’s frame is already on the air; node A starts backoff by randomly choosing an integer, 6 from the contention window. Node B also wants to send a frame during the transmission of C’s frame. As the channel is busy, node B picks a random integer, 4, and starts its backoff procedure. During node C’s transmission, both A’s and B’s backoff countdown are suspended. Once C’s transmission is finished, node A and B start decrementing their backoff counter, respectively. Since node B has chosen a smaller integer than node A, B’s backoff counter reaches to zero first, and it gains access to the medium. As soon as node B starts transmitting, node A freezes its counter decrement procedure. After node B is done transmitting, node A counts down to zero by waiting required idle time slots, and eventually gets access to the medium.
2.2.1.2 Enhanced Distributed Channel Access (EDCA)

DCF is based on best effort model and does not support quality of service (QoS). To enable QoS [23], the IEEE 802.11e introduced Enhanced Distributed Channel Access (EDCA).

EDCA provides distributed access to the wireless medium for QoS stations (QSTAs) for eight different user priorities (UPs). Network traffics are classified into four Access Categories (ACs), namely, voice, video, best effort, and background. Each access category has its own Arbitration Inter-frame Space (AIFS), the minimum contention window size ($CW_{\text{min}}$), the maximum contention window size ($CW_{\text{max}}$), and the transmission opportunity (TXOP) limit. A TXOP is a bounded time interval during which a station can send as many frames as possible. According to user priority, each data frame from upper layer is mapped to an appropriate AC (see Table 2-1)
Table 2-1: EDCA Access Categories

<table>
<thead>
<tr>
<th>Priority</th>
<th>User Priority (UP)</th>
<th>Designation</th>
<th>Access Category</th>
<th>WMM Designation</th>
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<td>High</td>
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<td>AC_BE</td>
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</tbody>
</table>
In EDCA, each of the ACs has its own transmission queue as shown in Figure 2-5. Therefore, there are four transmission queues which behave like stand-alone stations and contend for the medium. EDCA defines two types of collisions: classical collision and internal collision. The classical collision occurs when two stations try to seize the channel access, and is similar to the collisions defined in DCF. Internal collision occurs when at least two access categories within the same station try to access the medium at the same time.

EDCA uses the following set of rules for medium access:

- Prior to transmit a packet, a station must sense the medium idle for a complete AIFS or extended interframe space (EIFS) period from the end of the last busy channel, based on the last transmission status. If the last transmission is unsuccessful, the station must wait EIFS, otherwise it must wait AIFS. The duration of an AIFS is given by the following equation:

$$AIFS = SIFS + AIFSN \times aTimeSlot$$

Here \(aTimeSlot\), SIFS (short interframe space) are determined by the physical layer characteristics. The selection of AIFSN (a non-negative integer) depends on the priorities of the ACs; a higher priority AC has a smaller AIFSN (see Figure 2-6)

![Figure 2-6: Inter frame spaces](image-url)
• If the medium is busy, station waits for a random backoff time similar to DCF. However, there is a fundamental difference between DCF and EDCA backoff decrement process; in DCF, station does not decrement the counter after sensing the channel idle for a complete DIFS; however, in EDCA, the counter is decremented after a complete idle AIFS.
• Other rules are similar to DCF which we already discussed in subsection 2.2.1.1.

2.2.2 Physical Layer (PHY)

The IEEE 802.11 PHY layer consists of two sublayers: the physical layer convergence protocol (PLCP) and the physical medium dependent (PMD).

![Figure 2-7: PPDU Format](image)

2.2.2.1 Physical Layer Convergence Protocol (PLCP)

The PLCP works as a bridge between MAC and PHY, and handles the interaction between these two layers. The PLCP sublayer provides a mechanism for transmitting MAC Protocol Data Units (MPDUs) between stations (STAs) over the PMD sublayer. MPDU is also referred to as Physical layer Service Data Unit (PSDU) which is converted to PLCP Protocol Data Unit (PPDU) by
appending a PLCP preamble and signal header to the PSDU. As shown in Figure 2-7, the PPDU has three main parts:

- **PLCP Preamble**: This field is used at the receiver end to synchronize the demodulator. The PLCP preamble consists of 12 symbols: 10 short symbols and 2 long symbols.
- **SIGNAL**: The SIGNAL header contains the information about the bit rate and length of PSDU.
- **DATA**: The last portion of the frame consists of Service field (16 bits), data payload, 6 tail bits, and some padding bits.

The PLCP preamble is important for the receiver as it determines the start of a new frame. Therefore, this part of the frame is always transmitted at some common rate. The preamble is modulated with the lowest bit-rate using the most robust encoding technique (typically an encoding rate of \( \frac{1}{2} \) is used). The SIGNAL header contains bit rate and length information of the incoming frame which all stations need to know, and thus transmitted using the lowest bit rate available. The DATA part is transmitted using the rate specified in the SIGNAL field. The available data rates for the 802.11a are shown in Table 2-2.

**Table 2-2: OFDM Modulation**

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding Rate</th>
<th>Coded bits per subcarrier</th>
<th>Coded bits per OFDM Symbol</th>
<th>Data bits per OFDM Symbol</th>
<th>Data Rate (Mbps) For 20 MHz</th>
<th>Data Rate (Mbps) For 10 MHz</th>
<th>Data Rate (Mbps) For 5 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>1/2</td>
<td>1</td>
<td>48</td>
<td>24</td>
<td>6</td>
<td>3</td>
<td>1.5</td>
</tr>
<tr>
<td>BPSK</td>
<td>3/4</td>
<td>1</td>
<td>48</td>
<td>36</td>
<td>9</td>
<td>4.5</td>
<td>2.25</td>
</tr>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>2</td>
<td>96</td>
<td>48</td>
<td>12</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>2</td>
<td>96</td>
<td>72</td>
<td>18</td>
<td>9</td>
<td>4.5</td>
</tr>
<tr>
<td>16-QAM</td>
<td>1/2</td>
<td>4</td>
<td>192</td>
<td>96</td>
<td>24</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>16-QAM</td>
<td>3/4</td>
<td>4</td>
<td>192</td>
<td>144</td>
<td>36</td>
<td>18</td>
<td>9</td>
</tr>
<tr>
<td>64-QAM</td>
<td>2/3</td>
<td>6</td>
<td>288</td>
<td>192</td>
<td>48</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>64-QAM</td>
<td>3/4</td>
<td>6</td>
<td>288</td>
<td>216</td>
<td>54</td>
<td>27</td>
<td>13.5</td>
</tr>
</tbody>
</table>
2.2.2.2 Physical Medium Dependent (PMD)

Under the direction of PLCP, the Physical Medium Dependent (PMD) sublayer provides transmission and reception functionality of physical layer data units between two stations via wireless medium. To provide this service, the PMD interfaces directly with the wireless medium (that is, RF in the air) and provides modulation and demodulation of the transmitted and received frames.

2.2.2.3 Orthogonal Frequency Division Multiplexing (OFDM)

DSRC uses OFDM which is a digital multi-carrier modulation scheme that extends the concept of single subcarrier modulation by using multiple subcarriers within the same single channel. While single-carrier modulation techniques use the whole channel and modulate data onto a signal at a high rate, with one symbol occupying the entire bandwidth for a very short time, OFDM divides the entire bandwidth into subcarriers and modulate data on each subcarrier at a lower rate. The combination of all the subcarriers enables data rates similar to conventional single-carrier modulation schemes for equivalent bandwidths. Basically, OFDM is a specialized Frequency Division Multiplexing (FDM), where all the sub-carrier signals are overlapping, but orthogonal to each other, i.e., at the peak of each subcarrier, the other subcarriers have zero amplitude (as shown in Figure 2-8). The orthogonality is important here as lack of orthogonality will make the subcarriers interfere with each other.

In 802.11a, the total available bandwidth is split up into 64 subcarriers, of which only 52 are used in the OFDM technique. The unused (or inactive) subcarriers act as guard bands for upper and lower adjacent channels. Among the 52 active subcarriers, 4 are reserved to be used as "pilot subcarriers", which carry only timing and frequency information to help the receiver synchronize with the transmitted signal; the rest are used to carry user data. Each of the subcarriers has the capability of
transmitting a portion of the modulated user data. Based on the modulation technique used, each subcarrier transmits 1, 2, 4 or 6 coded bits. These grouped coded bits are mapped onto complex numbers according to the used modulation type. These complex numbers are called modulation symbols. Though convolutional coding is not a part of OFDM, it is used in conjunction with OFDM to allow error recovery at the receiver side. Furthermore, prior to transmission, data bits are scrambled before encoding to avoid long runs of zeros or ones.

![OFDM Subcarriers](image)

Figure 2-8: OFDM Subcarriers
Chapter 3: Simulation of DSRC

3.1 Measurement Campaign and Simulation Steps

In this work, we use the data collected by the Crash Avoidance Metrics Partnership (CAMP) Vehicle Safety Communications 3 (VSC-3) Consortium, in partnership with the United States Department of Transportation (USDOT) as part of the V2V safety communications scalability activity of the Interoperability Issues of Vehicle-to-Vehicle Based Safety Systems (V2V-Interoperability) Project. The field environment that was used in this campaign was a straight, flat 1400 meters 6-lane highway. Here a total of 400 cars were used, of which four were moving vehicles that were following each other keeping a distance of 75 meters between themselves in the middle lane. Each vehicle was equipped with two transceivers on the roof top. The rest of transceivers were placed on top of 65 carts that were arranged along the road. 6 transceivers were mounted on each cart to play the role of actual vehicles as shown in Figure 3-1. Transmission rate and transmission power were set to 10Hz and 20 dBm, respectively.

![Figure 3-1: 400 Cars Scenario](image-url)
In the field test, a group of vehicles were designated as loggers that recorded several metrics and log items such as Channel Busy Percentage (CBP), Received Signal Strength (RSS), TxPower, Message sequence number of the received packet.

Since the goal of this work is to develop and validate a new receiver model, we need an accurate model of the channel that was present when the field tests were carried out. Therefore, we identify two components that need to be modeled: channel model and receiver model (see Figure 3-2). It is important to note that the communication channel and receiver modeling are independent and can be modeled separately.

In this work, we model the communication channel using field test RSSI logs. Receiver modeling is done based on 802.11 specifications and available literature. After modeling both the channel and receiver, we validate our developed receiver model by comparing simulation results with field test data in terms of two metrics, CBP and PER.
• **Channel Busy Percentage (CBP)** is the fraction of time communication channel is sensed busy during a predefined period of time. In the field experiment CBP was calculated every 100 milliseconds.

• **Packet Error Rate (PER)** is the ratio of missed data packets to the total number of packets transmitted during a predefined time window. This metric is calculated for each sender-receiver pair.

### 3.2 Channel Model

![Figure 3-3: Effects of channel components](image)

Electromagnetic signal strength attenuates as it travels through the medium (air) from the sender to the receiver. Signals are usually influenced by three natural phenomena.

- **Reflection** occurs when the signal finds on the way some obstacles in the order of the signal wavelength. Usually, buildings, walls, or even ground can be reflectors of signals.
- **Diffraction** occurs when irregular-shaped objects are on the signal path, and several copies of the signal are produced from the irregular sharp edges of the objects. Different copies will have different amplitudes and phases, and will arrive at the receiver at different times.

- **Scattering** happens when the signal hits objects that are smaller than the signal wavelength and the original signal splits into several ones.

Considering the natural phenomena that can deteriorate signals, three types of modeling are required to describe a channel: large-scale path loss, shadowing or large-scale fading, and small-scale fading. Large-scale path loss describes the deterministic signal attenuation at a specific distance. Shadowing, in vehicular communications, occurs when signals have to pass through large objects obstructing the sender and the receiver. Vehicular networks are very dynamic in nature, and thus, shadowing changes quickly over time. Small-scale fading, sometimes referred to as just fading, captures the signal strength changes due to vehicle movements. All these models work together and describe a wireless channel (Figure 3-3).

### 3.2.1 Channel Modeling Procedure

From the field test data, received signal strength indicators (RSSIs) of the received signals are extracted based on distance between sender and receiver. This data is used to model the channel of this field experiment. The received power from a sender at an arbitrary distance $d$ can be found as

$$P_r(d) = P_t - L_{LS}(d) + g_{P, dB} \text{ (dB)},$$

where $P_t$ is the transmission power in dB, $L_{LS}(d)$ is the *deterministic, large-scale* path loss at distance $d$, and $g_{P, dB}$ is the *random, small-scale* fading in dB. Figure 3-4 shows all RSSI measurements versus distance $d$ for all of the logger vehicles in the test scenario. Here, the rate of transmission is 10 Hz and the transmission power is $P_t = 20$ dBm.
In this study, the two-ray propagation model [15] is used to model the deterministic, large-scale path loss component. This model is recently validated for vehicular networks and takes into account the interference caused by a single ground reflection ray at the receiver, as shown in Figure 3-5. Based on the two-ray interference model, the distance-dependent, large-scale path-loss in the wireless channel of a vehicular network can be found as [15]
\[
L_{LS}(d; \alpha, \epsilon_r) = 10 \alpha \log \left( \frac{4\pi d}{\lambda} |1 + \Lambda e^{i\phi}|^{-1} \right) \text{ (dB)},
\]
(2)

where \(\alpha\) denotes the path-loss exponent, and \(\lambda = \frac{c}{f}\) is the signal wavelength corresponding to the transmitted signal with center frequency \(f\) that is propagating in the environment with the speed of \(c\). In the above equation, the reflection coefficient \(\Lambda\) can be found as

\[
\Lambda = \frac{\sin \theta - \sqrt{\epsilon_r - \cos^2 \theta}}{\sin \theta + \sqrt{\epsilon_r - \cos^2 \theta}},
\]
(3)

where \(\epsilon_r\) is a fixed, unit-less constant dependent on the reflection medium, \(\sin \theta = \frac{h_t + h_r}{d_{\text{ref}}}\) and \(\cos \theta = \frac{d}{d_{\text{ref}}}\), \(d_{\text{ref}} = \sqrt{d^2 + (h_t + h_r)^2}\) shown in Figure 3-5, and \(h_t\) and \(h_r\) are the heights of the transmitter antenna and receiver antenna, respectively. Furthermore, the phase difference of the two interfering rays \(\phi\) can be found as

\[
\phi = 2\pi \frac{d_{\text{los}} - d_{\text{ref}}}{\lambda},
\]
(4)

where \(d_{\text{los}} = \sqrt{d^2 + (h_t - h_r)^2}\) is shown in Figure 3-5.

Two-ray ground reflection path-loss model has two unknown parameters that could be found based on the collected empirical data: path-loss exponent, \(\alpha\) and \(\epsilon_r\), which is a fixed, unit-less constant dependent on the reflection medium. A \textit{brute-force approach} is employed to find these two parameters by minimizing the mean-squared error (MMSE) between the (distance-dependent) mean of the empirical data and the model.

3.2.1.2 Small-Scale Fading Model

Previous studies have found that small-scale fading of wireless channel mainly have a Nakagami-\(m\) distribution. This distribution is used in our fading modeling as it has the ability to model a wide range of small-scale fading scenarios from strong line-of-sight (LoS) and Rician-distributed fading (larger values of \(m > 1\)), to non-LoS and Rayleigh-distributed fading (unit value for parameter \(m\)).
For large distances (e.g., beyond the Fresnel distance), Weibull distribution is used as it is widely used in the literature [16].

### 3.2.1.3 Procedure of Channel Model Derivation

The following steps are followed for finding the parameters of the large-scale path loss model for distances up to Fresnel distance, namely the path-loss exponent $\alpha$ and parameter $\epsilon_r$, and the parameter of the small-scale fading model, namely the parameter $m$.

1. The mean RSSI (in dBm) at each distance $d$ is found, as shown by the red line in Figure 3-4.
2. The statistical mean found in Step 1 is subtracted from the original RSSI to find the small-scale fading data, denoted by $g_{P,\text{dB}}$ in Equation (1).
3. The data found in Step 2 is converted to linear amplitude data as follows:
   $$ g = \sqrt{10^{g_{P,\text{dB}}/10}} $$
   Note that it is assumed that the small-scale linear amplitude fading $g$ has a Nakagami-$m$ distribution.
4. The linear amplitude data found in Step 3 is normalized to have unit power $\mathbb{E}[g^2] = \Omega = 1$.
5. The maximum likelihood (ML) estimator of the parameter $m$ is found using the normalized data. Let $\hat{m}$ denote the estimated parameter.
6. A representative realization of the Nakagami-$m$ distribution is generated based on the estimated parameter $\hat{m}$ and $\Omega$ as the power of the original data. This realization of the Nakagami-$m$ random variable, denoted by $\hat{g}$, is later used to calculate and subtract the effect of the small-scale fading component on the mean of the original data in dB. The above realization is converted to signal power in dB as follows:
   $$ \hat{g}_{P,\text{dB}} = 10 \log \hat{g}^2 $$
7. The mean of $\hat{g}_{P,\text{dB}}$ is found empirically.
8. The above estimated mean of the Nakagami-\(m\) distributed small-scale fading component is subtracted from the original RSSI data (in dB or dBm) to find the effect of large-scale path loss in the mean of the data.

9. A \textit{brute-force approach} is used to minimize the MMSE between the mean of the empirical data and the model defined in Equation (2) to find the optimal values of \(\alpha\) and \(\epsilon_r\). Note that as the parameter \(\epsilon_r\) depends on the characteristics of the reflecting medium, it is fixed for the entire range of distances and the parameter \(\alpha\) is optimized for each distance bin.

We assume this model applies for distances up to the \textit{Fresnel distance} defined as
\[
d_F = \frac{4h_ih_r}{\lambda} = 639
\] meters since the propagation environment has not changed much \cite{17}. However, for distances beyond the Fresnel distance, we use the same large-scale path-loss model combined with a Weibull small-scale fading, whose shape and scale parameters are optimized through ns-3 simulations. After modeling all the channel components, we chain them together in ns-3 as shown in Figure 3-6. The channel model derived based on this approach very closely matches the distance-dependent average of the empirical data, as shown in Figure 3-7.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3-6.png}
\caption{Propagation model chaining in ns-3}
\end{figure}
3.3 Receiver Model

Now that we have a channel model that promises a good accuracy, we start enhancing the receiver model.

3.3.1 Interference and SINR Calculation

In ns-3, receiver model keeps track of cumulative interference by maintaining a list of all signals that are currently on the medium. This list is populated by adding the RxPower, and the start and end time of a signal that has just arrived at the receiver. The Interference list helps to calculate instantaneous cumulative interference by simply summing all signals that are active at that time. Also, calculation of signal-to-interference-and-noise ratio (SINR) is possible for individual signals, which is frequently used for checking reception probability and making decision about reception continuation. Also, for capture effect implementation we need to calculate SINRs for both currently
receiving signal and the new signal so that we can decide on which signal to lock on. Since ns-3 does not account for frame capture, it simply accumulates the total interference in a single variable from which it is not possible to calculate SINRs for individual signals. So we have added a function which returns the interference of the signals that overlap with a particular signal. This function makes the calculation of SINR for any signals possible. During SINR calculation noise floor and noise figure are also considered. Noise floor is a measure of all unwanted background noise present in the system. In ns-3, thermal noise is modeled as:

\[ N_t = KT_B \]

Where \( K \) = Boltzmann constant, \( T \) = temperature in Kelvin, \( B \) = bandwidth in Hz

Noise figure, NF is a measure of degradation of SNR caused by the components in the radio signal chain, for a given bandwidth. Therefore, the total noise floor is calculated by

\[ noise\ floor = NF \times N_t \]

SINR of signal “i” is then calculated by

\[ SINR_i = \frac{RxPower_i}{\text{noise floor} + \sum_{j=\text{signal overlaps with } i} RxPower_j} \]

3.3.2 Overview of Existing ns-3 Receiver Model

Default ns-3 implementation of 802.11 PHY is based on YANS [18]. Using this model, the state machine for the ns-3 receiver allows the PHY to be in one of the following four states:

- Transmission mode (TX): The physical layer is currently transmitting a signal
- Reception mode (RX): The physical layer is synced and receiving a signal
- Idle mode (IDLE): The physical layer is idle
- Clear channel assessment busy mode (CCA_BUSY): The physical layer is not in the TX or RX state, but the total power in the medium is higher than the (non-OFDM) CCA Energy Threshold

As shown in Figure 3-8, when a new packet arrives at the receiver, the PHY layer starts the reception process by adding the new signal to the interference list. As explained earlier, this list accumulates all other signals during the packet's reception process; allowing for SNIR calculation of individual signals. After the signal is added to the interference, current receiver PHY state is checked. Based on the current state of the physical layer, the next set of steps follow.

![Diagram showing packet reception flow]

- If the PHY is in IDLE or CCA_BUSY state (Figure 3-9), the received signal strength (RSS) is compared against the *OFDM signal detection threshold* (OSDT). If the measured RSS is greater than OSDT, receiver starts receiving the packet, changes the state to RX, and schedules an *end receive* event. Otherwise, the receiver checks whether the RSS exceeds *CCA energy detection threshold*. The check is performed to update the duration of CCA_BUSY state. The *end receive* event (Figure 3-10) is triggered when the total packet is received. Then, the packet error rate is
calculated from BER calculations based on which a probabilistic decision is made to determine if the packet is received correctly.

**Packet Reception Flow: PHY State is IDLE or CCA_BUSY**

---

**End Receive Event**

- Check Packet Tag
  - No: Regular Mode
    - PER Calculation Based on Shifted SINR
  - Yes: PER Calculation Based on Regular SINR

**Packet Reception Decision**

- Calculate PER
  - Generate a Random Number
    - Random Number > PER
      - Error in Packet Reception (Packet Dropped)
    - Yes: Successful Packet Reception

---

**Figure 3-9: Packet reception flow when PHY state is IDLE or CCA_BUSY**

- If the PHY is in TX or RX state (Figure 3-11), the new packet that has just arrived is dropped and its RSS value is checked against the value of CCA energy detection threshold for updating the channel busy duration (see Figure 3-12).
3.3.3 ns-3 Receiver Model Enhancements

Default ns-3 receiver model has two main shortcomings:

1. It does not distinguish between different parts of a frame, i.e., preamble, PLCP header, payload are treated the same way.

2. It lacks the capability of capturing a new frame while another frame is being received, even if the new frame is stronger than the receiving one.
This chapter elaborates the functionalities we have integrated into existing ns-3 receiver model to address the above mentioned shortcomings.

3.3.3.1 Preamble Detection and PLCP Header Decoding

Based on the discussion in subsection 2.2.2.1, we divide the total frame duration into three phases: the packet preamble, PLCP header and the packet payload. Figure 3-13 illustrates the three phases along with the associated ns-3 events.

![Diagram of frame phases](image)

**Figure 3-13: Different phases of an incoming frame along with associated ns-3 events**

A preamble check event is added after the preamble duration each time the physical layer synchronizes to an incoming packet and goes to RX state. This event compares the observed SINR with the preamble successful decoding threshold (PSDT). If the SINR is less than the PSDT, receiver could not successfully decode the preamble. Therefore, the current packet that is being received is dropped and the PHY state is changed based on cumulative signal strength. If the total signal strength is below the CCA energy detection threshold, PHY goes to IDLE. Otherwise, PHY goes to CCA_BUSY. If the measured SINR is high enough for the device to be able to detect the preamble, the receiver enters the next phase which is the PLCP header decoding.

*PLCP header decoding* event is required to ensure that the receiver has correctly decoded the PLCP header. This check is scheduled at the end of the PLCP header of the frame. The observed SINR is compared with the *PLCP header decoding threshold*. If SINR is above the threshold, the header is considered successfully decoded. If header decoding fails, the ongoing reception is aborted and
cumulative signal strength is checked to decide about the PHY state transition. Like before, if the total signal strength is below the \textit{CCA energy detection threshold}, PHY goes to IDLE and it goes to CCA\_BUSY, otherwise. Figure 3-14 and Figure 3-15 illustrate the inclusion of preamble detection and PLCP header check when a new frame arrives and the receiver state is IDLE or CCA\_BUSY.

### 3.3.3.1.1 Threshold Value Selection

PSDT and \textit{PLCP header decoding threshold} are used to decide if the packet reception should continue at the end of the preamble and PLCP header, respectively. PSDT of 3 dB is chosen based on the frame success rate of a frame which is exactly equal to the preamble duration of an OFDM signal in length that is transmitted at 6Mbps. We observe that the transition to successful frame reception occurs when the SINR is above 3 dB. The same procedure is used for PLCP header decoding threshold and its value is chosen to be 2 dB.

---

![Figure 3-14: Inclusion of Preamble detection and PLCP header check when PHY state is IDLE or CCA\_BUSY](image-url)
Frame Capture

Frame capture allows a wireless receiver to lock on to a stronger signal in the presence of other signals (interferences) regardless of its arrival time. It occurs when two or more signals overlap with each other. In the simplest form of a receiver model, if multiple signals interfere with each other, the receiver cannot decode any of the signals because they are garbled. But in real-world wireless devices, receiver can decode the stronger signal provided that it is strong enough for successful decoding.

In DSRC based safety communications, frame captures are prevalent because the scenarios that can lead to overlapping of multiple signals are inherent in vehicular networks. DSRC enabled vehicles exchange information by periodically broadcasting BSMs. Since broadcast does not use RTS/CTS mechanism for node coordination, nodes are less aware of other ongoing transmissions in their surrounding areas. And thus, hidden terminal problems become common in vehicular networks. Due to the presence of hidden terminals, multiple frames can arrive at a receiver almost simultaneously and can lead the receiver to capture one of them. Though hidden nodes are responsible for most of the capture scenarios, there is another scenario, where two signals can overlap. If the backoff counter
of two stations reach zero at the same time, they can start transmission simultaneously.

![Capture Scenarios Diagram](image)

(a) Sender First (SF)

(b) Sender Last Capture (SLC): Preamble Capture

(c) Sender Last Capture (SLC): Frame body or Payload Capture

Figure 3-16: Capture Scenarios

3.3.3.2.1 Frame Capture Scenarios

In previous subsection we have explained the capture effect and the scenarios when it occurs. Now we classify those scenarios, and for classification purpose, we assume that only two frames are in collision, and the second frame arrives during the first frame’s reception. Considering the arrival timing and signal strength, physical layer frame capture can be classified as follows [6] (see Figure 3-16):

1. Sender First Capture (SF)
Stronger frame’s preamble detection is successful, but the Frame Check Sequence (FCS) suffers because of interference. The arrival timing of the weaker signal is not important here as it arrives after the receiver is locked to the stronger one.

2. Sender Last Capture (SLC)

In this capture, first frame (weaker frame) is received till the arrival of the stronger frame. When the second frame arrives, the first one is garbled; the receiver ceases receiving the first frame (given that the second frame’s SINR is above some threshold) and locked on to the second frame. Based on arrival time, SLC can be further classified in two cases; preamble capture and frame body/ payload capture.

3.3.3.2.2 Frame Capture Implementation in ns-3

To integrate frame capture capability, we have modified the existing ns-3 receiver model. Depending on the arrival time of the packet and the current PHY state, receiver uses different thresholds to capture an incoming frame.
• **Preamble capture**: If the new signal arrives during the reception of the preamble of another frame, SINR of the incoming signal is checked against the *preamble successful capture threshold* (PSCT). The receiver drops the receiving packet and synchronizes to the newly arrived packet if SINR is above PSCT. SINR below PSCT suggests that currently receiving signal is strong enough to be decoded and the receiver continues the reception. Figure 3-17 illustrates the preamble capture scenario.

• **Data/payload capture**: If the arrival of the new signal occurs during the payload of a receiving packet, SINR is checked against the *data capture threshold* (DCT). The receiver drops the currently receiving packet if SINR is above DCT. SINR below DCT suggests that the incoming signal strength is not strong enough for the receiver to lock to it, and the newly arrived packet should be discarded. Figure 3-18 shows the data capture scenario.

---

**Figure 3-18: Data/payload Capture**

Figure 3-19 illustrates the frame capture along with associated ns-3 events.
3.3.3.2.3 Threshold Value Selection

For capture effect implementation we use two threshold values to make decision about frame switching.

- A value of 8 dB is derived from the V2V-Interoperability Project radio hardware testing for DCT. A similar value of 7-8 dB of SINR for 100% frame success rate has been reported about validation of OFDM error rate model [11].

- Simulations for different PSCTs have been run to get the preamble successful capture threshold (PSCT) while the other threshold values were kept fixed. The results are compared with the V2V-Interoperability Project field tests to find a match. Using a value of 7dB for PSCT we find an acceptable match with the field result (see Figure 3-20).
a. Field vs. Sim (PSDT = 3 dB, DCT = 8 dB, PSCT = 5 dB)

b. Field vs. Sim (PSDT = 3 dB, DCT = 8 dB, PSCT = 6 dB)

(a) Field vs. Sim (PSDT = 3 dB, DCT = 8 dB, PSCT = 7 dB)

d. Field vs. Sim (PSDT = 3 dB, DCT = 8 dB, PSCT = 8 dB)

Figure 3-20: Selection of preamble successful capture threshold
By adding frame capture, preamble detection and PLCP header decoding capability, we have developed a new receiver model. Figure 3-21 and Figure 3-22 show the state machines for default and enhanced ns-3 receiver model.

![Diagram](image-url)

**Figure 3-21**: default ns-3 receiver model state machine

![Diagram](image-url)

**Figure 3-22**: Enhanced receiver model state machine
3.3.3.2.4 Packet Reception Decision Making

The receiver in the ns-3 simulator utilizes a probabilistic model which derived based on the analysis of the physical layer of the IEEE 802.11 standard. Based on this model, the receiver measures the SINR at the end of the reception of each packet. To measure the SINR, the received packet is divided into several chunks, for each one of which the SINR is calculated separately. The physical-layer analysis of the communication standard determines the probability of successful reception of the packet for the observed SINR. The receiver uses this probability to decide whether or not the current packet can correctly be received and decoded. The probability of correct reception of a packet depends on the physical-layer specifications, including the type of the modulation (e.g., BPSK, Quadrature Phase Shift Keying (QPSK), or Quadrature Amplitude Modulation (QAM)) and the coding rate. The IEEE 802.11p standard specifies a rate-1/2 convolutional code with constraint length 7 with optional puncturing to achieve a code rate of 2/3 or 3/4.

A packet is declared in error if at least one of its constituent bits is erroneous. Therefore, the theoretical PER for a packet of length \( L \) can be found as

\[
\text{PER} = 1 - (1 - \text{BER})^L
\]

Where BER denotes the Bit Error Rate for the given modulation and coding rate. It is important to note that above equation is based on the assumption that the bit errors within a packet occur independently and with identical probability BER. This assumption is usually valid for low packet error rates. The BER is found based on the equations derived in [11] for different modulation schemes, code rates, and decoding methods (i.e., hard-decision versus soft-decision decoding).

Figure 3-23 depicts the probability of successful reception of a packet (i.e., \( 1 - \text{PER} \)) versus the observed SINR for different bit rates (corresponding to different types of modulation schemes and code rates) supported by the IEEE 802.11a/g standard, when hard-decision decoding is used and the
packet length is $L = 200$ bytes Figure 3-23. Note that as the subcarrier spacing in the IEEE 802.11 standard is half of that in the IEEE 802.11a/g standard, the bit rate in the IEEE 802.11 standard is half of that in the IEEE 802.11a/g standard shown in Figure 3-23. For example, the curve shown in Figure 3-23 for the bit rate of 6 Mbps in the IEEE 802.11a/g standard corresponds to the curve for the bit rate of 3 Mbps if the IEEE 802.11 standard had been used. This model, namely the “NistErrorRateModel”, is implemented as the default ns-3 model for the probabilistic reception mechanism described above.

Instead of finding PER values as a function of the observed SINR using the BER equations derived in [11] (which is the approach followed in the default, built-in NIST error-rate model in the ns-3 simulator based on the results shown in Figure 3-23), we have developed our own error-rate model to model the corresponding PER performance for different values of the observed SINR based on the hardware testing results conducted by one of radio suppliers of the measurement campaign. This model along with the hardware testing results is shown in Figure 3-24. As shown in this figure,
hardware testing has shown that the PER is a function of the observed SINR for different values of the reception power.

$$\text{PER} = \frac{a}{1 + \exp(b \times \text{SINR} + c)} + d$$

Where $a = 1.046$, $b = 1.547$, $c = -5.11$, and $d = 0.003657$.

When the PER is determined for a specific value of the observed SINR, the process for determining whether or not the packet is successfully received is as follows: a random number is generated based on the uniform distribution and is compared against the PER. If the generated random number is larger than the PER value, then the packet is assumed to be successfully received without any error.

Hardware tests conducted during the field tests also suggest that frames that are received because of capture effect has higher SINR (as expected), and an average of 5-6 dB of higher SNR is reported for
those cases. Since our packet reception criteria are based on SINR of Sender First (SF) scenario, fixes are required to accommodate this SINR shift for captured frames. In our ns-3 implementation we distinguish between regular and captured frames, and do the SINR shift (5 dB) for captured frames while making decision whether they can be received correctly. For sanity check, we did the 3 node capture verification experiment which is explained in details in the next chapter (see Figure 3-25).

![Graph showing SINR shift impact]

Figure 3-25: Sanity Check of Error Model Change (Frames that are received by physical layer capture exhibits 5-6 dB higher SINR)

### 3.4 MAC Fixes

During the development of the receiver model, we found that in ns-3, EDCA has not been implemented according to the IEEE 802.11 specification. Therefore, we have made some changes to ns-3 implementation of EDCA to add the proper functionality:

- EDCA specifies that if a packet is given to the MAC layer to be sent at a time when the channel has already been idle for more than the arbitration inter-frame space (AIFS), the transmission of the packet can start immediately, without any back-off. On the other hand, if a packet is given to
the MAC layer to be sent at a time that is within the AIFS duration, the transmitter goes through the usual back-off process. This feature was missing in ns-3 and has been added in our simulator.

- In our study we also found that the EDCA backoff decrement implementation in ns-3 works similar to DCF except for EDCA has counter for different ACs. However, there is a subtle difference in backoff counter decrement procedure between EDCA and DCF. In both DCF and EDCA, station decrements its backoff counter after every idle time slot. In DCF, whenever a station starts its backoff procedure or resumes a suspended one, it decrements the counter after sensing one idle time slot following a DIFS. In contrast, in EDCA, decrement happens just after the completion of an idle AIFS. Figure 3-26, Figure 3-27 illustrate the difference in decrement rules.

![Figure 3-26: DCF backoff counter decrement rule](image1)

![Figure 3-27: EDCA backoff counter decrement rule](image2)

Another difference between these two coordination mechanisms is the time of transmission after backoff counter reaches zero. In DCF, transmission station starts transmission in the time slot the counter reaches zero. However, in EDCA, station must check the time slot following the slot in which backoff counter decrements to zero. If the medium is idle in that slot, station starts
transmission (Figure 3-27). Otherwise, station must wait one idle AIFS after channel becomes idle, and starts transmission after AIFS. Figure 3-28 illustrates this scenario.

![Figure 3-28: Transmission instant for an EDCA station after an interrupted time slot](image)

The difference in transmission instant arises from the fact that only one operation is allowed in a MAC time slot, either the counter decrement or transmission. DCF decrements counter at the end of a time slot, while EDCA does that at the beginning of the slot. Thus, in EDCA, one idle time slot must pass before station starts transmission.

These two subtle differences have some impact on performance when QSTAs share same channel with non-QSTAs. The decrement rule for EDCA counter allows for higher priorities for QSTAs as QSTAs can decrease their backoff counter more quickly than non-QSTAs can. The second difference may slightly increase access probabilities for non-QSTAs as, unlike DCF stations, the EDCA station must wait for an additional slot before transmission.
Chapter 4: Receiver Model Validation

4.1 Verification of Frame Capture Implementation

To verify the correctness of our frame capture implementation, we set up a three node simulation scenario (Figure 4-1) as follows:

- Node A (moving node) moves towards node 1 (receiver node) at a speed of 4 m/s. Node A works both as receiver and sender.
- Node B remains stationary and receives packet from A and C
- Node C remains stationary and receives and sends out packet

Both senders are initially placed in such way that they are hidden from each other. Node A always starts transmission earlier than node B. As node A gets closer to the receiver B, its signals get stronger.

In this simulation setup we use FriisPropagationLossModel for the sake of analysis simplicity. We can write the Friis equation (path loss in free-space) as follows

\[
\text{Path Loss} = \frac{K}{d^n}
\]

where 
- \(K\) is a constant
- \(d\) is the distance
- \(n\) is the path loss exponent

![Figure 4-1: Three Node Scenario for Capture Effect Verification](image-url)
\[ \frac{P_t}{P_r} = \frac{G_t G_r \lambda^2}{(4\pi d)^2 L} \]  \hspace{1cm} (5)

where \( P_t \) and \( P_r \) are the received and transmitted power in watt, respectively; \( G_r \) and \( G_t \) are the receiver and transmitter antenna gain, \( L \) is a dimensionless system loss coefficient, \( \lambda \) is the wavelength and \( d \) is the receiver-transmitter separation distance. From the above equation \( d \) can be solved as

\[ d = \frac{\lambda}{4\pi} \sqrt{\frac{P_t G_t G_r}{P_r L}} \]  \hspace{1cm} (6)

Here \( \lambda \) is determined as \( \frac{c}{f} \) where \( c \) = speed of light = \( 3 \times 10^8 \) m/s and \( f \) is the channel frequency band.

For DSRC channel, \( \lambda \) is calculated as \( \lambda = \frac{3 \times 10^8 \text{m/s}}{5.89 \text{GHz}} = 0.0509 \text{m} \)

In this test, default transmission power, \( P_t \) is set to 20 dBm and Energy detection threshold is set to -94 dBm. Thus using \( P_r = -94 \text{ dBm} \) in (2) will give us the range \( d \) of a transmitter in this simulation setup, and calculated \( d \) is 2032m which suggests that node A is hidden from node C till they are 2032 meters apart.
Depending on the timing relation of the two transmitted frames from senders A and C, receiver B observes preamble or payload capture effect. Node C starts transmitting first and the signal reaches node B after 6.6 µs. Node A starts sending after 6.6 µs to make sure its signal reaches receiver B after C’s signal, and thus triggers capture effect. The A-C separation distance decreases as node A moves towards node C. When A-C separation distance becomes 2032 meters, A can hear signals from C, and CSMA/CA mechanism does not allow node A to transmit. Below this separation distance, both signals could be received correctly. Figure 4-2 shows how the PER curve changes because of frame capture as sender A gets closer to receiver B.

4.2 Overall Model Validation

To validate the overall model, we simulate the same VANET scenario that was used by V2V-Interoperability Project to collect data. The mobility traces are extracted for the vehicles from the field test GPS data. Ten percent of the vehicles are loggers and distributed uniformly among other vehicles. Logger vehicles are capable of recording channel busy ratio (CBR), GPS data, and various transmissions (TX) and reception (RX) logs. Table 4-1 summarizes our simulation settings.

Table 4-1: Simulation Settings in ns-3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Run Time</td>
<td>250 Seconds</td>
</tr>
<tr>
<td>Receiver Noise Figure</td>
<td>6 dB</td>
</tr>
<tr>
<td>OFDM Signal Detection Threshold (OSDT)</td>
<td>-94 dBm</td>
</tr>
<tr>
<td>CCA Energy Threshold</td>
<td>-82 dBm</td>
</tr>
<tr>
<td>Preamble Successful Decoding Threshold (PSDT)</td>
<td>3.0 dB</td>
</tr>
<tr>
<td>PLCP Header Decoding Threshold</td>
<td>2.0 dB</td>
</tr>
<tr>
<td>Preamble Successful Capture Threshold (PSCT)</td>
<td>7.0 dB</td>
</tr>
<tr>
<td>Data Capture Threshold (DCT)</td>
<td>8.0 dB</td>
</tr>
</tbody>
</table>
We have done simulations for two different configurations: default ns-3 and enhanced ns-3, i.e., ns-3 with capture effect, preamble and header decoding features. To compare the results from default and enhanced ns-3 physical layer implementation, we look into two metrics: Channel Busy Ratio (CBR) and Packet Error Ratio (PER).

To calculate PER, we use RX logs. We employ a sliding window approach with a 2 second window and 1 second sub-window. PER values for logger vehicles are calculated w.r.t. vehicle 1 (a moving vehicle). Here we use 40 meter distance bins.

Figure 4-3: CBR for all moving nodes (Field)

Figure 4-4 through Figure 4-7 show the PER values for all vehicles that are within a 1000 meter range of vehicle 1. These figures indicate that messages from closer vehicles are received with high probability. As the distance between the sender and receiver increases, the PER is expected to go up. PER curves become more and more similar to the field PERs as the features are added one at a time.
Figure 4-4: ns-3 with feature 1 (Preamble detection)

Figure 4-5: ns-3 with feature 1 (Preamble detection), feature 2 (PLCP header decoding)
Figure 4-6: ns-3 with feature 1 (Preamble detection), feature 2 (PLCP header decoding), feature 3 (Preamble capture)

Figure 4-7: ns-3 with feature 1 (Preamble detection), feature 2 (PLCP header decoding), feature 3 (Preamble capture), & feature 4 (Data capture)
Figure 4-8: CBR at node 1: (top) Default ns-3, (middle) Field Test, (bottom) Enhanced ns-3
CBR is another metric that is measured at each logger vehicle. Each vehicle records the fraction of time it has sensed the channel busy over a 100 millisecond period. While Figure 4-3 shows the field CBR for all moving nodes, Figure 4-8 offers a more clear insight into the CBR curve. Here, CBR of vehicle 1 from the field test, default ns-3 and enhanced ns-3 are plotted and compared with each other. CBR measured at vehicle 1 for both the default ns-3 and enhanced ns-3 are slightly higher than the field result. However, CBRs from enhanced ns-3 show a better match with the field test.
Chapter 5: Conclusion and Future Works

In this work, we have studied existing ns-3 receiver model and enhanced it to accommodate the research demands of DSRC based vehicular communication. Our study found that modern network chipsets and ns-3 receiver model does not behave the same way. ns-3 receiver model uses a simplistic approach which does not distinguish between different parts of an incoming frame, and ignores the possibility of synchronizing to a stronger signal while another reception is in progress. This work has improved the accuracy of ns-3 physical layer simulation by integrating the functionalities of preamble detection, PLCP header decoding and frame capture into ns-3 receiver model. We compare the performance of our proposed receiver model and the existing ns-3 receiver model with field test data. The new model shows a better match with the field results, and thus can be used as a higher fidelity receiver model in ns-3.

Possible direction for future studies of this work can be listed as follows:

- In our implementation, both preamble detection and PLCP header decoding events decide about reception continuation based on threshold values. Decision making procedures can be implemented using a generalized model which should consider different levels of noise a packet experiences during reception, and should decide probabilistically.

- This work needs to be validated with field test data from very low and very high traffic load scenarios.
References


