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PHY Layer Enhancements for Next Generation V2X Communication

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Abstract— IEEE 802.11p is a robust and mature technology for dedicated short-range communication (DSRC) where several field trials have been carried out, and the performance of various vehicle-to-everything (V2X) communication scenarios has been investigated. On the other hand, other IEEE 802.11 or wireless local area network (WLAN) standards have evolved and offered some techniques to improve the 802.11p standard. The new task group IEEE 802.11bd (TGbd) was formed to explore the future roadmap for V2X and is working toward a new standard called next-generation V2X (NGV). This article investigates the performance of physical (PHY) layer amendments to 802.11p, i.e., the use of low-density parity-check (LDPC) and midambles, multi-input multi-output-space time block coding (MIMO-STBC), dual-carrier modulation (DCM), and extended-range mode. We build and simulate our system in several V2V channel environments, using the packet error rate (PER) and throughput as the performance metrics. Our investigations show a significant PER performance improvement of all techniques compared to the legacy 802.11p standard. In terms of throughput, the new PHY layer enhancements also give a better performance, except for the DCM technique that improves the reliability of the V2V communication in low SNR conditions at the expense of reducing the channel capacity in half.

Keywords—V2X, NGV, 802.11p, 802.11bd, PHY layer

1. INTRODUCTION

Since their first appearance, vehicular communications have shown their ability to support the deployment of intelligent transportation systems (ITS), which can provide benefits in the form of road safety, traffic management efficiency, energy savings, and also air pollution reduction. A lot of V2X applications, namely cooperative collision warning, traffic management, and infotainment in cars, have been developed. Nowadays, ITS is not only talking about connected cars on the road but also fully autonomous transportation systems as well. More advanced ITS applications such as platooning, remote vehicle control, cooperative driving, and autonomous driving are already in the development or implementation phase, so we can expect to see the emergence of a fully autonomous vehicle system soon [1-2].

IEEE 802.11p is one of the state-of-the-art radio access technologies for DSRC that are already available on the market. It is a robust and mature technology where several field trials have been carried out, and the performance of various V2X communication scenario has been investigated. All those studies show the ability of DSRC to support the development of ITS. It also pointed out several challenges for the various V2X applications which needed different and various requirements, i.e., higher reliability, lower latency, higher throughput, bigger packet size, larger Doppler shift, and more extended communication range. On the other hand, other IEEE 802.11 or WLAN standards have evolved. The first standard for V2X communication is 802.11p [3], which came out in 2010 and is derived from the 802.11a standard. Since then, the IEEE 802.11 family standard has issued newer standards like 802.11n/ac/ax [4-7]. These standards offer

many mature technologies that can be used to improve the performance of V2X applications. The use of LDPC coding and MIMO-STBC are introduced in 802.11n/ac standards and already deployed in today's wireless products in the market. The 802.11ax standard proposes advanced techniques such as DCM, extended-range mode, and midambles when LDPC coding is used.

With these new evolutions in IEEE 802.11, the new task group TGbd was formed recently, with the purpose to explore the future roadmap for V2X, and work toward a new standard called NGV. This new standard is expected to be published in 2021, and, until its publication, it should be referred to as P802.11bd. Based on the scope of the project of NGV project authorization request (PAR) [8], the P802.11bd is the amendment of the 802.11p that defines modifications to both the IEEE 802.11 Medium Access Control (MAC) and PHY layers for V2X communications in the 5.9 GHz band; and optionally in the 60 GHz frequency band (57 to 71 GHz) or mm-Wave. These amendments are expected to achieve at least two times higher throughput measured at the MAC layer, operate in high mobility channel in vehicles with relative speeds up to 500 km/h, achieve a 3 dB lower sensitivity level (or having more extended communication range), and also provide interoperability, coexistence, backward compatibility, and fairness with 802.11p devices.

This article aims to investigate the performance of the PHY layer enhancements that can be adopted for NGV communications. The recent article [9] describes the evolution of two present-day technologies for radio access in V2X communications, i.e., 802.11bd and 5G New Radio (NR) V2X, which is the next evolution of the cellular V2X (C-V2X) standard. Regarding the 802.11bd, several mechanisms are proposed to answer the challenge for NGV communications. This article describes several enhancement techniques to

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TABLE I. MODULATION SCHEMES, CODING RATE AND DATA RATE FOR V2X IN 10 MHz CHANNEL BANDWIDTH

MCS	802.11p in 10 MHz					Potential 802.11bd ^(a) in 10 MHz					
	Modulation scheme	R	NDBPS	NCBPS	Data rates (Mbps)	Modulation scheme	R	NDBPS 11ac/11ax	NCBPS 11ac/11ax	Data rates (Mbps) 1 SS 11ac/11ax	Data rates (Mbps) 2 SS 11ac/11ax
0	BPSK	1/2	24	48	3	BPSK	1/2	26/117	52/234	3.25/3.65	6.5/7.31
1	BPSK	3/4	36	48	4.5	QPSK	1/2	52/234	104/468	6.5/7.31	13/14.62
2	QPSK	1/2	48	96	6	QPSK	3/4	78/351	104/468	9.75/10.96	19.5/21.93
3	QPSK	3/4	72	96	9	16-QAM	1/2	104/468	208/936	13/14.62	26/29.25
4	16-QAM	1/2	96	192	12	16-QAM	3/4	156/702	208/936	19.5/21.93	39/43.87
5	16-QAM	3/4	144	182	18	64-QAM	2/3	208/936	312/1404	26/29.25	52/58.5
6	64-QAM	2/3	192	288	24	64-QAM	3/4	234/1053	312/1404	29.5/32.9	58.5/65.81
7	64-QAM	3/4	216	288	27	64-QAM	5/6	260/1170	312/1404	32.5/36.56	65/73.12
8	-	-	-	-	-	256-QAM	3/4	312/1404	416/1872	39/43.87	78/87.75

(a) 802.11bd could be derived from 802.11ac standard or 802.11ax standard.

improve the 802.11p standard, such as the use of LDPC coding and midambles for the Doppler recovery method; the use of MIMO-STBC, the higher modulation scheme (256-QAM) and higher bandwidth (20 MHz) to achieve higher throughput; and also the use of DCM and extended-range mode to improve the block-error-rate (BLER) performance and communication range. The work from a recent article [10] evaluates the performance of the physical layer of the 802.11p, 802.11bd, C-V2X, and 5G NR V2X in terms of reliability, range, latency, and data rates. It investigates different V2X applications, i.e., ultra-reliable low latency communication (URLLC), which has small size packets, and enhanced Mobile Broadband (eMMB), which has larger size packets in urban non-line-of-sight (NLOS) environments. The article [11] analyzes PHY layer reliability's performance on 802.11bd and NR V2X in terms of PER specifically for ultra-reliable communications. Our previous works in [18] proposes the use of MIMO spatial multiplexing zero-forcing Bell-labs layered space-time (ZF-VBLAST) alongside with transmit antenna selection and transmit power adaptation in the PHY layer. It also proposes to use selective repeat algorithm in upper data link layer to improve the throughput performance for unicast V2V communication in dense environments scenario. Using MIMO technique will give many advantages for V2X communications. The contributions of this article can be summarized as follows:

- We investigate the performance of the PHY layer enhancements that can be adopted for NGV communications. Namely, the use of LDPC and midambles, DCM and extended-range mode. We build and simulate our system in several V2V channel environments, using the packet error rate (PER) and throughput as the performance metrics.
- The V2V channel proposed by TGbd [12] does not support MIMO modeling. In order to evaluate the simulation of the MIMO-STBC enhancement, we build the new V2V-MIMO channel, based on the V2V channel proposed by the 802.11 DSRC group mentioned above and evaluate its performance.

This article is organized as follows: Section II explains 802.11p overview and possible PHY layer technology from other WLAN standards that could be adopted into the 802.11bd standard; Section III describes the system model, which describes performance analysis, the V2V channel model, and the system model used in our simulation; Section IV discusses the analytical and simulation results; and the final section is the conclusion and future works.

2. IEEE 802.11 ENABLING TECHNOLOGY

This section describes a review of the 802.11p standard and some of the key features in the IEEE 802.11 WLAN family standards that could be adopted to answer the challenge in NGV communication.

2.1. 802.11p PHY Layer Overview

The high relative speed between cars makes vehicular communication vulnerable to the Doppler effect. The 802.11p standard was issued in 2010 and is derived from the 802.11a standard. It uses the same PHY layer configuration but with some modification, i.e., halving the bandwidth and doubling the time parameter. This modification improves the robustness against the effect of mobility because the signal becomes robust to maximum delay spreads as high as twice the 802.11a signals. The PHY layer of 802.11p uses binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK), 16-point quadrature amplitude modulation (16-QAM), and 64-QAM as the digital modulation scheme. It also uses orthogonal frequency-division multiplexing (OFDM) as a multicarrier modulation technique that divides the available spectrum into several parallel narrow-band subchannels. Vehicular communication is considered as a frequency-selective environment. The OFDM technique will make every subchannel experience flat-fading, and thus the implementation of sophisticated equalizers is not required at the receiver side.

The 802.11a standard in the 20 MHz channel has 48 data subcarriers out of 64 subcarriers, 3.2 μ s symbol time, and 800 ns guard interval (GI). The 802.11p standard modified these parameters by halving the bandwidth and doubling the time

802.11p



Midamble



Fig. 1. Midambles technique introduced in 802.11ax.

parameters to improve against the Doppler shift. This technique is known as “2x down clock” and widely used to give a robust performance in the mobile outdoor wireless communication environment. 802.11p has a 10 MHz bandwidth channel, 24 data subcarriers, 6.4 μ s symbol time, and 1.6 μ s GI. Considering these parameters and the modulation order of each modulation coding scheme (MCS), we can calculate the data rate value ranging from 3 to 27 Mbps. The newer standard 802.11ac proposes the same number of subcarriers as 802.11a, but with 52 data subcarriers, and using a higher modulation scheme such as 256-QAM to achieve higher data rates, while the 802.11ax standard proposes the OFDM FFT size (number of subcarriers) modification from 64 to 256. The 802.11ax also adds 1.6 μ s and 3.2 μ s GI to improve the outdoor environment performance. By changing the subcarrier to 256, although the OFDM symbol time will be 4 \times longer (12.8 μ s), and even with longer GI, it can still have a data rate improvement due to OFDM efficiency. Using the code rate (R), the number of coded bits per symbol (NCBPS), and the number of data bits per symbol (NDBPS), we can calculate the data rate for each modulation scheme. [Table I](#) outlines the PHY layer comparison between 802.11p and its potential enhancements for 802.11bd.

2.2. LDPC and Midambles

Forward error correction (FEC) is an essential part of the V2X communication system. This channel technique is added to detect and correct the signal errors. 802.11p uses the binary convolutional coding (BCC) technique, where message bits are convoluted with predefined polynomials to encode the data. LDPC coding is introduced in the 802.11n standard and already deployed in today’s wireless products. The encoding process is based on a sparse matrix parity check H . Then, we determine the vector x , which fulfills $Hx = 0$, to decode the message [13].

802.11p uses a preamble at the beginning of the frame for the channel estimation process. Due to the fast-varying channel of the V2X communication, the initial channel estimation will quickly become obsolete, and the probability of error reception at the receiver side will increase. We can use midambles as an alternative channel tracking mechanism to solve this problem. The midamble technique is introduced in the 802.11ax standard. It has the same form and function as the preamble but is located between the data frame. [Fig. 1](#) shows the use of midambles in NGV communication. Using the midamble period $M = 2$, which means midambles will be inserted after two data frames, the channel tracking mechanism will be activated so that the channel estimation process will be more accurate. This technique simplifies the reception process at the receiver at the expense of efficiency $eff = M/(M + 1)$. It means that the higher value of midamble frequency will lead to better channel estimation and

TABLE II. PHY LAYER KEY FEATURES FOR NGV

Key Feature	802.11p	802.11bd
Radio bands operation	5.9 GHz	5.9 GHz and 60 GHz
Channel coding	BCC	LDPC
Technique for Doppler shift	None	Midambles
Communication range improvement	None	Extended-range mode
Reliable and robust transmission	None	DCM
MIMO support	None	STBC
Spatial stream	One	Multiple
Higher throughput	None	Higher MCS and wider bandwidth

reduce the PER, but the throughput will also reduce because it needs to send the midambles more frequently. For example, if we use the midamble technique in [Fig. 1](#), with $M = 2$, the channel efficiency will reduce to 66.7%.

2.3. MIMO-STBC

802.11p is a single-input single-output (SISO) system that only supports a single spatial stream. The MIMO support for the 802.11 families is introduced in 802.11n. As multi-antenna becomes available, multiple streams could be implemented in NGV communication. According to [14], 802.11bd proposes to use only a single-stream transmission mode for OCB broadcast communication. However, it is possible to use multiple streams for unicast transmissions. MIMO techniques like STBC will be useful for V2X applications that need higher throughput or bandwidth-hungry requirements such as road map update applications or infotainment applications in cars. We could adopt the MIMO-STBC technique for the 802.11bd standard.

2.4. DCM and Extended-Range Mode

Both DCM and extended-range mode techniques are introduced in the 802.11ax standard. According to [15], DCM transmits each OFDM symbol over two different subcarriers to improve transmission reliability. DCM must choose sufficiently far apart subcarriers in order to gain frequency diversity. This technique will improve the block error rate (BLER) performance at the expense of halving the throughput because it needs to transmit the same OFDM symbol twice. The extended-range mode is proposed to improve the performance in outdoor environments. By using the extended range packet structure, a longer communication range will be achieved. Adopting both DCM and extended-range mode in the 802.11bd standard gives the potential improvement to reliability and a more extended communication range for NGV communications.

To conclude this section, we summarize all the key features of the PHY layer enhancements adopted for the NGV 802.11bd standard in [Table II](#).

3. SYSTEM MODEL

In this section, we will discuss the system model used in this work. First, we will explain the performance analysis and also the channel model. Then, we describe the simulation model.

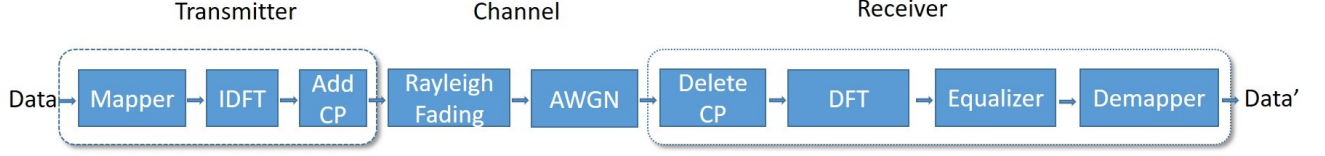


Fig. 2. A system model of OFDM transceiver with a simple frequency domain equalizer to evaluate PER.

3.1. Performance Analysis

The signal to noise ratio (SNR) at the receiver side is the ratio between the received signal P_r and the noise N_0 . Assuming a channel of bandwidth B , the SNR γ can be expressed as:

$$\gamma = \frac{P_r}{N_0 B}. \quad (1)$$

If E_b and E_s are the signal's energy per bit and the signal's energy per symbol, for an M-ary signal with modulation order $k = \log_2(M)$ bits per symbol, the SNR per symbol γ_s can be expressed as:

$$\gamma_s = \frac{E_s}{N_0} = k \cdot \frac{E_b}{N_0} = k \cdot \gamma_b, \quad (2)$$

where γ_s is SNR per symbol, and γ_b is SNR per bit.

The use of cyclic prefix in the OFDM data transmission system can lead to power loss. If N is FFT size or the total number of subcarriers and N_{cp} is the number of symbols in the cyclic prefix, the power loss a_g can be expressed as:

$$a_g = \frac{N}{N + N_{cp}}. \quad (3)$$

Using the power loss a_g , we can calculate the average SNR per symbol $\bar{\gamma}_s$ as:

$$\bar{\gamma}_s = a_g \cdot \gamma_s. \quad (4)$$

We consider the use of the additive white Gaussian noise (AWGN) channel and the Rayleigh flat-fading channel for theoretical analysis. BPSK has one bit per symbol, so the value of its symbol error rate (SER) is equal to its bit error rate (BER). The SER of the M-ary quadrature-amplitude modulation (M-QAM) calculates the QPSK, 16-QAM, and 64-QAM modulation scheme by substituting $M = 4, 16,$ and $64,$ respectively. The theoretical SER of all modulation schemes used in the 802.11p OFDM PHY in the AWGN channel can be calculated as:

$$SER_{BPSK} = Q\left(\sqrt{2\bar{\gamma}_s}\right), \quad (5)$$

$$SER_{MQAM} = 1 - \left[1 - 2\left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3\bar{\gamma}_s}{M-1}}\right)\right]^2. \quad (6)$$

The theoretical average probability of SER using all modulation schemes in the Rayleigh fading channel with AWGN noise is obtained using the moment generating function (MGF). Based on [16], the MGF for Rayleigh distribution is calculated using the equation as:

$$\mathcal{M}_{\gamma_s}\left(-\frac{g}{\sin^2 \phi}\right) = \left(1 + \frac{g\bar{\gamma}_s}{\sin^2 \phi}\right)^{-1}, \quad (7)$$

where the parameter g is calculated using $g = \frac{1.5}{(M-1)}$. The theoretical SER over a Rayleigh fading channel with AWGN noise is calculated as follows:

$$SER_{BPSK} = 0.5 \left(1 - \sqrt{\frac{\bar{\gamma}_s}{1 + \bar{\gamma}_s}}\right), \quad (8)$$

$$SER_{MQAM} = \frac{4}{\pi} \left(1 - \frac{1}{\sqrt{M}}\right) \int_0^{\frac{\pi}{2}} \mathcal{M}_{\gamma_s}\left(-\frac{g}{\sin^2 \phi}\right) d\phi - \frac{4}{\pi} \left(1 - \frac{1}{\sqrt{M}}\right)^2 \int_0^{\frac{\pi}{4}} \mathcal{M}_{\gamma_s}\left(-\frac{g}{\sin^2 \phi}\right) d\phi. \quad (9)$$

For the simulation, we decide to choose PER and throughput as the performance metrics. Considering the data packet size with L symbols and SER calculation from equations (5) through (9), each modulation scheme's PER is calculated as follows:

$$PER = 1 - (1 - SER)^L. \quad (10)$$

The term throughput we use in this article is over the air throughput of the PHY layer from the transmitter to the receiver. Based on [17], the throughput η is calculated as:

$$\eta = R \cdot (1 - PER), \quad (11)$$

where R is the data rate in Mbps, and its value is taken from Table I.

3.2. Channel Model

In the theoretical performance analysis above, we use frequency-selective Rayleigh fading with the AWGN noise channel to model our V2X communication system. For the past few years, several research and field trial measurements have been done to model realistic vehicle-to-vehicle (V2V) channels. The 802.11 DSRC group proposes a set of V2V channel models [12] for performance evaluation and testing of the PHY layer under time- and frequency-selective propagation conditions. A real or complex transmitted signal will be filtered by this channel to obtain the channel-impaired signal. These V2V channels have several V2X communication environments, i.e., rural line-of-sight (LOS), urban approaching LOS, urban crossing NLOS, highway LOS, and highway NLOS, which are differentiated by a set of delays, power, and Doppler spectrum. TGbd recommends this

TABLE III. V2V CHANNEL MODELS

Scenario	Power (dB)	Delay (ns)	Doppler (Hz)
Rural LOS	[0, -14, -17]	[0, 83, 183]	[0, 492, -295]
Urban approaching LOS	[0, -8, -10, -15]	[0, 117, 183, 333]	[0, 236, -157 492]
Urban crossing NLOS	[0, -3, -5, -10]	[0, 267, 400, 533]	[0, 295, -98, 591]
Highway LOS	[0, -10, -15, -20]	[0, 100, 167, 500]	[0, 689, -492, 886]
Highway NLOS	[0, -2, -5, -7]	[0, 200, 433, 700]	[0, 689, -492, 886]

TABLE IV. PARAMETERS FOR ANALYTICAL PERFORMANCE

Symbol	Value	Description
nSym	10000	Number of OFDM symbols to transmit
$\gamma_b = E_b/N_0$	10–35	Energy per bit to noise ratio in dB
N	64	FFT size or number of subcarriers
Ncp	16	Number of symbols in the cyclic prefix
T	10	Number of taps for the frequency-selective channel model

TABLE V. SIMULATION PARAMETERS FOR V2X SAFETY APPLICATION AND HIGH THROUGHPUT APPLICATION

Symbol	Safety Application	High Throughput Application
Bandwidth	10 MHz	10 MHz
Spatial stream	1	1–2 (multiple)
Channel model	V2Vchannel	MIMO-V2V channel
Packet size	100 bytes	300 bytes
MCS	QPSK-1/2	16-QAM 3/4
PHY layer enhancements	DCM, extended-range mode, LDPC, midambles	MIMO-STBC

channel model as a base reference for evaluating the performance of PHY layer enhancements. The specifications of each environment, taken from [11] and [12], are outlined in Table III.

The V2V channel proposed by TGbd does not support MIMO modeling. In order to evaluate the simulation of the MIMO-STBC enhancement, we build the new V2V-MIMO channel, based on the V2V channel proposed by the 802.11 DSRC group mentioned above.

3.3. Simulation Model

We choose a frequency-selective Rayleigh with AWGN noise channel to simulate theoretical performance analysis to model our vehicular communication system. The transmitter generates random data symbols, mapping them using the MPSK or MQAM modulator, converts the modulated symbols to the frequency domain using the IDFT operation, and finally adds the cyclic prefix to form OFDM symbols. The next step is filtering the OFDM symbols with the frequency-selective Rayleigh fading channel and then adding these filtered symbols with AWGN noise. On the receiver side, the cyclic prefix is removed from the OFDM symbols, the DFT operation and perfect domain equalization are performed to get the equalized symbols, and finally the equalized symbol is demapped to get an estimated source symbol. By comparing the source symbol with the estimated source symbol, we can evaluate our simulation’s performance in terms of PER and compare them with the theoretical calculation. Fig. 2 shows the system model to evaluate theoretical performance analysis.

The theoretical performance analysis using the Rayleigh frequency-selective channel is not very realistic to model V2X communication. However, it allows for a simple analytical performance comparison of the OFDM technique with different modulation schemes, i.e., BPSK, QPSK, 16-QAM, and 64-QAM of the 802.11p/bd standard. To build a more

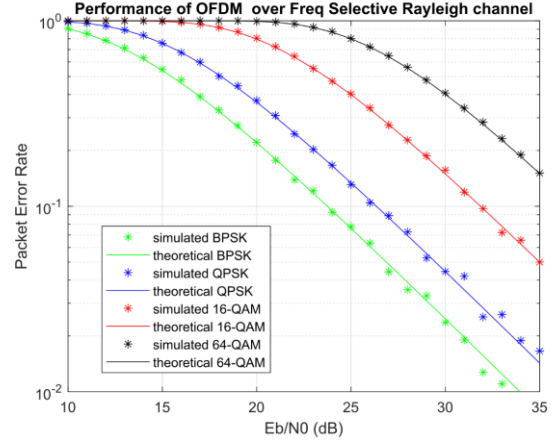


Fig. 3. PER Performance of OFDM transceiver over frequency-selective Rayleigh fading channel.

realistic simulation for V2X communication, we extend the simulation model based on Fig. 2 using MATLAB. The transmitter and receiver part is built using the WLAN Toolbox, and the frequency-selective Rayleigh fading channel is replaced by the V2V channel model proposed by TGbd. To design the PHY layer of 802.11bd, we use the other 802.11 WLAN standards with 20 MHz bandwidth as a baseline and half the subcarrier spacing to fit 10 MHz bandwidth as recommended by TGbd. PER is obtained from the ratio between the total number of error packets at the receiver and the total number of packets sent by the transmitter.

4. SIMULATION RESULTS AND DISCUSSION

This section discusses the simulation result of the theoretical performance evaluation and also the simulation-based evaluation.

4.1. Theoretical Evaluation

In this simulation, the PER of various modulation schemes is selected as the PHY layer’s performance metric. The PER is computed and compared against the theoretical PER calculation using (10). Using the simulation configuration in Table IV, we have Fig. 3 as a result. The simulation shows that if we want to have PER of 10%, we need SNR of 24 dB for BPSK, 26 dB for QPSK, 32 dB for 16-QAM, and more than 35 dB for 64-QAM. Indeed, a higher value of SNR is needed for the higher modulation order.

Although the theoretical PER is calculated using the flat-fading Rayleigh channel and PER of the simulation is computed using the frequency-selective channel, we can see from the curve that the simulation result does not significantly differ from the theoretical results. This result shows that an OFDM system’s performance with a perfect frequency domain equalization over a frequency-selective channel is equivalent to the performance over the flat-fading channel, which justifies the objective of the OFDM technique.

4.2. Simulation-based Evaluation

We want to simulate the performance of V2X applications in NGV communication. Many V2X applications need different quality of service (QoS) requirements characterized by latency or delay, packet size, reliability, throughput, and communication range. We consider two different types of applications, i.e., V2V safety applications like cooperative

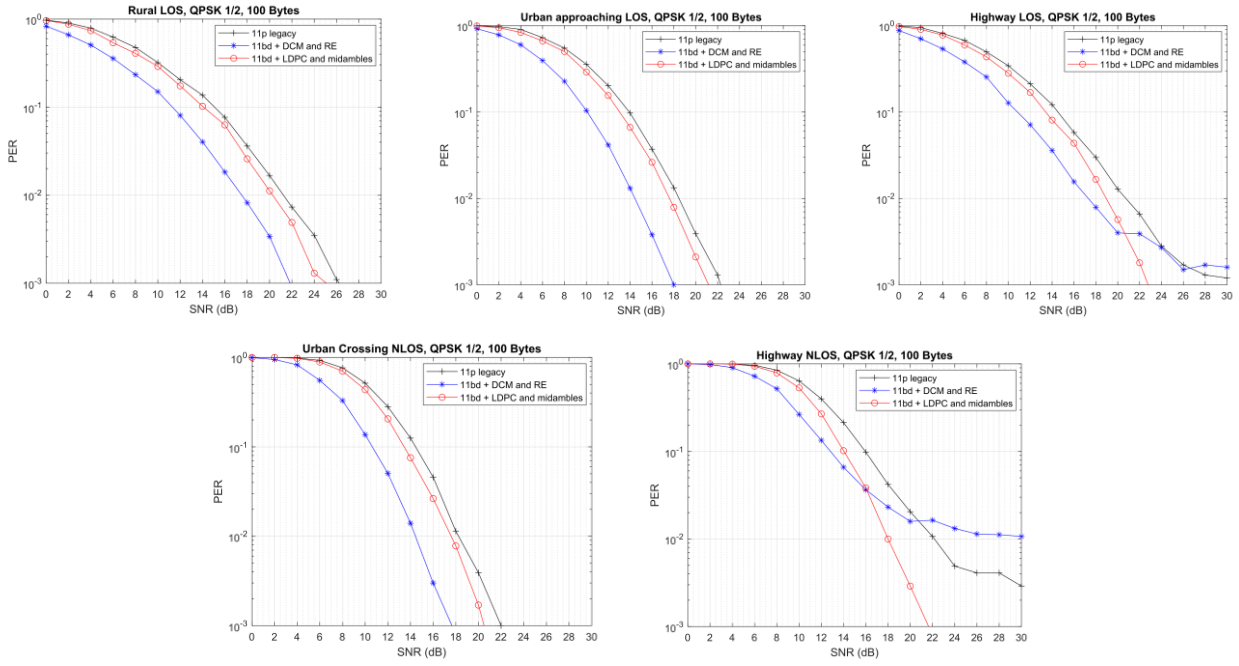


Fig. 4. PER performance of V2V safety application using 100 Bytes packet size and MCS of QPSK with coding rate of 1/2, at various V2V channel environments.

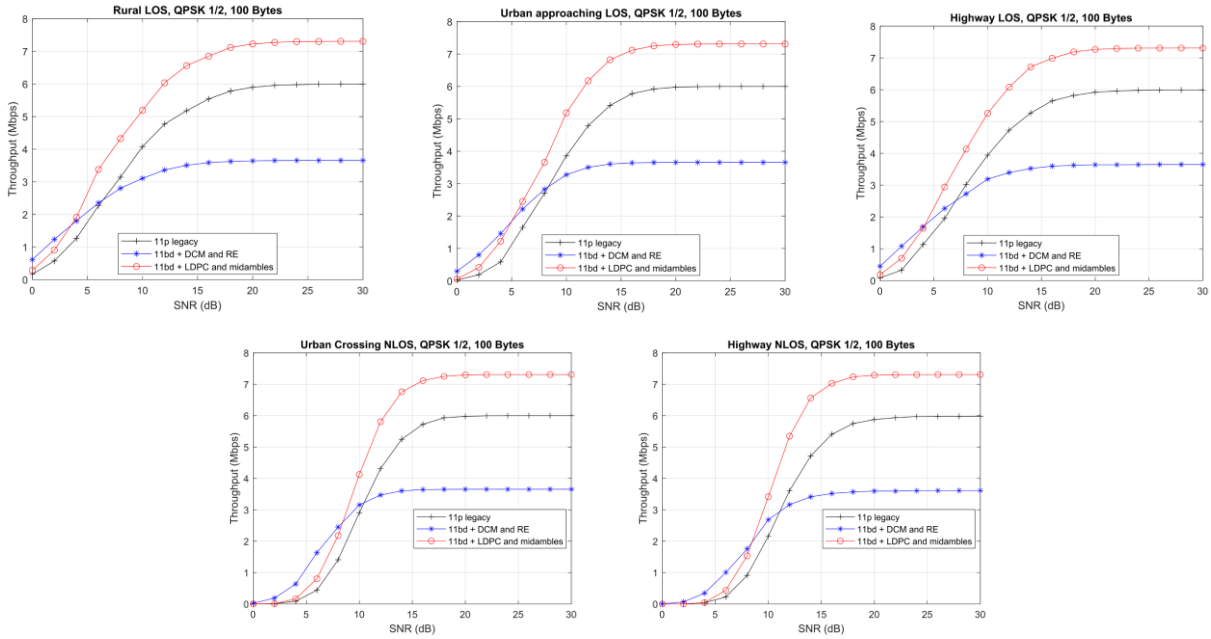


Fig. 5. Throughput performance of V2V safety application at various V2V channel environments.

collision warning, where reliability and latency are the most critical QoS requirements, and V2V applications that need higher throughput or bandwidth-hungry requirements like map update applications or infotainment applications in cars. For the V2V application, we use the 100 byte packet size and MCS of QPSK 1/2, and for the higher throughput application, we use 300 byte packet size and MCS of 16-QAM 3/4. The simulation settings for both scenarios are outlined in [Table V](#).

[Fig. 4](#) and [Fig. 5](#) show the PER and throughput performance of the V2V safety application. From [Fig. 4](#), we can see that PER performance of 802.11bd using LDPC and

midambles is always better than legacy 802.11p in all V2V environments. This result justifies using the LDPC and midamble technique as a countermeasure against the Doppler shift problem in V2X communication. The V2V safety application needs higher reliability as a QoS requirement, so we set the PER performance of 0.1% (or packet delivery ratio (PDR) of 99.9%). In a slow mobility environment like the rural LOS, urban LOS, and urban NLOS environments, the LDPC and midamble technique gives 1 dB improvement. For the high-speed mobility environment like the highway, we can see that the PER performance of 0.1% cannot be obtained by the legacy 802.11p standard, so we change to the PER

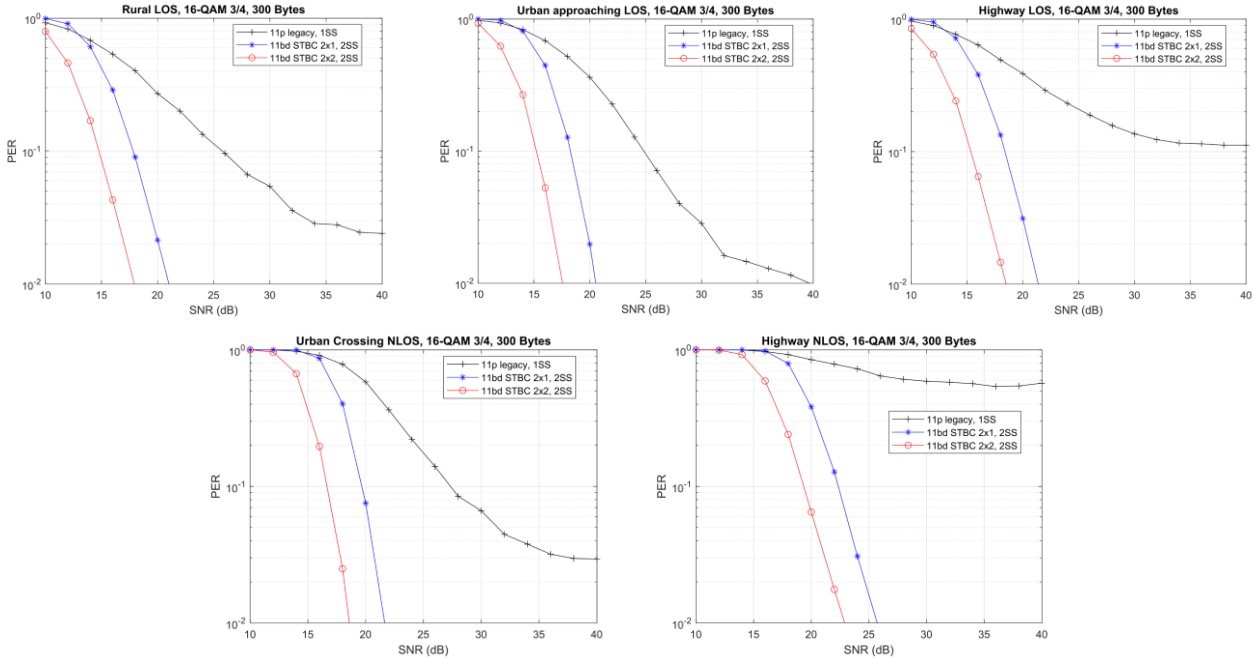


Fig. 6. PER performance of V2V high throughput application using 300 Bytes packet size and MCS of 16-QAM with coding rate of 3/4, at various V2V channel environments.

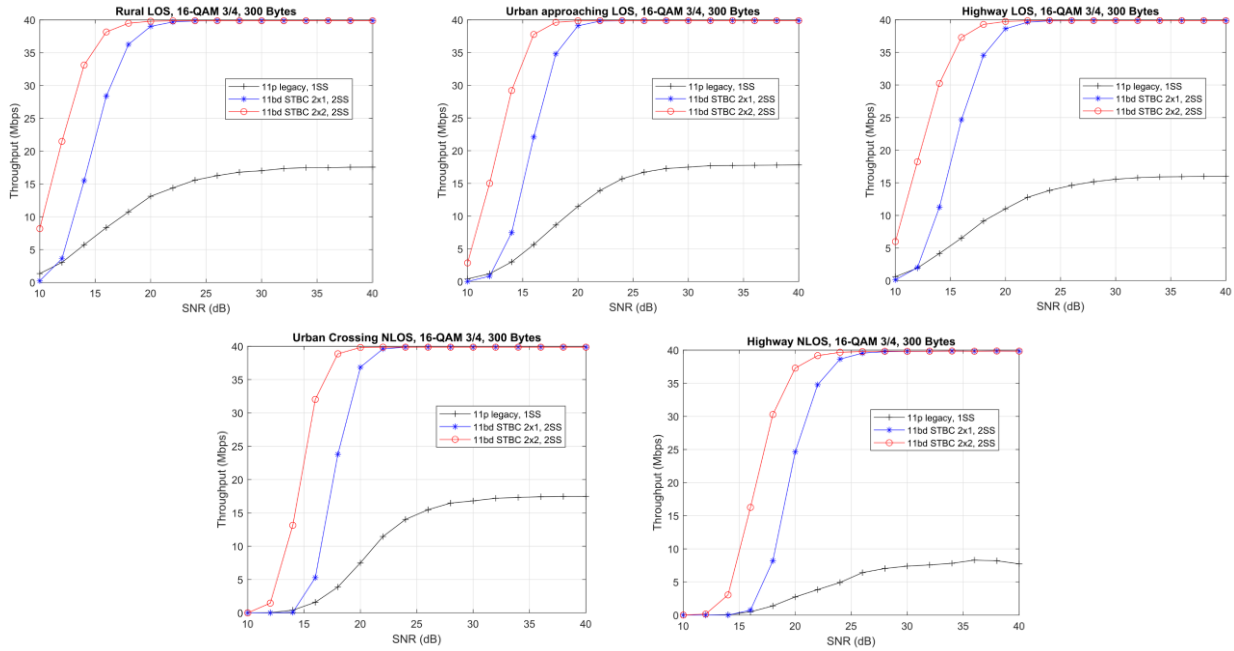


Fig. 7. Throughput performance of V2V high throughput application at various V2V channel environments.

performance of 1% (or PDR of 99%). In the highway LOS environment, the improvement is around 2 dB, while the highway NLOS environment obtained 4 dB improvement. Indeed, the more severe Doppler shift problem V2V channels experience like in the highway environment, the more LDPC and midamble technique will give a better PER performance. The channel tracking mechanism using midambles gives an up-to-date channel estimation to reduce the error probability of the received signal at the receiver side.

Compared to legacy 802.11p, the DCM and extended-range mode of a slow mobility environment always gives a better PER performance. In rural LOS, urban LOS, and urban NLOS environments, for PER performance of 0.1%, we obtained 4 dB improvement. In the highway LOS environment, for PER performance of 1%, the DCM and extended-range mode also obtained 4 dB improvement. For the highway NLOS environment, this technique gives almost the same performance compared to legacy 802.11p because

the receiver of legacy 802.11p can decode the transmitted OFDM symbols better due to the SNR's higher value. However, for the low/mid-SNR region, this technique always gives a better PER performance. Indeed, under the worst SNR, using DCM and extended-range will improve the PER performance because every OFDM symbol is transmitted twice using different subchannels in order to minimize the error probability of received OFDM symbols at the receiver side. From Fig. 5, we can see that the throughput performance of 802.11bd using LDPC and midambles is always better than legacy 802.11p in all environments, while 802.11bd using DCM and extended-range mode gives a better throughput performance in the low SNR region and gives the worst throughput performance in the mid/high SNR region. This phenomenon is caused by using the DCM technique that sends the same OFDM symbols twice so that the channel capacity will be reduced into half. We can still choose this technique for the application that needs high-reliability requirements like V2X safety applications.

Fig. 6 and Fig. 7 show the PER and throughput performance of the high throughput or bandwidth-hungry V2V application. We can see that both PER and throughput performance of 802.11bd using MIMO-STBC 2×2 with two spatial streams gives the best performance. In the slow mobility environment like rural-LOS, urban LOS, and urban NLOS, for the PER performance of 10% (or PDR of 90%), we obtained 10 dB improvement. In the high mobility environment, the PER performance of 10% cannot be achieved by legacy 802.11p due to larger packet size, higher-order modulation scheme, and high speed/high Doppler shift effect. However, PER performance of 10% can be obtained from the MIMO-STBC technique. For the highway LOS and highway NLOS environments, it needs an SNR value of 15 dB and 19 dB, respectively. We can see the improvement of more than twice the throughput of legacy 802.11p for the throughput performance because it uses two spatial streams (SS) and having better PER performance. Indeed, as the multi-antenna system becomes available for NGV communication, we can take advantage of the multiple streams to improve the throughput specifically for V2V applications that need higher throughput requirements. However, it must be noted that the support of two spatial streams is possible in NGV communication only for unicast transmission because TGbd agreed to choose a single stream as the only mode to be supported for broadcast transmission [14].

5. CONCLUSION AND FUTURE WORK

We implemented and simulated the possible PHY layer enhancements from other 802.11 standards to be possibly adopted into the 802.11bd standard for NGV communication. There are three PHY layer design considerations to be implemented in the 802.11bd standard, i.e., the use of LDPC and midambles, DCM and extended-range mode, and MIMO-STBC. Our simulation results shows a significant PER performance improvement resulting from the introduction of all techniques compared to the legacy 802.11p standard. In terms of throughput, the new PHY layer enhancements also give a better performance, except for the DCM technique that reduces channel capacity in half at the expense of having reliable communication in the worst SNR condition. The use of LDPC and midambles is recommended for all V2X applications because it can give a better channel tracking mechanism that leads to up-to-date channel estimation to minimize error probability of the received signal at the

receiver side. The use of DCM and extended-range mode is recommended for V2X applications that need a higher reliability requirement because it still can give better performance even in the worst SNR condition. Finally, MIMO-STBC is recommended for V2X applications that need higher throughput requirements in the unicast transmission scenario.

The NGV PAR demands several improvements, such as achieving at least two times higher throughput measured at the MAC layer and having a more extended communication range. Given the benefits and feasibility of PHY layer enhancements in the 802.11bd standard, it would be interesting to investigate the PHY/MAC cross-layer design to achieve the NGV PAR mentioned above.

DECLARATION OF COMPETING INTEREST

The authors declare that there are no known competing financial interests or personal relationships that could have appeared to influence the works reported in this paper.

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