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Présentée et soutenue par **Andy TRIWINARKO**

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Conception multi-couches (PHY/MAC/NET) pour les réseaux ad hoc véhiculaires (VANETS)

JURY :

Rapporteurs		
M. Daniel Roviras	-	Professeur, CNAM, Paris
M. Jalel Ben-Othman	-	Professeur, Université Paris-Saclay, Paris
Président:		
Mme. Christelle Aupetit-Berthelemot	-	Professeur, Université de Limoges, Limoges
Examinateurs:		
Mme. Soumaya Cherkaoui	-	Professeur, Université de Sherbrooke, Canada
M. Kais Hassan	-	Maitre de Conférences, Université du Maine, Le Mans
M. Elhadj Dogheche	-	Professeur, IEMN-DOAE, UPHF, Valenciennes
Directeur de Thèse:		
M. Iyad Dayoub	-	Professeur, INSA Hauts-de-France, Valenciennes

PhD Thesis

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UNIVERSITÉ POLYTECHNIQUE HAUTS-DE-FRANCE and INSA HAUTS-DE-FRANCE

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Cross-layer design for vehicular ad-hoc networks (VANETs)

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Directeur de Thèse:
M. Iyad Dayoub - Professeur, INSA Hauts-de-France, Valenciennes

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Résumé

La communication véhiculaire, ou réseaux ad hoc véhiculaires (VANETs), est une technologie de réseau véhiculaire sans fil qui peut soutenir le développement de systèmes de transport intelligents (STI). De nos jours, STI ne concerne pas seulement de voitures connectées sur la route, mais également le véhicule intelligent entièrement automatisé. De nombreuses applications émergentes de véhicule-à-tout (V2X) telles que l'avertissement de collision, la gestion du trafic, le peloton, le contrôle de véhicule à distance, la conduite coopérative et la conduite autonome sont déjà en phase de mise en œuvre ou de développement. Le nouveau groupe de travail IEEE 802.11bd (TGbd) a été récemment formé pour explorer la future feuille de route pour V2X et travaille actuellement sur une nouvelle norme appelée V2X de nouvelle génération (NGV). Le NGV devrait cibler des applications futures plus larges qui nécessitent un débit plus élevé et fonctionnent dans un environnement à haute mobilité avec une portée de communication étendue.

La conception transversale des couches (Cross-Layer design) est une solution émergente qui permet de supporter les nouvelles applications NGV. Ainsi, nous proposons dans cette thèse une nouvelle architecture cross-layer PHY/MAC/NET pour améliorer les performances des applications NGV. Nous commençons cette recherche en identifiant les améliorations des couches PHY et MAC d'autres normes Wi-Fi IEEE 802.11 qui pourraient être adoptées pour la norme 802.11bd.

Ensuite, nous proposons une première contribution originale, à savoir, une architecture cross-layer PHY/MAC/NET pour améliorer les performances des applications NGV dans un environnement à mobilité élevée. Les résultats de simulation montrent que notre solution permet d'obtenir un débit deux fois plus élevé au niveau de la couche MAC dans un environnement avec une vitesse relative entre les véhicules allant jusqu'à 500 km/h, comme l'exige la norme NGV.

Néanmoins, les performances en termes de débit se dégradent dans les VANETs denses en raison du problème de blocage dans la couche MAC. Pour résoudre ce problème, nous proposons une deuxième contribution cross-layer basée sur la sélection d'antennes émettrices et l'adaptation de la puissance émise. Les résultats obtenus montrent que cette conception permet à plus de véhicules de communiquer simultanément et améliore considérablement le débit moyen du réseau, en particulier pour les VANETs à haute densité.

MOTS-CLÉS : STI, V2X, NGV, IEEE 802.11bd, conception multicouche PHY/MAC/NET.

Abstract

Vehicular communication, or vehicular ad-hoc networks (VANETs), is a wireless vehicular networking technology that can support the development of Intelligent Transportation Systems (ITS). Nowadays, ITS is not only discussing about connected cars on the road but also a fully automated smart vehicle as well. Many emerging vehicle-to-everything (V2X) applications such as collision warning, traffic management, platooning, remote vehicle control, cooperative driving, and autonomous driving are already in the implementation or development phase. The new task group IEEE 802.11bd (TGbd) was recently formed to explore the future roadmap for V2X and is working toward a new standard called next-generation V2X (NGV). NGV is expected to target larger future applications that require higher throughput, operate in a higher mobility environment, and have extended communication range.

Cross-Layer design is an emerging solution that supports new NGV applications. Thus, in this thesis, we propose a new cross-layer PHY/MAC/NET architecture to improve the performance of NGV applications. We begin this research by identifying enhancements to the PHY and MAC layers of other IEEE 802.11 Wi-Fi standards that could be adopted for the 802.11bd standard.

Next, we propose our first contribution using a multi-layered design at the PHY/MAC/NET layers to improve the performance of NGV applications in a higher mobility environment. The simulation results show that our proposed cross-layer solution could achieve twice the throughput improvement at MAC layer level and also could work in environment with relative speed between vehicles of up to 500 km/h, as requested by the NGV standard.

However, the throughput performance decreased in dense VANETs due to the blocking problem in the MAC layer. We propose our second contribution to solve this problem by using a cross-layer design based on the selection of transmitting antennas and the adaptation of the transmitted power. The simulation results show that the proposed cross-layer design allows more vehicles to communicate simultaneously and significantly improves the average network throughput, especially for high density VANETs.

KEYWORDS: ITS, V2X, NGV, IEEE 802.11bd, PHY/MAC/NET cross-layer design.

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List of Abbreviations

3GPP	3rd Generation Partnership Project
5G NR	5G New Radio
5GAA	5G Automotive Association
ACK Packet	Acknowledgement Packet
A-MPDU	Aggregate MAC Protocol Data Unit
A-MSDU	Aggregate MAC Service Data Unit
APP	Application Layer
AQR	Antenna Quantity Restriction
ARQ	Automatic Repeat reQuest
ART	Adaptive Receiver Transmission
ASIRT	Association for Safe International Road Travel
AWGN	Additive White Gaussian Noise
BCC	Binary Convolutional Coding
BER	Bit Error Rate
BLER	BLock-Error-Rate
BPSK	Binary Phase-Shift Keying
BSM	Basic Safety Message
BTP	Basic Transport Protocol
CAM	Cooperative Awareness Messages
CCH	Control Channel
C-ITS	Cooperative-ITS
COMNUM	Communications Numeriques
CSI	Channel State Information
CSMA/CA	Carrier-Sense Multiple Access with Collision Avoidance
C-V2X	Cellular-V2X
CW	Contention Window

DCC	Decentralized Congestion Control
DCF	Distributed Coordination Function
DCM	Dual Carrier Modulation
DENM	Decentralized Environmental Noti cation Messages
DFD	Decision-Feedback Detection
DFT	Discrete Fourier Transform
DIFS	Distributed Coordination Function Inter-Frame Space
DOAE	Departement Opto-Acousto-Electronique
DSRC	Dedicated Short Range Communication
EDCA	Enhanced multimedia Distributed Control Access
EIFS	Extended Interframe Space
eMMB	enhanced Mobile Broadband
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FCS	Frame Check Sequence
FEC	Forward Error Correction
FNT	Fast NAV (Network Allocation Vector) Truncation
GBN	Go Back N
GN6	Geonetworking to IPv6
HARQ	Hybrid Automatic Repeat Request
HT	High Throughput
ICRW	Intersection Collision Risk Warning
IDFT	Inverse Discrete Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IEMN	Institut d'Electronique de Microelectronique et de Nanotechnologie
ITS	Intelligent Transportation Systems
IVI	In-Vehicle Information
LCRW	Longitudinal Collision Risk Warning
LDPC	Low Density Parity Check
L-LTF	Legacy-Long Training Field
LoA	Level of Automation
LOS	Line of Sight
L-SIG	Legacy-Signal
L-STF	Legacy-Short Training Field

LTE	Long-Term Evolution
MAC	Medium Access Control Layer
MANETs	Mobile Ad Hoc Networks
MAP	Map Data
MCE	Midambles Channel Estimation
MCS	Modulation Coding Scheme
MGF	Moment Generating Function
MIMO	Multiple Input Multiple Output
MPC	Multi Path Components
M-QAM	M-ary Quadrature Amplitude Modulation
MRT	Multiple Receiver Transmission
MU-MIMO	Multi User-MIMO
NET	Network Mayer
NGV	Next-Generation V2X
NLOS	Non Line of Sight
OBV	OFDMA-based MAC protocol for VANETs
OCB	Outside the Context of a BSS
OECD	Organization for Economic Cooperation and Development
OFDM	Orthogonal Frequency Division Multiplexing
OSTBC	Orthogonal Space-Time Block Code
PAR	Project Authorization Request
PDR	Packet Delivery Ratio
PER	Packet Error Rate
PHY	Physical Layer
PLCP	Physical Layer Convergence Procedure
PPDU	PLCP protocol data unit
PSDU	Physical Service Data Unit
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RAT	Radio Access Technologies
RHS	Road Hazard Signalling
RTS/CTS	Request To Send / Clear To Send
SAE	Society of Automotive Engineers
SCH	Service Channel

SER	Symbol Error Rate
SIFS	Short Inter-Frame Space
SNR	Signal to Noise Ratio
SPaT	Signal Phase and Timing
SR	Selective Repeat
SRM	Signal Request Message
SS	Spatial Stream
SSK	Space Shift Keying
SSM	Signal Status Message
STBC	Space Time Block Coding
SVD	Singular Value Decomposition
TAS	Transmit Antenna Selection
TCP	Transmission Control Protocol
TCP/IP	Transmission Control Protocol/Internet Protocol
TDL	Tapped Delay Line
TGbd	The Task Group for IEEE 802.11bd Standard
TPA	Transmit Power Adaptation
TRA	Transport Layer
UDP	User Datagram Protocol
URLLC	Ultra-Reliable Low Latency Communication
US	United States
V2I	Vehicle-To-Infrastructure
V2N	Vehicle-To-Network
V2P	Vehicle-To-Pedestrian
V2V	Vehicle-To-Vehicle
V2X	Vehicle-To-Everything
VANETs	Vehicular Ad-Hoc Networks
WAVE	Wireless Access in Vehicular Environments
WHO	World Health Organization
Wi-Fi	Wireless Fidelity
WSMP	WAVE short message protocol
ZF-VBLAST	Zero Forcing Vertical Bell Labs Layered Space Time

General Introduction

This chapter describes some general introductory knowledge about the thesis with the title Cross-Layer Design for Vehicular Ad-hoc Networks (VANETs). The research work was done in the laboratory of Institut d'Electronique de Microélectronique et de Nanotechnologie - Département Opto-Acousto-Electronique (IEMN – DOAE) UMR 8520. Since the research is related to the VANETs communication system, this work is incorporated in the communications numériques (COMNUM) group.

Context

According to the World Health Organization (WHO) global status report on road safety 2018 [1], nearly 1.35 million people die in road crashes each year. On average, 3,700 people lose their lives every day, and every 24 seconds, someone dies on the road. Road crashes are also the leading cause of death among children aged 5-14 and young people aged 15-29. Road traffic injuries are becoming the eighth leading cause of death, where 54% of death are pedestrian, cyclist, and motorcyclist. In France alone, based on Organization for Economic Cooperation and Development (OECD) online library statistical data [2], in 2017, the number of accidents involving casualties is 58,613, the number of injuries is 73,384, and the number of death caused by road accidents is 3,448. While in the United States (US), based on annual US road crash statistics by Association for Safe International Road Travel (ASIRT) [3], the US traffic fatality rate is 12.4 deaths per 100,000 inhabitants, and more than 38,000 people die every year in road crashes. The total loss caused by road crashes costs around $871 billion, where more than $380 million is for direct medical costs.

Other than the safety problem, all cities in the world are experiencing traffic jams and congestion problems. Based on 2019 mobility scorecard data by The Texas A&M Transportation Institute and INRIX [4], Paris is the most congested city in France and ranked seventh in the world where drivers spent 165 hours in congestion or wasted 70 hours per year in traffic. In the US, there are 99 hours of extra time lost due to congestion in 2017. It costs $179 billion and leads to an environmental problem where 3.3 billion gallons of fossil fuel is wasted [5].

From the business point of view, according to a recent market study by Price Waterhouse Cooper [6], in Europe, 78.52 million cars will be connected in 2020, and it is projected to 261.33 million connected cars by 2035. Meanwhile, in the US, the total number of connected cars in 2020 is 89.92 million and is projected to 322.04 million by 2035. The surveys also state that the consumer wants to have connected service in their vehicles, where safety and navigation are the most important services.

All the statistical data above has led to more research in the intelligent transportation systems (ITS) that can overcome all the problems in conventional transportation systems. Vehicular communication, other literature called it VANETs, is a wireless vehicular networking technology that can support ITS development. The term VANETs generally refers to the vehicles' ability to communicate with its surroundings using wireless communication and mainly used in scientific papers, presentations, and white–papers [7]. A more recent term to use is vehicular-to-everything (V2X) communications, which defines a continuous and high-speed data communication between vehicles, roadway infrastructures, pedestrians, and cellular networks. It classifies the vehicular communications into the vehicle to vehicle (V2V), vehicle to infrastructure (V2I), vehicle to pedestrian (V2P), and vehicle to network (V2N) communications. In this thesis, we use both VANETs and V2X terms to describe the vehicular communications system.

The new task group IEEE 802.11bd (TGbd) was recently formed to explore the future roadmap for V2X and is working toward a new standard called next-generation V2X (NGV). This new standard is made to answer future vehicular communication challenges that require varying data rates, bigger frame sizes, and broader communication ranges. Based on their project authorization request (PAR), NGV should targets a wider variety of V2X applications that have higher throughput, operate in higher mobility environments, and have a wider communication range. This new standard is expected to be published in 2021, and, until its publication, it should be referred to as P802.11bd. One possible solution to support the large and diverse applications in NGV is cross-layer design. This thesis investigates the benefit of cross-layer design to improve the overall network performances of the NGV applications.

Objectives

This research aims to improve network performance in VANETs, using the cross-layer design approach. The layers that were taken into consideration for cross-layer design are the physical (PHY) layer, Medium Access Control (MAC) layer, and network (NET) layer. We build the

IEEE 802.11p and potential 802.11bd standard-comply simulator. We simulate our proposed cross-layer design performances and choose the packet error rate (PER) and throughput as the performance metrics. The key objectives of this research are:

- Design and develop VANETs system having a reliable transmission by minimizing the PER.
- Design and develop VANETs system having a better network performance by improving data throughput.
- Evaluate the performance of the cross-layer design approach at various stringent VANETs environments.

Contributions

The contributions of this research 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 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 propose the PHY/MAC/NET cross-layer design to improve future NGV applications' performance and achieve the NGV standard's PAR. We consider using midambles channel estimation (MCE), DCM, and MIMO-STBC at the PHY layer; frame aggregation, contention window (CW) size, and retransmission limit at the MAC layer; and also broadcast single-hop and unicast single-hop transmission at the NET layer.
- We propose the PHY/MAC cross-layer design based on transmit antenna selection (TAS) and transmit power adaptation (TPA) to overcome the blocking problem in dense VANETs. We consider spatial multiplexing zero-forcing Bell-labs layered space-time (ZF-VBLAST) architecture in the PHY layer and automatic repeat request (ARQ) protocol using selective repeat (SR) in the MAC layer.

Thesis Outline

The remainder of this thesis is organized into five chapters, as follows:

Chapter 1. The first chapter is a brief overview of the VANETs state of the art. First, we present the radio access technologies for V2X communication. Then, we explain the VANETs standard and challenge, starting from radio propagation and the challenge from each communication protocol layers. We also describe the type of VANETs applications and their quality of service (QoS) requirements. Finally, we present the state of the art of thesis research.

Chapter 2. In this chapter, we start by describing the PPDU of the 802.11p and 802.11bd standards and its OFDM numerology. Then, we present the modeling and performance analysis used in this thesis research. The system modeling describes the transmitter, channel, and the receiver model, while the performance analysis shows the performance metrics calculation, i.e., PER and throughput, theoretical evaluation and simulation model. Finally, we present the problem statement of the IEEE 802.11p legacy standard, where its performance is degrading due to several parameters such as the VANETs environments, packet size, and vehicle density.

Chapter 3. We investigate the performance improvement of the VANETs due to PHY layer enhancement in this chapter. In the first part, we describe advanced techniques from other 802.11 Wi-Fi standards that could potentially be adopted into 802.11bd standard, such as using low-density parity-check (LDPC) channel coding and midambles for MCE, DCM, and MIMO-STBC. Then, we present the simulation results of the PER and PHY layer throughput performance in several VANETs environments.

Chapter 4. We present in this chapter the PHY/MAC/NET cross-layer design for the NGV communications. We investigate the performance of safety-related and non-safety-related NGV applications. First, we describe the cross-layer consideration for each layer. Then, we present the simulation results of our proposed cross-layer design to achieve two objectives requested by the NGV standard's PAR, i.e., having two times higher throughput in the MAC layer and operating in high mobility channel.

Chapter 5. This chapter applies the cross-layer design to overcome the blocking problem in the VANETs with high density. We start by describing the cross-layer design based on TAS and TPA algorithms. Then, we present the simulation results.

General Conclusion and Perspectives. This last chapter is a general conclusion. A contribution of the works performed in this research works, and the simulation results of the proposed cross-layer design will be presented. Several problems and other approach remains open and need to be developed for future works.

Scientific Productions

Journals:

- Andy Triwinarko, Iyad Dayoub, and Soumaya Cherkaoui (2021) "PHY layer enhancements for next-generation V2X communication," *Vehicular Communication Journal*, Volume 32, December 2021.
  (This work is presented in Chapter 2 and 3)

- Andy Triwinarko, Iyad Dayoub, Marie Zwingelstein-Colin, Mohamed Gharbi, and Basma Bouraoui (2020) "A PHY/MAC cross-layer design with transmit antenna selection and power adaptation for receiver blocking problem in dense VANETs", *Vehicular Communication Journal*, Volume 24, August 2020.
  (This work is presented in Chapter 5)

Conferences:

- Andy Triwinarko, Iyad Dayoub, and Prasaja Wikanta (2017) "Using MIMO and cross layer design for VANETs: A review", *International Conference on Signals and Systems (ICSigSys 2017)*, May 2017, Bali, Indonesia.
  (This work is presented in Chapter 1)

Oral Presentations and Posters:

- Andy Triwinarko and Iyad Dayoub, "Cross-Layer Design (PHY/MAC/NET) For Vehicular Ad-Hoc Networks (VANETs)", *la dixième édition du MdC : le Mardi des Chercheurs 2019)*, 05 March 2019, University of Mons, Mons, Belgium. (Poster).

- Andy Triwinarko and Iyad Dayoub, "Cross-Layer Design for VANETs", *La matinée des Doctorants IEMN/DOAE 2018)*, 19 October 2018, UPHF, Valenciennes, France. (Oral Presentation format Pecha Kucha).

- Andy Triwinarko and Iyad Dayoub, "Conception multicouche (PHY/MAC/NET) pour les réseaux ad-hoc véhiculaires (VANETs)", *La finale Indonésienne Ma Thèse en 180 Secondes 2018*, 26-27 June 2018, Université Confédérale Léonard de Vinci, Poitiers, France. (Oral Presentation format MT en 180s).

- Andy Triwinarko and Iyad Dayoub, "Cross-Layer Design (PHY/MAC/NET) For Vehicular Ad-Hoc Networks (VANETs)", *Journée des nouveaux entrants à l'IEMN 2017)*, 10 November 2017, IEMN, Villeneuve-d'Ascq, France. (Poster).

- Andy Triwinarko and Iyad Dayoub, "Cross-Layer Design For Vehicular Communication", *PHD Welcome, Lille Nord de France 2017)*, 12-13 January 2017, Ecole Doctorale Lille Nord de France, Marcq-en-Baroeul, France. (Poster).

Chapter 1

State of the Art

The emergence of ITS can overcome the classical problems in the conventional transportation system. The improvement of road safety, traffic management efficiency, energy savings, and also air pollution reduction are some of the goals that can be achieved by deploying the ITS. Vehicular communication, other literature called it VANETs, is a wireless vehicular networking technology that can support the development of ITS. The vehicles' ability to communicate with its surrounding, such as other vehicles (V2V), roadside infrastructure (V2I), pedestrians (V2P), or other networks (V2N), is also known as V2X communications.

Since their first appearance, VANETs has shown its ability to ensure the safety of human life on the road. In recent years, researchers, government, and the automotive industry were interested in VANETs, where several ITS applications have been emerged not only for safety applications but also for applications that provide more comfort to drivers and passengers. Therefore, many applications are proposed for VANETs such as early warning and prevention for an accident, best routes to the destination, decrease congestion, preventing traffic jams, internet access, and peer-to-peer application. The design and implementation of protocols, applications, and systems for VANETs requires to considere its distinctive characteristics such as high mobility, intermittent connectivity, rapid change of topology, predictable path and varying density. At the same time, it must also consider several factors, such as different QoS requirements for various VANETs applications.

Two potential solutions that can be used to support the large and diverse applications in VANETs are cross-layer designs among the original layers and MIMO processing techniques. The cross-layer designs that operate in multiple layers were proposed by many researchers to provide a better network performance in the VANETs system. In addition, with its multiple antennas, MIMO systems offered several techniques, such as spatial multiplexing, spatial diversity, and beamforming, that could improve VANETs performances. This chapter will review the benefit of employing the cross-layer designs and MIMO to answer all the characteristics and challenges in the VANETs systems. In the next section, we will describe the current state of VANETs standard, challenges, applications and state of the art of this research.

1.1 Radio Access Technology

Based on references [8], [9], [10], and [11], there are two existing radio access technologies (RAT) for V2X communications, i.e., Wi-Fi-based and Cellular based. The Wi-Fi-based V2X communication is standardized by the Institute of Electrical and Electronics Engineers (IEEE). Its first V2X standard was published in 2010 called IEEE 802.11p, also known as a dedicated short-range communication (DSRC) or ITS-G5. This technology supports V2V and V2I direct communications. As the first V2X communication technology, many automotive industries had already adopted DSRC into their market products. In 2015, Toyota was the first automakers to sell and commercialize their products with DSRC using an ITS safety package called ITS-Connect for Japan market [12]. It uses Japan's standardized ITS frequency of 760 MHz to receive and share data using V2V and V2I communication. Toyota and Lexus also plan to start the deployment of the DSRC system on vehicles in the US in 2021 [13]. In the US, General Motors company announced the arrival of the 2017 Cadillac CTS with V2V technology for the US market. The car will be equipped with a DSRC and GPS, which can handle 1,000 messages per second from other cars up to nearly 300 meters away [14]. While in Europe, from 2019 onwards, Volkswagen Group will use IEEE 802.11p as standard equipment on volume models ranging from compact cars to commercial vehicles [15]. The Golf 8th generation was the first passenger car launched by Volkswagen that was equipped with DSRC chipset from American Dutch semiconductor manufacturer NXP [16].

The more recent V2X specification was issued in 2016 by the 3rd Generation Partnership Project (3GPP). It was based on cellular communication using 4G Long-Term Evolution (LTE) under the umbrella of LTE release 14, hence referred to as Cellular-V2X (C-V2X) or LTE-V2X. It employed two complementary transmission modes, i.e., direct communications (using V2V, V2I, or V2P) and network communications (using conventional mobile cellular networks or V2N). Ford is one of the automakers that support this standard. It targets the production of the first vehicles equipped with C-V2X in 2021 in China [17] and commits to deploy C-V2X on all new vehicles in the US in 2022 [18].

Some studies and analyses by 5G Automotive Association (5GAA) have shown the superiority of the C-V2X in direct communication mode over DSRC. It has better performance, a wider communication range, and better reliability. Based on that results, 5GAA submitted the petition for a waiver to allow the deployment of the ITS C-V2X technology to the Federal Communications Commission in the US [19] and also proposed the coexistence of C-V2X and ITS-G5 at 5.9 GHz in Europe [20]. However, this superiority claim is disputed, as stated by NXP in its white paper [21] and [22]. Based on their field test results, DSRC is 2dB better in the communication range as opposed to what is claimed in the 5GAA reports. In the additional field measurements, the sensitivity of DSRC is confirmed, and the result of the C-V2X was not provided by the 5GAA report. Another review of the 5GAA test report also has been carried out by U-Blox [23]. It highlighted that the test result is not fair due to several reasons, such as the comparison is based on a DSRC device which has worse sensitivity, the C-V2X device was utilizing less than 5MHz bandwidth (leads to significantly lower noise floor), and the use of Hybrid Automatic Repeat Request (HARQ) mechanism to increase the probability of reception. Using its own DSRC commercial chip and under a fair condition, a competitive DSRC device provides similar performance with C-V2X under lab conditions and better performance in field trials. Furthermore, please refer to the response to the FCC notice of proposed rulemaking issued in March 2020 by the US Department of Transportation that highlights the importance of the preservation of the entire 5.9 GHz band for V2X communication [24].

1.2 VANETs Standard

Several organizations have created the standardization of VANETs architecture. In this research, we are focusing only on Wi-Fi-based V2X communications. In Europe, the architecture standard for this vehicular communication is called cooperative-ITS (C-ITS), also known as ITS-G5 standard. While in the US, this standard is called wireless access in vehicular environments (WAVE), also known as dedicated short-range communications (DSRC).

1.2.1 C-ITS Standards in Europe

The PHY and MAC layer of the C-ITS used the IEEE 802.11p standard as the basis and regulated in ETSI EN 302 663 that specified ITS-G5 access layer specification for ITS operating in the 5GHz frequency band. C-ITS also has a MAC layer extension of using decentralized congestion control (DCC) mechanism, as stated in the ETSI TS 102 687 standards. Furthermore, ETSI TS 103 175 proposes the DCC's cross-layer approach using several techniques, namely transmit rate control, transmit power control, transmit data rate control, DCC sensitivity control, and transmit access control. This cross-layer approach's general idea is that several techniques can be combined to control the channel load depending on the channel's

Table 1.1: ITS-G5 protocol standards

Layers	**Standards**	**Description**
PHY and MAC	ETSI EN 302 663 [25]	Intelligent Transport Systems (ITS); ITS-G5 Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band
	ETSI TS 102 724 [26]	Intelligent Transport Systems (ITS); Harmonized Channel Specifications for Intelligent Transport Systems operating in the 5 GHz frequency band
	ETSI TS 102 687 [27]	Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part
	ETSI TS 103 175 [28]	Intelligent Transport Systems (ITS); Cross Layer DCC Management Entity for operation in the ITS G5A and ITS G5B medium
NET and TRA	ETSI EN 302 636-1 [29]	Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 1: Requirements
	ETSI EN 302 636-2 [30]	Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 2: Scenarios
	ETSI EN 302 636-3 [31]	Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 3: Network Architecture
	ETSI EN 302 636-4-1 [32]	Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 4: Geographical addressing and forwarding for point-to-point and point-to-multipoint communications; Sub-part 1: Media-Independent Functionality
	ETSI EN 302 636-5-1 [33]	Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 5: Transport Protocols; Sub-part 1: Basic Transport Protocol
APP	ETSI EN 302 637-2 [34]	Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service
	ETSI EN 302 637-3 [35]	Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service
	ETSI TS 101 539-1 [36]	Intelligent Transport Systems (ITS); V2X Applications; Part 1: Road Hazard Signalling (RHS) application requirements specification
	ETSI TS 101 539-2 [37]	Intelligent Transport Systems (ITS); V2X Applications; Part 2: Intersection Collision Risk Warning (ICRW) application requirements specification
	ETSI TS 101 539-3 [38]	Intelligent Transport Systems (ITS); V2X Applications; Part 3: Longitudinal Collision Risk Warning (LCRW) application requirements specification
	ISO/TS 19091:2019 [39]	Intelligent transport systems — Cooperative ITS — Using V2I and I2V communications for applications related to signalized intersections (SPaT, MAP, SSM, and SRM)
	ISO/TS 19321:2020 [40]	Intelligent transport systems — Cooperative ITS — Dictionary of in-vehicle information (IVI) data structures
Security	ETSI TS 102 941 [41]	Intelligent Transport Systems (ITS); Security; Trust and Privacy Management
	ETSI TS 103 097 [42]	Intelligent Transport Systems (ITS); Security; Security header and certificate formats

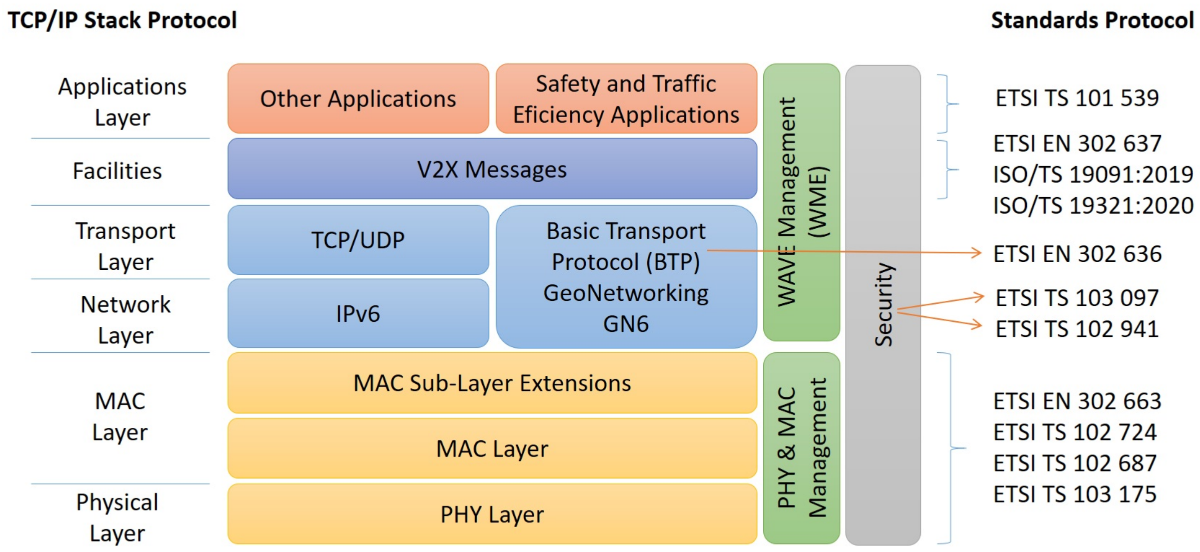


Figure 1.1: Comparison of ITS-G5 protocol stack with TCP/IP protocol stack.

current state. The simple case would be to utilize only one of the proposed techniques, where the most often used techniques found in the literature are transmit rate control or transmit power control.

The NET and TRA layers of the C-ITS Safety and traffic efficiency applications use the basic transport protocol (BTP), Geonetworking, and Geonetworking to IPv6 (GN6). While the non-safety-related application used the standard unicast, broadcast, multicast transmission using TCP/UDP or IPv6 protocol. All this protocol is regulated in the ETSI EN 302 636 standards for ITS, Vehicular Communication, Geonetworking. This standard consists of five-part describing the requirements, scenarios, network architecture, media-independent functionality, and basic transport protocol.

The facilities and APP layer of the ETSI C-ITS have many standards based on their application types. The facilities layer regulated the messages used in the V2X communications. It is classified into four types of messages as follows:

- Cooperative awareness messages (CAM) basic service regulated in ETSI EN 302 637-2.
- Decentralized environmental notification messages (DENM) basic service that is regulated in ETSI EN 302 637-3.
- V2I and I2V communications for applications related to signalized intersections. This message is consisting of signal phase and timing (SPaT), which describes the signal state of the intersection; map data (MAP), which describes the physical geometry of one or

more intersection; signal status message (SSM), which describes the internal state of the signal controller; and signal request message (SRM), which requests preempt or priority services for selected user groups. All the signalized intersection messages were regulated in ISO/TS 19091:2019).

- Dictionary of in-vehicle information (IVI) data structures that are regulated in ISO/TS 19321:2020.

The example of the APP layer of the C-ITS standard are ETSI TS 101 539-1 that specified requirements for the Road Hazard Signaling (RHS) application; ETSI TS 101 539-2 that specified requirements for the Intersection Collision Risk Warning (ICRW) application; and ETSI TS 101 539-3 that specified requirements for the Longitudinal Collision Risk Warning (LCRW) application.

Finally, there is a security layer for C-ITS that is regulated in the ETSI TS 102 941 standards for Intelligent Transport Systems (ITS); Security; Trust and Privacy Management; and ETSI TS 103 097 standards for Intelligent Transport Systems (ITS); Security; Security header and certificate formats. Figure 1.1 illustrates the comparison of ITS-G5 architecture stack with TCP/IP model protocol stack and its corresponding standard protocol in each layer, and Table 1.1 summarizes each protocol standards.

1.2.2 WAVE Standards in US

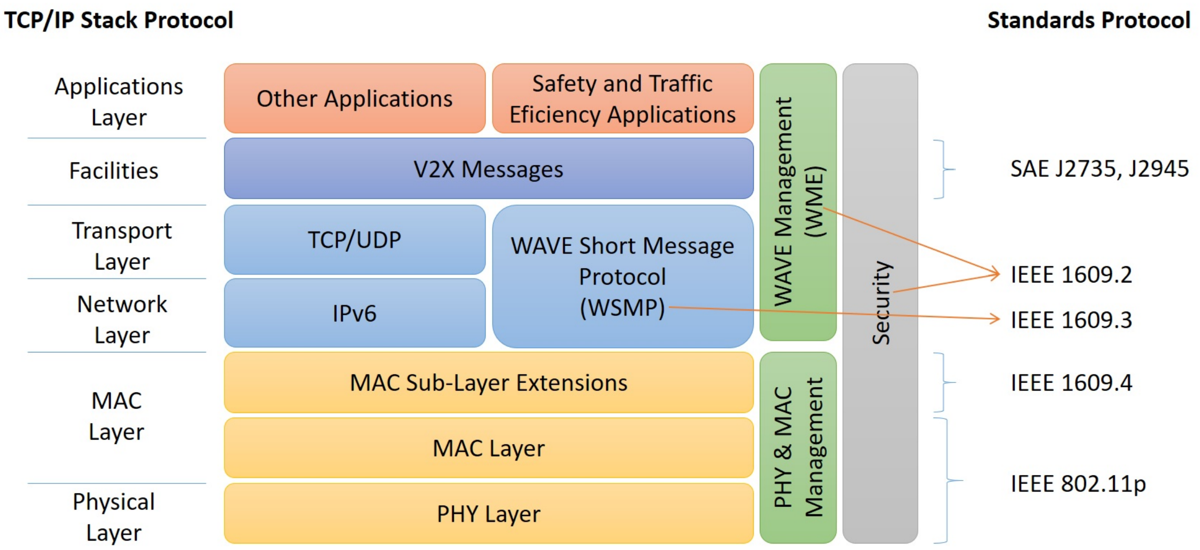


Figure 1.2: Comparison of WAVE protocol stack with TCP/IP protocol stack.

Table 1.2: WAVE protocol standards

Layers	Standards	Description
PHY and MAC	IEEE 802.11p [43]	Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments
	IEEE 1609.4 [44]	IEEE Standard for Wireless Access in Vehicular Environments (WAVE) – Multi-Channel Operation
NET and TRA	IEEE 1609.3 [45]	IEEE Standard for Wireless Access in Vehicular Environments (WAVE) – Networking Services
APP	SAE J2735 [46]	V2X Communications Message Set Dictionary
	SAE J2945 [47]	On-Board System Requirements for V2V Safety Communications
Security	IEEE 1609.2 [48]	IEEE Standard for Wireless Access in Vehicular Environments –Security Services for Applications and Management Messages

The WAVE architecture is specified in the IEEE 1609.0 standard. This architecture is optimized for the fast, reliable broadcast transmission of the safety message. The PHY and MAC layer of the WAVE used the IEEE 802.11p standard as the basis, the same as the ITS-G5 in European standard. The difference between them lies in the MAC layer extension, where WAVE utilizes the multi-channel operation and is regulated in the IEEE 1609.4 standard. This standard provides the MAC layer improvement by supporting the multi-channel WAVE operations. It separated the channels into the control channel (CCH) and service channel (SCH) and allowing a DSRC system to switch among the channel efficiently.

The NET and TRA layers of the WAVE of non-safety-related application is the same as ITS-G5 that used the ordinary IP addressing for unicast, broadcast, multicast transmission using TCP/UDP or IPv6 protocol. It used its own WAVE short message protocol (WSMP) for efficient single-hop networking communications for safety and traffic efficiency applications. All this protocol is regulated in the IEEE 1609.3 networking services standard.

The WAVE facilities and APP layer used the standard issued by the Society of Automotive Engineers (SAE). The standard SAE J2735 defined basic safety message (BSM) over a DSRC wireless communications link. This BSM is also known as CAM in the ETSI ITS-G5 standard.

For the security layer, WAVE used IEEE 1609.2 Security Services for Applications and Management Messages standard. It defines secure message formats and processing for DSRC systems. It also provides authentication and optional encryption of DSRC messages based on digital signatures and certificates. Figure 1.2 illustrates the comparison of WAVE architecture stack with TCP/IP model protocol stack and its corresponding standard protocol in each layer, and Table 1.2 summarizes each protocol standards.

1.3 VANETs Challenges

Several literature [49, 50, 51, 52, 53, 54, 55] state the characteristics of the VANETs such as highly mobility of the vehicles, rapid change of topology, intermittent connectivity, and predicted path. In the next section we will describe several challenges for VANETs communications system.

1.3.1 Signal Propagation

The communication between transmitter and receiver in the VANETs scenario, need to consider some existing problems in the wireless communication. The propagated signals will fade as they move away from the transmitter, thus one vehicle cannot communicate with other vehicle if it is located too far. According to literature [53], we need to consider the different type of environments in VANETs communication scenario. For example, communication in highway area will be assumed to be free space path loss, while communication in the city will be assumed to be NOT free space because it exists surrounding obstacles such as other vehicles, buildings, trees and other objects that cause shadowing and multipath-fading. And also, the potential interference from other vehicles or objects must been taken into consideration when we modelling the signal propagation in wireless communication for VANETs.

There are four attenuation patterns that can be taken into consideration when modelling the signal propagation: Path Loss (there are two model known in the literature i.e. Freespace model and Two-Ray Ground Model), Shadowing, Multipath Fading (the well-known models are Rayleigh, Rice and Nakagami) and Doppler Effect. We will provide a more detailed explanation of the channel model in Chapter 2

1.3.2 Physical Layer

There are three communication zones in the VANETs environment, i.e., Detection zone, Transmission zone, and Interference zone as depicted in Figure 1.3. PHY layer defines the transmission and reception of data through wireless communication. It ensures data encoding and decoding, modulation, antenna, etc. The standard for this PHY layer is regulated in IEEE 802.11p. This standard uses the orthogonal frequency-division multiplexing (OFDM) technique for modulation. It also use the 10 MHz bandwidth, which is narrower from other wireless LAN standard, in order to answer high mobility characteristic of VANETs. It must establish fast communication regardless the speed of the vehicles in VANETs environments.

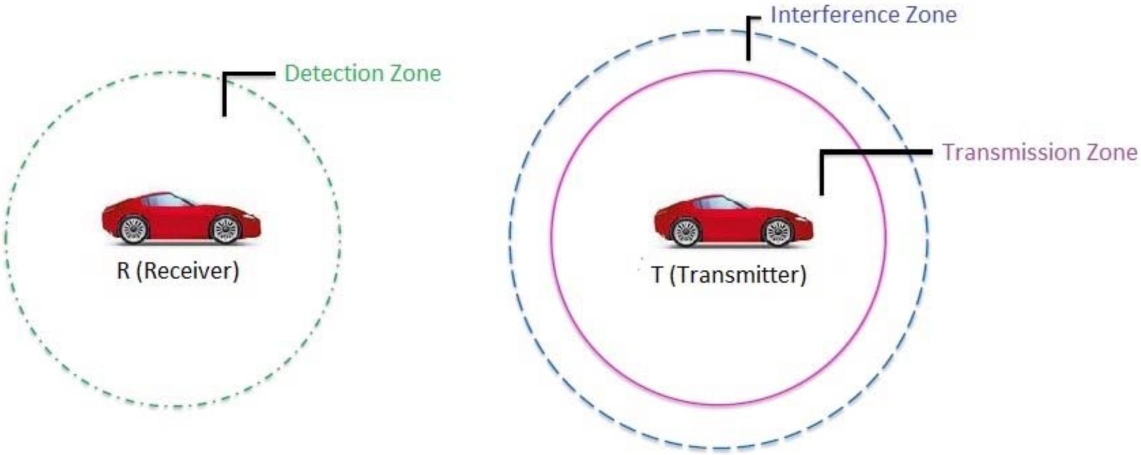


Figure 1.3: Transmission, Detection and Interference Zone in vehicular communication.

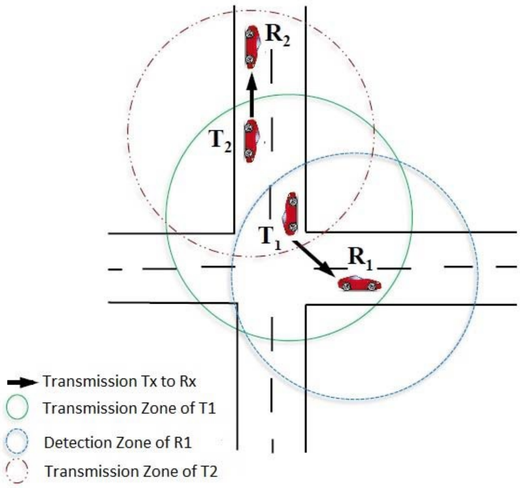
Based on literature [56], the performance of PHY layer is one important factor for communication process. Due to special characteristics of VANETs, the PHY layer should be robust, scalable, reliable, low latency and have minimum BER. There are several challenge that exist in the 802.11p PHY layer i.e.: effect of noise in bit and symbol energy, multipath effect (Rayleigh fading, frequency selective fading, delay spread), channel variation and channel estimation, network coverage range and bit rate enhancement techniques.

In the literature [57], we can modify some parameters in this PHY layer, i.e. transmission power, modulation scheme and beaconing frequency. The increase of the transmission power will have the advantage of large coverage area but have the drawback of the high interference due to the existing of many neighboring vehicles. The increase of the modulation scheme will achieve high data rate but the communication coverage will be reduced. And the high beaconing frequency will enhance the context-awareness with the sacrifice of bandwidth utilization which cause other service to be blocked.

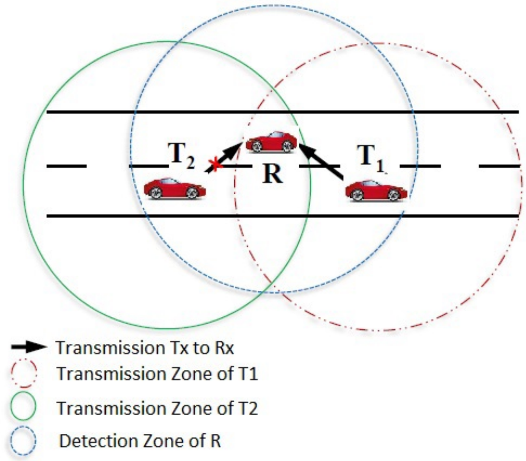
1.3.3 Medium Access Control Layer

The MAC protocol layer in VANETs is regulated in the IEEE 802.11p, IEEE 1609.4, ETSI EN 302 663, ETSI TS 102 687, and ETSI TS 103 175 standards. In general, The MAC protocol layer must manage the vehicle access to the network and ensuring the sharing channel, in order to provide a reliable, fair and efficient channel access by avoiding transmission collision. This standard uses OFDM technology in the PHY layer to control the medium access and used the CSMA/CA technique that was designed to provides reliability and has low latency requirements.

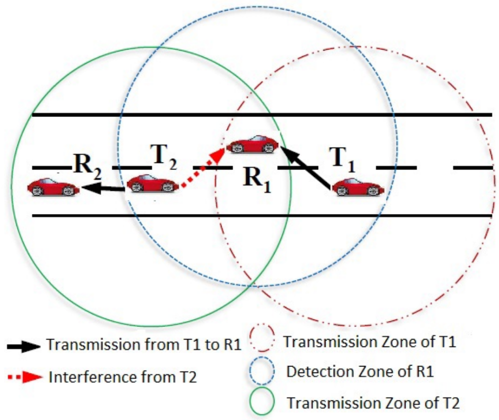
However, CSMA/CA has a drawbacks of the lacks QoS and not suitable for realtime traffic. It can be found in the literature [58, 59, 60, 61, 62, 63], that network performance of MAC layer has been evaluate and new approach has been proposed to increase the performance based on VANETs characteristics and the type of applications.



(a) Exposed node problem.



(b) Hidden node problem.



(c) Blocking problem.

Figure 1.4: Exposed node, hidden node and blocking problems in the VANETs MAC layer.

The workings of MAC layer protocol using CSMA/CA prohibits transmissions simultaneously in the same detection zone in order to avoid possible interference between neighboring vehicles. This prohibition results in problem called blocking problem, a temporary blocking of data reception, which reduces the overall throughput of the network. Other issues that might occur in MAC layer are prioritized access, unpredictable response and reliability. Providing a reliable communication in the wireless system is difficult due to hidden terminal and exposed terminal problems. In addition, The MAC protocol layer in VANETs system should consider the high mobility and rapid topology changes. All the VANETs problems in the MAC layer is depicted in Figure 1.4.

Based on literature [57], we can modify some parameters in this MAC layer, i.e. the size of contention window (CW) and retransmission limit. We must use the proper CW size to increase the throughput and decide which priority to be given to each node in order to guaranty the fairness. And by setting the retransmission limit based on the number of neighboring vehicles, we can optimize bandwidth utilization.

1.3.4 Network Layer

The NET layer is regulated in the IEEE 1609.3 standard. In this layer, the routing protocol have to provide a reliable wireless communication by using routing strategies based on the application (safety application or comfort application) and the type of communication (V2V or V2I). The wireless routing communication in VANETs can be categorized as three type i.e.: unicast communication, multicast/geocast communication and broadcast communication.

The performance of the routing protocol in the NET layer of VANETs system will be depends on several factor such as predicted path (road layout), data traffic and mobility model. The survey of the existing proposed routing protocol in VANETs can be found in literature [64, 65].

1.3.5 Transport Layer

Like NET layer, the Transport protocol in the VANETs is regulated in the IEEE 1609.3 standard. It use TCP, UDP and IPv6 protocol. Based on VANETs characteristics such as high mobility and rapid topology changes, the designer of the application in VANETs must consider which transport protocol to be used. TCP protocol will provide a reliable communication but have poor performance, while UDP protocol can be used to broadcasting scenario. For example, in the application that is used for safety application, the protocol should minimize the end-to-end communication delay because it is a delay sensitive application and must provide emergency information. While for comfort application it should provide high data throughput, reliable communication and small end-to-end delay to make the real time multimedia application available to the user.

Based on literature [66], designing end-to-end transmission control to guarantee a desired level of performance in the VANETs is a very challenging task. Wireless data transmission in VANETs need to consider the mobility of the vehicles and also wireless channel conditions

Table 1.3: Summary of problematics in VANETs protocol layers

Challenge	Problematics
Radio propagation model	Modeling and simulating realistic signal propagation in vehicular communication, such as : signal attenuation (path loss, shadowing, multipath fading, Doppler effect) and VANETs environment (highway, rural or city area)
PHY Layer	Interference, Coverage, and Bandwidth utilization
MAC Layer	Reliable link communication (due to receiver blocking problem, exposed and hidden terminal problems), Fairness, Throughput, and Latency
NET Layer	Routing strategies based on the application (safety application or comfort application) and the type of communication (V2V or V2I). There are three type of routing communication that can be used, i.e.: unicast communication, multicast/geocast communication and broadcast communication.
TRA Layer	Different type of application need different type of QoS

(such as path loss, shadowing, multipath fading). The summary of VANETs challenge in each layers are shown in table 1.3.

1.4 VANETs Applications

The wide variety of V2X applications can be classified based on their purpose and minimum requirements. Literature [11] classified V2X application into four major categories, i.e., traffic safety, traffic efficiency, cooperative driving, and infotainment. The use case examples of traffic safety applications are pre-sense crash warning or vulnerable road user warning, and having the requirements of 20-100 ms latency and 0.5-700 Mbps throughput. The traffic efficiency applications examples are navigation system or stationary vehicle warning and having the requirements of 100-500 ms latency and 10-45 Mbps throughput. The examples of cooperative driving are cooperative adaptive cruise control or cooperative overtake, and having the requirements of 2-10 ms latency and 5 Mbps throughput. Examples of infotainment applications are music or video streaming, which require 500-1000 ms latency and 80 Mbps throughput.

Other than V2X application mentioned in the VANETs standard section, The European telecommunication standards institute (ETSI) also releases the service requirements of the enhanced V2X scenarios for the 5G system [67]. It includes transport layer support for both safety-related V2X scenarios, like automated driving and vehicle platooning, and non-safety-related V2X scenarios such as mobile high data rates entertainment, mobile hotspot/office/home, and dynamic digital map update. This technical specification categorizes V2X scenarios into five

Table 1.4: Enhanced V2X applications and their requirements

Applications	Payload (Bytes)	Tx rate (Message/s)	Latency (ms)	Reliability (%)	Data rates (Mbps)	Range (m)
Vehicle platooning	50 - 6500	2 - 50	10 - 500	90 - 99.99	50 - 65	80 - 350
Advanced driving	300 - 12000	10 - 100	3 - 100	90 - 99.999	0.25 - 53	360 - 700
Extended sensors	1600	10	3 - 100	90 - 99.999	10 - 1000	50 - 1000
Remote driving	-	-	5	99.999	1 - 25	-

areas, i.e., general V2X scenarios, vehicles platooning, advanced driving, extended sensors, and remote driving. It also defines the level of automation (LoA) of the advanced V2X applications into six levels, i.e., level 0 (no automation), level 1 (driver assistance), level 2 (partial automation), level 3 (conditional automation), level 4 (high automation), and level 5 (full automation). The difference between the lowest and highest levels is based on the subject responsible for monitoring the driving environment, whether the human driver or the automated system. Table 1.4 shows a summary of the performance requirements for each advanced V2X applications. The detailed information of the scenarios, LoA degree, and performance requirement for each advanced V2X applications can be seen in [67].

In this thesis, We consider two types of V2X applications, i.e., safety-related V2X applications where reliability and latency or delay are the critical factors of their QoS, and non-safety-related or comfort V2X applications where data rates and packet size are the main factors for their QoS.

1.5 State of the Art of the Research

In the previous section, we have discussed about the challenges that might occur in VANETs communications system. The designer of protocol and applications in VANETs system must consider those characteristics and challenges to provide a better network performance such as high data throughput and also minimized the interference. Multiple-Input Multiple-Output (MIMO) processing techniques and cross-layer design among the original layers are potential solutions to answer this problems. In this following section we will discuss about the benefit of employing those two technologies and the evolution of the VANETs standard.

1.5.1 Cross-Layer Approach

Due to its special characteristics, VANETs applications will have a bad network performance, if we use a standard network protocol layer approach. Many researchers proposed cross layer approach to improve the performance of a wireless network by jointly optimizing the parameters of different layers. Cross layer protocols that operate in multiple layers are used to provide a better performance in the VANETs. To provide more efficient and robust protocol that can answer different QoS, the cross layer design allowing data and information of each protocol layer to be shared and exchange to other protocol layers.

A Surveys of cross layer network approach for VANETs is found in the literature [68]. In this literature, if we want to make cross layer design for PHY/MAC layer we must consider transmission rate adaptation, channel selection and transmission range adaptation. PHY/-MAC/NET cross layer design need to consider the channel quality information of the PHY layer for maintaining connectivity in MAC and NET layer. And for NET/MAC cross layer design, it need to consider routing selection, packet collision avoidance, application QoS and multi-hops broadcasting. Other survey for cross layer design also found in literature [69] and also in the literature [70] that survey cross layer design specifically for multimedia application.

Other cross layer design approach for VANETs that found in the literature are : Literature [57] proposed PHY/MAC cross layer design to enhance overall performance of vehicular communication by adjusting some parameter such as transmission power, modulation scheme and beaconing frequency in the PHY layer and also contention window and retransmission limit in the MAC layer. Literature [71] use cross layer design with the purpose to enhance link stability and improve network throughputs. Literature [72] proposed a cross layer routing for VANETs and consider various parameters from PHY and MAC layers. Literature [73] proposed a PHY/MAC/NET cross layer design in the multi-hops ad-hoc networks.

1.5.2 MIMO VANETs

In wireless communication domain, MIMO is a method to increase the capacity of the radio link by using multiple antennas both at transmitter and receiver side to exploit multipath propagation. There are three transmission techniques from the MIMO systems that can give benefit for VANETs, i.e. Spatial Multiplexing, Spatial Diversity and Beamforming. Spatial Multiplexing is a technique to increases the throughput by sending multiple data streams in parallel. On the transmitter side, each data sequence is divided into several sub-sequences (as much as the number of transmitting antennas) and then sent over several antennas. On the receiving side, the received subsequences are detected and then ordered to find the signals issued. Spatial Diversity is used when the signal to noise ratio (SNR) is low. The transmitter sends several copies of the signal to be transmitted on all the antennas, and then the receiver combines the signals to recover a less attenuated signal than the signals received by each antenna. Beamforming was first proposed in 1990 for radar technology and then generalized for various ad-hoc communications systems. The basic idea is to use antenna arrays to transmit and receive signals from/to a precise direction in order to improve the received SNR.

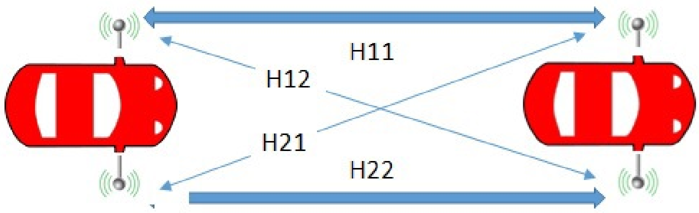


Figure 1.5: Using MIMO for vehicular communication system.

Figure 1.5 depicted the use of MIMO for vehicular communications, where both cars having two antennas that can be used to communicate. MIMO will be a key enabling technology when implemented in vehicular network scenario, because MIMO technology could answer all the major challenges in VANETs scenarios and applications. MIMO technology has a lot of advantages when compared to single-input single-output (SISO) systems. MIMO systems can be designed to provide either reliable transmission using space-time coding, or large spectral efficiency through spatial multiplexing techniques. Recent review on MIMO VANETs [74] discusses various possible benefits that can be taken when implementing MIMO processing techniques in VANETs. The spatial multiplexing technique will improve the network performance by increasing the throughput. The spatial diversity technique will improve the reliability of the wireless communication. And the beamforming technique will increase communication range.

1.5.3 Cross Layer Design in MIMO-VANETs

The literature [75] evaluates the performance of multiantenna system for VANETs communication according to IEEE 802.11p standard. It deploys three MIMO schemes, Alamouti, vertical BLAST (V-BLAST) and space shift keying (SSK) scheme and consider the driving speed and Line of Sight (LoS). Based on simulation, the performance result shows that V-BLAST scheme is good for increasing the data rate, while Alamouti and SSK could improve the reliability and robustness.

Other work of utilization of cross layer design and MIMO can be found in literature [76]. This paper considers multiple antennas implementation to wireless ad hoc communication. It investigates PHY/MAC cross layer design performance in MIMO systems for mobile ad hoc communication. In the physical layer, it used the optimum antenna combination selection approach, while the new MAC layer approach by minimize the effect of blocking node also proposed. It used the Zero-Forcing Bell Labs Layered Space Time (BLAST) that make the MIMO system to allow the neighboring nodes communicate simultaneously. Based on the simulation, the performance of the proposed cross layer PHY/MAC design can leverage the network throughput compared to the case with no antennas selection and using conventional MAC protocol.

Other literature [77] is continuing the work in literature [76], by using the cross layer design based on transmit antenna selection, but in the VANETs environment. It still uses the PHY/MAC cross layer design to increase the throughput and overcome the receiver blocking problem. To solve this problem, the authors propose a PHY/MAC cross-layer architecture based on transmitter's antenna selection algorithm and a dedicated MAC protocol to reduce the blocking problem. This cross-layer approach, let the receiver to choose the best combination of transmitting antennas to improve the throughput of each V2V link. The algorithm is presented with a detection method that cancels the multi-user interference and allows multiple vehicles to transmit data simultaneously. The associated MAC protocol ensures the coordination between vehicles during communications. Simulation results show improved network throughput of the new approach compared to the current standard. But these good performances decrease when the vehicular density increases. To overcome this decline, in the later work the authors propose to add a new PHY/MAC cross-layer architecture to the first solution. This architecture is based on an algorithm for adapting the power emitted as a function of the density of the neighboring receiver. It is also accompanied by a dedicated MAC protocol. The Simulation results show that this solution allows more vehicles to communicate simultaneously and thus significantly improves the throughput in vehicular networks with high density.

1.5.4 The Evolution of the Standards

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.

On the other hand, for the last decade, 802.11 Wi-Fi family standards have evolved and offer performance improvements such as higher throughput, improved reliability, and more extended communication range. We will provide more detailed explanation of the several mature techniques from other 802.11 standards, which could be adopted for future V2X applications in Chapter 3.

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) [78], 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 several objectives as follows:

- Achieving at least two times higher throughput measured at the MAC layer,
- Operating in high mobility channel in vehicles with relative speeds up to 500 km/h,
- Achieving at least one mode transmission having a 3 dB lower sensitivity level (or having more extended communication range),
- Defineing procedures for one form of positioning in conjunction with V2X communications.
- Providing interoperability, coexistence, backward compatibility, and fairness with deployed OCB devices using 802.11p.

1.6 Conclusion

In this chapter we discuss about the standard, characteristics and challenges of wireless communication in VANETs system. Two potential solutions that can be used to support the large and diverse applications in VANETs are MIMO processing techniques and cross-layer design among the original layers. By employing these two technologies, it will support the large and diverse applications and also will answer the characteristics and the challenge in the future VANETs applications. This thesis will exploit the benefits of employing MIMO and cross layer design in VANETs communication systems. [1]

[1] This chapter is a slightly modified version of Using MIMO and cross layer design for VANETs : A review [79] published in 2017 International Conference on Signals and Systems (ICSigSys) and has been reproduced here with the permission of the copyright holder.

Chapter 2

VANETs Modeling and Analysis

2.1 IEEE 802.11p and 802.11bd PPDU

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 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 802.11p is categorized as non-high throughput (non-HT) or legacy Wi-Fi standard. The physical layer convergence procedure (PLCP) protocol data unit (PPDU) of 802.11p is a packet-based protocol that consists of preamble and data fields. The preamble field consists of PLCP legacy preamble that contains legacy-short training field (L-STF), legacy-long training field (L-LTF), and legacy-signal (L-SIG). L-STF is used for detecting packet and acquiring coarse time and frequency synchronization; L-LTF is used for performing channel estimation and fine synchronization; and L-SIG will contain packet information such as modulation, coding rate, and message length. The data field consists of the service, tail and pad bits, and physical service data unit (PSDU) containing user payload and the higher layer headers, like the MAC layer header and frame check sequence (FCS) field.

As we know about the IEEE 802.11standards' convenience, where they always keep the compatibility with the previous standard, 802.11bd should maintain the backward compatibility with 802.11p standard. The approach to achieve this objective can be obtained by structuring the PPDU of 802.11bd packet in a generic way, which contains two parts, i.e., the preamble and the data field, but keeping the legacy preamble of 802.11p in the 802.11bd preamble fields. We will have two distinctions of preamble section, where the first preamble encoded according to the legacy 802.11p standard and the second section for the new 802.11bd standard that adopts the latest techniques from other Wi-Fi standards to increase the performance of NGV applications. The comparison between 802.11p and 802.11bd PPDU adapted from [80] and [81] is shown in Fig. 2.1.

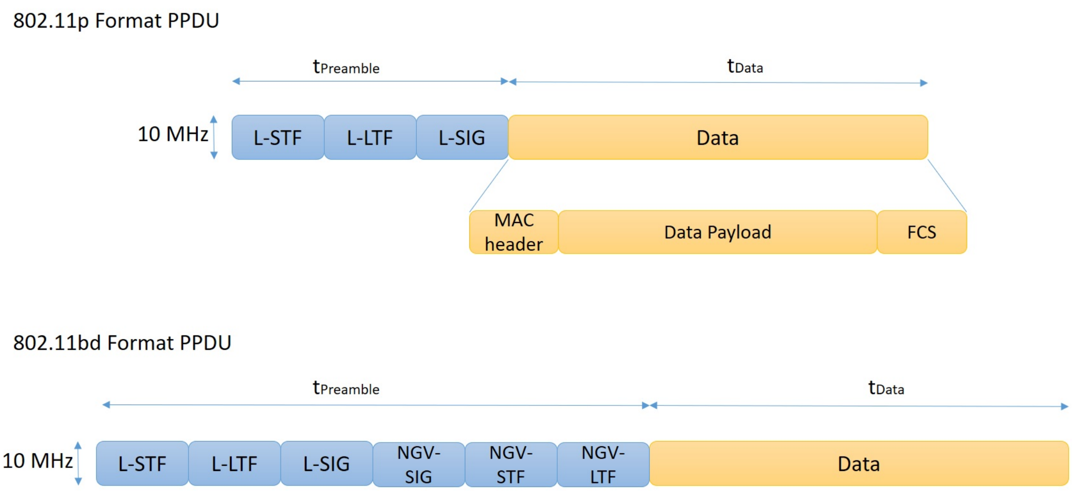


Figure 2.1: Comparison between 802.11p and 802.11bd format PPDU.

2.2 OFDM Numerology

Considering N_{SD} is the number of data sub-carriers, N_{BPSCS} is the number of coded bits per sub-carriers per stream, R is the coding rate, N_{SS} is the number of spatial streams, T_{sym} is OFDM symbol duration, and T_{GI} is guard interval duration, the theoretical data rates of each modulation coding scheme (MCS) can be calculated as follows:

$$DataRate = \frac{N_{SD} * N_{BPSCS} * R * N_{SS}}{T_{sym} + T_{GI}} \tag{2.1}$$

The PHY layer of a non-HT legacy standard like 802.11a is OFDM based and has 64 sub-carriers that consists of 48 sub-carriers for data, four sub-carriers for the pilot, and 12 for null sub-carriers. Having a T_{sym} of 3.2 μs and operates in 20 MHz channel, the 802.11a has a sub-carriers spacing of 312.5 kHz. The 802.11p is derived from 802.11a with some modification by halving the bandwidth channel and doubling the symbol duration. Having a T_{sym} of 6.4 μs and operates in 10 MHz channel, the 802.11p has a 156.25 kHz sub-carriers spacing. Halving the sub-carriers spacing is known as a 2× down-clock technique and is needed to overcome the multi-path fading and relative Doppler spread problem for a typical high mobility environment.

The 802.11bd could be derived from the 802.11ac standard with the same 64 sub-carriers but having 52 sub-carriers of data. Using the 2× down-clock technique, 802.11bd has the same sub-carrier spacing as in IEEE 802.11p and has a little improvement in the theoretical data rates due to having more sub-carriers of data. TGbd investigates to increase the OFDM efficiency by exploring narrower sub-carrier spacing while still using a 10 MHz channel ([82],[83]). Although TGbd recommends using 802.11ac with 2× down-clock, in this research, we consider using the 802.11ax, which has 234 data sub-carriers out of total 256 sub-carriers. 802.11ax, also known as high efficiency (HE) standard, is designed to support outdoor and high mobility environments using longer symbol duration and longer GI. Using the same 2× down clock technique, by halving the data sub-carriers to operate in 10 MHz channel, and having the T_{sym} of 12.8 μs and T_{GI} of 3.2 μs, 802.11ax has sub-carriers spacing of 78.125 kHz. Although having a longer symbol duration, it can still achieve data rates improvement due to OFDM efficiency.

Table 2.1 compares theoretical data rates calculation for IEEE 802.11p and IEEE 802.11bd (based on IEEE 802.11ac and IEEE 802.11ax) using equation 2.1. From Table 2.1, using the 802.11ac with 2× down-clock technique gives theoretical data rates improvement of 8% while using the 802.11ax with 2× down-clock technique will give a 22% improvement due to the increasing number of data sub-carriers. Both 802.11ac and 11ax standard support the MIMO-STBC technique, so they can have more than one spatial stream. Using the MIMO-STBC 2×2 system with two spatial streams, we can have theoretical data rates of 117% and 144%, respectively. 802.11bd also proposes the use of higher modulation up to 256-QAM with a code rate of 5/6. Using this MCS with one spatial stream, we can have the theoretical data-rates of 43.33 Mbps (using 802.11ac 2× down-clock) or 48.75 Mbps (using 802.11ax 2×down-clock), while adding MIMO-STBC with two spatial streams will achieve 86.66 Mbps and 97.5 Mbps, respectively.

Table 2.1: Theoretical data rates for 802.11p and potential 802.11bd standard

MCS	802.11p in 10 MHz			Potential 802.11bd in 10 MHz [a]					
	Modulation scheme	R	Data rates (Mbps)	Modulation scheme	R	Data rates 1 SS (Mbps)		Data rates 2 SS (Mbps)	
						11ac (2× DC)	11ax (2× DC)	11ac (2× DC)	11ax (2× DC)
0	BPSK	1/2	3	BPSK	1/2	3.25	3.65	6.5	7.31
1	BPSK	3/4	4.5	QPSK	1/2	6.5	7.31	13	14.62
2	QPSK	1/2	6	QPSK	3/4	9.75	10.96	19.5	21.93
3	QPSK	3/4	9	16-QAM	1/2	13	14.62	26	29.25
4	16-QAM	1/2	12	16-QAM	3/4	19.5	21.93	39	43.87
5	16-QAM	3/4	18	64-QAM	2/3	26	29.25	52	58.5
6	64-QAM	2/3	24	64-QAM	3/4	29.5	32.9	58.5	65.81
7	64-QAM	3/4	27	64-QAM	5/6	32.5	36.56	65	73.12
8	-	-	-	256-QAM	3/4	39	43.87	78	87.75
9	-	-	-	256-QAM	5/6	43.33	48.75	86.66	97.5

[a] 802.11bd could be derived from 802.11ac or 802.11ax standard with 2x down-clock technique.

2.3 VANETs Performance analysis

In this research, we choose the PER as the performance metric. The PER is used to evaluate the performance in the PHY layer. We can also derive another performance evaluation of the VANETs communication system using PER, such as the packet delivery ratio (PDR), to describe the VANETs system's reliability. We also choose throughput as the second performance metric. It should be noted that there are two types of throughput used in this research. The first one is the throughput of the PHY layer, where its value depends directly on the PER, and the second one is the throughput at the MAC layer.

2.3.1 PER calculations

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:

$$\gamma = \frac{P_r}{N_0 \cdot B} \tag{2.2}$$

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:

$$\gamma_s = \frac{E_s}{N_0} = k \cdot \frac{E_b}{N_0} = k \cdot \gamma_b \tag{2.3}$$

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:

$$a_g = \frac{N}{N + N_{cp}} \tag{2.4}$$

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

$$\bar{\gamma_s} = a_g \cdot \gamma_s \tag{2.5}$$

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:

$$SER_{BPSK} = Q(\sqrt{2\bar{\gamma_s}}) \tag{2.6}$$

$$SER_{MQAM} = 1 - \left[1 - 2\left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\sqrt{\frac{3\bar{\gamma_s}}{(M-1)}}\right)\right]^2 \tag{2.7}$$

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:

$$M_{\gamma_s}\left(-\frac{g}{\sin^2\phi}\right) = \left(1 + \frac{g\bar{\gamma_s}}{\sin^2\phi}\right)^{-1} \tag{2.8}$$

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:

$$SER_{BPSK} = 0.5\left(1 - \sqrt{\frac{\bar{\gamma_s}}{1 + \bar{\gamma_s}}}\right) \tag{2.9}$$

$$SER_{MQAM} = \frac{4}{\pi}\left(1 - \frac{1}{\sqrt{M}}\right)\int_0^{\frac{\pi}{2}} M_{\gamma_s}\left(-\frac{g}{\sin^2\phi}\right) d\phi - \frac{4}{\pi}\left(1 - \frac{1}{\sqrt{M}}\right)^2 \int_0^{\frac{\pi}{4}} M_{\gamma_s}\left(-\frac{g}{\sin^2\phi}\right) d\phi \tag{2.10}$$

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 2.6 through 2.10, each modulation scheme's PER is calculated as follows:

$$PER = 1 - (1 - SER)^L \tag{2.11}$$

Based on [84], the throughput η at the PHY layer is calculated as:

$$\eta = R \cdot (1 - PER) \tag{2.12}$$

where R is the data rate in Mbps, and its value is taken from Table 2.1.

2.3.2 MAC Throughput calculations

We want to investigate the performance of throughput at the MAC layer in VANETs environment using the PER results from the PHY layer and considering the transmission scenario in the NET layer, whether using broadcast or unicast transmission. In this research, we consider single-hop transmission, which means that all vehicles are within the communication range, so there is no hidden nodes problem. We also assume saturated conditions where each vehicle always has a packet ready for transmission. The V2X communications standard in the

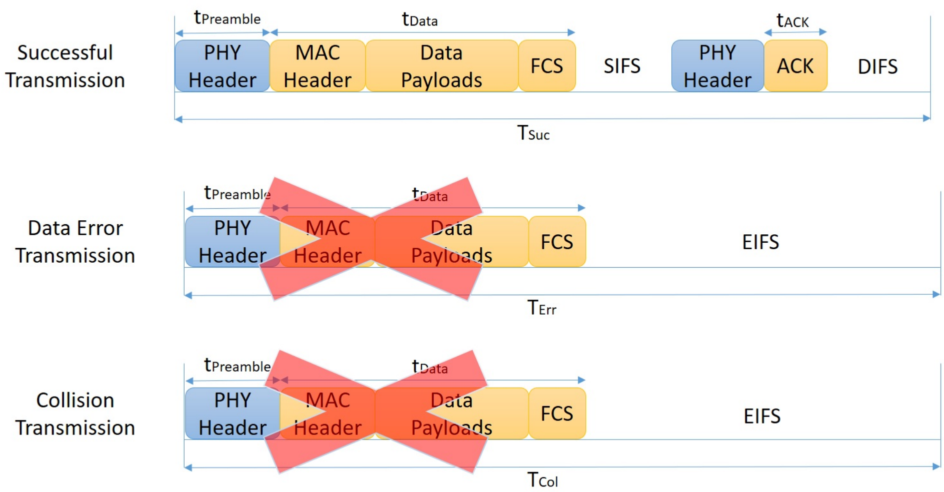


Figure 2.2: CSMA/CA using the DATA/ACK mechanism and the possible state of the channel.

MAC layer uses CSMA/CA without back-off and RTS/CTS packets. Each vehicle will choose a random number in the interval [0, CW] before initiating a packet transmission. When the medium is sensed idle, the vehicle with the smallest value of CW will start the transmission. The CSMA/CA technique is known to have a limitation or bottleneck of blocking problem where during the transmission process, other vehicles will sense the medium as busy and wait until the current transmission is finished. It means that there is only one transmission during a slot of time. There will be two possible transmission conditions, i.e., successful transmission or error transmission caused by data transmission error or collision. Data transmission error is happened due to a received signal power below the sensing power threshold or due to the propagation effect where a received packet has SNR that is not sufficient to be decoded correctly. The collision error will happen when two or more vehicles generate CW with the same value. Fig. 2.2 describes the CSMA/CA technique using a basic access scheme and the channel's possible state. Based on the PPDU frame format of the 802.11p and 802.11bd standards in Fig. 2.1, considering $t_{preamble}$ is the time duration for PHY header transmission, and t_{Data} is the time duration for PSDU transmission, we can express the transmission duration of the packet as follows:

$$T_{Data} = t_{preamble} + t_{Data} \tag{2.13}$$

The difference between the 802.11p and 802.11bd calculation is located only in the $t_{preamble}$, where 802.11bd will have longer PHY header duration. For the next section, we use the 802.11p PPDU format for the performance analysis. However, we can change the analysis to the 802.11bd by changing the value of $t_{preamble}$ of the 802.11bd accordingly. On Fig. 2.1, we can see that the PHY header is consists of L-STF, L-LTF, and L-SIG, while PSDU is consists of MAC header, FCS, data payloads, plus 16-bit service and 6-bit tail. Having data bits per OFDM symbols N_{DBPS}, where its value depends on the MCS, now we can express equation 2.13 as:

$$T_{Data} = (T_{STF} + T_{LTF} + T_{SIG}) + T_{Sym} \times \left\lceil \frac{16 + L_{MAC} + L_{Payload} + L_{FCS} + 6}{N_{DBPS}} \right\rceil \tag{2.14}$$

For the ACK packet, the transmission duration can be expressed as:

$$T_{ACK} = (T_{STF} + T_{LTF} + T_{SIG}) + T_{Sym} \times \left\lceil \frac{16 + L_{ACK} + L_{FCS} + 6}{N_{DBPS}} \right\rceil \tag{2.15}$$

Based on Fig. 2.2, for unicast with ACK transmission, the duration of successful transmission consists of data transmission duration, short inter-frame space (SIFS) duration, ACK transmission duration, and distributed coordination function inter-frame space (DIFS) duration. Considering the propagation time T_{Prop}, and we need to send Data and ACK packets, respectively, we can express the successful transmission duration in the unicast scenario as follows:

$$T_{Succ,ACK} = T_{Data} + T_{ACK} + T_{SIFS} + T_{DIFS} + 2 \times T_{Prop} \tag{2.16}$$

If the vehicles receive the error packet, it has to defer for extended interframe space (EIFS) duration that calculated as follows:

$$T_{EIFS} = T_{ACK} + T_{SIFS} + T_{DIFS} \tag{2.17}$$

Using equation 2.16 and 2.17, the calculation of $T_{Err,ACK}$, and $T_{Col,ACK}$ will have the same value as the $T_{Succ,ACK}$. The Broadcast transmission does not require the ACK frame, so that we can simplify the successful transmission duration as:

$$T_{Succ,no\_ACK} = T_{Data} + T_{DIFS} + T_{Prop} \tag{2.18}$$

The value of $T_{EIFS} = T_{DIFS}$ due to no ACK in broadcast transmission. For the same reason as unicast transmission, the value of T_{Err,no_ACK}, and T_{Col,no_ACK} will also have the same value as the T_{Succ,no_ACK}. To calculate the throughput performance in the MAC layer, we use the famous Bianchi model that uses the Markov chain model [85, 86]. This model only considers two states of the channel, i.e., successful transmission and unsuccessful transmission due to collision. We consider the cross-layer technique by considering the PER obtained from the PHY layer and use it for throughput performance analysis in the MAC layer. We derive the Bianchi model by considering the PER in the successful transmission so that there will be the possibility that the data transmission is failed due to PER. We can calculate the channel state's probability considering τ as the probability that a vehicle transmits a packet in a randomly chosen slot time, n the number of contending vehicles, and PER the packet error rate obtained from the PHY layer. There will be a P_{tr} the conditional probability that at least one transmission occurs, P_{idle} the probability of empty slot time or idle condition, and P_{Succ} the conditional probability that this transmission is successful that can be express as follows:

$$P_{tr} = 1 - (1 - \tau)^n \tag{2.19}$$

$$P_{idle} = 1 - P_{tr} \tag{2.20}$$

$$P_{Succ} = \frac{n \cdot \tau \cdot (1 - \tau)^{n-1}}{P_{tr}} \cdot (1 - PER) \tag{2.21}$$

From Fig. 2.2, we can have two possible unsuccessful transmissions, i.e., P_{Err} the conditional probability that a packet has received an error and P_{Col} the conditional probability that an occurring transmission is having a collision, which can be expressed as follows:

$$P_{Err} = \frac{n \cdot \tau \cdot (1 - \tau)^{n-1}}{P_{tr}} \cdot PER \tag{2.22}$$

$$P_{Col} = 1 - \frac{n \cdot \tau \cdot (1 - \tau)^{n-1}}{P_{tr}} \tag{2.23}$$

Considering $E[DATA]$ is the mean value of the successfully transmitted data payload, and $E[slot]$ is the mean value of the channel's duration, whether it is idle, successful transmission, or unsuccessful transmission due to transmission error or collision, we can express the saturation throughput in the MAC layer as:

$$S = \frac{E[DATA]}{E[slot]} \tag{2.24}$$

Using equation 2.16 through 2.23, we can rewrite the saturation throughput S as:

$$S = \frac{P_{Succ} \cdot L_{Payload}}{T_{Slot} \cdot P_{idle} + T_{Succ} \cdot P_{Succ} + T_{Err} \cdot P_{Err} + T_{Col} \cdot P_{Col}} \tag{2.25}$$

Finally, we can normalize the throughput by:

$$\bar{S} = \frac{S}{R} \tag{2.26}$$

where R is the theoretical data rate value based on their MCS taken from Table 2.1.

2.4 VANETs System model

In this section, we will discuss the system model used in this research. First, we will explain the system model, which consists of Transmitter, Receiver, and channel model, and also performance analysis for the theoretical evaluation. Then, we describe the simulation model of the VANETs simulator used in this research.

2.4.1 VANETs Transceiver based on OFDM

We build a discrete-time baseband OFDM to model our vehicular communication system and choose a frequency-selective Rayleigh with AWGN noise channel to simulate theoretical performance analysis. The essential parameter for the OFDM system is the number of subcarriers used for data transmission. As stated in the PHY layer of the IEEE 802.11 standards, the number of subcarriers for 802.11p and 802.11ac is 64, while 802.11ax has 256 subchannels. We set the size of the inverse discrete Fourier transform (IDFT) and discrete Fourier transform (DFT) based on that value. To maintain perfect orthogonality among the subcarriers, we add a cyclic prefix in each OFDM block. Figure 2.3 shows the system model to evaluate theoretical performance analysis.

The transmission begins with the transmitter generating random data symbols and converting the data into N parallel subcarriers. Each subcarrier's data symbol is mapped into BPSK, QPSK, 16-QAM, or 64-QAM modulation, using MPSK or MQAM modulator. Since our system is a baseband discrete-time model, we use the IDFT operation to convert the modulated

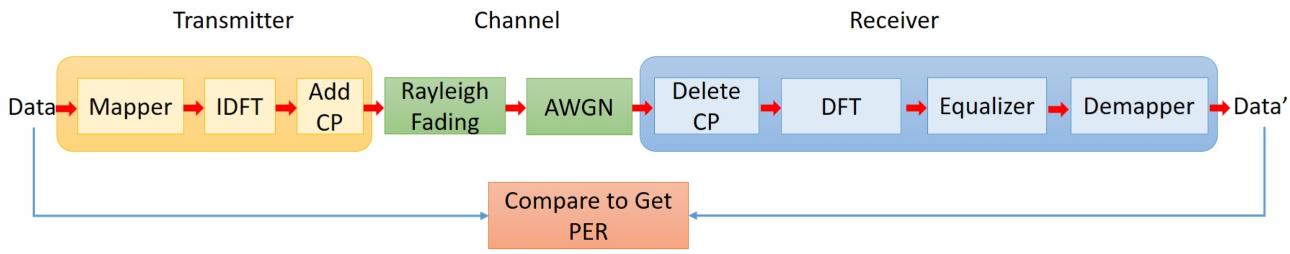


Figure 2.3: A system model of OFDM transceiver with a simple frequency domain equalizer to evaluate PER.

symbols from the frequency domain into the time domain. Due to delay distortion in a time dispersive channel, the subcarriers' perfect orthogonality is hard to maintain. To address this problem, we add the cyclic prefix to the 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.

2.4.2 Theoretical Evaluation

Table 2.2: Parameters for analytical performance

Symbol	Value	Description
n_{Sym}	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
N_{cp}	16	Number of symbols in the cyclic prefix
T	10	Number of taps for the frequency-selective channel model

We want to simulate IEEE 802.11p legacy standard performance for difference modulation on the frequency selective Rayleigh channel. 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 equation 2.10. Using the simulation configuration in Table 2.2, we have Figure 2.4 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.

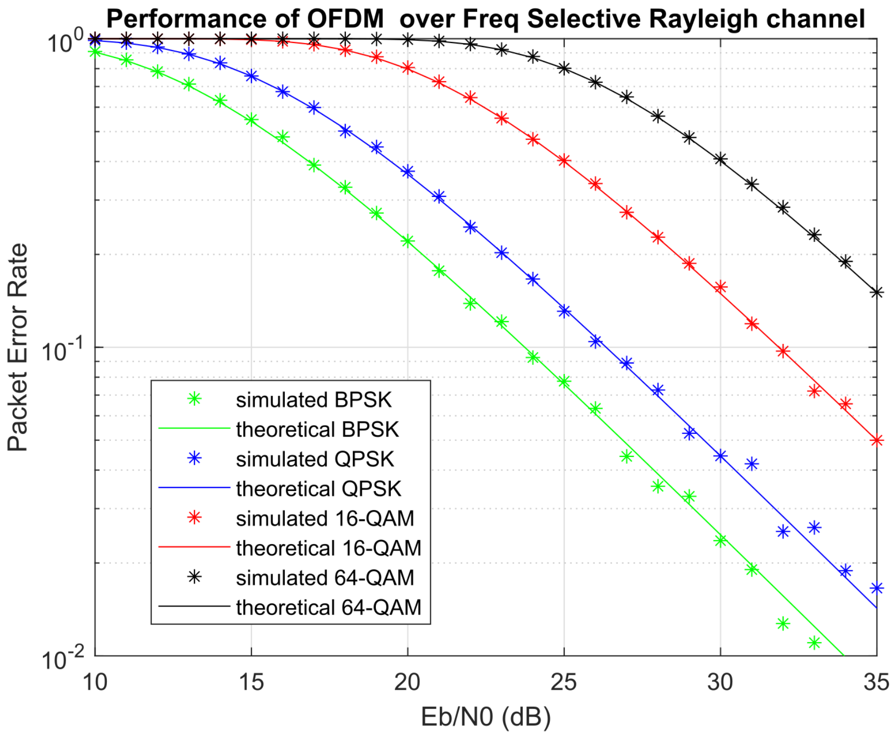


Figure 2.4: PER Performance of OFDM transceiver over frequency-selective Rayleigh fading channel.

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.

2.4.3 Simulation Model

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 realistic simulation for V2X communication, we extend the simulation model based on Figure 2.3 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 802.11ac/ax standards with 20 MHz bandwidth as a baseline and half the subcarrier spacing using the 2× down clock technique 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. Figure 2.5 describe our VANETs simulator built using MATLAB.

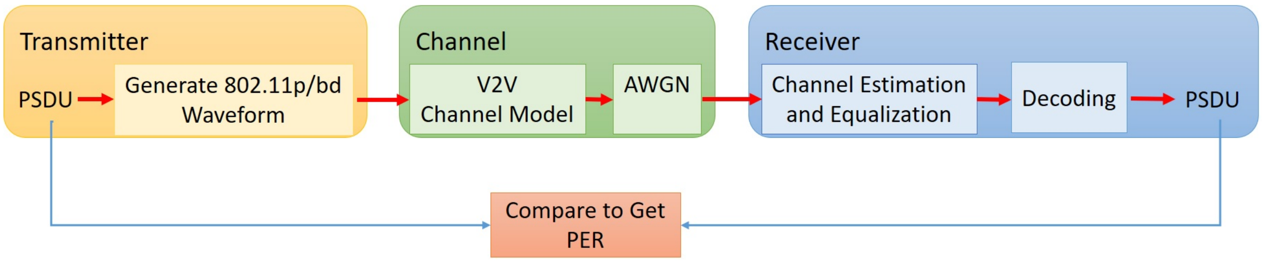


Figure 2.5: VANETs simulator model using MATLAB and WLAN Toolbox.

2.4.4 Channel model

Channel models or propagation models are the essential part of the VANETs communication system. When the signals travel from the transmitter to the receiver, it experienced several phenomena, like attenuation, reflection, transmission, diffraction, and scattering. Due to this conditions the signal strength is decaying as the distance increase between transmitter and receiver. The channel models for V2X communications in the 5.9 GHz band also need to consider several important factors, such as the high-speed mobility, which leads to the Doppler effect, and the rich multi-path fading due to several replicas of the same signal can reach the receiver, which have bounced from different objects during propagation. Figure 2.6 ilustrates an example of multipaths scenario of the signal propagation from the transmitter to the receiver [87], where the multipath components (MPC) will have the longer distance and arrive at the receiver after the LOS component.

There are several common channel models that can be used for VANETs communications, where its complexity increased when more propagation phenomena are added to the system. The simplest channel model is the deterministic path loss model, where the signal attenuation

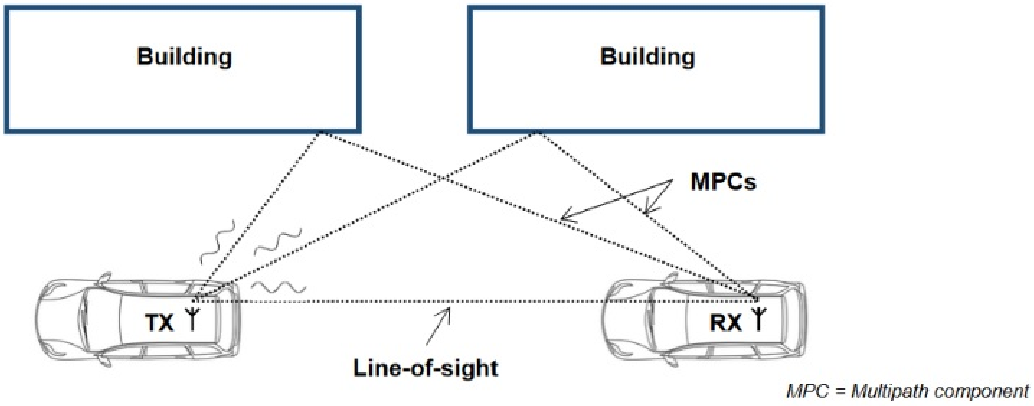


Figure 2.6: Multipath scenario, where two replicas of the signal (MPC components) besides the LOS component reach the receiver.

is only affected by the distance between transmiter and receiver. There are two well-known deterministic path loss model, i.e., the free-space path loss model and the two-ray ground reflection model. The difference between them is that the free-space only has one LOS component, while the two-ray ground has one LOS component, and also one MPC component came from ground reflection.

The more advanced models would be the statistical models, which add fading phenomena to the path loss model. Fading is the fluctuation of the signal strength and modeled as a random process. It occurs due to multipath propagation (also known as small-scale fading) or shadowing from the obstacles during the propagation of the signals (also known as large-scale fading). For the small-scale fading, there are three well-known statistical channel models, i.e., Rayleigh, Rician, and Nakagami distribution. Rician is used when there is a LOS component, Rayleigh is used when there is no LOS component, and Nakagami is used for both conditions. For the large-scale fading (shadowing), it is common to use a random Gaussian process.

The more complex channel model is the tapped delay line (TDL) model, where each MPCs (or "tap") are treated separately, and it also considers the Doppler shift. Each tap will have its own fading statistic (e.g. Rayleigh or Rician), phase shift (to cover difference phase between MPCs), and Doppler spectrum. The summary of the common channel model for VANETs communications taken from [87] is outlined in Table 2.3.

In the theoretical performance analysis above, we use statistical model of frequency-selective Rayleigh fading with the AWGN noise channel to model our V2X communication system. Several studies and field trials have been carried out to model realistic V2X environments

Table 2.3: Summary and description of different channel models

Channel Model	Path Loss	Fading	Doppler	Description
Path loss model	✓			Path loss models describe the deterministic signal attenuation based on the transmitter's distance from the receiver and the carrier frequency. It means that the same value of the carrier frequency and the distance will always give the same value of the path loss.
Statistical model	✓	✓		Adds a fading component (both small-scale and large-scale) to the path loss. Models only one received signal component.
TDL model	✓	✓	✓	Models several MPCs individually using statistics but can also add Doppler effects due to speed differences between transmitter and receiver.

[88, 89, 90, 91, 92]. It models into three environments, i.e., urban, rural, and highway, and two different scenarios, i.e., LOS and NLOS condition. The 802.11 DSRC group proposes a set of V2V channel models [93] to evaluate and test the PHY layer under time- and frequency-selective propagation conditions. ETSI ITS-G5 standard also proposes to use tap-delay-lines (TDL) models for system testing and link-level simulations [87]. 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. The scenario description for each environments taken from [87, 93, 94] is describe in Table 2.4.

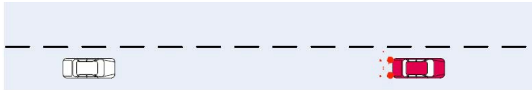
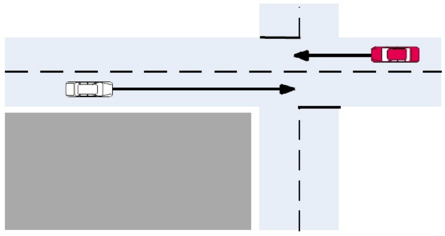
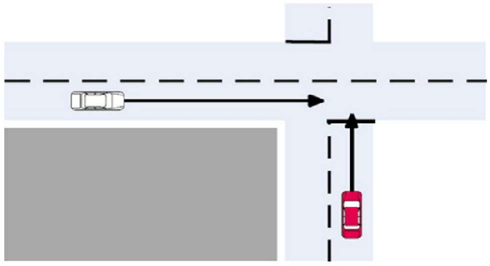
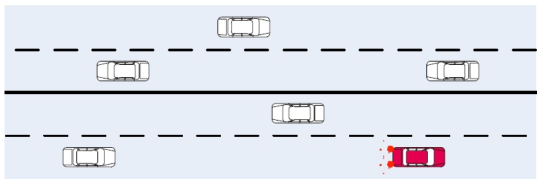
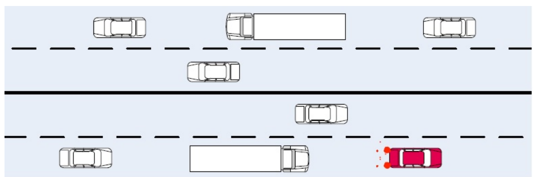
TGbd recommends the TDL channel model as a base reference for evaluating the performance of PHY layer enhancements. It classifies the TDL channel models into the classical and enhanced models [94]. The enhanced model is still the TDL model with the same channel profile, i.e., rural LOS, urban approaching LOS, urban crossing NLOS, highway LOS, and highway NLOS. However, it provides more taps with more extended delay spread and higher Doppler shifts to reflect more challenging fading channels and having channel characteristics that were intended to match the real-world empirical measurement. Considering Δf is the Doppler shift, and λ is the wavelength in meters calculated by dividing the speed of light with the carrier frequency, the maximum relative speed between vehicles can be derived from the Doppler shift parameter of the TDL model and can be calculated as:

$$v_{rel} = \Delta f \cdot \lambda \tag{2.27}$$

The specifications of each environment, taken from [93] and [94], which are differentiated by a set of delays, power, and Doppler spectrum, and also the maximum differential speed calculates using equation 2.27 are summarized in Table 2.5.

Both the classical and enhanced TDL model does not support MIMO modeling. In order

Table 2.4: Scenario for the VANETs environments

Scenario	**Description**
Rural LOS : Intended primary as a reference result, this channel applies in very open environments where other vehicles, buildings, and large fences are absent	
Urban Approaching LOS : Two vehicles approaching each other in an Urban setting with buildings nearby.	
Urban Crossing NLOS : Two vehicles approaching an Urban blind intersection with other traffic presents. The building, fences present on all corners	
Highway LOS : Two cars following each other on Multilane inter-region roadways such as Autobahns, Signs, overpasses, hill sides and other traffic presents	
Highway NLOS : As for Highway LOS but with occluding truck present between the vehicles	

to evaluate the performance of the MIMO-STBC 2×2 system, we build the new MIMO V2X channel model based on the values of the parameters of power, delay spread, and Doppler shift from the classical and enhanced TDL model.

Table 2.5: Power, delay, doppler and relative speed comparison between classical and enhanced TDL model for VANETs environments

Scenario	**Power (dB)**	**Delay (ns)**	**Doppler (Hz)**	**Max differential speed (km/h)**
Classical rural LOS	[0, -14, -17]	[0, 83, 183]	[0, 492, -295]	144
Classical urban approaching LOS	[0, -8, -10, -15]	[0, 117, 183, 333]	[0, 236, -157, 492]	119
Classical urban crossing NLOS	[0, -3, -4, -10]	[0, 267, 400, 533]	[0, 295, -98, 591]	126
Classical highway LOS	[0, -10, -15, -20]	[0, 100, 167, 500]	[0, 689, -492, 886]	252
Classical highway NLOS	[0, -2, -5, -7]	[0, 200, 433, 700]	[0, 689, -492, 886]	252
Enhanced rural LOS	[0, -12, -15]	[0, 84, 183]	[0, 94, -1176]	232
Enhanced urban approaching LOS	[0, -11, -13, -15]	[0, 222, 334, 533]	[0, 224, 1173, 588]	215
Enhanced urban crossing NLOS	[0, -3, -4, -7, -15]	[0, 220, 266, 475, 630]	[0, -142, -542, -155, 320]	158
Enhanced highway LOS	[0, -11, -13, -17]	[0, 167, 433, 600]	[0, 1941, -1176, -391]	571
Enhanced highway NLOS	[0, -2, -5, -7, -15]	[0, 100, 500, 867, 1152]	[0, 50, 1157, -2352, 1573]	718

2.5 VANETs Problem Statement

In the beginning, 802.11p was developed for safety applications using broadcast transmission and using small size packets. For example, the V2X collision avoidance application used a basic safety message (BSM), also known as a cooperative awareness message (CAM) in Europe. It has a small frame size requirement, which is only 200 Bytes. Today's 802.11p devices support this application, typically using MCS3 (QPSK with a code rate of 1/2) with data rates of 6Mbps. However, the future NGV applications, like sensor sharing or map downloading, need a bigger frame size, around 1500 Bytes, and higher data rates. This section describes the problem statement of the 802.11p legacy standard, where its performance is affected by the frame size and data rates (MCS) used in the transmission. First, we simulate the 802.11p standard's performance in the ideal condition, where there are only two vehicles, one transmitter and one receiver so that there will be only one transmission without interference. We want to investigate the impact of the frame size and MCS on VANETs performances. Then, we also want to investigate the MAC layer's throughput performance in a dense environment. The simulation parameters are summarized in Table 2.6.

2.5.1 The Impact of Packet Size on VANETs Performance

We want to achieve two times higher throughput and operate in higher mobility with vehicles having relative speed up to 500 km/h, as stated in the PAR of the 802.11bd standard. So in this simulation, we choose the enhanced highway LOS as our VANETs environment because it has a maximum differential speed of 571 km/h. Figure 2.7 shows the throughput performance

Table 2.6: Simulation parameters for problem statement of the 802.11p legacy standards.

Parameters	Value	Description	Parameters	Value	Description
T_{slot}	13μs	Slot time	CW	15	Contention window size
T_{SIFS}	32μs	SIFS time	L_{MAC}	32 Bytes	Data MAC header
T_{DIFS}	58μs	DIFS time	$L_{Payload}$	100 - 1500 Bytes	Data payload
$t_{preamble}$	40μs	PHY header duration	L_{FCS}	4 Bytes	FCS size
T_{Sym}	8μs	OFDM symbol time	L_{ACK}	10 Bytes	ACK MAC header
T_{Prop}	1μs	Propagation time	MCS	All Modulation	Modulation coding scheme
Channel	Enhanced highway LOS	V2X environment scenario			

in the enhanced highway LOS environment for ideal transmission without interference using different MCS and different frame sizes.

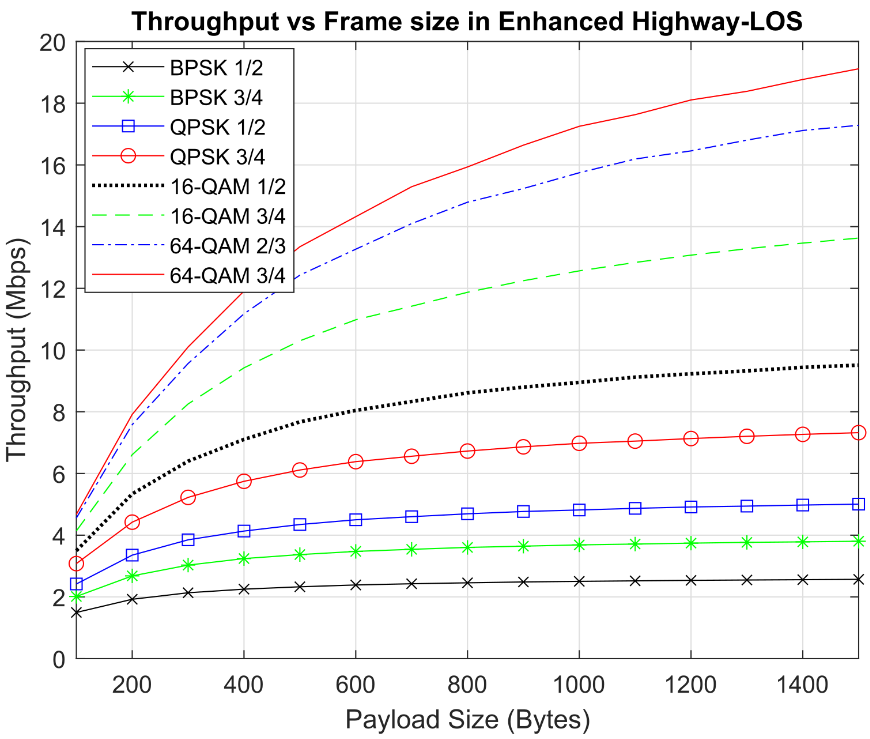


Figure 2.7: Throughput performance in ideal conditions with one transmission without interference, using different payload sizes for all MCS in enhanced highway LOS environment.

We can see from Figure 2.7 that to improve the throughput performance; we can use a bigger frame size and higher MCS. However, using a bigger frame size will increase the PER (reducing the reliability) and delay/latency, while using higher MCS needs higher SNR to decode the packet successfully. On the contrary, using a smaller frame size will reduce the throughput efficiency due to packet preamble overheads. There is a trade-off between frame size, MCS, and performance (throughput and reliability) of the NGV applications.

2.5.2 The Impact of Vehicles Density on VANETs Performance

The second problem statement concerns the limitation of the CSMA/CA protocol and is called the blocking problem. During a transmission, CSMA/CA will defer other vehicles so that there will only be one transmission in a slot time. This technique will reduce the MAC layer's throughput efficiency in a dense environment where many vehicles compete on the same channel. We simulate the throughput performance of a small size frame (100 Bytes) and use a minimum value of CW = 15 to show the worst possible condition where the preamble overhead is high, and the probability of collision is also high. Figure 2.8 shows the simulation results of the throughput performance of the various vehicles (up to 50 vehicles), using all MCS in enhanced highway LOS environments.

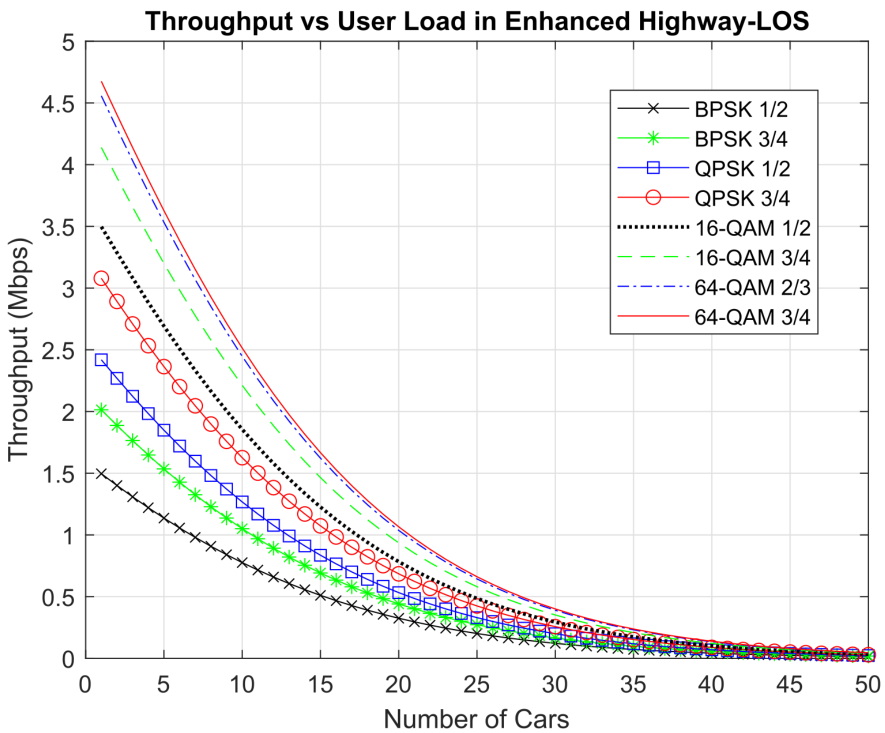


Figure 2.8: Throughput performance of the various number of vehicles using CW = 15 with 100 Bytes frame size for all MCS in enhanced highway LOS environment.

In Figure 2.8, we can see the degradation of the throughput efficiency of the CSMA/CA protocol due to a dense environment. A greater number of cars competing on the same channel will reduce the throughput due to the small value of CW that leads to a high probability of collision.

2.6 Conclusion

We choose the PER of various modulation schemes for the PHY layer's performance metric. The PER is simulated and compared against the theoretical PER calculation. Our simulation result 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. It should be noted that 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 OFDM technique's objective.

We also investigate the MAC layer's throughput performance for the VANETs communication system. We highlighted two problematics regarding the throughput performance of the legacy standard IEEE 802.11p in the high mobility environment. The first problem statement is about the impact of frame size and data rates (MCS). Bigger frame size and higher MCS could improve the throughput performance in the ideal condition with only one transmission without interference. However, using a bigger frame size will increase the PER (reducing the reliability) and delay/latency, while using higher MCS needs higher SNR to decode the packet successfully. On the contrary, using a smaller frame size will reduce the throughput efficiency due to packet preamble overheads. There is a trade-off between frame size, MCS, and performance (throughput and reliability) of the NGV applications.

The second problem statement is concerning the limitation of the CSMA/CA called the blocking problem. During a transmission, CSMA/CA will defer other vehicles to prevent interference and collision. This technique will reduce the MAC layer's throughput efficiency in a dense environment where many vehicles compete on the same channel. We simulate the throughput performance of a small size frame (100 Bytes) and use a minimum value of CW = 15 to show the worst possible condition where the preamble overhead is high, and the probability of collision is also high. Our simulation result shows the MAC layer's throughput degradation in a dense VANETs environment. In the next chapter, we investigate several PHY layer enhancements from other 802.11 family standards that could be adopted into IEEE 802.11bd and address the two aforementioned problems.

Chapter 3

PHY Layer Enhancements for Next-Generation VANETs

3.1 Motivation

IEEE 802.11p is a robust and mature technology for DSRC where several field trials have been carried out, and the performance of various V2X communication scenarios has been investigated. On the other hand, other IEEE 802.11 or wireless local area network (WLAN) family standards have evolved and offered some techniques that could be adopted 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 NGV. In the previous chapter, we identify two problematics of the IEEE 802.11p standard, i.e., the impact of frame size and vehicle density in the VANETs performance. This chapter investigates the performance of PHY layer amendments to 802.11p, i.e., the use of LDPC and midambles, MIMO-STBC, DCM, and extended-range mode. We build and simulate our NGV system in several V2V channel environments as proposed by TGbd. We use the packet error rate (PER) and throughput in the PHY layer as the performance metrics, and compare it with legacy IEEE 802.11p standard.

3.2 Background

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 [43], 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 [95, 96, 97, 98]. 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 channel estimation especially when LDPC coding is used.

This chapter 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 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 [99] 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 [100] analyzes PHY layer reliability's performance on 802.11bd and NR V2X in terms of PER specifically for ultra-reliable communications.

The contributions in this chapter 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 as proposed by TGbd, using the PER and throughput at the PHY layer as the performance metrics.

- The V2V channel proposed by TGbd [93, 94] 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.

3.3 PHY Layer Enhancements for NGV

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.

3.3.1 LDPC and Midambles

Forward error correction (FEC) is an essential part of the V2X communication system. This channel coding 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 [101].

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.

Figure 3.1 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 $eff = \frac{M}{(M+1)}$. It means that the higher value of midamble frequency will lead to better channel estimation and 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 Figure 3.1, with $M = 2$, the channel efficiency will reduce to 66.7%.

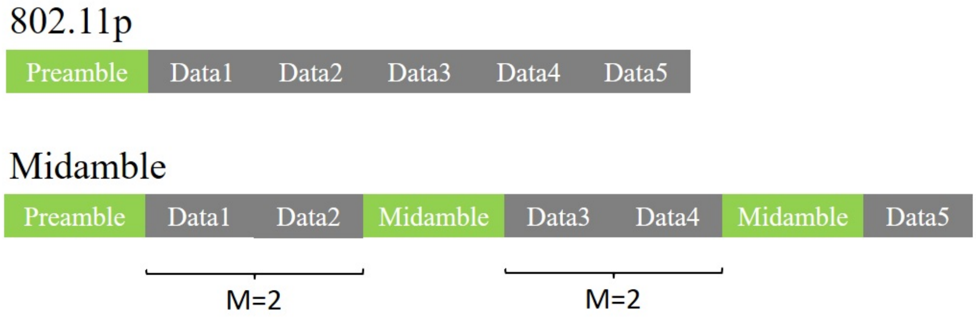


Figure 3.1: Midambles technique introduced in 802.11ax.

3.3.2 DCM and Extended-Range Mode

Both DCM and extended-range mode techniques are introduced in the 802.11ax standard. According to [102, 103], 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 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.

3.3.3 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 [104], 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.

To conclude this section, we summarize all the key features of the PHY layer enhancements adopted for the NGV 802.11bd standard in Table 3.1.

Table 3.1: 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

3.4 Simulation results

Table 3.2: Simulation parameters for V2X safety and high throughput (non-safety) application.

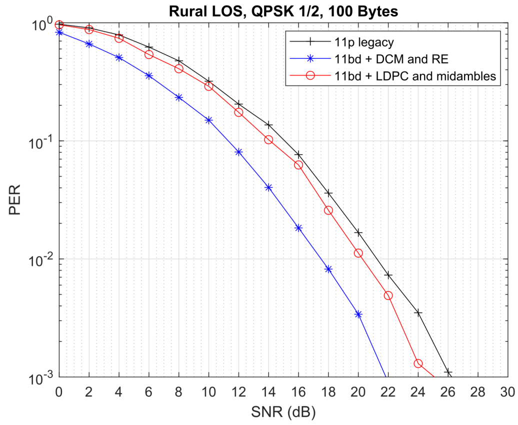
Parameter	Safety Application	High Throughput Application
Bandwidth	10 MHz	10 MHz
Spatial stream	1	1–2 (multiple)
Channel model	V2Vchannel	MIMO-V2V channel
Packet size	100 bytes	300 bytes
MCS	QPSK-1/2	16-QAM 3/4
PHY layer enhancements	DCM, extended-range mode, LDPC, midambles	MIMO-STBC

We want to simulate the performance of V2X applications in NGV communication. Many V2X applications need different 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 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 safety 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 3.2.

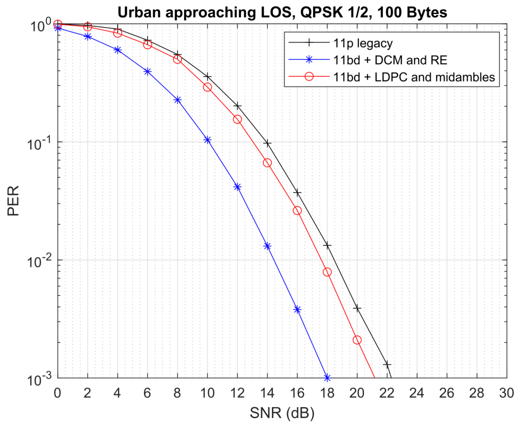
Figure 3.2 and Figure 3.3 show the PER and throughput performance of the V2V safety application. From Figure 3.2, we can see that PER performance of 802.11bd using LDPC and midambles is always better than legacy 802.11p in all V2V environments. This result justifies using the LDPC and midamble technique 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 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.

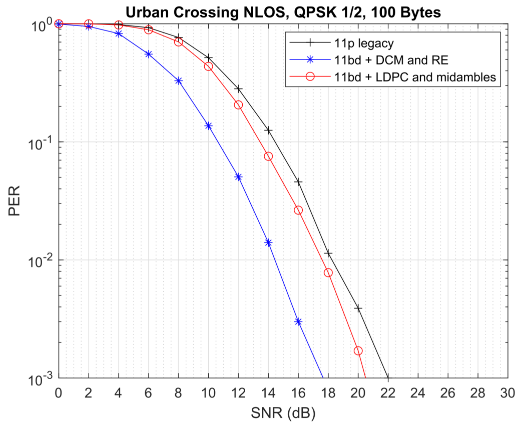
From Figure 3.3, we can see that the throughput performance of 802.11bd using LDPC and midambles is always better than legacy 802.11p in all environments, while 802.11bd using DCM and extended-range mode gives a better throughput performance in the low SNR region and gives the worst throughput performance 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.



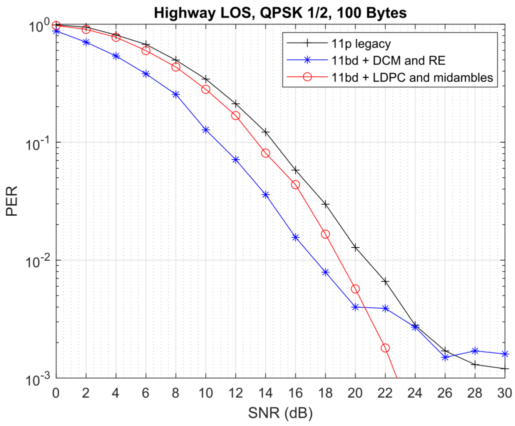
(a) Rural LOS.



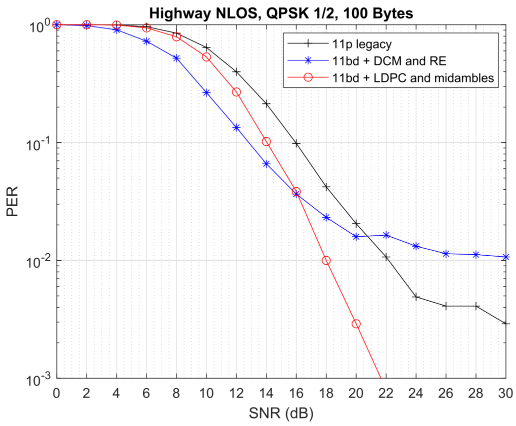
(b) Urban approaching LOS.



(c) Urban crossing NLOS.

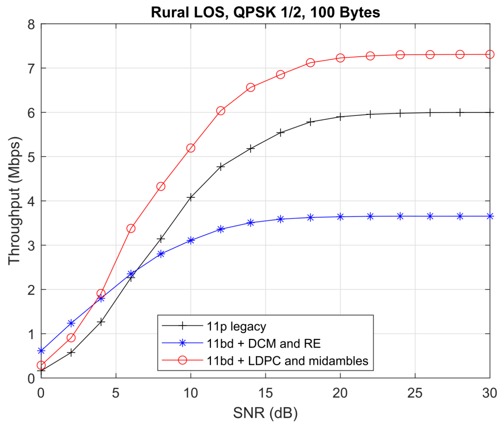


(d) Highway LOS.

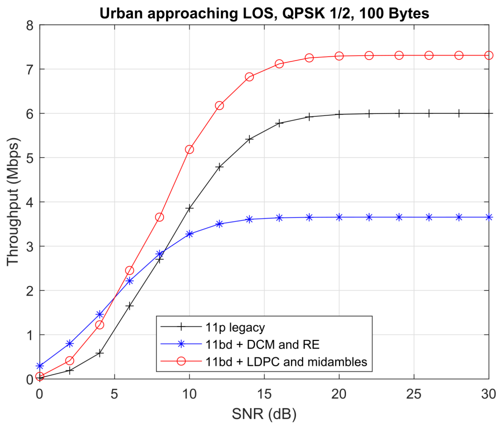


(e) Highway NLOS

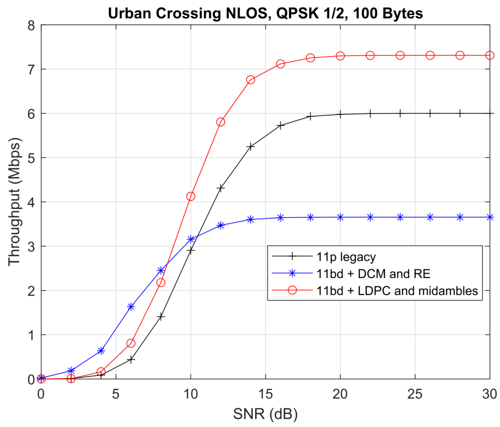
Figure 3.2: PER performance of V2V safety application using 100 Bytes packet size and MCS of QPSK with coding rate of 1/2, at various V2V channel environments.



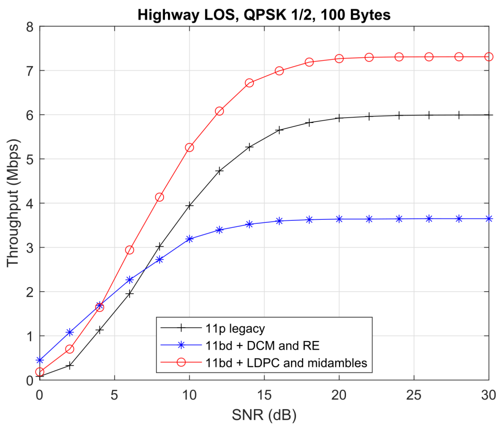
(a) Rural LOS.



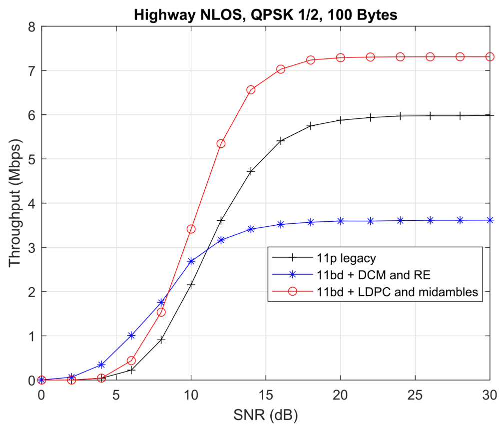
(b) Urban approaching LOS.



(c) Urban crossing NLOS.

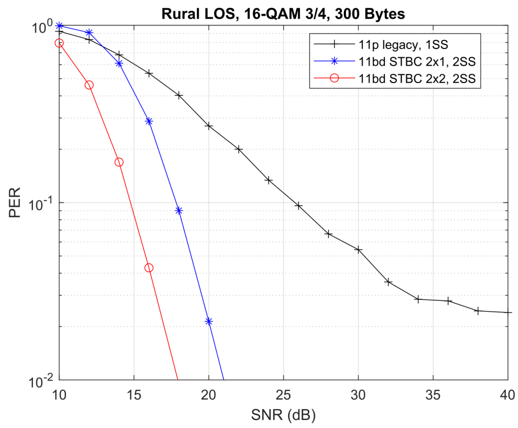


(d) Highway LOS.

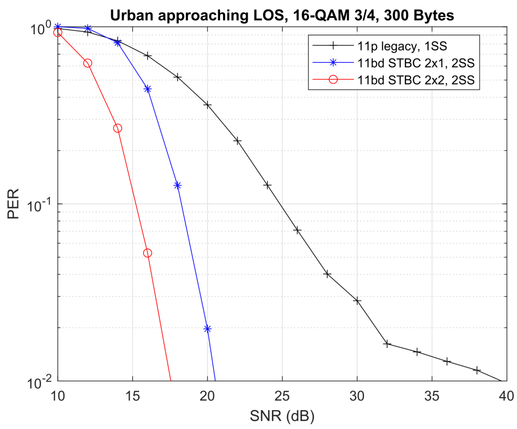


(e) Highway NLOS

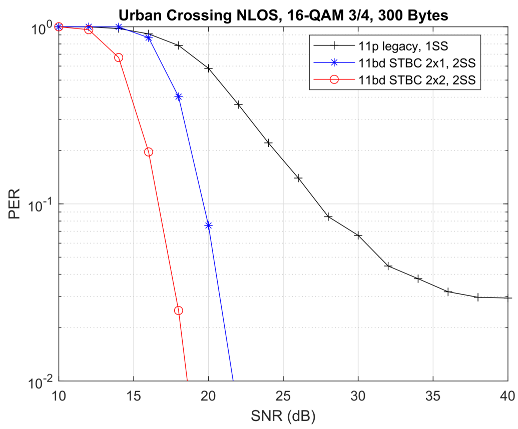
Figure 3.3: Throughput performance of V2V safety application using 100 Bytes packet size and MCS of QPSK with coding rate of 1/2, at various V2V channel environments.



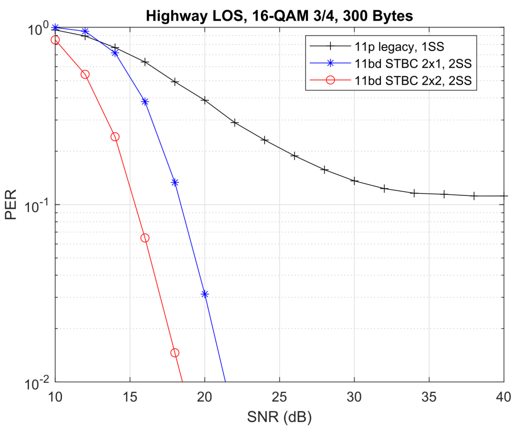
(a) Rural LOS.



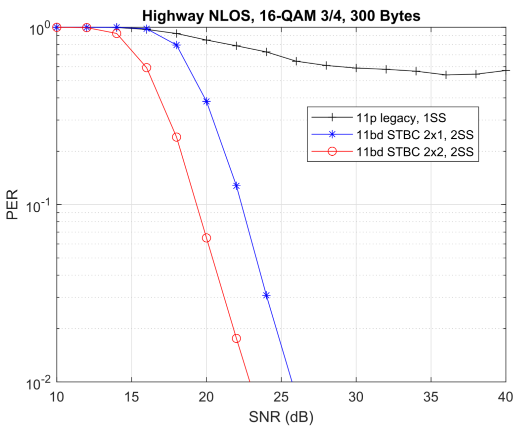
(b) Urban approaching LOS.



(c) Urban crossing NLOS.

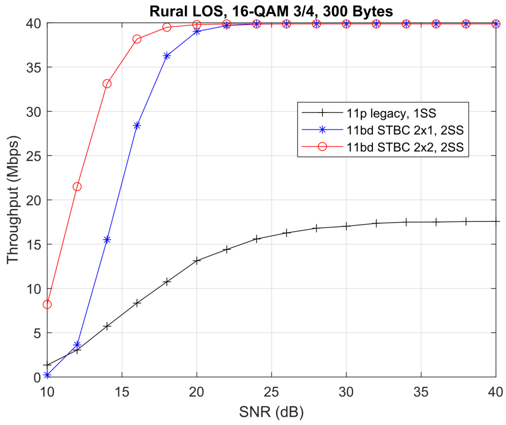


(d) Highway LOS.

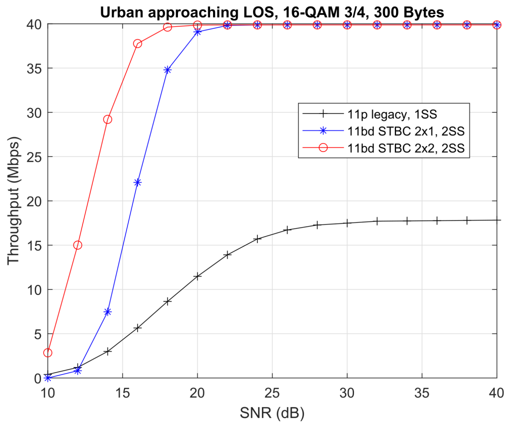


(e) Highway NLOS

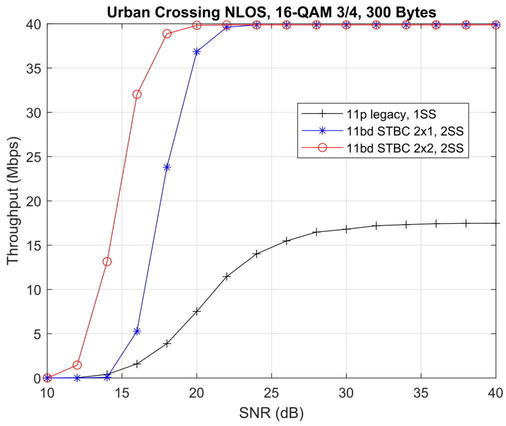
Figure 3.4: PER performance of V2V high throughput application using 300 Bytes packet size and MCS of 16-QAM with coding rate of 3/4, at various V2V channel environments.



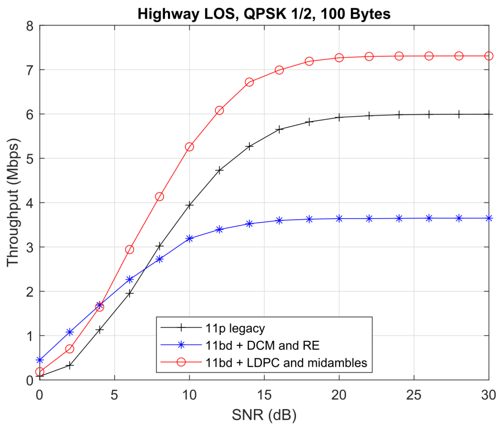
(a) Rural LOS.



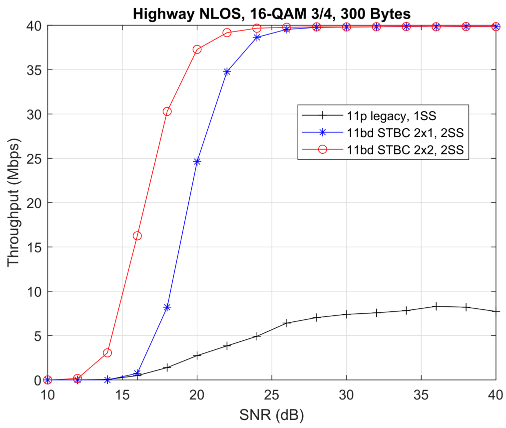
(b) Urban approaching LOS.



(c) Urban crossing NLOS.



(d) Highway LOS.



(e) Highway NLOS

Figure 3.5: Throughput 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.

Figure 3.4 and Figure 3.5 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 $\times 2$ 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 or 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 [104].

3.5 Conclusion

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 show 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/NET cross-layer design approach to achieve the NGV PAR. [1]

[1] This chapter is a slightly modified version of PHY layer enhancements for next generation V2X communication (https://doi.org/10.1016/j.vehcom.2021.100385), published in Vehicular Communications Journal Volume 32, December 2021, and has been reproduced here with the permission of the copyright holder.

Chapter 4

PHY/MAC/NET Cross-Layer Design for Next-Generation VANETs

4.1 Motivation

IEEE recently created a NGV task group, known as TGbd, to amend the legacy standard of 802.11p to 802.11bd. This new standard was written to answer the future vehicular communication challenges that require a different QoS with various data rates, frame sizes, and communication ranges. Based on their PAR, 802.11bd defines several objectives, such as having higher throughput, operating in higher mobility environments, and improving communication range. This chapter investigates the use of PHY, MAC, and NET cross-layer design to achieve two objectives defined by NGV's PAR, i.e. having two times higher throughput at the MAC layer and operating in a highly mobile environment with relative speed between vehicles of up to 500 km/h. We consider using MCE, DCM, and MIMO-STBC at the PHY layer; frame aggregation, CW size, and retransmission limit at the MAC layer; and also broadcast or unicast single-hop transmission at the NET layer. In this chapter, we simulate the throughput efficiency performance for two types of NGV applications (i.e. safety-related and non-safety-related V2X applications) in the enhanced highway line of sight (LOS) environments.

4.2 Background

For the last decade, 802.11 Wi-Fi family standards have evolved and offer performance improvements such as higher throughput, improved reliability, and more extended communication range. We could adopt some techniques from those Wi-Fi standards to improve the performance of the NGV applications. Recently, IEEE created the NGV task group, also known as TGbd, to amend the legacy standard 802.11p. It works toward a new standard for NGV called 802.11bd. This new standard is made to answer future vehicular communication challenges that require varying data rates, frame sizes, and communication ranges. Based on their PAR, NGV should targets a wider variety of V2X applications that have higher throughput, operate in higher mobility environments, and have a more extensive communication range.

We proposed to use the cross-layer design in all layers to achieves two objectives define by the PAR of 802.11 bd [78]. The first objective is that at least one communication mode achieves two times higher throughput measured at the MAC layer operating at maximum mandatory data rates as defined in 5.9 GHz band, i.e., using 16-QAM with a code rate of 1/2 modulation that has data rates of 12 Mbps in a 10 MHz channel. The second objective is that the standard should operate in a high mobility channel environment at vehicle speeds up to 250 km/h (or having relative speed up to 500 km/h). In the PHY layer, we consider to use MCE, DCM, and MIMO-STBC techniques; in the MAC layer, we consider to use the frame aggregation, the proper CW size, and limited retransmission techniques; in the NET layer, we consider the broadcast and unicast single-hop transmission; while in the application layer, we consider the safety and non-safety V2X application. We choose to simulate the NGV applications in the enhanced highway LOS environments to represent the high mobility channel having relative speed up to 500 km/h, because it has maximum differential speed of 571 km/h.

4.3 Cross-Layer Design for NGV 802.11bd

As mentioned in the introduction section, we use the cross-layer design approach to achieve two objectives of 802.11bd, as stated in their PAR, i.e., having two times higher throughput measured in the MAC layer and operating in high mobility channel environments. This section describes the consideration of advanced techniques to be used in each layer. All techniques are adopted from other 802.11 Wi-Fi standards that have already evolved for the last decade, and we use the cross-layer design approach to improve the performance of future NGV applications.

4.3.1 PHY Layer Consideration

MCE

In the PHY layer, we use FEC, also known as channel coding, to handle the communication system's error. This FEC technique will make the transmitter coding the data first and then sends the coded data, while the receiver will receive the coded data and tries to decode it.

If there is an error in the decoded data, the receiver will try to correct it. There are two types of channel coding, i.e., convolutional coding and block coding. 802.11p is a legacy non-HT standard that uses the BCC technique. It is a state machine-based and uses the Viterbi algorithm in the decoding process widely used in the communication system. LDPC technique is a block coding technique using a complex algebra approach and introduced in 802.11n/ac as the optional part of PHY layer specification, and then gets regularized in 802.11ax standard. The performance of LDPC compare to BCC provides significant gains in standard indoor and low mobility scenarios.

TGbd proposes to use the LDPC technique for the enhanced FEC schemes of the 802.11bd. However, the performance evaluation of LDPC in the context of V2X communication (outdoor and high mobility scenario) is inferior to BCC techniques due to the high latency of the LDPC decoding process [105, 106]. The legacy frame format was designed to assume that the channel coherence time is greater than the maximum packet duration. This assumption is easily violated in the V2X environment that has a Doppler effect problem even at moderate speeds. Indeed, the fast time-varying channel of V2X communication within the frame duration and the high latency of the LDPC decoding make the receiver unable to decode the frame properly. The current state-of-the-art V2X products usually using a data-aided channel estimation (DACE) algorithm for a better channel tracking in the wireless environment [107, 108]. Alternatively, TGbd proposes using the MCE technique, which uses reference symbols in-between data fields known as midambles, to have a better channel tracking against high Doppler effect. Midambles are introduced in the 802.11ax standard. The content of the midambles is the same as the NGV-LTF part in the preamble field and presents every certain number of OFDM symbols, known as midambles frequency. The MCE technique gives an up-to-date channel estimation process that leads to better channel tracking and improves the PER performance in the wireless V2X environments at the expense of channel efficiency. The higher midambles frequency will give a better PER performance, but it will also reduce the channel capacity because the MCE technique needs to send the midambles more often.

DCM

DCM technique is first introduced in the 802.11ax standard. This technique will send the same symbols on a pair of sub-carriers with a frequency diversity [102, 103]. It is applied for low data rates, i.e., MCS0, MCS1, MCS3, and MCS4, up to 2 spatial streams, and enabled only for a single-user case or not applicable for MU-MIMO nor STBC. Other than adding complexity, there is no change to be made in the transmitter or receiver block. By implementing the DCM, we will have frequency diversity gain and more reliable communication because of its robustness to narrow-band interference. These advantages will lead to significant PER performance improvement at the expense of halving the data-rates because it needs to send the same symbol twice. It means that to achieves the same throughput performance of 802.11p with MCS0 (BPSK with a code rate of 1/2), the 802.11bd with DCM technique should use the MCS1 (QPSK with a code rate of 1/2). The same rule will apply for other modulation schemes, where the throughput performance of QPSK modulation in 802.11p can be achieved by 16-QAM modulation using the same code rate in the 802.11bd using the DCM technique.

MIMO-STBC

Despite all the MIMO system benefits, very few papers have investigated the possibility of adopting this technique for V2X communications. MIMO is considered too challenging for V2X because it requires a pre-coding based on precise knowledge of the channel state information (CSI).

TGbd agrees that single-stream OCB broadcast transmission is the only mode to be supported for in IEEE 802.11bd standard [109]. The nature of V2X applications for safety-related that use a broadcast transmission with no acknowledgment (no-ACK) from the receiver, make the receiver could not get the CSI. However, the future NGV Applications for the non-safety applications that use unicast transmission scenarios and needs higher throughput requirement could adopt the MIMO technique because it uses unicast transmission, and the receiver could send the ACK data.

STBC is a transmitter diversity scheme with multiple antennas in the transmitter side and works regardless of the number of receiver antennas. MIMO-STBC 2x2 system will have two spatial streams sent from the transmitter to the receiver, where both are having two antennas. Multiple streams can be used for NGV applications that need higher throughput requirement as multiple antennas become available, but limited only for unicast transmissions scenario. The recent work of TGbd [104] simulated the goodput of two antennas MIMO system using D2D channel models where two spatial streams transmission provides 50%-100% gain compare to one spatial stream.

4.3.2 MAC Layer Consideration

The MAC layer of 802.11p uses CSMA/CA in distributed coordination function (DCF). The V2X communications use the CSMA/CA without a RTS and CTS packets. It also implements the priority of media access by the QoS, known as enhanced multimedia distributed control access (EDCA). The 802.11p also introduces the new operation mode called the outside context of a basic service set (OCB) ([110], [111]). OCB can make the vehicle communicate directly without any authentication or association process, and the only parameters to set are the central channel frequency and the channel bandwidth. The next section will discuss the possible MAC layer enhancements techniques used to improve NGV applications' performances.

Frame Aggregation

The future NGV applications must support the wide variety of applications that need larger data payloads size, such as sensor sharing applications, infrastructure applications, and automated driving assistance applications [112]. 802.11p is a non-HT standard that does not support frame aggregation. TGbd proposes to use the frame aggregation technique for higher rates to improve overall performance or efficiency ([113] and [114]). The frame aggregation technique is introduced in 802.11n and the newer 802.11 family standards. The reason behind the aggregation of several sub-frames into a single frame transmission is to reduce the PHY header overhead and to improve the MAC layer's efficiency. A literature study on frame aggregation for 802.11 standards can be found in [115], [116], [117], [118], and [119], and it provides the improvement of throughput performance around 50-100 Mbps. There are two types of aggregation, i.e., aggregate MAC service data unit (A-MSDU) and aggregate MAC protocol data unit (A-MPDU). Both frame aggregation techniques have their advantages and disadvantages that will affect their use in 802.11bd.

Figure 4.1 describes the comparison between the packet without aggregation, packet with A-MPDU, and packet with A-MSDU. A-MSDU allows multiple MSDU to be aggregated in a single MPDU and sent to the same receiver. This technique provides a better MAC layer efficiency because it reduces the PHY header and MAC header overhead. A-MSDU can only be used for unicast transmission (cannot be used for broadcast and multicast transmission) because all sub-frames share the same MAC header. On the other side, the A-MPDU technique allows multiple MPDU subframes to be concatenated with a single PHY header. In terms of efficiency, A-MPDU is inferior to A-MSDU because it only considers the PHY header overhead. However, in terms of reliability, it is superior compare to A-MSDU because each sub-frame has its own FCS. It also offers higher MAC throughput and can be used for broadcast, multicast, and unicast transmission because each sub-frame has its own MAC header. We consider using the A-MPPDU technique because it works for OCB with broadcast, multicast, or unicast transmission and offers higher MAC throughput.

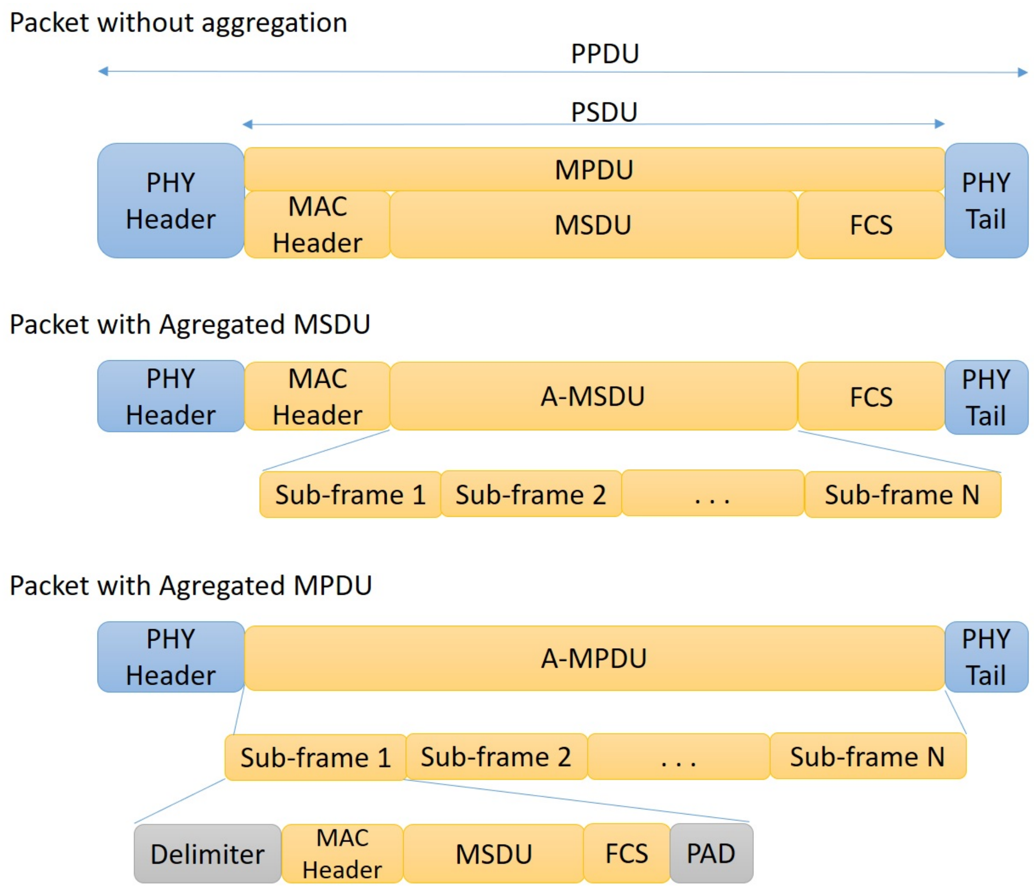


Figure 4.1: Comparison between A-MSDU and A-MPDU technique.

CW Size

The MAC protocol in the V2X communication system uses CSMA/CA with no exponential back-off. It means the value of the CW is fixed in the MAC protocol. The reason behind this approach is because, in the beginning, the 802.11p was designed for a broadcast-based system that does not send the acknowledgment frame back to the transmitter, and also the use of exponential back-off has a drawback that can lead to large CW size, which can increase the latency or delay. According to the 802.11p standard, CW's value in the MAC layer protocol is 15 to 1023. For broadcast transmission, setting the CW's fixed value will be crucial due to the blocking problem limitation of the CSMA/CA that only allows one transmission at a slot time. The fix CW with the small value will reduce the throughput performance of the MAC layer due to many collisions, while the fix CW with the enormous value will increase the delay. We consider using the proper value of the CW size for the broadcast transmission to improve the throughput performance.

Retransmission

In the PHY layer, we use FEC or channel coding to handle errors in the communication system. While in the MAC layer, we use the retransmission technique. Retransmission can be used only for unicast transmission scenarios because the transmitter needs to know whether the data has been successfully delivered or not by waiting for the ACK from the receiver. If it does not receive the ACK, the transmitter will apply the retransmission scheme. This technique will improve the reliability of the V2X communication system. However, we need to consider limiting the number of retransmission because it can lead to higher latency or delay. We consider using retransmission with a limitation for the V2X application that uses pairwise unicast acknowledge transmission scenario.

4.3.3 NET Layer Consideration

In the NET layer, both DSRC and ITS-G5 use the broadcast, unicast, and multicast (geocast or geo networking in ITS G5 standard) in single-hop or multi-hop scenarios. We only consider the broadcast and unicast with a single-hop transmission scenario. The MAC layer of the V2X application use CSMA/CA using basic access schema with data and ACK mechanism without RTS and CTS. It also introduced OCB, and it should be noted that OCB for V2X communication works with two modes, i.e., broadcast unacknowledged and pairwise unicast acknowledged transmission. We use broadcast transmission for safety-related V2X applications, while the unicast transmission is used for non-safety-related V2X applications that need higher throughput, also known as bandwidth-hungry applications.

4.3.4 Cross-Layer Design for NGV Applications

We want to achieve the two goals demanded by the NGV standard, i.e., two times higher throughput in the MAC layer and operates in a high mobility environment, using a cross-layer design approach. Our cross-layer designs are based on the NGV application type, whether for safety applications or non-safety applications. We assume that the safety applications use small frame size and broadcast single-hop transmission, while the non-safety applications use big frame size and unicast single-hop transmission. Table 4.1 summarizes the PHY, MAC, and NET layer considerations for the NGV applications.

Table 4.1: PHY, MAC and NET consideration for the future NGV applications

Consideration	**802.11bd NGV Application**	
	Safety-related	**Non-safety related**
PHY layer	MCE (LDPC + Midambles), DCM	MCE (LDPC + Midambles), MIMO-STBC 2x2 with 2 Spatial Stream
MAC layer	CSMA/CA without ACK, A-MPDU Frame Aggregation, Proper CW size	CSMA/CA with ACK, A-MPDU Frame Aggregation, Retransmission limit
NET layer	Broadcast, single-hop	Unicast, single-hop

4.4 Simulation Results

This section simulates the PER and throughput performance of both the safety-related and non-safety-related NGV applications, and the simulation parameters are summarized in Table 4.2.

4.4.1 The Performance of Safety Related NGV Applications

This sub section simulates the throughput performance of the safety-related NGV applications that usually have the characteristics of using broadcast transmission and having a small size frame. In this scenario, we assume that the NET layer will use broadcast transmission in single-hop, which means all vehicles are within the communication range, and there will be no hidden node. As stated in the NGV cross-layer design in sub section 4.3.4, we consider to use MCE and DCM technique in the PHY layer, frame aggregation and choose proper CW size in the MAC layer, to improve the performance of safety-related NGV applications. First, we want to investigate the PER performance in the PHY layer for 802.11bd standard.

We can see from Figure 4.2, in the enhanced highway LOS environment, for the PER performance of 10%, or having the reliability of 90%; the legacy 802.11p standard needs a minimum SNR of 25 dB to decode the packet correctly. Using the MCE technique (LDPC and midambles) in the 802.11bd standard, we will have the PER improvement of 5 dB because MCE offers a better channel tracking mechanism than the legacy standard. By adding the DCM technique, that sent the packet twice into different sub-carriers, we can obtain 2 dB more improvement. Indeed, by implementing the PHY layer enhancement technique in the 802.11bd standard, we can obtain a total of 7 dB performance improvement for 90% reliability.

Table 4.2: Simulation parameters for 802.11p and 802.11bd standards

Parameters	**802.11p**	**802.11bd**	**Description**
T_{slot}	13 μs		Slot time
T_{SIFS}	32 μs		SIFS time
T_{DIFS}	58 μs		DIFS time
$t_{preamble}$	40 μs	80 μs	PHY header duration
T_{Sym}	8 μs	16 μs	OFDM symbol time
T_{Prop}	1 μs		Propagation time
CW	15		Contention window size
L_{MAC}	32 Bytes		Data MAC header
$L_{Payload}$	100-300 Bytes	300-1500 Bytes	Data payload
L_{FCS}	4 Bytes		FCS size
L_{ACK}	10 Bytes		ACK MAC header
M_{frames}	64		Maximum number of sub-frames for A-MPDU
M_{length}	64 KBytes		Maximum packet length for A-MPDU
M_{time}	5484 μs		The maximum time duration for A-MPDU
$L_{delimiter}$	4 Bytes		Delimiter size for A-MPDU
MCS	16-QAM 1/2		Modulation coding scheme
$Channel$	Enhanced highway LOS		V2X environment scenario

The improvement of PER performance will affect the throughput performance in the MAC layer because, based on the cross-layer design in the throughput performance analysis, a better PER will increase the probability of successful transmission in the MAC layer. We simulate the MAC layer throughput performance for 90% reliability and consider the worst condition scenario, i.e., using a smaller frame size of (100 Bytes) and minimum CW=15. From Figure 4.3, for the ideal transmission with only one transmitter without interference, we can see that the MAC layer throughput efficiency performance is only 29% for 802.11p and only 34% for 802.11bd. However, when we use cross-layer design by implementing the A-MPDU frame aggregation technique in the MAC layer, we can obtain throughput efficiency improvement to 160%. Indeed, combining several sub-frames into one big aggregated frame can reduce the preamble overhead and improve throughput. In a dense environment, for example, when the total number of the vehicle is 20 (more prominent than the size of CW), we can see the performance degradation of MAC throughput, where 802.11p only has 6.5% efficiency, and the

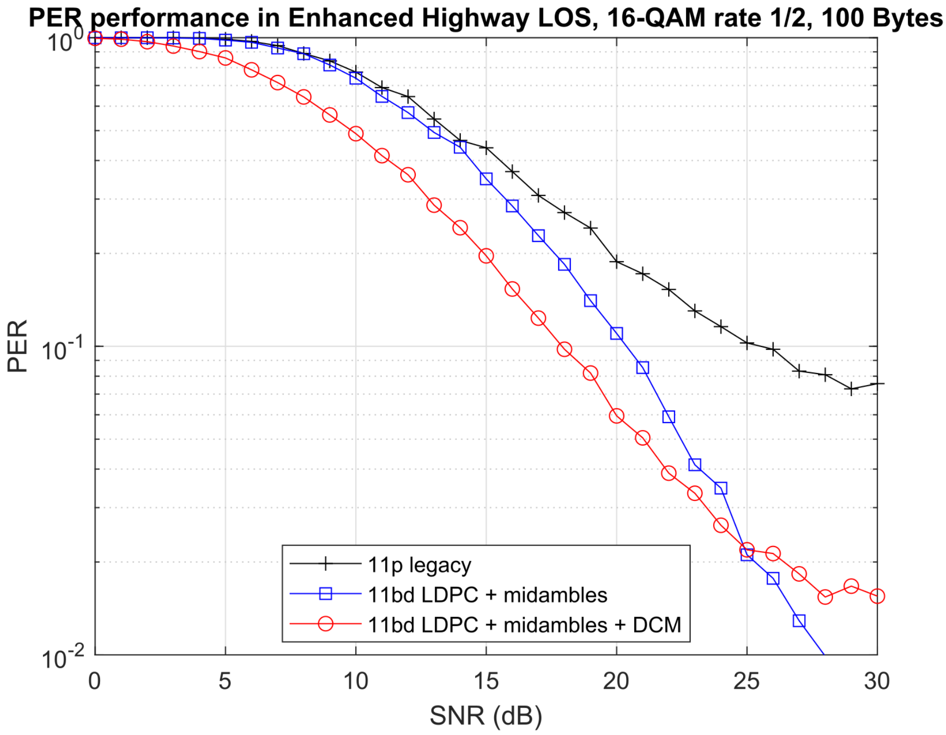


Figure 4.2: PER performance of safety-related NGV applications using PHY layer enhancement for 802.11bd.

802.11bd cross-layer design only has 34% efficiency. To improve the performance in a dense environment, we propose to use a proper CW size. If the size of CW is bigger than the number of contending vehicles, then the collision will be reduced because the probability of having the same CW value is small. For example, by changing the value of CW to 31, the 802.11bd cross-layer design gives 81% throughput efficiency.

Finally, from Figure 04 in the problem statement section, we can improve the throughput by using a bigger packet size. However, the nature of safety V2X applications is using small size packet and broadcast transmission without ACK. We simulate the future safety NGV applications using a 300 bytes frame, as shown in Figure 4.4. For ideal transmission, the cross-layer design achieves the MAC throughput efficiency of 205%, which meets the expectation stated by the PAR of the 802.11bd only by changing the frame size of the NGV application from 100 Bytes to 300 Bytes. Indeed, a bigger frame size will reduce the preamble overhead and improves throughput. For the dense environment, the improvement of MAC throughput efficiency for 20 vehicles using a CW value of 15 and 31 is 43% and 103%, respectively. The bigger CW size compared to the number of vehicles will significantly improve the MAC throughput efficiency. However, it should be noted that a bigger CW size will lead to frame delay or latency.

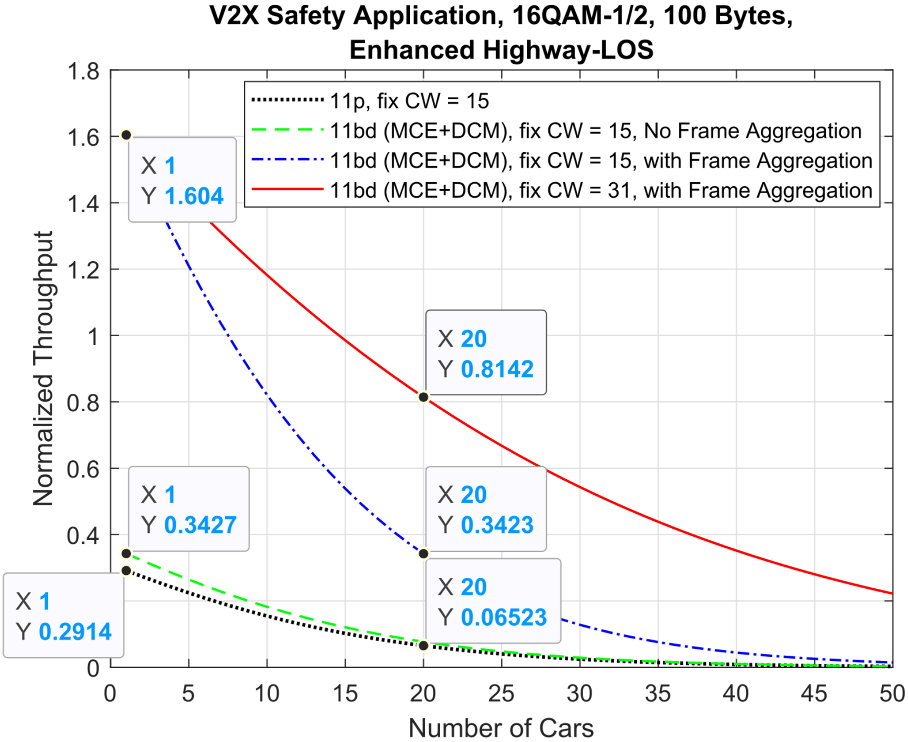


Figure 4.3: Normalized throughput performance of the MAC layer for NGV safety applications using 16QAM rate 1/2 for a frame size of 100 Bytes in enhanced highway LOS.

4.4.2 The Performance of Non-Safety Related NGV Applications

For the non-safety NGV applications simulation, we will use a bigger frame size and pairwise unicast transmission using ACK frames. Unlike broadcast transmission in safety NGV applications where the transmitter does not know the receiver condition, transmitter using unicast transmission scenario will know the data is received or not based on ACK frames sent by the receiver. The transmitter can implement more advanced techniques such as MIMO-STBC in the PHY layer and retransmission technique in the MAC layer because it knows the transmission is a success or failure. This section simulates 802.11bd cross-layer design using MCE and MIMO-STBC 2x2 using two spatial streams in the PHY layer and frame aggregation and retransmission in the MAC layer.

First, we simulate the PER performance for the frame size of 300 Bytes using a 16-QAM rate 1/2 and CW = 15 in enhanced highway LOS, as shown in Figure 4.5. Due to the bigger frame size, higher MCS, and high Doppler effect, the PER performance of 802.11p legacy standard is worst and cannot achieve 90% reliability. However, 802.11bd using MCE and MIMO-STBC with two spatial streams could reach the reliability of 90% around SNR with the value of 23dB.

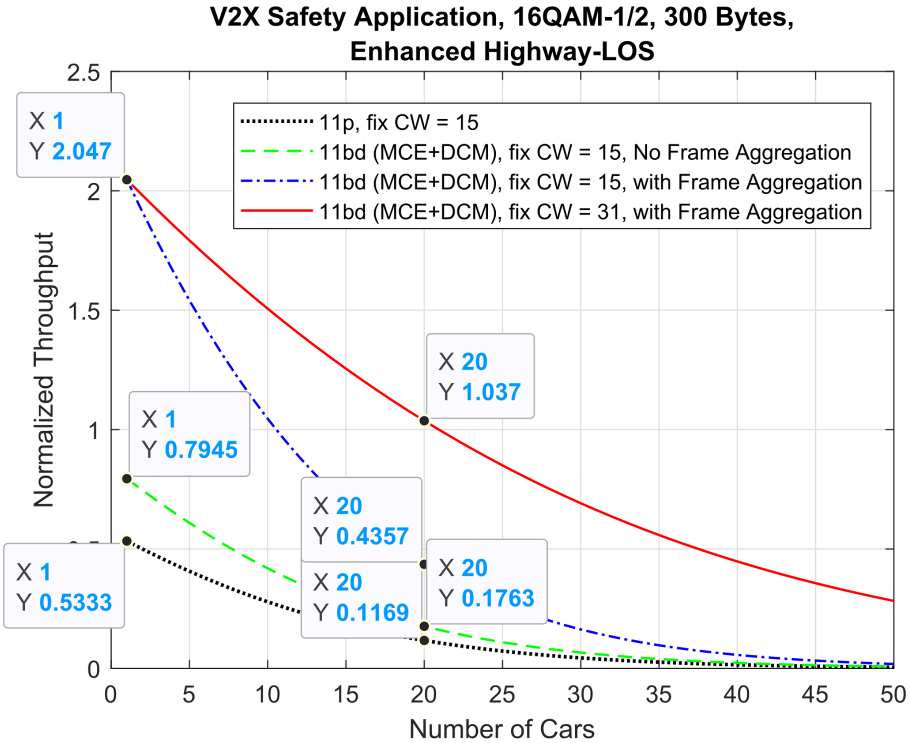


Figure 4.4: Normalized throughput performance of the MAC layer for NGV safety applications using a bigger frame size of 300 Bytes in enhanced highway LOS.

Indeed, with a better channel tracking mechanism and spatial stream diversity, we can improve the PER performance in the PHY layer of the 802.11bd standard.

We simulate the throughput efficiency in the MAC layer, as shown in Figure 4.6. We can see from Figure 10 that in the ideal condition with only one transmission and no interference, the throughput efficiency of the 802.11p is 23%, while the 802.11bd is 49%. Using the cross-layer design, by adding the frame aggregation technique, for reliability performance of 90%, we can have 185% throughput efficiency improvement. In the dense environment with 20 vehicles competing for the channel, we can see the throughput efficiency's performance degradation with a value of 39%. To overcome this problem, we adding one more technique in the MAC layer, i.e., the retransmission technique, which is possible because we use the unicast transmission with ACK. If the transmitter receives ACK from the receiver, it will continue with the next transmission cycle, while if it does not receive ACK, the transmitter will do the retransmission process. Using the cross-layer design, with MCE and MIMO-STBC in the PHY layer and also frame aggregation and retransmission in the MAC layer, the performance of the MAC layer throughput in a dense environment with 20 vehicles can be improved to have an efficiency of 82%.

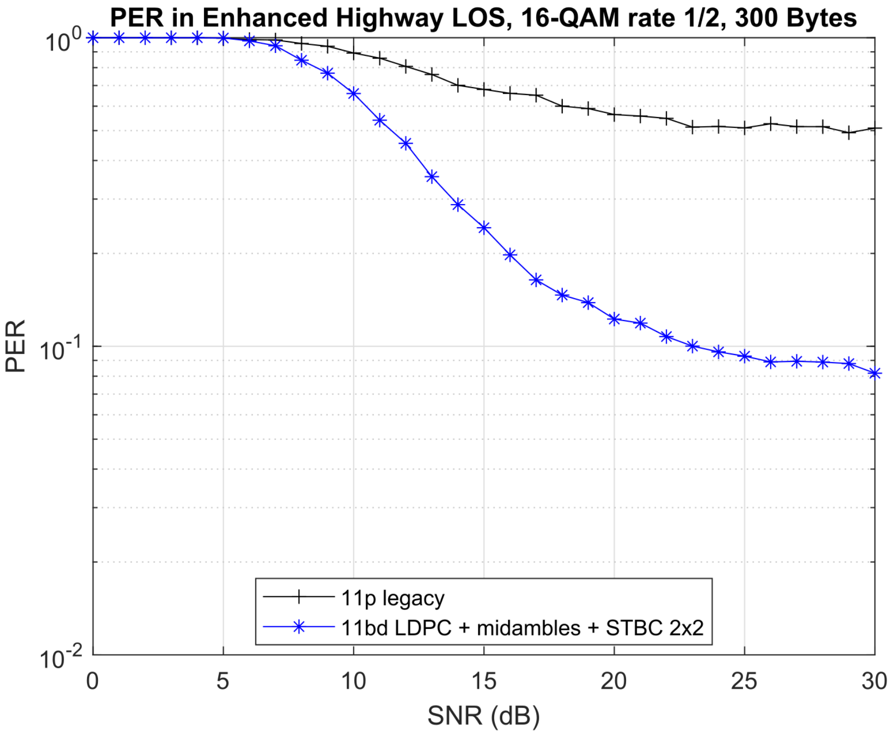


Figure 4.5: PER of non-safety-related NGV with a bigger frame size of 300 Bytes using 16-QAM with code rate 1/2 in the enhanced highway LOS environment.

We can improve throughput performance by using the bigger frame size. The simulation result of non-related NGV applications using 1500 Bytes frame size is shown in Figure 4.7. An ideal one transmission without interference, we obtain the MAC layer throughput efficiency performance of 204%, which answers the PAR of 802.11bd standards. While in the dense environment, we obtain 90% throughput efficiency. We can improve the throughput efficiency in a dense environment by finding the optimum number of retransmission because the high number of retransmission could lead to higher delay or latency and decreasing the throughput efficiency of the MAC layer.

Finally, Table 4.3 summarizes the throughput efficiency performance improvement in safety NGV application and non-safety NGV application for many vehicles. As stated in sub section 4.3.4, the cross-layer design for safety NGV applications are considering the MCE and DCM in the PHY layer, frame aggregation and the size of CW in the MAC layer, and using single-hop broadcast unacknowledged transmission; while non-safety NGV applications are considering the MCE and MIMO-STBC 2× 2 with two spatial streams in PHY layer, frame aggregation and retransmission in MAC layer, and single-hop pairwise unicast with acknowledgment in the NET layer. We can see from Table 4.3, for one vehicle transmission without interference in both

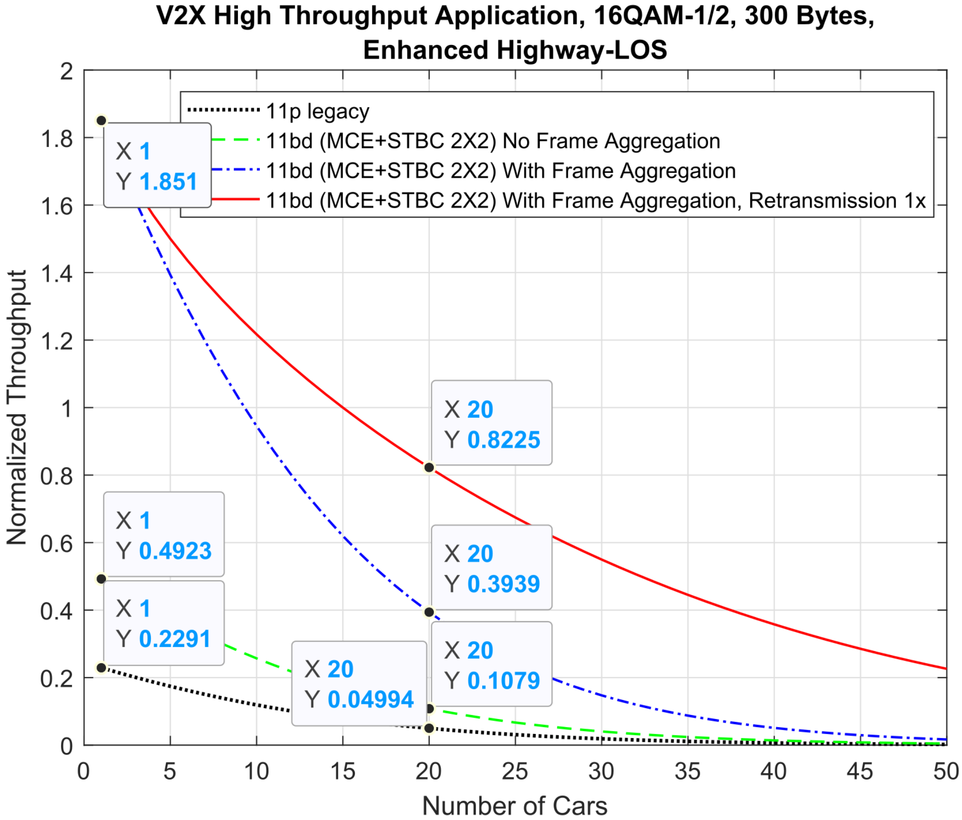


Figure 4.6: The throughput efficiency performance of non-safety-related NGV application using a frame size of 300 Bytes, MCS 16-QAM with code rate 1/2, and CW =15 in enhanced highway LOS environment.

safety and non-safety NGV applications, using the proposed cross-layer design could obtain the two times higher throughput in the MAC layer, as stated in the PAR of the 802.11bd standard. The cross-layer design also gives a better throughput performance in dense environments.

4.5 Conclusion

We design the potential 802.11bd standard using a cross-layer approach by considering other mature techniques used in other Wi-Fi family standards. For the safety-NGV applications, we consider MCE and DCM in the PHY layer, frame aggregation, and proper CW size in the MAC layer, and broadcast single-hop transmission in the NET layer. For the non-safety NGV applications, we consider MCE and MIMO-STBC with two spatial streams in the PHY layer, frame aggregation and retransmission limit in the MAC layer, and unicast single-hop with ACK transmission in the NET layer. We build the simulation of cross-layer NGV 802.11bd standard

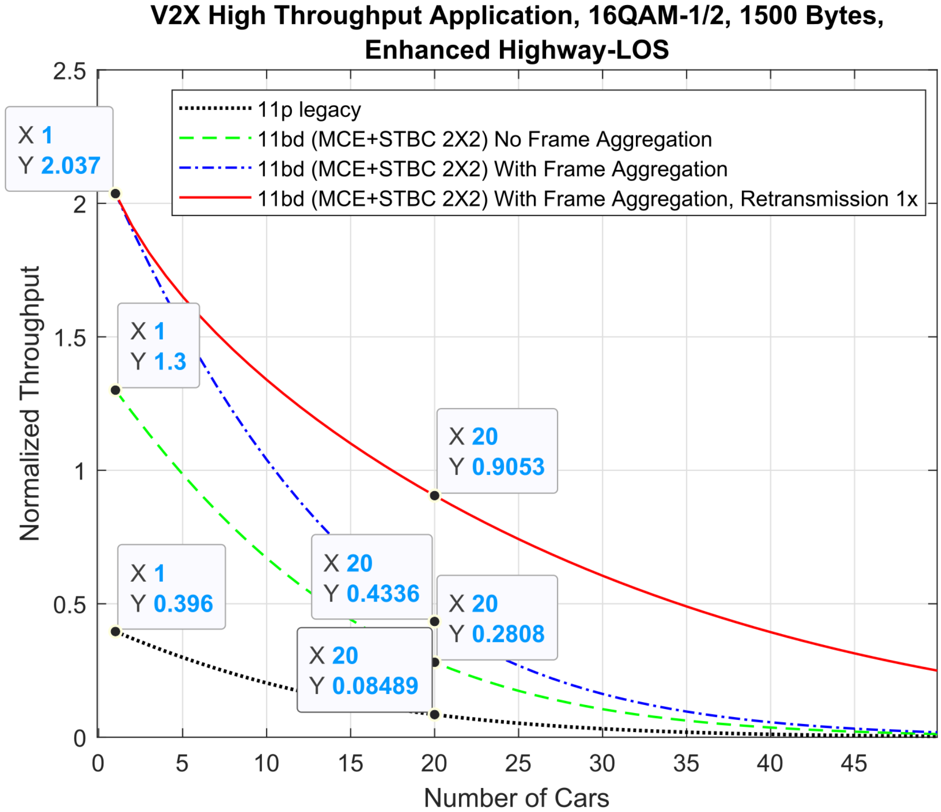


Figure 4.7: The throughput efficiency performance of non-safety-related NGV application using a frame size of 1500 Bytes in enhanced highway LOS environment

Table 4.3: Throughput efficiency improvement of safety and non-safety NGV applications

Number of vehicles	Safety NGV application				Non-safety NGV application			
	802.11p		802.11bd		802.11p		802.11bd	
	100 Bytes	300 Bytes	100 Bytes	300 Bytes	300 Bytes	1500 Bytes	300 Bytes	1500 Bytes
1 vehicle	29%	53%	160%	205%	23%	40%	185%	204%
10 vehicles	15%	28%	118%	150%	12%	20%	121%	134%
20 vehicles	7%	12%	81%	103%	5%	9%	82%	91%
30 vehicles	2%	4.3%	54%	69%	2%	3%	55%	61%
50 vehicles	0.3%	0.5%	22%	28%	0.5%	0.4%	23%	25%

using MCS4, i.e., 16-QAM with a code rate of 1/2, in an enhanced highway LOS environment. Based on the simulation result, the cross-layer design could answer two objectives requested by the PAR of 802.11bd standard, i.e., having two times higher throughput in the MAC layer and operates in a higher mobility environment having a relative speed of 500 km/h. For the ideal condition of one transmission without interference, the safety NGV application using a frame size of 300 Bytes could obtain 2.05x higher throughput. In comparison, the non-safety-related NGV applications using a frame size of 1500 Bytes could obtain 2.04x higher throughput compared to theoretical data rates of MCS5 (i.e., 12 Mbps) in 802.11p standard. The cross-layer design also gives a better throughput performance in a dense environment where many vehicles compete on the same channel.

In this chapter, we only consider how to improve the throughput performance using the cross-layer design. However, other performance metrics are needed to consider, such as delay, latency, or the NGV applications' reliability. For example, although a larger size of the CW and retransmission technique could improve the throughput performance, we need to find an optimum CW and the number of retransmission due to both two techniques are increasing the delay or latency of frame transmission. We are also considering only broadcast and unicast single-hop transmission in the NET layer. There are other scenarios to consider like multicast, geocast, geo networking in ETSI ITS-G5 standard, and a multi-hop transmission, where we need to consider hidden node problems in the MAC layer protocol. For the future work, we need to consider all the possibilities like broadcast, unicast, or multicast (geocast) in single and multi-hop transmission to have a better routing strategy for future NGV applications.

Chapter 5

Cross-Layer Design with Transmit Antenna Selection and Power Adaptation for Blocking Problem in Dense VANETs

5.1 Motivation

The MAC protocol of IEEE 802.11p dedicated to VANETs employs CSMA/CA with DCF which prohibits simultaneous transmissions in the same detection area in order to avoid possible interference and collision between neighboring vehicles. This prohibition results in temporary blocking of data reception, which reduces the average network throughput. To solve this problem, we propose a PHY/MAC cross-layer design based on TAS and TPA. We consider spatial multiplexing ZF-VBLAST over MIMO time-varying flat fading channel to be implemented in V2V communication. The cross-layer approach is implemented to get the maximal network throughput on the MAC layer by using the CSI obtained from the PHY layer, while the MIMO spatial multiplexing technique is used to increase the spectral efficiency. This design helps transmitters select the best combination of transmitting antennas to maximize throughput and choose the adequate transmit power level to minimize neighbors' interference and collision. This solution also comes with a multi-user interference cancellation method that allows simultaneous transmissions as long as the transmit antennas within the same radio range do not exceed the number of receive antennas. In this research work, we investigate the proposed cross-layer architecture by calculating the average network throughput per V2V links concerning different network parameters such as the number of vehicles and antennas.

5.2 Background

The recent development of wireless communication, such as using the MIMO system in the PHY layer, offers several advantages adapted to VANETs. Article [74] provide a review of research challenges, opportunities, and the benefits of employing MIMO signal processing techniques in VANETs. Article [120] explain that although MIMO systems are already used in both infrastructural wireless LAN and the mobile cellular network, the IEEE 802.11p standard for V2V communication still comes without any multi-antenna approach. Therefore they implemented MIMO-enabling PHY layer enhancement for VANETs using Orthogonal Space-Time Block Code (OSTBC). The simulation study shows that the MIMO-enabling approach offers higher robustness against short-term fading caused by the vehicle's mobility and other channel-caused adverseness. Our previous work in [79] also reviews the benefit of employing a MIMO system and cross-layer design in VANETs to improve the overall network performances. By using antenna diversity and spatial multiplexing, we can create a multi-user MIMO (MU-MIMO) system for VANETs, which offers a possibility of higher network throughput.

Moreover, the cross-layer approach that operates in multiple layers can provide a more efficient and robust protocol for answering the distinctive characteristics of VANETs such as high mobility of the vehicles, rapid change of topology, and the ability to predict paths. Article [121] compare the performance of MU-MIMO with single-user (SU-MIMO) in realistic VANET urban and highway road scenarios. They indicate that MU-MIMO is a better choice in commercial and safety applications of VANETs, as it doubles the throughput, increases PDR significantly, and reduces end-to-end delay nearly half. They proposed MU-MIMO in VANETs using combined user and transmitter antennas selection considering linear precoding and Singular Value Decomposition (SVD).

The current MAC standard of IEEE 802.11p dedicated to VANETs uses CSMA/CA with DCF that only allows one transmission at a time and prohibits simultaneous transmissions [43, 97]. A receiver can detect data from all transmitters within its detection range. All neighbors are forbidden to transmit data during an ongoing transmission to avoid potential interference and collision. This mechanism raises a problem called blocking problem, i.e., temporary blocking of reception at the nearby vehicles, resulting in the degradation of the average network throughput. This MAC protocol underutilizes the capability of the MU-MIMO VANETs system, in a way that even though the throughput for one V2V link improves (due to the use of MIMO system), it still suffers from the overall network throughput degradation because the blocking problem still exists. However, wireless ad-hoc communication preferably uses a randomly based access protocol like CSMA/CA due to its simplicity for allowing users to access the medium. Therefore, over the past few years, some research effort has been made to mitigate this blocking effect by proposing a cross-layer PHY/MAC design using MIMO capability in the PHY layer and also enabling multiple clients to do simultaneous transmission while keeping the random access property in the MAC layer.

Article [122] proposed an OFDMA-based MAC protocol for VANETs (OBV) to overcome the grave traffic condition. The simulation results show that OBV outperforms all reference MAC protocols, even doubling their throughput under heavy-load network conditions. However, the article does not mention whether this solution can be implemented on the MU-MIMO architecture. Article [123] proposed cross-layer TAS for decision-feedback detection (DFD) in correlated Ricean MIMO channels. The proposed cross-layer architecture is a point-to-point single-user MIMO wireless system with N_t transmit antennas and N_r receive antennas, where $N_t \leq N_r$. The transmitter implements some $1 : K(K \leq N_t)$ spatial multiplexer and the receiver employ a DFD using the ZF detector to cancel interference and improve the detection of the transmitted packets. The network throughput is calculated using an adopted go-back-n (GBN) protocol at the link level. The simulation result reveals that although the capacity-based antenna selection (AS) is more robust to imperfect channel estimation, the proposed cross-layer AS delivers higher throughput gains than the capacity-based AS. This transmission scheme is then adopted in [76] for multi-user mobile ad hoc networks (MANETs) environment. To maximizing the network throughput of the MANETs, they design the cross-layer architecture using ZF-BLAST by selecting the optimum transmitter's antenna combination. The network throughput is calculated using two adopted ARQ retransmission protocol at the data link layer, i.e., GBN and SR protocols. The simulation shows the improvement of network throughput by allowing more than one pair of nodes to communicate simultaneously for both ARQ protocols. Article [77] extend the work of [76] for VANETs-V2V communication by proposing a PHY/-MAC cross-layer design based on transmit AS with a dedicated MAC protocol. The proposed solution allows vehicles to transmit data simultaneously without interfering with each other as long as the hypothesis called antenna quantity restriction (AQR), i.e., the total number of transmit antennas within the receiver's detection range does not exceed the number of antennas of the receiver, is fulfilled. Indeed, the blocking problem is mitigated, and the simulation results show the improvement of the average network throughput. However, we can observe that the AQR condition is very restrictive in VANETs with high density. The detection area likely contains a large number of transmitting vehicles.

Recent work in [124, 125] study the cooperative vehicular communication at a road intersection in the presence of interference. They show that, in LOS scenario, direct transmission is better for high densities of vehicles. In this research, we extend the work in [77] to mitigate the blocking problem in dense VANETs by proposing a PHY/MAC cross-layer design based on TAS and TPA. We consider spatial multiplexing ZF-VBLAST over MIMO time-varying flat fading channel to be implemented in V2V communication. The cross-layer approach is implemented to get the maximal network throughput on the MAC layer by using the SER information obtained from the PHY layer, while the MIMO spatial multiplexing technique is used to increase the spectral efficiency. The critical idea added to the work in [77] is to add a TPA mechanism to prevent high interference from nearby vehicles. The use of a constant transmit power could lead to unnecessary large transmission ranges and, consequently, to the saturation point that violates the AQR condition. We propose to enhance the cross-layer architecture using transmit AS by adding the TPA algorithm so that the number of simultaneous transmission in the same detection zone always satisfies the AQR condition event in dense VANETs. The contribution of our research in this chapter is summarized as follows:

- We consider a ZF-VBLAST encoding schema with greedy QR decomposition and ordered successive interference cancellation (OSIC) in the PHY layer.
- We are also implementing the TAS and TPA algorithm.
- We consider the retransmission ARQ protocol using GBN and SR in the MAC layer.

5.3 Cross-Layer Design Based on TAS and TPA

This section provides an overview of the system model and the PHY/MAC cross-layer design based on TAS and TPA algorithm. First, we describe the system modeling and then explain the blocking problem in dense VANETs environment. Then summarize the work in [77] by describing the cross-layer design using TAS and the interference-free symbol detection in case of simultaneous transmission for V2V communication. Furthermore, we describe the proposed PHY/MAC cross-layer design.

5.3.1 System Modeling

The radio propagation modeling for V2V communication in this research is based on the empirical adaptation of free-space propagation for non-ideal channel condition by considering additional environment-dependent path loss exponent α [126] given by :

$$P_L = \frac{(4\pi)^2 d^\alpha}{\lambda^2} \tag{5.1}$$

where d is the distance between the transmitter and receiver, α is the path loss exponent, and $\lambda = c/f$ is the wavelength where c is the speed of light and f is the carrier frequency. And then the average received power P_r is calculated as :

$$P_r = P_t + G_t + G_r - 10log_{10}(P_L) \tag{5.2}$$

where P_t is the transmission power, G_t and G_r are the antenna gains of the transmitting and receiving antennas respectively, and P_L is the path loss. The communication between vehicles depends on the transmission power of the transmitter P_t and the receiver sensitivity of the receiver R_s. We define the radio communication range R as the distance where $P_r = R_s$. So, the radio communication range is calculated as :

$$R = \left(\frac{P_t G_t G_r \lambda^2}{(4\pi)^2 R_s} \right)^{1/\alpha} \tag{5.3}$$

Let us refer to Figure 5.1, where d_1 is the distance between vehicles V_1 and V_2, d_2 is the distance between V_3 and V_2, and R is the distance for radio communication range of V_2 calculated using equation 5.3. When d_1 is less than R, it means that the vehicles V_1 is in the communication zone with V_2; thus the data transmission from V_1 is possible but with a probability of transmission error due to the noise of the channel. On the contrary, d_2 is greater than R which means the vehicles V_3 is outside the communication range with V_2; Thus the data transmission will not occur.

The mobility of the vehicles in our system is considered using the time-varying nature of the channel that characterized by the maximum Doppler shift f_D [127], which is proportional to the relative velocity between the transmitter and the receiver. It is given by $f_D = v/\lambda$, where v is the relative velocity between vehicles, and λ is the wavelength. Therefore, the channel is assumed stationary for a coherence time T_c which is inversely proportional to f_D, i.e., $T_c \approx 1/f_D$. In our simulation model, we define the maximum value of the relative velocity between the transmitter and receiver as v_max, and calculate the value of T_c based on the v_max. Although each vehicle has different speeds, the relative speed between vehicles never exceeds the value of v_max. So the value of T_c of each vehicles will never be smaller than the value of T_c based on the v_max.

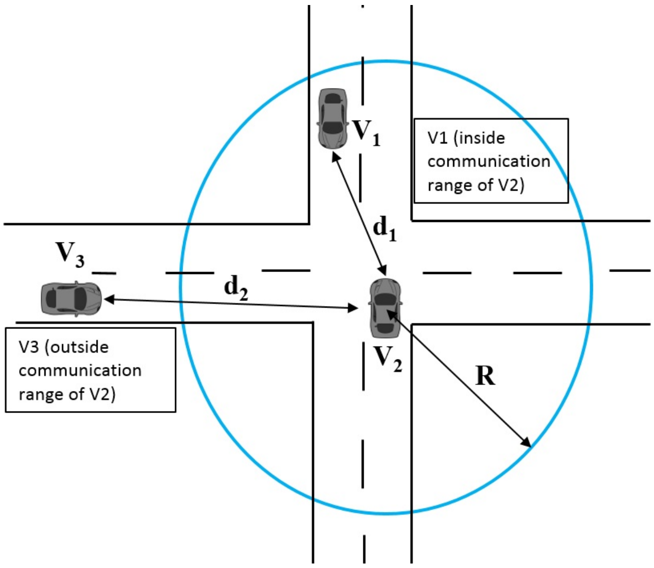


Figure 5.1: A communication range between vehicles.

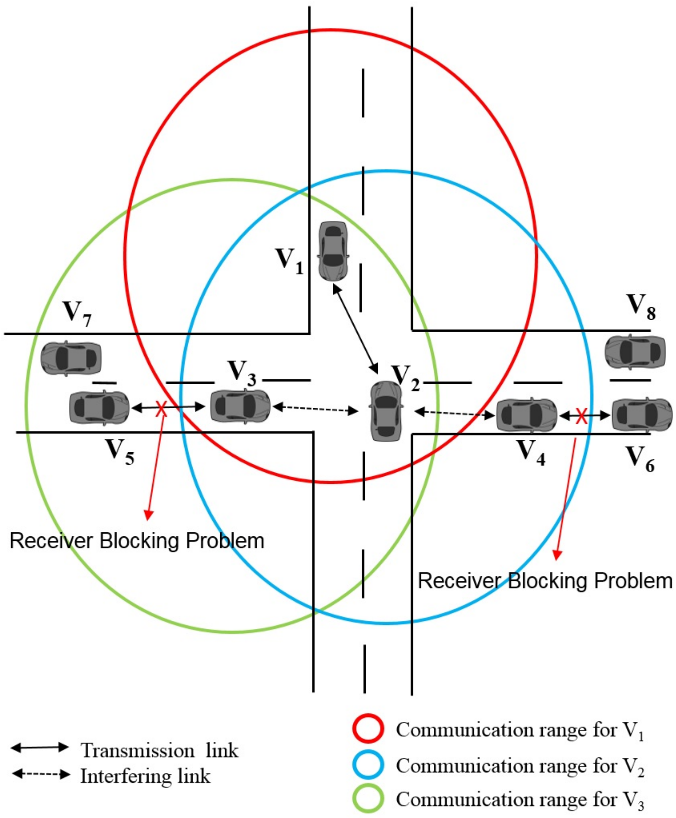


Figure 5.2: Blocking problem in dense VANETs.

5.3.2 Blocking Problem in Dense VANETs

The IEEE 802.11p MAC protocol standard using CSMA/CA can cause the hidden node and exposed node problem. The use of optional RTS/CTS mechanism can solve these problems and cause another problem called the blocking problem. To provide more understanding of the blocking problem in dense VANETs scenario, let us refer to the vehicle mobility scenario in Figure 5.2. When V_1 established a communication with V_2 by sending the RTS/CTS acknowledgements, the MAC protocol forbids the simultaneous transmissions within the same communication range, in this case, from V_3 and V_4, to prevent the potential interference and collision. V_3 becomes an exposed node and V_4 becomes a hidden node; thus both vehicles become defer nodes that will be blocked during the transmission from V_1 to V_2. When V_5 want to make a communication with V_3, it will send RTS to V_3. But V_3 cannot respond or send CTS to V_5 because he is still a defer node. As long as V_5 does not received the CTS respond from V_3, it will continuously send RTS packets to the VANETs network. The same blocking problem also happens when V_6 also want to make a communication to V_4 (the hidden nodes). V_6 will keep send the RTS, while V_4 cannot respond because it will be blocked during the transmission from V_1 to V_2. This problem will get worse in high-density VANETs because many vehicles will be blocked. In Figure 5.2, we can see that V_7 and V_8 will also became defer nodes, because both vehicles know that both V_5 and V_6 sent RTS to V_3 and V_4 respectively.

Over the past years, some research effort has been made to mitigate the blocking effect in ad-hoc networks. For example, article [128] propose a MAC protocol using a dual-channel (DUCHA); it uses one channel for data and the other for the packet's control. This solution improves the throughput comparing to the conventional MAC protocol. However, it did not consider realistic due to hardware limitations and cost. Article [129] present a multiple receiver transmission (MRT), a fast NAV (Network Allocation Vector) truncation (FNT), and an adaptive receiver transmission (ART) scheme to mitigate this blocking problem without the adoption of additional control channels. Each node transmits to multiple receivers in the MRT scheme, and the NAV duration in the RTS packet reduces in FNT protocol. They observe a throughput improvement considering the drawbacks of the MRT and FNT schemes. However, their proposal did not describe for use in the vehicular environment. Considering MIMO and cross-layer design, article [77] propose a PHY/MAC cross-layer design based on transmit AS for VANETs V2V communication. This solution comes with a dedicated MAC protocol that allows vehicles to transmit data simultaneously without interfering with each other by implementing ZF linear detection. Hence, the blocking problem is mitigated because the vehicles can transmit simultaneously and significantly improve the network throughput compared to the existing IEEE 802.11.p MAC protocol standard. However, this solution still suffers from the blocking problem in high-density VANETs environment.

5.3.3 TAS Algorithm

We consider spatial multiplexing over MIMO time-varying flat fading channel to be implemented in V2V communication. Each vehicle equipped with multiple antennas with N_t transmit antennas and N_r receive antennas for transmission and reception, where $N_t \leq N_r$. The received MIMO symbol at the receiver is expressed by :

$$y = Hx + n \tag{5.4}$$

where $y \in \mathbb{C}^{N_r \times 1}$ is the received signal vector, $H \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix, $x \in \mathbb{C}^{N_t \times 1}$ is the transmitted signal vector with transmit power $P_t = E_b\left[x^H x\right]$, and $n \sim \mathcal{CN}(0, N_0 I N_r)$ is the circularly symmetric complex Gaussian noise vector. We assume a channel state information at the receiver side (CSI-R), which means that the channel matrix is entirely known at the receiver, and the receiver uses the ZF-VBLAST detection technique with OSIC. The MIMO channel defined by the H matrix can be broken down into several parallel SISO channels using the QR-decomposition method as follows :

$$H = QR\Pi \tag{5.5}$$

where $Q \in \mathbb{C}^{N_r \times N_t}$ is a unitary matrix, $R \in \mathbb{C}^{N_t \times N_t}$ is an upper triangular matrix and $\Pi \in \{0,1\}^{N_t \times N_t}$ is the permutation matrix that corresponds to the optimal order of detection, that can be written as matrix :

$$Q = \begin{bmatrix} q_{11} & \cdots & q_{1N_t} \\ \vdots & \ddots & \vdots \\ q_{N_r 1]} & \cdots & q_{N_r N_t} \end{bmatrix}; R = \begin{bmatrix} r_{11} & \cdots & r_{1N_t} \\ \vdots & \ddots & \vdots \\ 0 & \cdots & r_{N_t N_t} \end{bmatrix}; \Pi = \begin{bmatrix} \pi_{11} & \cdots & \pi_{1N_t} \\ \vdots & \ddots & \vdots \\ \pi_{N_t 1]} & \cdots & \pi_{N_t N_t} \end{bmatrix}. \tag{5.6}$$

By multiplying the two sides of equation 5.4 by Q^H, the Hermitian matrix of Q, we obtain :

$$\tilde{y} = R\bar{x} + \tilde{n} \tag{5.7}$$

where $\tilde{y} = Q^H y$, $\bar{x} = \Pi x$ and $\tilde{n} = Q^H n$. Knowing that R is an upper triangular matrix so that $r_(i,j) = 0$ if $i > j$, then the i^th element of $\tilde{y}$ is given by :

$$\tilde{y}_i = r_{i,i}\bar{x}_i + \sum_{j=i+1}^{N_t} r_{i,j}\bar{x}_j + \tilde{n}_i, \qquad i = 1, 2, \cdots, N_t \tag{5.8}$$

The signal-to-noise ratio (SNR) of each channel is determined by the diagonal elements of the matrix R. At the i^th antenna, it is obtained by :

$$SER_i = \frac{r_{i,i}^2 E_b}{N_t N_0}, \qquad i = 1, 2, \cdots, N_t \tag{5.9}$$

Using Binary Phase-Shift Keying (BPSK) modulation, the symbol error rate (SER) at the i^th antenna given by [127] is :

$$SER_i = Q(\sqrt{2SNR_i}), \qquad i = 1, 2, \cdots, N_t \tag{5.10}$$

where $Q(.)$ is the complementary error function under the Gaussian statistic. Considering the packet's length of L MIMO symbols, the packet error rate (PER) is calculated as :

$$PER = 1 - \left[\prod_{i=1}^{N_t}(1 - SER_i)\right]^{L/N_t} \tag{5.11}$$

Employing GBN with a window size W and SR ARQ retransmission protocol, the throughput is calculated as :

$$\eta(GBN) = \frac{K \times (1 - PER))}{[1 + (W - 1) \times PER]} \tag{5.12}$$

$$\eta(SR) = K \times (1 - PER) \tag{5.13}$$

where $\eta(GBN)$ and $\eta(SR)$ are throughput for GBN protocol and SR protocol, respectively, K is the number of transmit antennas used for transmission, W is window size for GBN protocol, and PER is the packet error rate for the transmitted packet.

The PHY/MAC cross-layer techniques are implemented by finding the maximum throughput in the MAC layer based on the PHY layer's SER information. The receiver finds the best combination of transmitting antennas among all the possible combinations that give the best network throughput based on the SER information. Then, the receiver feeds back to the transmitter a sorted list of the best transmit antennas subsets of $1, 2, ..., N_t$ Antennas. This list is called the AS list, which includes the number of transmit antennas, the corresponding antenna's ID, and the associated throughput. Furthermore, it is assumed that the receiver sends the list to the transmitter over an error-free feedback channel. Table 5.1 shows an example of the AS list sends from receiver to transmitter in the 4x4 MIMO system, where $\eta4 > \eta2 > \eta3 > \eta1$. So now, the transmitter can select the best transmit antenna that has the maximum throughput.

Table 5.1: An example of the AS list in the 4×4 MIMO system.

Antenna Quantity	Selected Antennas ID's	Associated Throughput
4	1, 2, 3, 4	η_4
2	2, 4	η_2
3	1, 2, 4	η_3
1	2	η_1

5.3.4 Interference Free Symbol Detection

Our proposed solution comes with a multi-user interference cancellation method that allows simultaneous transmissions to overcome the blocking problem in VANETs V2V communication. Let us consider the typical VANET scenario depicted in Figure 2, where V_1 and V_3 act as the transmit vehicles, while V_2 act as a receiver vehicle. We assume that V_1 and V_3 have selected K_1 and K_2 transmit antennas respectively. Thus, when V_1 and V_3 send data simultaneously, the received signal at V_2 is represented by :

$$y = \begin{bmatrix} H_1 & H_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + n \tag{5.14}$$

where $H_1 \in \mathbb{C}^{N_r \times K_1}$ is the channel matrix between V_1 and V_2, $H_2 \in \mathbb{C}^{N_r \times K_2}$ is the channel matrix between V_3 and V_2, $x_1 \in \mathbb{C}^{K_1 \times 1}$ is the desired symbol vector from V_1, $x_2 \in \mathbb{C}^{K_2 \times 1}$ is the interferences symbol vector from V_3.

We considered a ZF-VBLAST encoding schema with greedy QR decomposition and OSIC as in [130]. Like equation 5.5, we can write the channel matrix as $[H_1 H_2] = QR\Pi$, where $Q \in \mathbb{C}^{N_r \times N_r}$ is a unitary matrix, $R \in \mathbb{C}^{N_r \times (K_1+K_2)}$ is an upper triangular matrix, and $\Pi \in \mathbb{R}^{(K_1+K_2)\times(K_1+K_2)}$ is the permutation matrix corresponding to the optimal detection order. Now equation 5.7 can be written as

$$\tilde{y} = R \overline{\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}} + \tilde{n} \tag{5.15}$$

and now we can express the $i^t h$ element of $\tilde{y}$ in equation 5.8 as:

$$\tilde{y}_i = r_{i,i}\bar{x}_i + \sum_{j=i+1}^{(K_1+K_2)} r_{i,j}\bar{x}_j + \tilde{n}_i, \qquad i = 1, 2, \cdots, (K_1 + K_2) \tag{5.16}$$

The multi-user interference cancelation is done as follows: first, the receiver will detect the symbols of $\bar{x}$ one after the other, starting from the symbol of $\bar{x}_{K_1+K_2}$. This estimated symbol is symbolized as $\hat{\bar{x}}$ and represented as :

$$\hat{\bar{x}}_{K_1+K_2} = q\left(\frac{\tilde{y}_{K_1+K_2}}{r_{K_1+K_2,K_1+K_2}}\right) \tag{5.17}$$

where $q(.)$ Is the quantification function. Then, the detected symbol $\hat{\bar{x}}_{K_1+K_2}$ is removed in the next step to detect $\hat{\bar{x}}_{(K_1+K_2)-1}$. This operation is repeated until all components are detected. So we will get :

$$\hat{\bar{x}}_i = q\left(\frac{\tilde{y}_i - \sum_{j=i+1}^{(K_1+K_2)} r_{i,j}\hat{\bar{x}}_j}{r_{i,i}}\right), \qquad i = ((K_1+K_2)-1), ((K_1+K_2)-2), \cdots, 1 \tag{5.18}$$

Assuming no error propagation, symbol detection can be correctly carried out sequentially in K_1+K_2 steps [131], from the last symbol $\tilde{y}_{K_1+K_2}$ to $\tilde{y}_1$. The interference free symbol detection is only possible if the sum of transmit antennas within the same communication range K_1+K_2 does not exceed N_r (i.e., $K_1+K_2 \leq N_r$). Otherwise, the system is under-determined. This condition is referred to as the AQR. Then finally, the receiver V_2 retains the desired data from V_1 and ignores the rest.

From Figure 5.2, it is also possible for the V_4, as the hidden node in the communication range of V_2, doing the simultaneous transmission. Using the same ZF-VBLAST architecture as mentioned above, we can do the interference nulling and cancelation process from both V_3 and V_4 as the interference vehicles. Indeed, this mechanism will unblock many vehicles and allows them to communicate simultaneously. For this purpose, vehicles negotiate with each other the number of selected transmit antennas so that the AQR is satisfied and maximize the network throughput.

5.3.5 TPA Algorithm

The AQR condition requires that the number of transmitting antennas in a receiver detection range does not exceed the number of its receiving antennas (i.e.,$\sum K_x \leq N_r$). Hence, AQR limits the maximum number of transmitters within the receiver detection range to N_r transmitters if each one uses one transmitting antenna. However, in dense VANETs, it is common for a receiver to have more than N_r nearby transmitters. Therefore, some of them may remain blocked during an ongoing transmission, despite the cross-layer using the transmit AS mechanism described in the previous section.

In what follows, we address this problem in terms of transmit power adaption. Researchers have investigated power adaptation in VANETs. Article [132] propose a transmit power algorithm to solve node isolation in rural zones and keep the connection time longer. The criteria used for power adaption is the neighbors' density. The algorithm increases or decreases transmission power so that the number of neighbors of each node is always within a minimum and maximum threshold. We adapt this TPA algorithm to our MU-MIMO VANETs using transmit AS so that the number of simultaneous transmission in the same detection zone will satisfy the AQR condition.

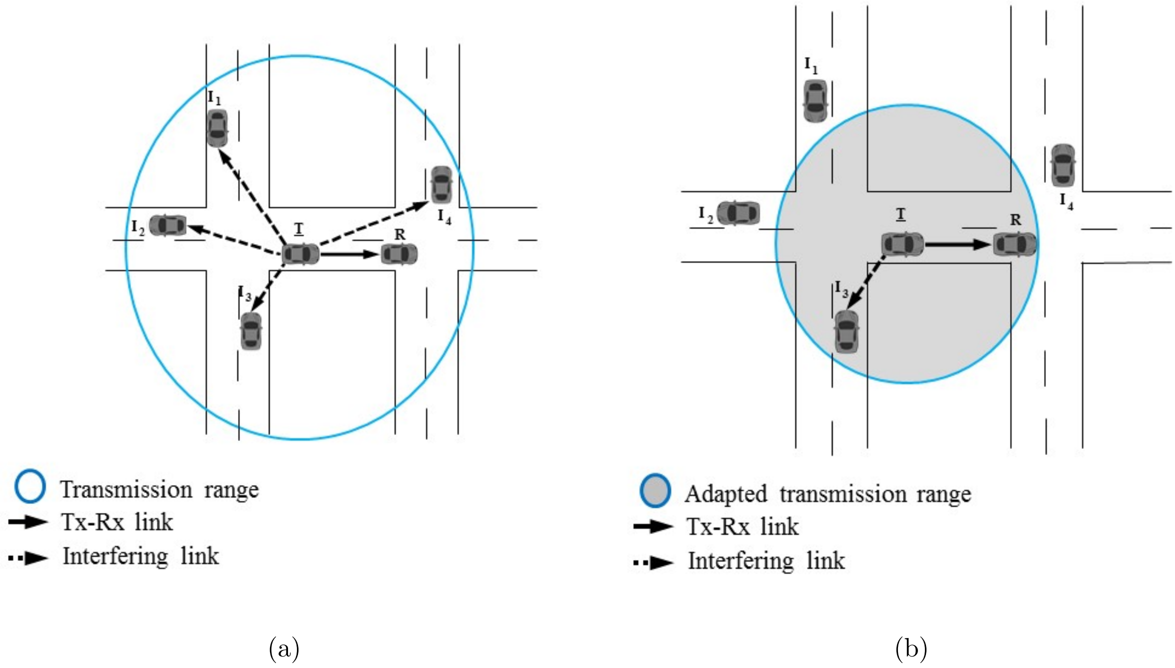


Figure 5.3: Transmission power adaptation (TPA), (a) is the scenario without TPA where there are four interfered vehicles, and (b) is a scenario using TPA and only has one interfered vehicles.

Let us refer to Figure 5.3 for describing the scenario of using the TPA algorithm in dense VANETs. We deploy VANETs using 4×4 MIMO systems, which means each vehicle will be equipped with four transmit antennas and four receive antennas. In Figure 5.3(a), the transmitter T uses the maximum transmit power level. As seen, this creates an unnecessary broad transmission range and thus a large number of interfered vehicles (four vehicles in this case). If all transmitter (T, I_1, I_2, I_3, and I_4) want to transmit simultaneously, the total number of transmit antennas in one of the receiver detection zones may be more than the number of receive antennas; hence the violation of the AQR condition. However, in Figure 5.3(b), T

reduces the transmit power, and therefore the number of interfered vehicles is also reduced (to one vehicle in this case). Thus these two vehicles are allowed to communicate simultaneously because it respects the AQR condition. An adapted transmit power level, decreases the number of blocked neighbors to mitigate the blocking problem.

For this purpose, we propose to add a PHY/MAC cross-layer design where the MAC layer collects the receiver's neighborhood information, which is then used by the PHY layer for the transmission power adaptation. This adaptation is made progressively with a step off Δ to keep the connectivity between the vehicles. Each transmitter adapts its transmit power P_t according to its corresponding receiver's neighborhood density, noted $N(R)$. It starts with an initial power P_{ini} and then it increases or decreases the power level by Δ without exceeding the maximal transmission power P_max, as described by algorithm 1, where $P_t(t.T_c)$ is the transmit power level during the t^th period of T_c.

Algorithm 1: Transmit power adaptation

```
Input: N(R), Δ, T_c, P_ini, P_max, P_min, t ;
Output: P_t ;
if t = 1 then
    P_t(1.T_c) = P_ini ;
else
    if N(R) > N_r then
        P_t(t.T_c) = max{P_t((t − 1).T_c) − Δ, P_min} ;
    else
        if N(R) = N_r then
            P_t(t.T_c) = P_t((t − 1).T_c) ;
        else
            P_t(t.T_c) = min{P_t((t − 1).T_c) + Δ, P_max} ;
        end
    end
end
```

Indeed, if $N(R)$ exceeds N_r the transmitter decreases the power with a step of Δ to decrease the communication range and minimize the number of interfering vehicles so that the neighboring vehicles are still allowed to communicate simultaneously because it respects the AQR condition. If $N(R)$ is less than N_r, it increases the transmit power with a step-off Δ to expand the communication range to improve the transmission links and network throughput. Otherwise, it maintains the same power level. This process is repeated after each round of T_c period and until the end of the transmission.

5.3.6 Cross-Layer Design Based on TAS and TPA

In this section, we propose a MAC protocol for VANETs adapted from [76, 77], to support the cross-layer design based on transmit AS and TPA. The use of the AS algorithm proposed above requires an exchange of antenna list between the vehicles. The RTS/CTS control packets used in the IEEE 802.11p MAC protocol are not sufficient. We proposed a new MAC protocol using new control packets and RTS/CTS packets, to be implemented in the VANETs networks. This protocol is broken down into four phases: a phase to exchange the AS list, a phase for the negotiation of the number of antennas used by each vehicle between neighboring vehicles, a phase for simultaneous data transmission, and a phase for transmitting power adaptation. To describe the protocol, let us consider again the V2V communication scenario presented in Figure 5.2, where V_2 act as a receiver and detects three other vehicles, i.e. V_1, V_3 (an exposed node) and V_4 (a hidden node) that want to communicate simultaneously. We focus on the exposed node problem of V_3, and describe how it can transmit simultaneously with V_1 to V_2, and at the same time, it still can communicate with V_5, hence it will not be a deferred node. The protocol advances through the following phases:

AS list exchange phase. This phase is also defined as the handshake step, where vehicles share their AS list with the neighbors. Assuming that V_1 is the first to have the channel access, it sends a transmission request of request-of-antenna-selection-list (RASL) to V_2, and V_2 responds with request-for-antenna-selection-list-acknowledgment (RASL-ACK) to accept the connection. Then, V_1 broadcasts a training sequence to all vehicles in its transmission area, to allow them to estimate the channel between them and V_1. The estimation of the channel by the neighbors will allow them to cancel any interference during the communication between V_1 and V_2. Based on the channel estimation, V_2 also looks for the best-transmitting antenna subsets of $1, 2, ...N_t$ at V_1 in terms of maximum throughput calculated using equation 5.12 and 5.13. Then, it creates a list of sorted AS with the number of antennas, the identifiers of the antennas, and the corresponding throughput, as described in Figure 5.3. V_2 retransmits this list via antenna-selection-list (ASL) to V_1. This list is then broadcast by V_1 to the neighbors via broadcast-AS-RTS (B-RTS). Whenever a transmitter receives an AS list from the neighborhood, it forwards the AS list to its receiver. This phase is repeated successively until all vehicles exchange their AS lists (in this example, between V_3 and V_5). Figure 5.4 details the packet exchange and the examples of control packets of this phase.

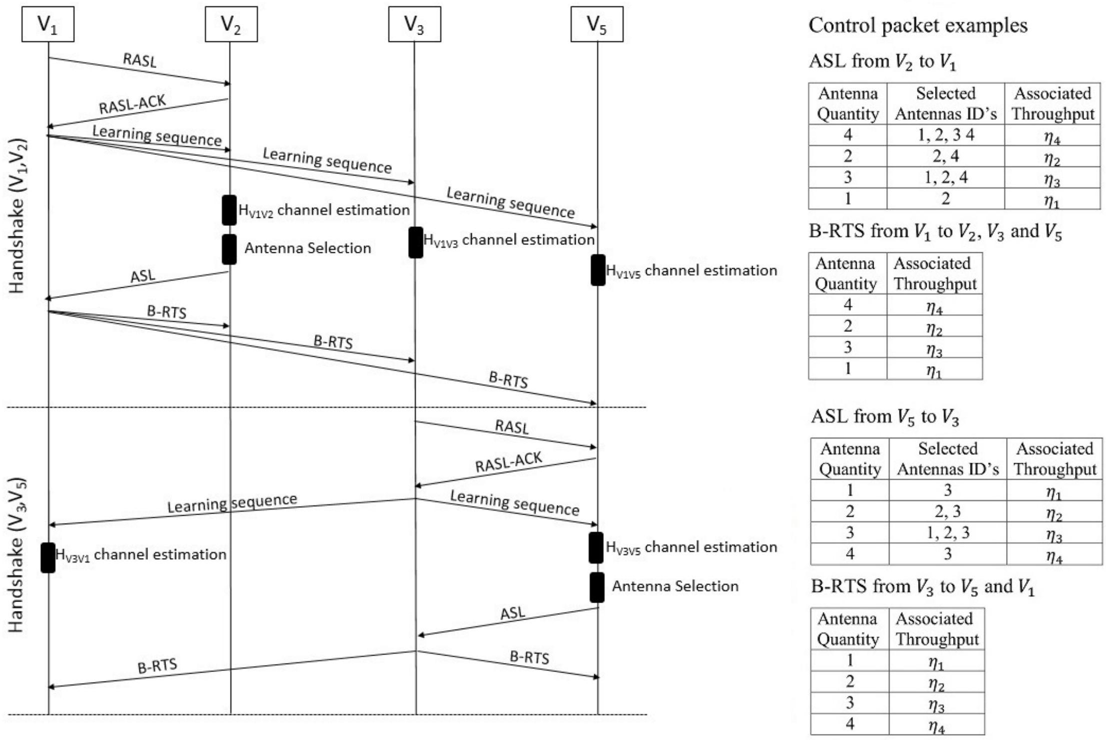


Figure 5.4: The AS list exchange phase and its control packet examples. V_1 and V_3 act as the transmitters, while V_2 and V_5 act as the receiver.

Negotiation phase. This phase aims to negotiate the number of transmitting antennas used by each vehicle to allow simultaneous transmission and ensure the AQR condition. Assuming that V_1 first has access to the channel, it verifies whether it reaches the AQR. At first, the AQR is not violated, so V_1 sends broadcast-CTS (B-CTS) to all neighboring vehicles to use all of its antennas, in this case, four antennas. When the channel is released, V_5 accesses in turn to the channel for the negotiation phase. V_5 know that AQR is violated, so V_5 selects another combination from the AS list to satisfy the AQR, and it maximizes the network throughput, based on previous B-RTS. It chooses two antennas for V_1 (η_2) and one antenna for V_3 (η_1). Once it is done, it broadcasts the selected list to V_3 and the neighbors (V_2 and V_1) via B-CTS. Then, V_3 and V_1 updates the AS list accordingly and informs the neighborhood with RTS. Figure 5.5 details the AS list negotiation phase and also the examples of control packets of this phase.

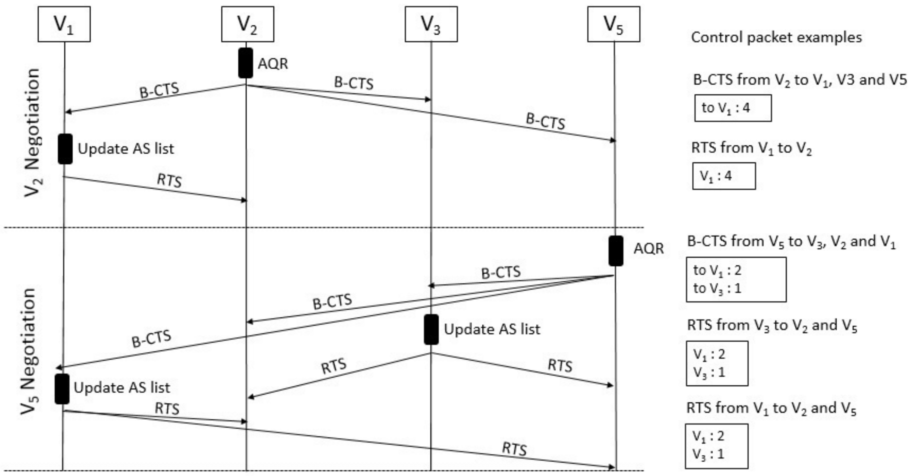


Figure 5.5: The negotiation phase and its control packet examples.

Data transmissions phase. In this phase, V_1 and V_3 send a CTS respectively to V_2 and V_5 , and start to send data simultaneously through the final subsets of selected antennas. Then V_2 and V_5 extract the data using the ZFVBLAST detector, as described in section 5.3.4. The lost and damaged packets are retransmitted using the SR protocol, and received packets are acknowledged with ACK. The V2V between vehicles lasts for each T_c round. When the connection is over, it waits until the channel is fully released before going on to the next step.

Transmit power adaptation phase. At this phase, if V_1 and V_3 continue to transmit data; they account for the number of AS list at their disposal. This stage will give them the neighbor's density of their respective receivers, and depending on this, and they choose the new transmit power level for the next T_c period, as mentioned in section 2.5. The four phases of the proposed MAC protocol are summarized in Algorithm 2.

5.4 Performance Analysis

5.4.1 Simulation Environment

We use SUMO (Simulation of Urban MObility), MATLAB (MATrix LABoratory), and TraCI4Matlab [133] as the simulation tools. We choose SUMO to generate the mobility of the vehicles in our scenario, MATLAB to modeling our MU-MIMO VANETs system, and also to calculate the performance of our proposed cross-layer design, and TRACI4Matlab as an

Algorithm 2: Antenna selection with transmit power adaptation

```
while Vehicles ask for data transmission do
    if distance ≤ communication range then
        AS list exchange phase ;
    else
        if AQR is not satisfied then
            Negotiation phase ;
        else
            repeat
                Simultaneous data transmission ;
            until the end of T_c;
            Wait until all transmission are finished ;
        end
        Receiver's neighbors' density estimation ;
        Transmit power adaptation;
    end
end
```

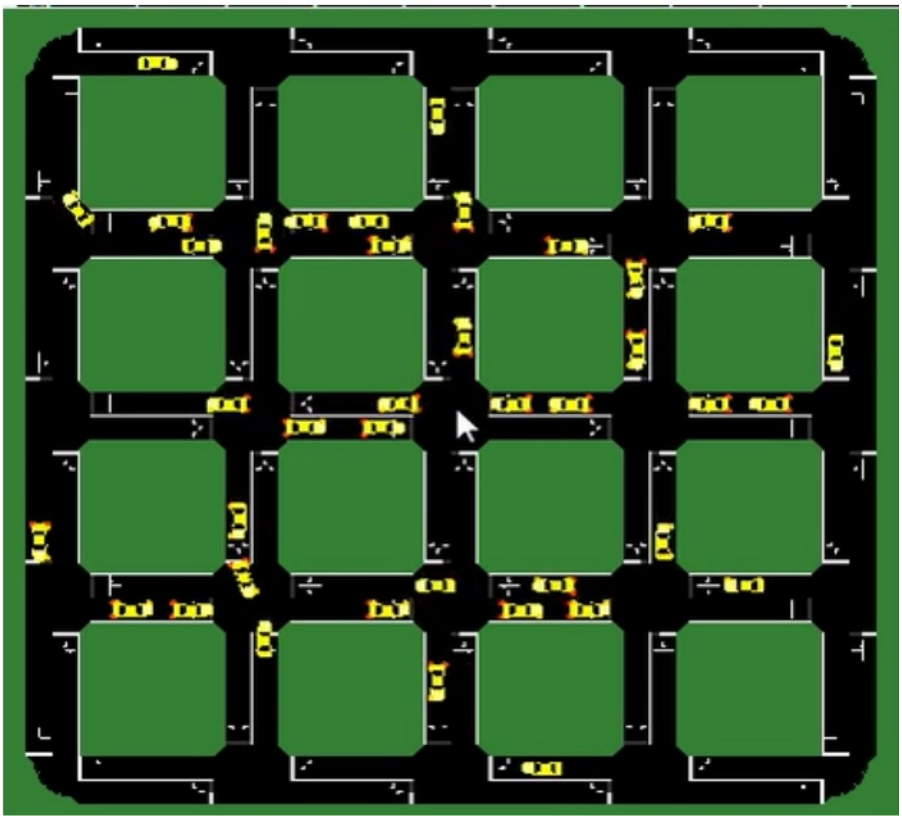


Figure 5.6: Manhattan grid for simulation in SUMO environment.

interface between SUMO and MATLAB. We design a V2V VANETs scenario where all vehicles distributed randomly in a predictable area of $100m \times 100m$ Manhattan grid (as depicted in Figure 5.6), $N_t = N_r = 4$ antennas (or 4×4 MIMO systems) equipped in each vehicle and the maximum relative velocity between vehicles is $40km/h$. In this research, using Monte Carlo simulation, we evaluate the performance of the proposed cross-layer design in terms of normalized network throughput versus signal-to-noise ratio (SNR) in term of E_b/N_o. To get the network throughput value, we calculate the average throughput of each vehicle over the number of simulations and the number of potential V2V communication links. Then the network throughput value is normalized by dividing with the maximum value. Unless otherwise specified, the numerical values obtained in the rest of this research are all based on network parameters listed in Table 5.2.

Table 5.2: Simulation parameters for cross-layer design using TAS and TPA

Parameter	Symbol	Value
Simulation Scenario		Manhattan grid
Simulation Area		100m $\times$ 100m
Simulation Time	T_{sim}	50 s
Number of Simulations		30
Carrier Frequency	f	5.9 GHz
Number of Vehicles		40
Relative velocity	v	40 km/h
Time coherence	T_c	4.6 ms
Network Configuration		Single hop
Channel Model		Rayleigh flat fading
Frame Length	L	180 BPSK symbols
ARQ Protocol		Selective Repeat (SR)
Throughput	η	$K(1 - PER)$ [123]
Symbol Duration	T_s	8 μs
Initial Power	P_{ini}	30 dBm
Maximal Transmission Power	P_{max}	30 dBm
Step of power	Δ	5 dBm
Receiver Sensitivity	R_s	-70 dBm
Transmitting Antennas Gain	G_t	0 dBi
Receiving Antennas Gain	G_r	0 dBi
Path Loss Exponent	α	3

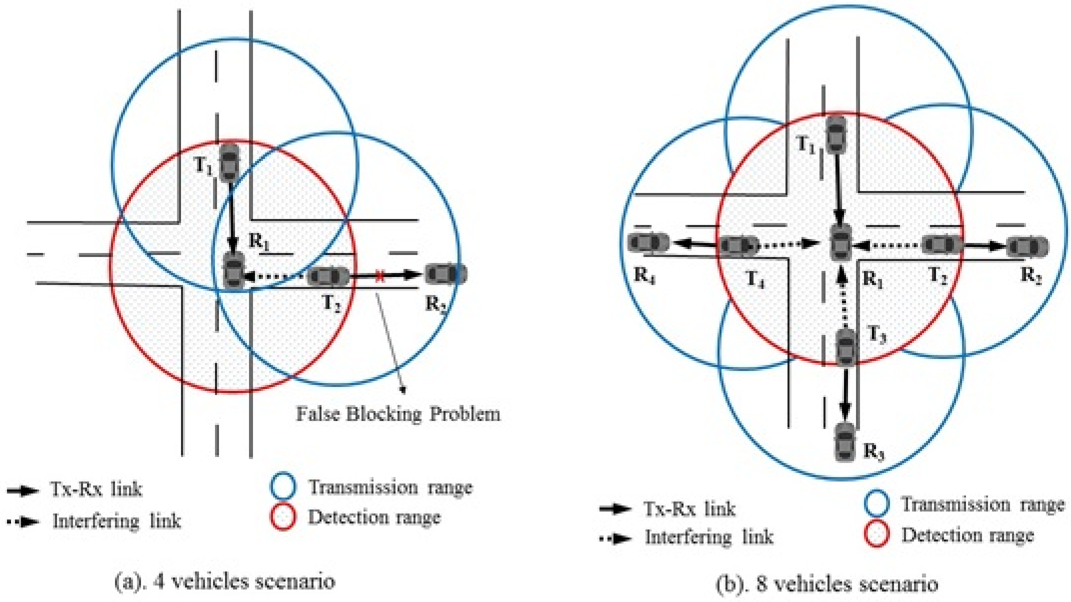


Figure 5.7: Vehicle mobility scenario, (a) is the four vehicles scenario where R_2 will have a receiver blocking problem, and (b) is the eight vehicles scenario where the blocking problem will get worse

5.4.2 Simulation Results

First, we describe the blocking problem in dense VANETs. Let us refer to the vehicle mobility scenario in Figure 5.7 to describe how the transmitter AS mitigates the blocking problem, but it still has the limitation in dense VANETs environment. Assuming that each vehicle is using four transmit antennas and four receive antennas (4×4 MIMO system), in scenario 5.7(a), we can see only two vehicles (i.e., T_1 and T_2) detected in the detection range of R_1. Using AS architecture with interference-free symbol detection and considering AQR condition, we assume T_1 and T_2 are doing transmission simultaneously, and each transmitter will use two transmit antennas. The total potential V2V communication links in this scenario are 3. In the denser VANETs scenario, like the eight vehicles scenario in scenario 5.7(b), we can see four vehicles (i.e., T_1, T_2, T_3, and T_4) detected in the detection range of R1. We assume T_1, T_2, T_3, and T_4 will transmit simultaneously and each transmitter will use only one transmit antenna to satisfy the AQR condition. The total potential V2V links in this scenario are 7. We calculate the network performance in terms of the normalized throughput per potential V2V-links based on equation 5.12 and 5.13.

In Figure 5.8, compared to without the AS algorithm, we can see that the AS algorithm gives better network throughput performance, and using SR protocol gives slightly better per-

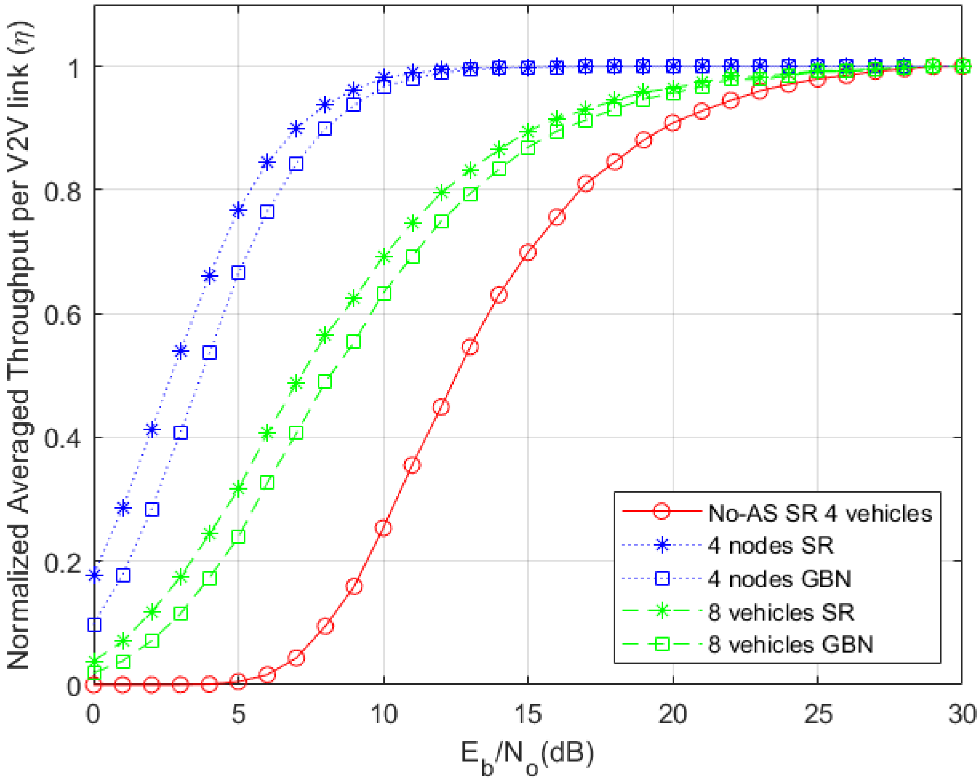


Figure 5.8: The throughput is degrading in dense VANETs because there was still a receiver blocking problem even though we used the proposed AS selection.

formance than using GBN. Also, the four vehicles scenario has better throughput than eight vehicles scenario. Indeed, dense VANETs has more V2V links, which results in frequent violation of the AQR condition. Some transmitters are blocked, and the blocking problem reappears; hence the network throughput performance decrease.

Now, we want to investigate our proposed cross-layer design by adding the TPA algorithm. In Figure 5.9, we provide the throughput performance in the following cases: (i) without AS and TPA, (ii) with AS and without TPA, (iii) with AS and TPA. Note that when we do not use the TPA algorithm, the transmit power is by default $P_{ini} = P_{max}$ and we do not consider the transmit power adaptation phase of the MAC protocol. First, to see the cross layers gain based on AS, let us compare the throughput obtained in the cases (i) and (ii). In (ii), with AS, at lower of $E_b/N_o = 10dB$, the throughput grows up to more than 1.73 times of that given without AS in (i). However, at better of $E_b/N_o = 20dB$, the throughput reaches until 6% of gain than that given without AS. In fact, at low of E_b/N_o, the AS algorithm tends to choose less number of transmit antennas. However, at a high E_b/N_o, the optimal subset of all available transmit

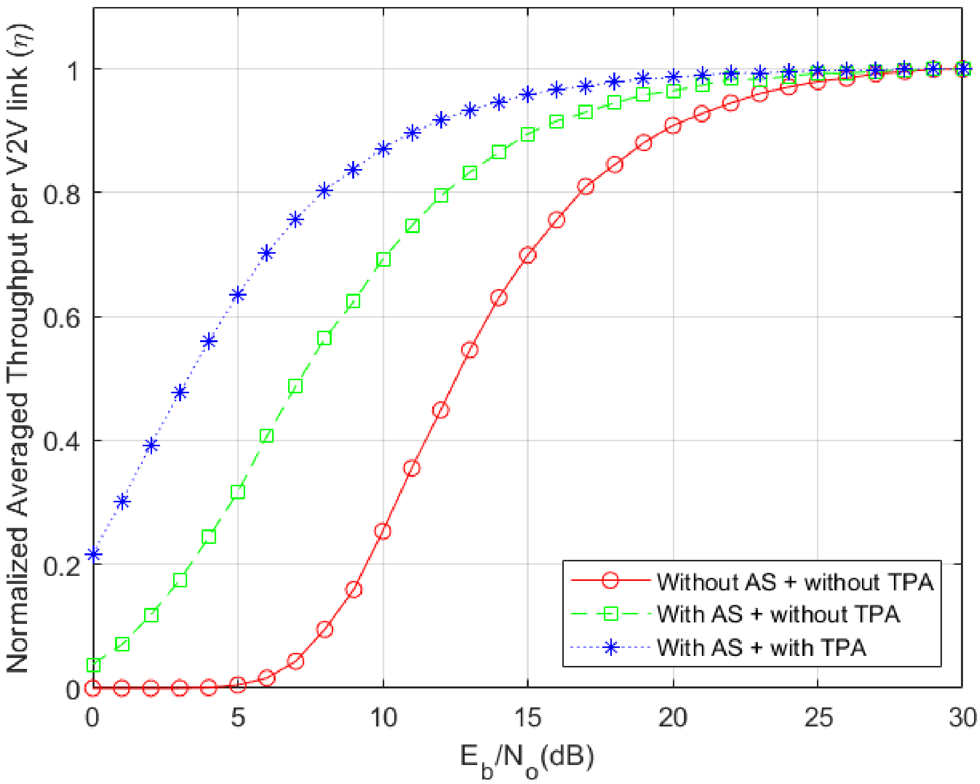


Figure 5.9: Throughput without antenna selection and power adaptation; with antenna selection and without power adaptation; with antenna selection and power adapta-tion.

antennas can be chosen as long as the AQR is satisfied. As the authors concluded in [76], using a cross-layer based on the TAS algorithm improves each V2V link's throughput. Besides, it allows more nearby transmissions, and therefore, it improves the average network throughput. Now, to see the gain brought by the cross-layer based on transmit power adaptation, we compare the throughput achieved with (case (iii)) and without TPA (case (ii)), both cases with AS. The throughput given by AS with TPA is higher, especially for low noise power level. At of $E_b/N_o = 20dB$, the gain can achieve 2%. However, at of $E_b/N_o = 10dB$ (i.e., link quality is poor), we recorded a gain of 26%. Indeed, decreasing the transmit power does not affect the throughput per each V2V-link, but it increases the average network throughput. In sum, compared to the conventional case, at of $E_b/N_o = 10dB$, the performance improvement is about 173% for AS without TPA, whereas it is about 244% for AS with TPA. At of $E_b/N_o = 20dB$, the performance improvement is 6% for AS without TPA and 9% for AS with TPA.

In Figure 5.10, we evaluate the proposed approach with two different network density. The throughput improvement with TPA is remarkable in both scenarios (i.e., 40 and 100 vehicles).

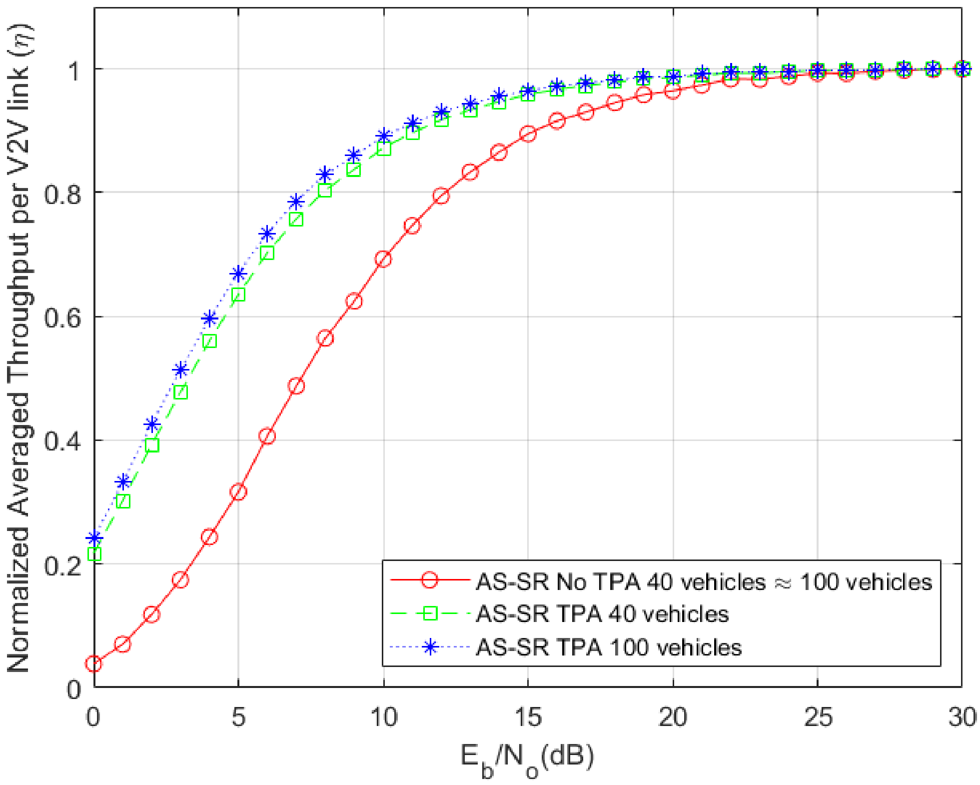


Figure 5.10: Throughput in a network for 40 and 100 vehicles.

The most significant improvement comes from the dense network where our proposed solution mitigates the blocking problem; hence, more vehicles can transmit data simultaneously.

In Figure 5.11, we study the impact of the total number of transmitting and receiving antennas on our proposed design. As illustrated, the 8×8 MIMO system gives better network throughput performance compared to 4×4 MIMO systems for both 40 and 100 vehicles scenario. The AQR condition depends on the total number of the receive antennas; thus, the more receive antennas means more transmit vehicles doing simultaneous transmission. Hence, in terms of normalized average throughput per V2V link, the 8×8 MIMO system in 100 vehicles scenario gives the best performance, which proves our proposed cross-layer design overcame the blocking problem in dense VANETS. Indeed, the more antennas mean more vehicles can transmit simultaneously. However, it also means more time needed to synchronize between vehicles. We can see that the time needed to do the negotiation phase in our MAC protocol also increase. It is interesting to add the delay parameter as one of the performance analysis in our future research.

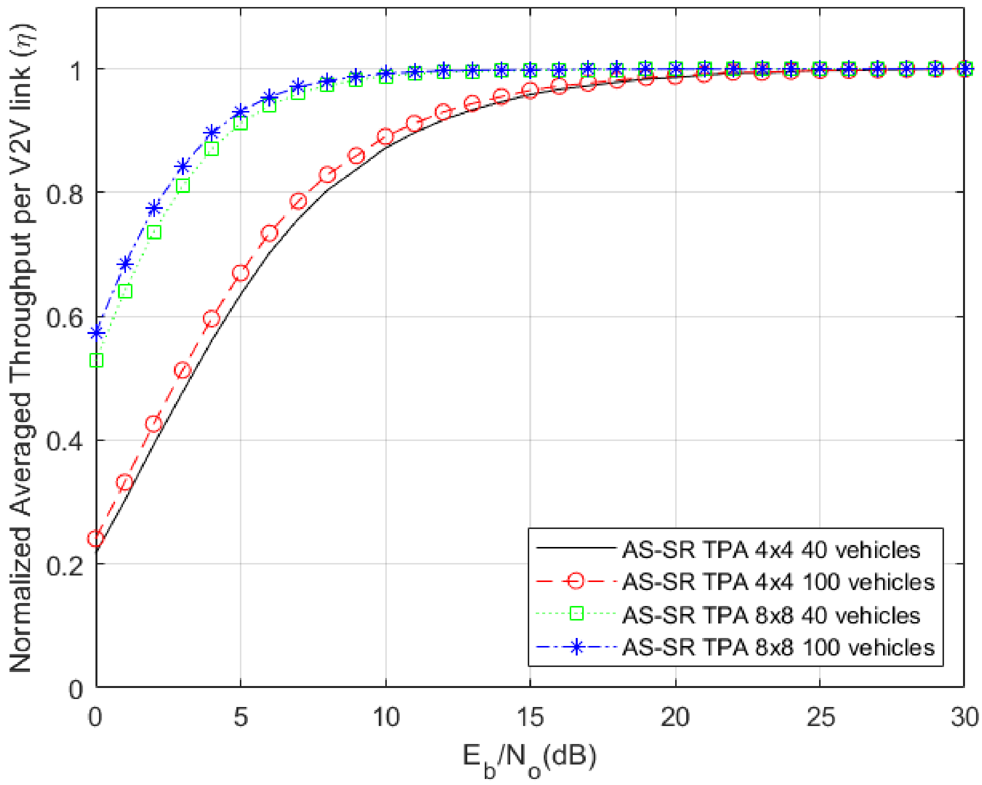


Figure 5.11: Throughput comparison for 4×4 MIMO system and 8×8 MIMO system in 40 and 100 vehicles scenario.

5.5 Conclusion

This research has proposed a solution to mitigate the blocking problem in dense VANETs environment. We consider using MIMO with ZF-VBLAST architecture in the PHY layer and retransmission using SR protocol in the MAC layer. This solution also uses TAS and TPA algorithms. This design lets the transmitter choose the best combination of transmitting antennas to maximize throughput and minimize interferences. Furthermore, it allows transmitters to send data simultaneously, with its interference-free symbol detection, which improves the network performance in terms of throughput. The simulation results show that this solution allows more vehicles to communicate simultaneously and significantly improves the average network throughput compared to the 802.11p MAC standard, particularly for VANETs with high density.

It should be noted that this solution can be used only for the VANETs system using unicast transmission because the transmitter needs the CSI before applying the TAS and TPA algorithm. Another drawback of this proposed cross-layer design is the use of RTS/CTS, which needed to overcome the hidden node problem, at the expense of increasing the transmission delay or latency due to the synchronization process before data transmission.[1]

[1] This chapter is a slightly modified version of A PHY/MAC cross-layer design with transmit antenna selection and power adaptation for receiver blocking problem in dense VANETs. [134] published in Vehicular Communications Journal and has been reproduced here with the permission of the copyright holder.

General Conclusion and Perspectives

This thesis's work has been focused on studying the cross-layer design for next-generation VANETs while taking into account some matured technique from other 802.11 family standards. We were mainly interested in cross-layer designs in PHY, MAC, and NET layers, while considering two objectives stated in the NGV's PAR, i.e., having two times higher throughput in the MAC layer and operating in the higher mobility environments with vehicles' speed up to 500 km/h. We also use a cross-layer design approach to address the blocking problem caused by the CSMA/CA technique used in V2X communication.

General Conclusion

The main results of this thesis are summarized as follows:

- In the first chapter, we have presented the state of the arts of the VANETs communication system. Furthermore, we have given a brief general overview of the standards, challenges, applications, and evolution of the VANETs. Cross-layer designs and MIMO techniques motivated us to improve the performance of the VANETs communication system.

- In the second chapter, we choose the PER and throughput as our performance metrics. The PER is simulated and compared against the theoretical PER calculation. We justified the OFDM technique's objective, where the performance of an OFDM system with a perfect frequency domain equalization over a frequency-selective channel is equivalent to the performance over the flat-fading channel. Our simulation result 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.

  We simulate the throughput performance of a small size frame (100 Bytes) and use a minimum value of CW = 15 to show the worst possible condition where the preamble overhead is high, and the probability of collision is also high. We also highlighted two problematics regarding the throughput performance of the legacy standard IEEE 802.11p in the high mobility environment, i.e., the impact of frame size and data rates (MCS) and the impact of vehicle density on the VANETs performance. Our simulation results showed a trade-off between frame size, MCS, and the NGV applications' performance, where bigger frame size and higher MCS improved the throughput performance but reduced the reliability due to the delay and PER. On the contrary, using a smaller frame size will reduce the throughput efficiency due to packet preamble overheads. Concerning the impact of the vehicle density, our simulation results showed the MAC layer's throughput degradation in a dense VANETs environment due to the CSMA/CA technique's blocking problem.

- Chapter 3 investigated the possible PHY layer enhancements to be possibly adopted into the 802.11bd standard for NGV communication. We considered some mature techniques from other 802.11 family standards. There are three PHY layer design considerations to be implemented in the 802.11bd standard, i.e., LDPC and midambles, DCM and extended-range mode, and MIMO-STBC. Our simulation results show a significant PER and throughput performance improvement resulting from the introduction of all techniques compared to the legacy 802.11p standard. It should be noted that the DCM technique reduced the channel capacity in half at the expense of having reliable communication in the worst SNR condition. LDPC and midambles are 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 gave better performance even in the worst SNR condition and improved the communication range. Finally, MIMO-STBC is recommended for V2X applications that need higher throughput requirements in the unicast transmission scenario.

- Chapter 4 designed the potential 802.11bd standard using a cross-layer approach in PHY, MAC, and NET layers. We simulated our cross-layer designs for the NGV 802.11bd standard using 16-QAM with a code rate of 1/2 modulation in an enhanced highway LOS environment. For the ideal condition of one transmission without interference, the safety NGV application using a frame size of 300 Bytes could obtain 2.05x higher throughput. In comparison, the non-safety-related NGV applications using a frame size of 1500 Bytes could obtain 2.04x higher throughput compared to theoretical data rates in 802.11p standard (12 Mbps). Our cross-layer design answered two objectives requested by the PAR of

802.11bd standard, i.e., having two times higher throughput in the MAC layer and operating in a higher mobility environment with a relative speed of 500 km/h. The cross-layer design also gave a better throughput performance in a dense environment where many vehicles compete on the same channel.

- In chapter 5, we proposed a solution to mitigate the blocking problem in dense VANETs environment. We consider using MIMO with ZF-VBLAST architecture in the PHY layer and retransmission using SR protocol in the MAC layer. This solution also used TAS and TPA algorithms. This design lets the transmitter chose the best combination of transmitting antennas to maximize throughput and minimize interferences. Furthermore, it allows transmitters to send data simultaneously, with its interference-free symbol detection, which improves the network performance in terms of throughput. The simulation results show that this solution allows more vehicles to communicate simultaneously and significantly improves the average network throughput compared to the 802.11p MAC standard, particularly for VANETs with high density.

Perspectives

Despite the results that have been proposed in this thesis, there are still several aspects that could be further investigated in future works. Some of the related topics for future research are highlighted as follows:

- In chapter 3, we considered only two objectives defined by the NGV's PAR. The first objective is achieving at least two times higher throughput (measured at the MAC data service access point) than the maximum mandatory data rate as defined in the 5.9 GHz band (12 Mb/s in a 10 MHz channel). The second objective is operating in high mobility channel environments at vehicle speeds up to 250 km/h (closing speeds up to 500 km/h). The simulation results showed that our cross-layer design answered these two objectives. We could implement our cross-layer design for future work to do real-world field testing and measurement campaign.

  There is another objective defined by the NGV's PAR, such as at least one mode that achieving 3dB lower sensitivity level (more extended range) than that of the lowest data rate defined in IEEE 802.11^{TM}-2016 operating in 5.9 GHz band (3 Mb/s in a 10 MHz channel); and providing interoperability, coexistence, backward compatibility, and fairness with deployed OCB (Outside the Context of a BSS) devices using IEEE 802.11p. For future work, we need to investigate the cross-layer design to address those objectives.

- In chapter 4, we only considered how to improve the throughput performance using the cross-layer design. However, other performance metrics are needed to consider, such as delay, latency, or the reliability of the NGV applications. For example, although a larger CW and retransmission technique could improve the throughput performance, we need to find an optimum CW and the number of retransmission due to both techniques increasing the delay latency of frame transmission. We also considered only the broadcast and unicast single-hop transmission in the NET layer. There are other scenarios to consider like multicast, geocast, geo networking in ETSI ITS-G5 standard, and a multi-hop transmission, where we need to consider hidden node problems in the MAC layer protocol. For future work, we need to consider all the possibilities like broadcast, unicast, or multicast (geocast) in single and multi-hop transmission to have a better routing strategy for future NGV applications.

- Chapter 5 investigated that the proposed cross-layer design can be used only for the VANETs system using unicast transmission because the transmitter needs the CSI before applying the TAS and TPA algorithm. Another drawback of this proposed cross-layer design is the use of RTS/CTS, which is needed to overcome the hidden node problem, at the expense of increasing the transmission delay or latency due to the synchronization process before data transmission. This solution is limited only to close-range low-speed NGV applications, e.g., urban low-speed V2I high definition map update. We need further investigation to know this solution's performance in other VANETs environments by considering the delay or latency performances. Furthermore, the NGV PAR also considered the use of the 60 GHz frequency band optionally. We could consider other MIMO techniques such as beamforming that could give the benefit to improve the future NGV performances.

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