IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received February 15, 2022, accepted February 27, 2022, date of publication March 2, 2022, date of current version March 10, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3155814

A Study of Channel Bonding in IEEE 802.11bd Networks

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The research has been carried out at the Institute for Information Transmission Problems of the Russian Academy of Sciences and supported by the Russian Science Foundation (Grant No 20-19-00788, https://rscf.ru/en/project/20-19-00788/).

ABSTRACT In recent years, Vehicle-To-Everything (V2X) applications have been actively developing, and the Quality of Service (QoS) requirements are becoming more stringent. To support V2X applications, IEEE developed the IEEE 802.11p standard in 2010. However, systems based on this standard fail to fulfill requirements on very low frame transmission delay and packet loss ratio imposed by modern V2X applications, such as applications for autonomous driving and platooning. To satisfy new requirements, IEEE has launched a new IEEE 802.11bd project to design the next generation of IEEE 802.11p. An important feature of IEEE 802.11bd is the channel bonding technique, which allows transmitting data in two adjacent channels simultaneously. Thus, it increases data rates and may reduce delays and packet loss ratio. The current version of IEEE 802.11bd specifies two channel bonding techniques, which differ from that used in modern Wi-Fi networks. This work evaluates the performance of the three aforementioned techniques from the IEEE 802.11 family of standards considering frame transmission delays and packet loss ratio. With rigorous simulations, it is shown that, in most cases, the channel bonding techniques highly decrease the percentage of both IEEE 802.11bd and legacy stations with unsatisfied QoS requirements on delays and packet loss ratio. Unfortunately, sometimes, the IEEE 802.11bd channel bonding techniques significantly worsen performance. Moreover, the work highlights that the choice of the primary channel for channel bonding techniques significantly affects the network performance. As a result, the paper provides a recommendation for selecting both the most suitable channel access method and primary channel.

INDEX TERMS Channel bonding, IEEE 802.11bd, IEEE 802.11p, ITS, V2X.

I. INTRODUCTION

In recent years, Intelligent Transport Systems (ITS) are actively developing. It is expected that their deployment will highly reduce the number of road accidents and improve driving comfort. Such benefits can be achieved, for instance, by using applications that anticipatorily alert a driver about a road accident, a sudden appearance of a pedestrian, or a maneuver of a neighboring vehicle. Moreover, in the future, ITS will be utilized to provide coordinated autonomous driving.

It is hardly possible to deploy full-fledged ITS without creating underlying Vehicle-To-Everything (V2X) networks. In turn, both an increasing amount of traffic generated by V2X applications [1] and growing demands on reliability and throughput [2] shall be taken into consideration while developing Next Generation V2X (NGV) networks.

V2X networks are expected to be deployed in several phases [3].

The Day1 phase implies implementing Cooperative Awareness (CA) services used to disseminate vehicle state information, Decentralized Environmental Notification (DEN) services utilized to disseminate information about hazardous road situations, and infrastructure-based services providing information about the road infrastructure.

- The CA services are based on periodically broadcast messages that contain information about the position, the velocity, the acceleration, and the size of the transmitting vehicle [4]. Examples of such messages are Basic Safety Messages (BSMs) [5] used in the USA, and

The associate editor coordinating the review of this manuscript and approving it for publication was Stefano Scanzio.

Cooperative Awareness Messages (CAMs) [6] used in the EU.

- The DEN services are provided by event-driven messages that include information about the location, the class, and the severity of the event [7]. An example of an event-driven message is a DEN message used in the EU [8].
- The infrastructure-based services are based on periodically broadcast messages by Roadside Units (RSUs). Examples of such messages are Signal Phase and Timing (SPaT) and MAP (Map Data) messages, which carry information about the traffic light signal and the geometry of the intersection where the RSU is located [5].

The Day2 phase mainly implies the deployment of technologies that provide sensing of the environment and sharing information about detected objects. These technologies will allow receiving vehicles to be aware of obstacles detected by neighboring cars. An example of such an obstacle is a pedestrian hidden behind a corner in an intersection area. The information about obstacles can be shared using Cooperative Perception Messages (CPMs) that contain information from sensors of transmitting devices [9].

The Day3+ phase implies providing vehicles, which are expected to be highly automated, with an ability to share planned trajectories, routes, and maneuver intentions with other stations (STAs). Moreover, in the Day3+ phase, vulnerable road users (pedestrians, cyclists, motorcyclists, etc.) are assumed to be equipped with a radio that will allow them to detect risky situations and exchange data with vehicles and RSUs.

At the time of writing, the most widely deployed radio access technology for V2X networks is Dedicated Short Range Communications (DSRC). The DSRC is based on a set of standards for Wireless Access in Vehicular Environment (WAVE) [10]. This set of standards includes the IEEE 802.11p [11] standard, which specifies the Physical Layer (PHY) and Medium Access Control Layer (MAC) operation, and the IEEE 1609 family of standards [12]–[16], which define upper-layer protocols. DSRC networks operate in the 5.9 GHz frequency band, which is dedicated for V2X in Europe, the USA, Korea, and other countries [17].

The studies on IEEE 802.11p networks [18], [19] show that they can satisfy the requirements of most safety and traffic efficiency applications implemented in the Day1 deployment phase if network traffic is moderate. Such applications require latencies below 50–500 ms, and Packet Loss Ratios (PLRs) below 10% [20], [21].

Nevertheless, it is expected that IEEE 802.11p networks will unlikely meet strict requirements of Day2 and Day3+ applications [2]. These applications will impose heterogeneous requirements. The most stringent ones set 3 ms for the maximum latency and 0.001% for the maximum PLR [2]. Therefore, IEEE 802.11 has established the IEEE 802.11bd Task Group (TGbd) to develop a new standard that will support emerging V2X applications.

TABLE 1. List of acronyms.

Acronym	Full-form
ACK	Acknowledgment
BPSK	Binary Phase Shift Keying
BSM	Basic Safety Message
CAM	Cooperative Awareness Message
CCH	Control Channel
CDF	Cumulative Distribution Function
CPM	Cooperative Perception Message
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
C-V2X	Cellular V2X
DCC	Decentralized Congestion Control
DCM	Dual Carrier Modulation
DEN	Decentralized Environmental Notification
DSRC	Dedicated Short Range Communications
ED	Energy Detection
EDCA	Enhanced Distributed Channel Access
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
GNSS	Global Navigation Satellite System
ICI	Inter-Carrier Interference
ITS	Intelligent Transport System
LDPC	Low-Density Parity-Check
MAC	Medium Access Control Layer
MCS	Modulation and Coding Scheme
MSDU	MAC Service Data Unit
NGV	Next Generation V2X
NR-V2X	New Radio V2X
OCB	Outside the Context of Basic Service Set
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OSI	Open System Interconnection
PHY	Physical Layer
PLR	Packet Loss Ratio
PPDU	Physical Layer Protocol Data Unit
PRR	Packet Reception Rate
QoS	Quality of Service
RSU	Roadside Unit
SAE	Society of Automotive Engineers
SPaT and MAP	Signal Phase and Timing and Map Data
STA	Station
STBC	Space-Time Block Coding
SU-MIMO	Single-User Multiple Input Multiple Output
V2X	Vehicle-To-Everything
WAVE	Wireless Access in Vehicular Environment
WSA	WAVE Service Advertisement

The IEEE 802.11bd standard is aimed at improving transmission reliability, increasing throughput and transmission range compared with the legacy IEEE 802.11p standard [22], [23]. Moreover, the IEEE 802.11bd standard shall also provide interoperability, coexistence, backward compatibility, and fairness with legacy IEEE 802.11p STAs (non-NGV STAs). So, the IEEE 802.11bd STAs (NGV STAs) shall be able to exchange data with non-NGV STAs without degrading the performance of non-NGV STAs. This requirement is crucial because road safety may depend on the stable work of already deployed IEEE 802.11p networks.

Nowadays, the IEEE 802.11bd standard [24] is under development, and it is expected to be finished by September 2022. However, Draft 2.0 is already available [25]. A significant novelty of IEEE 802.11bd is the channel bonding technique, which permits simultaneous data transmission in two adjacent channels. The usage of the channel bonding obviously increases data rates and, as shown in Section VI, may also substantially decrease the percentage of STAs with unsatisfied Quality of Service (QoS) requirements on the frame transmission delay and the PLR. Thus, channel bonding is fruitful in achieving several goals of the IEEE 802.11bd standard at the same time.

The IEEE 802.11bd draft specifies two channel bonding techniques: the first one is basic, extended with the second one. Notably, both techniques differ from that existing in Wi-Fi since IEEE 802.11n [26]. The main difference of the new techniques is that IEEE 802.11bd STAs perform the backoff procedure in two channels at once, whereas legacy STAs perform it only in the primary channel. Consequently, the performance of the channel bonding techniques from IEEE 802.11bd and the technique from IEEE 802.11n significantly differ in some scenarios. Nevertheless, the three aforementioned channel bonding techniques have similar complexities because all of them require the implementation of channel sensing in two channels.[1]

Naturally, the IEEE 802.11bd standard does not specify when to use the introduced channel bonding techniques, i.e., this decision is implementation-dependent. Thus, it raises the problem of selecting the most suitable channel bonding technique. This problem is especially important because of the lack of papers that thoroughly evaluate the channel access methods of IEEE 802.11bd in various scenarios close to reality.

The main contributions of our paper are as follows:

- In contrast to the existing studies, using extensive simulations in ns-3 [27], we provide a comparative analysis of the three channel bonding techniques defined in the IEEE 802.11 family of standards and the single-channel access method, taking into account both frame transmission delays and the PLR for both NGV and non-NGV STAs. Moreover, unlike [28], we also consider the effect of hidden nodes by simulating a more realistic highway scenario.
- We provide the recommendation on selecting the most suitable channel access method. In our recommendation, we take into account not only the performance of NGV STAs but also the impact of NGV STAs on non-NGV STAs.
- We examine how the channel bonding techniques from IEEE 802.11bd improve the performance of ITS.
- We propose selecting different primary channels for STAs on different highway sides and reveal that this method noticeably boosts the performance of channel access and can be utilized in real deployments.

The rest of the paper is organized as follows. In Section II, we describe the channels used by the DSRC networks and the main features of the IEEE 802.11p/bd standards. Section III provides a detailed description of the channel bonding techniques of IEEE 802.11n and IEEE 802.11bd standards. In Section IV, we give a review of papers devoted to the features of IEEE 802.11bd. Section V depicts a considered scenario and used performance metrics. In Section VI, we evaluate the performance of the considered channel bonding techniques via simulation. Section VII gives an insight on open problems and further research directions. In Section VIII, we provide a conclusion. A list of acronyms used in this paper is outlined in Table 1.

II. EVOLUTION OF THE IEEE STANDARDS FOR VEHICULAR NETWORKS

A. DSRC CHANNELS AND THEIR USAGE

In 1999, the Federal Communications Commission (FCC) allocated seven 10 MHz channels in the 5.9 GHz frequency band for the DSRC [29]. The channels with their initial assignment [30] are shown in Fig. 1.

A Control Channel (CCH) was assigned for the transmission of control messages, such as WAVE Service Advertisement (WSA) messages [13], and also for safety applications. In turn, Channel 172 was allocated for safety applications, and Channel 184 was designed for the higher-powered vehicle to infrastructure applications. Channels 174 and 176 were designed as medium-power service channels, whereas Channels 180 and 182 are low-power service channels. Consequently, the simultaneous transmission in two channels at once was possible either in Channels 174 and 176 or in Channels 180 and 182.

In 2021, the FCC reallocated the 5.9 GHz frequency band authorizing unlicensed use in the lower 45 MHz of the band (5.850–5.895 GHz) [31]. However, the FCC retained the upper 30 MHz of the band (5.895–5.925 GHz) for ITS, particularly for the DSRC. Because of the band reallocation, some deployed IEEE 802.11p networks have already moved to the upper 30 MHz band [32], and in particular to Channels 180 and 182, where the channel bonding techniques studied in the paper can be applied.

B. MAIN FEATURES OF IEEE 802.11p

The primary purpose of the IEEE 802.11p standard development was to describe the functions and services which will allow STAs to operate in the fast varying vehicular environment in situations where transactions must be completed in time frames much shorter than the minimum possible with infrastructure or ad hoc IEEE 802.11 networks [33]. To achieve this goal, both MAC and PHY were changed compared with the legacy IEEE 802.11–2007 standard [34].

The philosophy of the IEEE 802.11p PHY was to make minimum necessary changes to IEEE 802.11–2007, which are needed to allow efficient communications in the fast-changing vehicular environment [35]. IEEE 802.11p is based on the Orthogonal Frequency Division Multiplexing (OFDM) PHY with 10 MHz channels instead of 20 MHz channels, typical for IEEE 802.11–2007 devices.

[1] During the standardization process of IEEE 802.11bd, the standard developers considered alternative implementation of channel bonding requiring the ability to detect preambles in the secondary channel and, as a consequence, two independent transceivers. However, since such an approach significantly increases the complexity of devices, it was not included in the draft standard. Because of that, we also do not consider it in our paper.

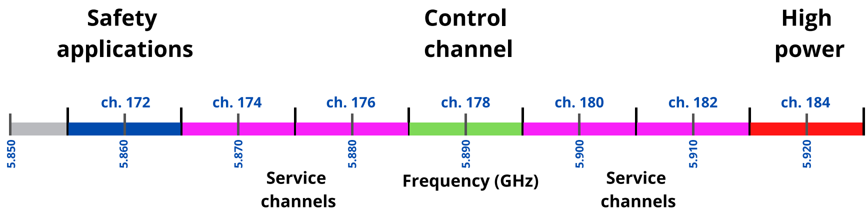


FIGURE 1. The DSRC channels and their initial usage.

In turn, the usage of 10 MHz channels implies 2x scaling of all OFDM timing parameters. The reason for this scaling is two-fold [35]. Firstly, the guard interval in the 20 MHz channel, which equals 0.8 μs, is not long enough to prevent inter-symbol interference in the vehicular environment. Secondly, to simplify the implementation of the IEEE 802.11p PHY, the appropriate scaling was selected from 1x, 2x, and 4x options, which had already been defined in IEEE 802.11–2007. Another feature of the IEEE 802.11p PHY is the operation in the 5.9 GHz frequency band allocated for DSRC.

The main novelty of the IEEE 802.11p MAC is Outside the Context of Basic Service Set (OCB) operations. These operations permit data exchange without authentication, association, and data confidentiality services used in infrastructure and ad hoc IEEE 802.11 networks. The OCB mode was introduced to reduce the connection establishment delays, which are excessively long for vehicular networks, where the connection lifetime can be extremely short.

C. MAIN NOVELTIES OF IEEE 802.11bd

As already mentioned, the IEEE 802.11bd standard aims to improve transmission reliability, increase the throughput and the transmission range over the legacy IEEE 802.11p standard. To achieve these goals, several new features were included in the IEEE 802.11bd standard. Let us briefly indicate the main novelties. For the detailed description, please see [36], [37].

First, to improve transmission reliability in highly mobile scenarios, IEEE 802.11bd introduces midambles that are a sort of preambles additionally inserted between OFDM symbols. Midambles are inserted with the period of K OFDM symbols and improve channel estimation of a fast-varying channel. Also, the standard permits the usage of Low-Density Parity-Check (LDPC) codes in addition to convolutional codes used in the IEEE 802.11p standard. It is expected that the combination of midambles and LDPC codes will give up to 2.5 dBm signal-to-noise ratio gain at the 5% packet error rate level [38].

Second, to improve reliability and reduce delays in case of sporadic interference, IEEE 802.11bd introduces adaptive blind retransmissions [39]. They allow an NGV STA to repeat a frame up to 3 times with a time gap of Short Interframe Space (SIFS) between every two transmissions. The station can decide on the number of retransmissions based on the channel busy ratio, i.e., the portion of the time when the channel is sensed as busy.

Third, to improve reliability at high distances and enlarge the maximum transmission range, IEEE 802.11bd provides a Modulation and Coding Scheme (MCS) with Binary Phase Shift Keying Dual-Carrier Modulation (BPSK DCM). Upon using the BPSK with DCM, data is duplicated and redundantly modulated on two adjacent 5 MHz channels, which constitute a 10 MHz channel.

Forth, an important novelty of the IEEE 802.11bd standard, which will provide higher throughput for bandwidth-hungry applications such as road map update applications and infotainment applications, is the Single-User Multiple Input Multiple Output (SU-MIMO) technology [37]. This technology allows the transmission of 2 spatial streams in the unicast mode.

Fifth, for the same reason, i.e., to increase data rates, IEEE 802.11bd introduces higher-order MCS with 256 quadrature amplitude modulation.

Sixth, IEEE 802.11bd allows operating in the 60 GHz frequency band in addition to the already used 5.9 GHz frequency band. The usage of the 60 GHz frequency band will enable communications at small distances with extremely high throughput.

Seventh, the IEEE 802.11bd standard introduces two channel bonding techniques that allow 20 MHz transmissions, which is fruitful for achieving all the targets thanks to an increase in data rates and reliability, and a reduction in delays. A detailed description of channel bonding techniques in IEEE 802.11bd networks is provided in Sections III-C and III-D.

The IEEE 802.11bd standard specifies two Physical Layer Protocol Data Units (PPDUs) formats: an NGV PPDU and a non-NGV PPDU. The non-NGV PPDU is used for interoperability and backward compatibility with non-NGV STAs and can be decoded by them. In contrast, the NGV PPDU was introduced to support the new IEEE 802.11bd features and cannot be decoded by non-NGV STAs.

III. CHANNEL ACCESS IN IEEE 802.11bd NETWORKS

A. EDCA CHANNEL ACCESS METHOD

Both modern Wi-Fi and IEEE 802.11p/bd networks use Enhanced Distributed Channel Access (EDCA) as a basic channel access method. Let us briefly describe it.

EDCA is based on a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). With EDCA,

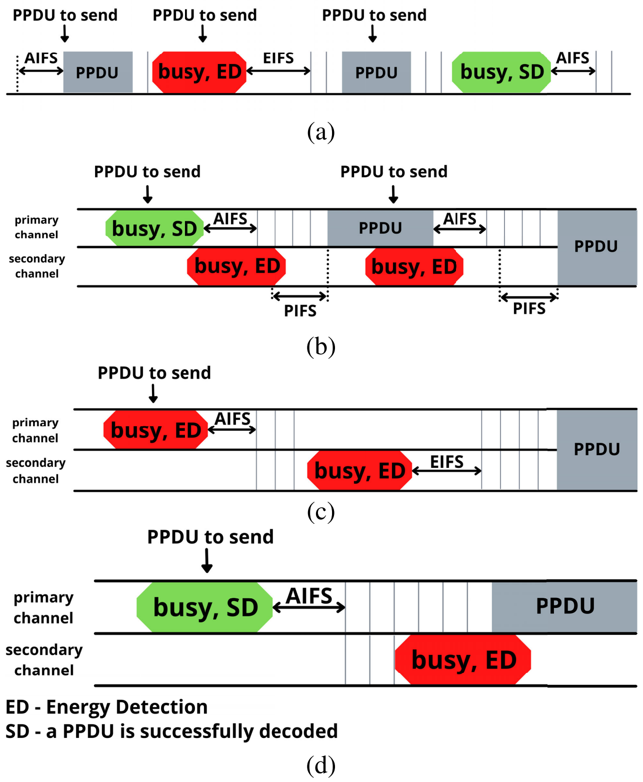


FIGURE 2. The operation examples of (a) EDCA; (b) the channel bonding technique of IEEE 802.11n; (c) the channel bonding technique of IEEE 802.11bd without fallback; (d) the channel bonding technique of IEEE 802.11bd with fallback.

a STA performs a backoff procedure before every transmission attempt. The STA initializes the backoff counter with a value uniformly distributed in the range $[0, W]$, where W is the current contention window. The backoff counter is decremented every time when the channel is sensed idle for a time σ. Otherwise, i.e., if the channel is busy, the backoff counter is suspended. The decrementing is resumed when the channel becomes idle for interval T, where T equals an Extended Interframe Space (EIFS) if the STA was unable to successfully decode the packet transmitted when the channel was busy, and an Arbitration Interframe Space (AIFS), otherwise. The STA begins a data transmission attempt when the backoff counter reaches zero.

However, there is one exception allowing the STA to perform a data transmission attempt immediately when the packet arrives in an empty MAC queue. Specifically, immediate channel access is allowed if the STA has finished the backoff procedure (i.e., its backoff counter reached zero) after the previous transmission attempt, and the channel is idle for more than the AIFS before the arrival of the packet. Otherwise, e.g., if the channel is busy when the packet arrives, the STA invokes the backoff procedure.

Unicast transmissions are acknowledged, and the STA changes the contention window W after reception or loss of the Acknowledgment frame (ACK). However, in the paper, we consider only broadcast transmissions, which are not acknowledged. Thus, the contention window W remains constant.

B. IEEE 802.11n CHANNEL BONDING

At first sight, 20 MHz channels can be easily used as the IEEE 802.11 standard by default supports 20 MHz transmissions. However, the usage of legacy channel access rules and PPDU formats to simultaneously operate in the same area in 20 MHz and 10 MHz overlapping channels breaks the virtual carrier sense and is inefficient. That is why TGbd considered the channel bonding technique developed within IEEE 802.11n to expand default 20 MHz channels of IEEE 802.11a/g and tried to adapt this technique for expansion of 10 MHz channels of IEEE 802.11p to 20 MHz ones of IEEE 802.11bd.

This channel bonding technique was later extended in IEEE 802.11ac, IEEE 802.11ax, and IEEE 802.11be for even wider channels [40].

IEEE 802.11n splits the wide 40 MHz channel into the primary and secondary 20 MHz channels, see Fig. 2 (b). The primary channel is a channel where the STA detects PPDU preambles and counts down the backoff. In the secondary channel, during the backoff procedure, the STA can only determine that the energy in the channel is above the Energy Detection (ED) threshold. If so, the secondary channel is busy. The state of the secondary channel does not affect the backoff procedure that only depends on the state of the primary channel.

Thus, when the backoff counter reaches zero, the STA checks the state of the secondary channel. If the secondary channel is idle for at least the time x defined below, the STA transmits a PPDU in the whole wide channel at once. Otherwise, the STA can operate in two ways. It may either transmit the PPDU only in the primary channel or defer transmission by invoking the backoff counter again with the old W value. In our simulation, we consider only the first option.

For IEEE 802.11n STAs operating in the 5 GHz frequency band, x equals a Point Coordination Function Interframe Space (PIFS), which is shorter than the AIFS.

The main rule of the usage of wide channels in IEEE 802.11bd networks is that non-NGV STAs shall have the same opportunities to access the channel as NGV STAs. However, the usage of the channel bonding technique from IEEE 802.11n may be unfair for non-NGV STAs that operate in the secondary channel of the wide channel used by NGV STA. Indeed, NGV STAs may have more opportunities to access the channel because they do not use the backoff procedure on the secondary channel.

TGbd has studied the technique with x = AIFS as a candidate solution because a higher x decreases the influence of NGV STAs on non-NGV STAs. However, after an investigation, the technique was not accepted as it is still unfair to non-NGV STAs, especially when the load in the primary channel is low [41], [42].

Because of that, TGbd has developed two completely new channel bonding techniques, which we describe in detail below.

C. IEEE 802.11bd CHANNEL BONDING WITHOUT FALLBACK

To access the channel, an NGV STA can use the legacy EDCA and the IEEE 802.11bd channel bonding technique without or with fallback.

The IEEE 802.11bd channel bonding technique without fallback differs from the IEEE 802.11n channel bonding techniques by the following rules.

In contrast to the IEEE 802.11n channel bonding technique, if at least one channel (i.e., primary or secondary) becomes busy during the backoff procedure, the STA freezes the backoff counter and resumes it only when both channels are idle for τ. The value of τ depends on the success of the previous frame reception. If the STA did not successfully decode a transmission when the secondary channel or both channels were busy last time, τ equals the EIFS. Otherwise, τ equals the AIFS.

When the backoff counter reaches zero, the STA transmits in both the primary and the secondary channels at once.

Figure 2 (c) illustrates the channel bonding technique without fallback.

D. IEEE 802.11bd CHANNEL BONDING WITH FALLBACK

IEEE 802.11bd also specifies an optional channel bonding technique with fallback, which differs from that described in Section III-C by the following rule.

If the secondary channel becomes busy during the backoff procedure but the primary channel stays idle, the STA may switch to the single-channel operation on the primary channel. If the STA switches, it finishes the backoff procedure in the primary channel and transmits the PPDU only in the primary channel. After the transmission, the STA goes back to the channel access procedure in two channels at once.

Figure 2 (d) illustrates the channel bonding technique with fallback. Note that in the paper, we consider that it always switches to the primary channel. Thus, by comparing the techniques with and without fallback, we study when it is worth switching to the 10 MHz operations.

IV. RELATED PAPERS

Various aspects of IEEE 802.11bd networks are studied in many papers [28], [37], [43]–[51]. Paper [43] provides a comparison of IEEE 802.11bd, IEEE 802.11p, and Cellular V2X (C-V2X). The authors show that networks based on C-V2X and IEEE 802.11bd can decrease the number of road accidents compared with networks based on IEEE 802.11p.

Papers [44], [45] compare throughputs and PLRs of IEEE 802.11bd, IEEE 802.11p, C-V2X, and New Radio V2X (NR-V2X) networks. They show that IEEE 802.11bd provides a lower PLR than C-V2X and NR-V2X because of lower Inter-Carrier Interference (ICI), which is caused by higher carrier spacing. Moreover, IEEE 802.11bd also outperforms IEEE 802.11p thanks to LDPC codes. However, NR-V2X provides higher throughput because of lower overhead compared with IEEE 802.11p and IEEE 802.11bd.

The authors of [37], [46]–[48] compare the performance of IEEE 802.11p and IEEE 802.11bd. The results show that adaptive blind retransmissions of broadcast frames and the MCS with DCM can highly enlarge the maximum transmission range of NGV STAs and improve their PLR compared with non-NGV STAs. Moreover, the paper [37] reveals that MIMO Space-Time Block Coding (STBC) can magnify throughput and significantly improve reliability for unicast transmissions, whereas the combination of midambles and LDPC codes can noticeably reduce the PLR for both broadcast and unicast thanks to enhanced channel estimation and error resilience. Furthermore, [47], [48] show that networks based on IEEE 802.11bd can satisfy the QoS requirements of some safety applications that are not supported by IEEE 802.11p networks. An example of such an application is a rear-end collision warning application that helps to avoid collision with a vehicle at the rear-end.

In turn, authors of [49] review the usage of millimeter-wave spectrum by IEEE 802.11bd and NR-V2X and analyze the related challenges related. With simulation, the authors show that when an NR-V2X system operates in the millimeter-wave band, it achieves noticeably higher throughput and lower delays at the application layer at distances lower than 300 meters compared with the operation in the 5.9 GHz frequencies. The increase in throughput and the decrease in delays are provided by a higher channel bandwidth used in the millimeter-wave band.

A new channel access method for IEEE 802.11bd networks based on an Orthogonal Frequency-Division Multiple Access (OFDMA) is proposed and studied in [50]. The results of the study reveal that the proposed method can decrease the PLR thanks to reduced channel contention. In turn, [51] evaluates the performance of a broadcast acknowledgment mechanism in IEEE 802.11bd networks. This mechanism allows retransmitting a broadcast frame if preselected STAs do not receive it. The authors show that, in some cases, the considered mechanism improves CPMs transmission reliability.

However, the IEEE 802.11bd channel bonding techniques have not been well investigated in the literature. To the best of our knowledge, only two papers study IEEE 802.11bd channel bonding techniques, namely [28], [52]. However, a substantial drawback of [28] is that the authors compare the channel bonding techniques only in terms of frame transmission delays neglecting the PLR, although V2X applications impose QoS requirements on both transmission delays and the PLR, and the PLR also has a significant impact on the performance. Moreover, the authors do not consider the effect of hidden nodes, assuming that all the STAs are located in the transmission range of each other, which is unrealistic for vehicular networks.

A conference paper [52] briefly explores the performance of the channel bonding techniques from IEEE 802.11bd with different W in a simplified scenario. However, the paper has two noticeable disadvantages. First, [52] does not take into account the impact of NGV STAs on non-NGV STAs, although the requirement that NGV STAs shall not degrade the performance of non-NGV STAs is vital. Second, it considers only a scenario with the same number of vehicles on both road sides.

In contrast to [28], we examine a more realistic scenario, which includes vehicles moving on a highway and RSUs located on the highway. Moreover, assessing the performance of NGV STAs and their impact on non-NGV STAs, we take into account not only frame transmissions delays but also the PLR. The aforementioned drawbacks of [52] are also addressed in this paper.

V. CONSIDERED SCENARIO

This section specifies the considered scenario. Section V-A describes the considered mobility model and primary channel selection cases. In Section V-B, we depict the main parameters of the channel, MAC, and PHY used in the simulation. Section V-C describes the considered network traffic. In Section V-D, we define considered QoS metrics.

For convenience, Table 2 shows the main parameter values used in the simulation.

A. MOBILITY MODEL AND PRIMARY CHANNEL SELECTION CASES

In this paper, we consider the scenario where vehicles move along a 1 km long highway [53]. On one side, the selected highway is long enough to observe the effect of hidden nodes. On the other side, it is short enough to obtain the simulation results in a reasonable time. The highway has two sides, each of which consists of four 4 m wide lanes, i.e., the highway has eight lanes in sum. The sides are separated from each other by a 25 meters wide median, as shown in Fig. 3.

There are three types of STAs on the highway: (i) non-NGV vehicles that support only IEEE 802.11p, (ii) RSUs that support only IEEE 802.11p, and (iii) NGV vehicles that support IEEE 802.11bd and, consequently, IEEE 802.11p.

The vehicles are evenly placed in each road lane and move towards the appropriate end of the road. The speeds of the vehicles are evenly distributed from 10 to 30 m/s. In turn, the RSUs do not move and are located on both highway sides with a distance of 100 m between neighboring RSUs.

To maintain a constant number of vehicles on the road, when a vehicle reaches the end of the lane, we virtually move it back to the other end of the road and randomly select a new speed evenly from the range [10, 30] m/s. Also, we select a new lane uniformly among all the lanes on the same highway side. In the experiments, we consider various densities of vehicles on the highway by varying the total number of vehicles in all lanes. In the densest situation, the average inter-vehicle distance in a lane is higher than 25 meters, which is significantly longer than the typical vehicle length.

In this work, we consider two cases of how the primary channel is selected. In the **asymmetric case**, all the STAs use

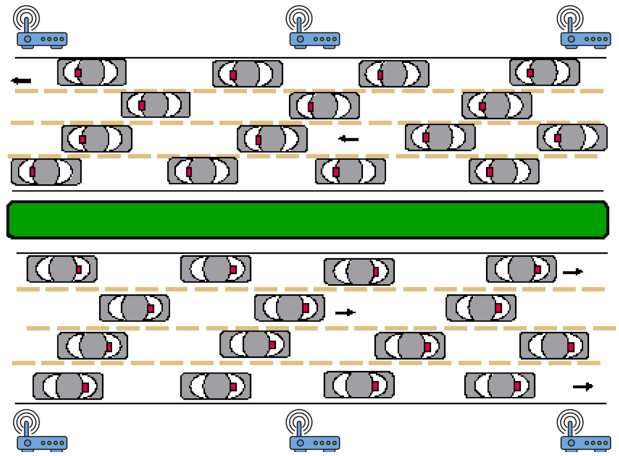


FIGURE 3. The considered highway.

the same Channel 180 as primary. In the **symmetric case**, the STAs on the bottom side of the highway use Channel 180 as primary, and the STAs on the top side select Channel 182 as primary.

The asymmetric case corresponds to the situation when the V2X service is bound on a fixed channel in a region.

The symmetric case can be realized by WSA messages obtained by vehicles from the RSUs. WSA messages contain information about the location of the transmitting STA with 0.1 microdegree resolution and also information about the channel where the transmitter provides various services [54]. Thus, knowing the location of the RSU, the vehicles can use the information about their coordinates obtained from a Global Navigation Satellite System (GNSS) to determine their highway side. Importantly, to use the proposed primary channel selection method, the vehicle does not need to know its own location with high accuracy because only the direction of the movement is required, and it is quite an easy task for modern GNSS devices. Given the highway side, the vehicles can tune to the appropriate channel specified in the WSA message.

As IEEE 802.11p, and, consequently, IEEE 802.11bd, impose stricter requirements on the spectrum mask than other IEEE 802.11 standards [35], in the paper, we neglect the impact of adjacent channel interference.

B. PROPAGATION MODEL AND PARAMETERS OF PHY AND MAC

In this paper, we consider the log-distance path loss model. Thus, a path loss is determined as follows:

$$PL(d) = PL(d_0) + 10\gamma \cdot lg\left(\frac{d}{d_0}\right), \tag{1}$$

where $d_0 = 1$ m is a reference distance, $PL(d_0) = 44$ dB is a reference loss, $\gamma = 2.83$ is a path loss exponent [55]. The receiver sensitivity and the ED threshold equal -92 dBm for the NGV STAs and -95 dBm for the non-NGV STAs [55]. In turn, the noise power for the reception in a 20 MHz

TABLE 2. Parameter values used in simulation.

Parameter	Value
Highway length	1 km
Number of lanes on a side	4
Lane width	4 m
Median width	25 m
Minimum and Maximum vehicle speed	10 m/s; 30 m/s
Simulation duration	1000 s
Number of runs	100
RSUs period	100 m
σ	13 μs
SIFS	32 μs
MCS	MCS 1
Nominal data rate (non-NGV STAs)	6 Mbps/s
Nominal data rate (NGV STAs, 20 MHz)	13.5 Mbps/s
Nominal data rate (NGV STAs, 10 MHz)	6.5 Mbps/s
Receiver sensitivity for NGV STAs	-92 dBm
Receiver sensitivity for non-NGV STAs	-95 dBm
Noise power for a 10 MHz channel	-95 dBm
Noise power for a 20 MHz channel	-98 dBm
CPM, SPaT and BSM generation rate	10 Hz
MAP and WSA generation rate	1 Hz
CPM base size	250 bytes
CPM per-neighbor extra-size	30 bytes
SPaT size	120 bytes
SPaT and MAP size	1200 bytes
BSM size	250 bytes
WSA size	100 bytes
Sensors range	150 m

channel equals −95 dBm and for the reception in a 10 MHz channel equals −98 dBm [55]. The transmission power is 23 dBm [56], and the MCS 1 is chosen [54] for data transmission.

C. CONSIDERED NETWORK TRAFFIC

As mentioned in Section II-A, some real deployments moved to Channels 180 and 182 after the FCC spectrum reallocation. Thus, in these deployments, BSMs, which are used by most non-NGV STAs in the USA, are transmitted in the channels that may be utilized by the channel bonding techniques. Therefore, in this study, the NGV STAs transmit two types of messages: BSMs and CPMs. BSMs are standardized by the Society of Automotive Engineers (SAE) [5] and carry information about the position, the velocity, the acceleration, and the size of a transmitting vehicle. The typical generation rate of these messages equals 10 Hz [1], and the typical size is nearly 250 bytes [57]. In turn, CPMs are the messages for emerging sensor sharing applications. They are standardized by the European Telecommunications Standards Institute (ETSI) [9] and carry information from sensors, e.g., from cameras, radars, lidars, and ultrasonic sensors [58]. The size of CPMs depends on the number of vehicles in the sensors range R_s. The base size of CPM is L_b bytes, and each vehicle in the sensors range induces additional L_a bytes. The generation rate of CPMs equals 10 Hz [1]. In this research, $R_s = 150$ m [58], $L_b = 250$ bytes, $L_a = 30$ bytes [1].

Also, we consider that the NGV STAs transmit CPMs in NGV PPDUs using the channel bonding technique. Nevertheless, the NGV STAs transmit BSMs in non-NGV PPDUs with EDCA in the primary channel. The non-NGV vehicles also transmit BSMs.

In the considered scenario, RSUs transmit three types of messages: WSA, SPaT, and MAP messages. As already mentioned, SPaT and MAP messages are standardized in the SAE [5] and used to transmit data about the traffic light signal and the geometry of the intersection where RSU is located. SPaT and MAP messages are commonly used in real deployments and testbeds [59].

MAP messages are transmitted more rarely than SPaT messages: the typical generation rate of SPaT messages equals 10 Hz, whereas the typical generation rate of MAP messages is equal to 1 Hz [1], [32]. Moreover, MAP messages are typically transmitted in the same packet as SPaT messages. The typical size of a packet with both SPaT and MAP messages equals 1200 bytes, whereas the typical size of a packet with only a SPaT message is equal to 120 bytes [1], [32].

In turn, WSA messages are transmitted by RSUs with a periodicity that depends on the service provided by WSA messages. In our simulation, RSUs transmit WSA messages only in the symmetric case. The size of WSA messages is 100 bytes [13], and the generation rate is set to 1 Hz. The generation rate is low because the information provided by WSA messages is supposed to be static.[2]

For convenience, we summarize how different STAs communicate with each other in Table 3.

D. QoS METRICS

In this paper, we consider the packet transmission delay and the PLR as the main QoS metrics. Both metrics are widely used to explore the performance of vehicular networks [18], [28], [60], [61]. Moreover, many studies propose methods for assessing the values of these metrics. For instance, the authors of [62] developed an analytical model for exploring the performance of DSRC networks in terms of frame transmission delays and a Packet Reception Rate (PRR) defined as $PRR = 1 - PLR$. In turn, new analytical and neural networks-based approaches to predict an outage probability, which is an analog of the PLR for mobile vehicular networks with relaying, are proposed in [63]. An analytical model for delay analysis of IEEE 802.11p networks was also proposed in [64]. In our paper, we define the PLR and the frame transmission delay similar to [62].

The packet transmission delay includes the queue waiting time, the backoff procedure duration, and the packet transmission time. Note that as packet aggregation is not used, each message is transmitted in a separate packet.

As outdated packets are not needed to be delivered anymore, we consider the following behavior. If the queue contains a packet with a message of type m and a new packet with a message of the same type arrives in the queue, the old

[2]A proper operation of the symmetric channel selection is provided if each vehicle obtains just one WSA message from any RSU. Moreover, the QoS requirements for WSA messages are not specified. Thus, we do not provide numerical results for these messages.

TABLE 3. Communications between different STAs and QoS requirements of various types of traffic.

Type of message	Transmitters	Receivers	PPDU format	Delay requirement	PLR requirement
BSM	non-NGV vehicles	all STAs	non-NGV (11p)	100 ms	10%
BSM	NGV vehicles	all STAs	non-NGV (11p)	100 ms	10%
CPM	NGV vehicles	NGV vehicles	NGV (11bd)	10 ms	10%
SPaT and MAP messages	RSUs	all vehicles	non-NGV (11p)	100 ms	10%
WSA message	RSUs	all vehicles	non-NGV (11p)	-	-

packet is replaced by a new one. Besides, the queue waiting time of the old packet is added to the transmission time of the new packet when we calculate delays.

When we compute the PLR, we consider packet delivery events only for the STAs on the same highway side as the transmitter:

$$PLR_m = 1 - \frac{\sum_{i=1}^{N_m} S_m^i}{\sum_{i=1}^{N_m} E_m^i},$$

where $m \in \{\text{“}CPM\text{”}, \text{“}BSM\text{”}, \text{“}SPaT\text{”}\}$ is the type of messages,[3] N_m is the total number of transmitted messages of type m. Since BSMs and CPMs are dedicated for all STA, whereas SPaT and MAP messages are dedicated only for vehicles, E_m^i and S_m^i for these types of messages are defined in different ways:

- For $m = \text{“}CPM\text{”}$ or $\text{“}BSM\text{”}$, E_m^i is the total number of STAs in the R_s range of the STA that transmitted message i and S_m^i is the total number of STAs that successfully decoded message i and are in the R_s range of the transmitter.
- For $m = \text{“}SPaT\text{”}$, E_m^i is the total number of vehicles in the range R_s of the RSU that transmitted SPaT message i, S_m^i is the total number of vehicles that successfully decoded SPaT message i and are in the range R_s of the transmitter.

In this study, we compare the efficiency of various channel bonding techniques by estimating the ratio of unsatisfied STAs. A STA is unsatisfied with a message delivery service if the packet transmission delay exceeds D or the PLR exceeds L. For SPaT, MAP and BSM, $D = 100$ ms and $L = 10\%$ [20], [21], [65]. For CPMs, $D = 10$ ms and $L = 10\%$ [2]. In other words, the considered ratio of unsatisfied STAs is a complex metric that takes into account how well both delay and PLR requirements are satisfied. For convenience, we summarize the QoS requirements of different types of traffic in Table 3.

VI. NUMERICAL RESULTS

To model the considered scenario, we use the WAVE module of ns-3 [66], which allows simulating IEEE 802.11p networks. Originally, the module did not support IEEE 802.11bd. So we have implemented new functionality of IEEE 802.11bd, including the channel bonding techniques (the one of IEEE 802.11n adapted to the IEEE 802.11bd bandwidth and two of IEEE 802.11bd) and the NGV PPDU format. Also, we have developed the highway mobility model, SPaT and MAP messages, CPMs, and the QoS metrics mentioned above.

In our simulation, four main factors degrade the performance of the channel access methods:

- PPDU collisions caused by contention for the channel. Such collisions happen if backoff counters of several STAs reach zero simultaneously or when new packets arrive in empty queues of several STAs with expired backoff counters. Such collisions increase the PLR and delays and can happen even if the STAs are in the transmission range of each other.
- PPDU collisions caused by hidden STAs. These collisions occur when two STAs cannot detect transmissions of each other because of a long distance between them, and one STA starts to transmit its PPDU during an ongoing transmission by another STA. As a result, a STA that hears both transmitters loses the PPDU of a more distant STA and can also lose the PPDU of a closer STA.
- The delay induced by the backoff procedure. This delay is especially significant when the density of STAs and their traffic intensities are high.
- The delay induced by the PPDU transmission itself. This delay is noticeable for CPMs because the size of these messages rises with the number of neighboring vehicles.

A. THE IMPACT OF MOBILITY

To show how the considered mobility affects the density of vehicles and its fluctuation, we consider an experiment where the number of vehicles on both sides of the highway is the same, and the total number of vehicles on the highway equals 100. We randomly select several vehicles and compute the number of their neighboring vehicles in the range R_s every 100 ms. Fig. 4 shows a Cumulative Distribution Function (CDF) for the number of neighboring vehicles and the dependency of the number of neighboring vehicles on time, which confirm that the number of neighbors significantly and quickly varies.

We also study the impact of vehicles speeds on network performance. Specifically, we consider the default case with random speeds and the cases where all the vehicles have the same speed. As observed effects are similar for all channel access methods and scenarios considered in the paper, we present only plots for the channel bonding technique from

[3] As the MAP messages are transmitted together with the SPaT ones, and SPaT messages are more frequent, we show results only for the SPaT messages.

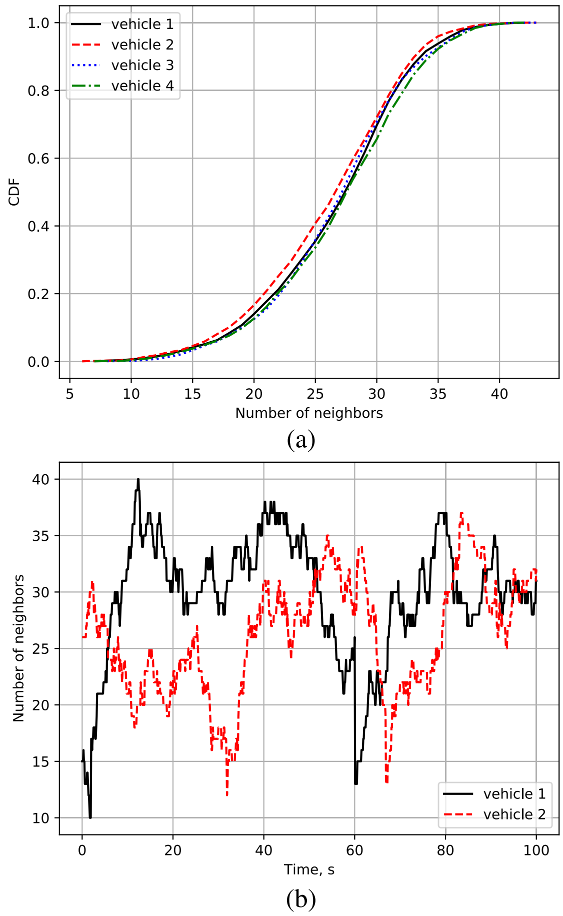


FIGURE 4. **(a) The CDF for the number of vehicle neighbors, (b) the dependency of the number of vehicle neighbors on time.**

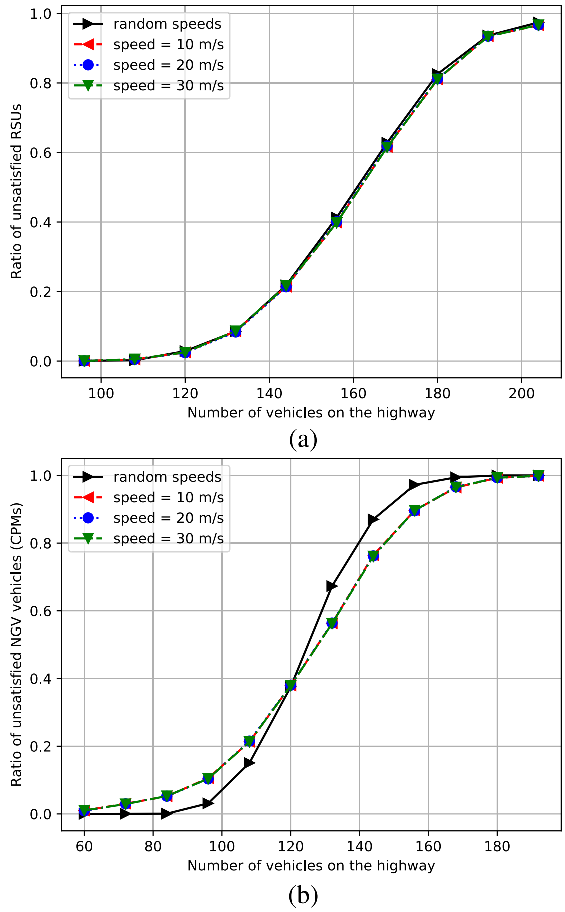


FIGURE 5. **The influence of vehicles speeds on the performance of the channel bonding technique from IEEE 802.11bd without fallback in the symmetric case when the number of vehicles on both sides of the highway is the same in terms of (a) the percentage of unsatisfied RSUs; (b) the percentage of unsatisfied NGV vehicles (CPMs).**

IEEE 802.11bd without fallback in the symmetric case when the number of vehicles on both sides of the highway is the same, see Fig. 5.

As we can see, in the case of random speeds, the performance is improved for low numbers of STAs and degraded for high numbers of STAs. The explanation is as follows. For any speed distribution and time moment, the highway has areas with different densities of vehicles. For low numbers of vehicles, only a few of them located in dense areas may be unsatisfied. If speeds are constant, vehicles from different areas do not mix, and unsatisfied vehicles remain such during the whole experiment. On the contrary, in the case of random speeds, vehicles actively mix, and the number of neighbors notable varies in time, see Fig. 4. So, vehicles from dense areas move to sparse areas where their QoS is improved. Therefore, in the case of random speeds, the ratio of unsatisfied vehicles decreases for low total numbers of vehicles. Similarly, for high total numbers of vehicles and constant speeds, only a few vehicles located in the sparse areas may be satisfied. If speeds are random, these vehicles come to dense areas, where they become unsatisfied. Consequently, the ratio of unsatisfied vehicles goes up compared with the case of constant speeds.

In turn, we do not observe the aforementioned effect for RSUs because sparse and dense areas move past all RSUs for all speed distributions.

Notably, the curves for various constant speeds are very close to each other. The reason for it is two-fold. First, in the case of constant speeds, vehicles from dense and sparse areas do not mix. Second, even the slowest vehicle with a speed of 10 m/s drives the highway 10 times during the simulation time of 1000 s. This averaging is enough to smooth the results, making them very close to each other.

We do not include the results for other traffic types because the observed effects are the same as for the CPM traffic.

To show the impact of the initial distribution of vehicles on the performance of the network, we run additional experiments where vehicles on the top side of the highway are initially located in the right part of the highway, and vehicles on the bottom side are initially located in the left part of the highway. At the beginning of the experiments, vehicles occupy all eight lanes, and the inter-vehicle distance equals 7 m. The experiments correspond to the movement after the green light switches on. In the experiments, we consider the asymmetric case, where the total number of vehicles

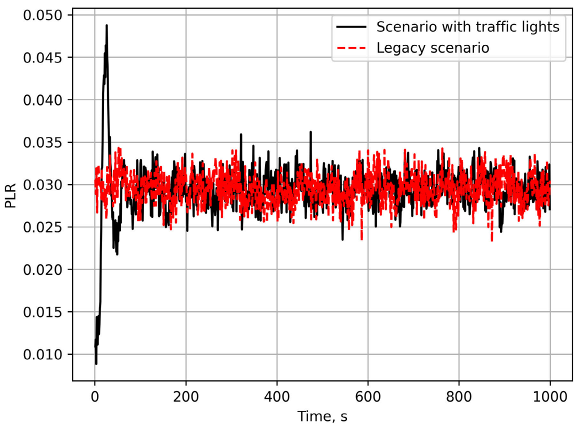


FIGURE 6. **The influence of the initial distribution of vehicles on the PLR of CPMs in the asymmetric case.**

on the highway equals 40, and the number of vehicles on two sides of the highway is the same. The NGV STAs use the channel bonding techniques from IEEE 802.11bd without fallback, and the PLR is computed separately for each interval of 1 s. Fig. 6 presents the results of the experiments.

As we can see, the effect of the initial distribution of vehicles is short-lasting. Moreover, in the scenario with traffic lights, the PLR is initially lower than in the legacy scenario, then it rises, and, finally, becomes nearly the same as the PLR in the legacy scenario. The reason is that in the scenario with traffic lights, all vehicles initially sense the transmissions of each other, i.e., there are no hidden nodes, which improves performance. However, when two crowded groups of vehicles on different highway sides cross past each other, many hidden nodes appear, degrading the overall performance.

B. SCENARIO WITH THE SAME NUMBER OF VEHICLES ON TWO HIGHWAY SIDES

Fig. 7 shows the percentage of unsatisfied STAs for the asymmetric case, i.e., when all STAs use the same primary channel. We see that the curves corresponding to all channel bonding techniques are very close to each other. The explanation is as follows. In the asymmetric case, 10 MHz transmissions in the secondary channel never happen. Thus, the STAs that use the channel bonding technique from IEEE 802.11bd with fallback never switch to the single-channel mode. Similarly, the IEEE 802.11n STAs transmit all NGV PPDUs in the 20 MHz channel because the secondary channel becomes busy only due to 20 MHz transmissions, which affect the backoff procedure. Therefore, the NGV STAs that use channel bonding techniques transmit all NGV PPDUs in the 20 MHz channel, which leads to close results.

Some discrepancy between the channel bonding techniques occurs because the IEEE 802.11bd STAs always wait for the AIFS after the busy interval on the primary channel, whereas the IEEE 802.11n STAs wait for either the AIFS or the EIFS. As the values of AIFS and EIFS are close to each other and much smaller than the typical durations of packets, the discrepancy is minuscule.

The obtained results also demonstrate that the usage of the channel bonding techniques significantly reduces not only the number of unsatisfied NGV STAs but also the number of unsatisfied non-NGV STAs. It happens because the usage of the secondary channel reduces the transmission time of NGV PPDUs. In turn, it mitigates the congestion in the primary channel, decreasing the PLR and the frame transmission delay.

In Fig. 8, we compare the performance in the asymmetric and symmetric cases (in the symmetric case, all STAs on the bottom side of the highway have primary channel 180 and all STAs on the top side have primary channel 182). We show only the best curve for the asymmetric case, i.e., a curve for a channel bonding technique, because all channel bonding techniques demonstrate similar results in this case.

In the symmetric case, the percentage of unsatisfied STAs is significantly lower than in the asymmetric case. As we present the best curve for the asymmetric case, we can conclude that the usage of the symmetric primary channel selection noticeably increases the performance of both NGV and non-NGV STAs. The asymmetric channel selection increases the portion of unsatisfied STAs because of the inefficient utilization of the secondary channel, which cannot be used for transmissions of non-NGV STAs. In turn, this inefficiency leads to a significantly higher contention in Channel 180 used by all STAs. In particular, this congestion leads to a significantly lower performance of the channel bonding technique from IEEE 802.11bd without fallback in the asymmetric case compared with the performance of EDCA in the symmetric case. As a result, to enhance the performance of STAs, it is fruitful to select different primary channels on two sides of the highway.

Let us consider the symmetric case in more detail. In this case, the ratio of unsatisfied STAs is determined exclusively by the PLR for BSMs, SPaT, and MAP messages, and mainly by the PLR for CPMs. It is illustrated by Fig. 9, which shows the average frame transmission delay and the PLR for BSMs transmitted by NGV vehicles and corresponds to Fig. 8 (c). As we can see, the delays for all channel bonding techniques are much lower than 100 ms, which is the delay requirement for BSMs, SPaT, and MAP messages. Fig. 9 also shows that the channel bonding technique from IEEE 802.11bd without fallback, which initiates transmissions of CPMs only in the 20 MHz channel, provides the lowest delay among all the considered channel access methods. The reason for it is twofold. First of all, the transmission range of 20 MHz PPDUs is lower than of 10 MHz PPDUs due to a lower power density. In turn, the decrease in the transmission range leads to a lower channel busy ratio and, consequently, lower frame transmission delays. Furthermore, 20 MHz transmissions are nearly twice shorter than 10 MHz ones, which decreases the duration of the backoff procedure in case of the appearance of an interfering PPDU.

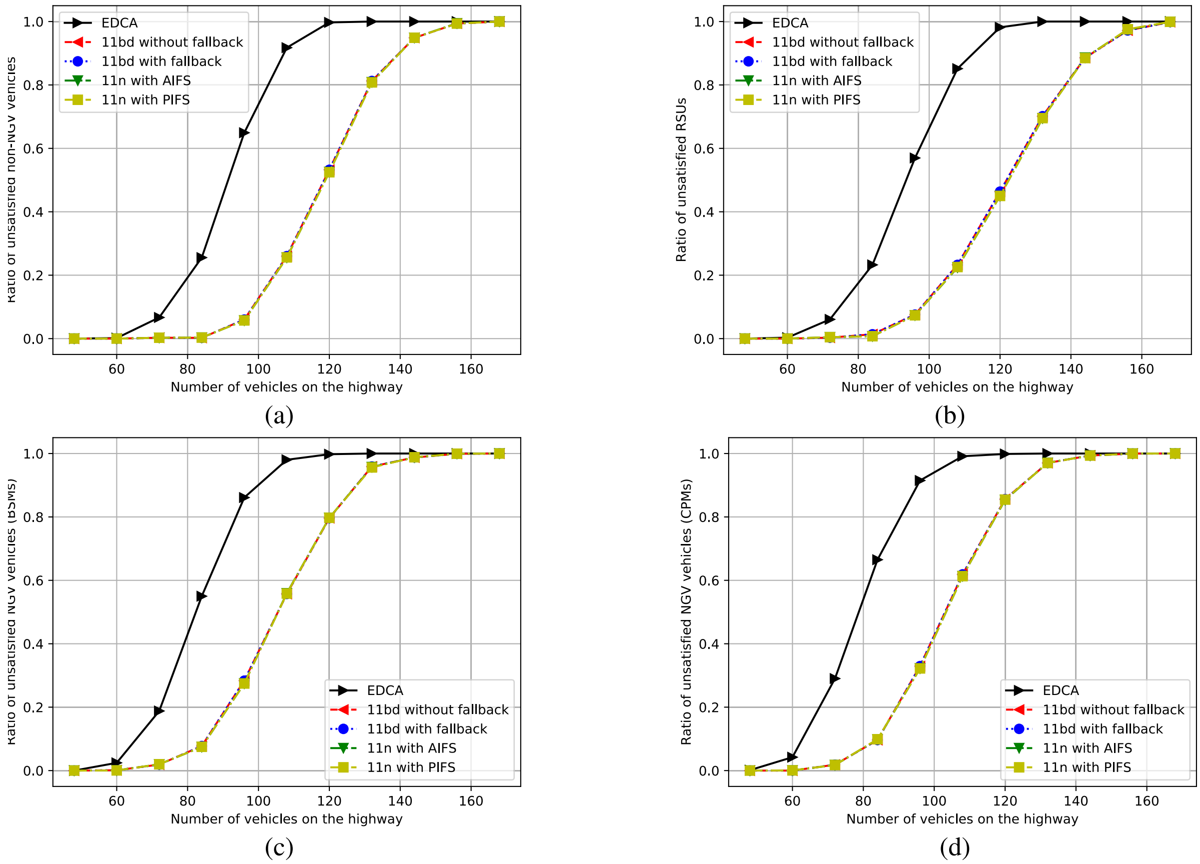


FIGURE 7. **The results for the asymmetric case and the same number of vehicles on both sides of the highway: (a) the percentage of unsatisfied non-NGV vehicles; (b) the percentage of unsatisfied RSUs; (c) the percentage of unsatisfied NGV vehicles (BSMs); (d) the percentage of unsatisfied NGV vehicles (CPMs).**

As Fig. 8 shows, the IEEE 802.11bd channel bonding technique without fallback provides the best QoS for BSMs, SPaT, and MAP messages. The explanation is as follows. Since BSMs, SPaT, and MAP messages are transmitted only in 10 MHz channels, the channel bonding techniques are used only for CPMs, which can be transmitted either in a 10 MHz or the 20 MHz channel. In turn, 20 MHz transmissions are almost twice shorter than 10 MHz transmissions. Furthermore, when a STA uses the channel bonding from IEEE 802.11bd without fallback, the STA transmits all CPMs in the 20 MHz channel. It decreases the number of new packets arriving during the transmissions of CPMs and reduces the contention right after CPMs, which leads to a lower PLR of BSMs, SPaT, and MAP messages.

We can also see that the channel bonding technique from IEEE 802.11bd without fallback provides worse QoS for CPMs compared with other channel bonding techniques and EDCA. It happens because the PLR for 20 MHz PPDUs is higher than the PLR for 10 MHz PPDUs. The reason for it is that a 20 MHz PPDU can interfere with a PPDU of any other STA, whereas a 10 MHz PPDU cannot interfere with 10 MHz PPDUs in the adjacent channel.

Moreover, Fig. 8 reveals that the channel bonding techniques from IEEE 802.11n show similar results. The only difference between them is the duration of the interframe space in the secondary channel. This duration affects the decision of a STA whether to transmit in the primary or in the 20 MHz channel only when the following conditions are met. Firstly, the last transmission is detected in the secondary channel. Secondly, the backoff counter of the STA reaches zero in the interval between PIFS and AIFS upon the end of this transmission. Thus, as we consider the unsaturated case, the duration of the interframe space in the secondary channel rarely affects the decision of the STA.

We evaluate the impact of this effect by running an experiment with NGV STAs that use the channel bonding technique from the IEEE 802.11n with the PIFS. In this experiment, we measure the percentage of transmissions where the usage of the AIFS instead of the PIFS changes the decision of the channel access method whether to transmit in the 10 or 20 MHz channel. When the number of vehicles equals 160, this percentage is equal to 8%. Furthermore, the percentage quickly falls with the decrease in the number of vehicles on the highway.

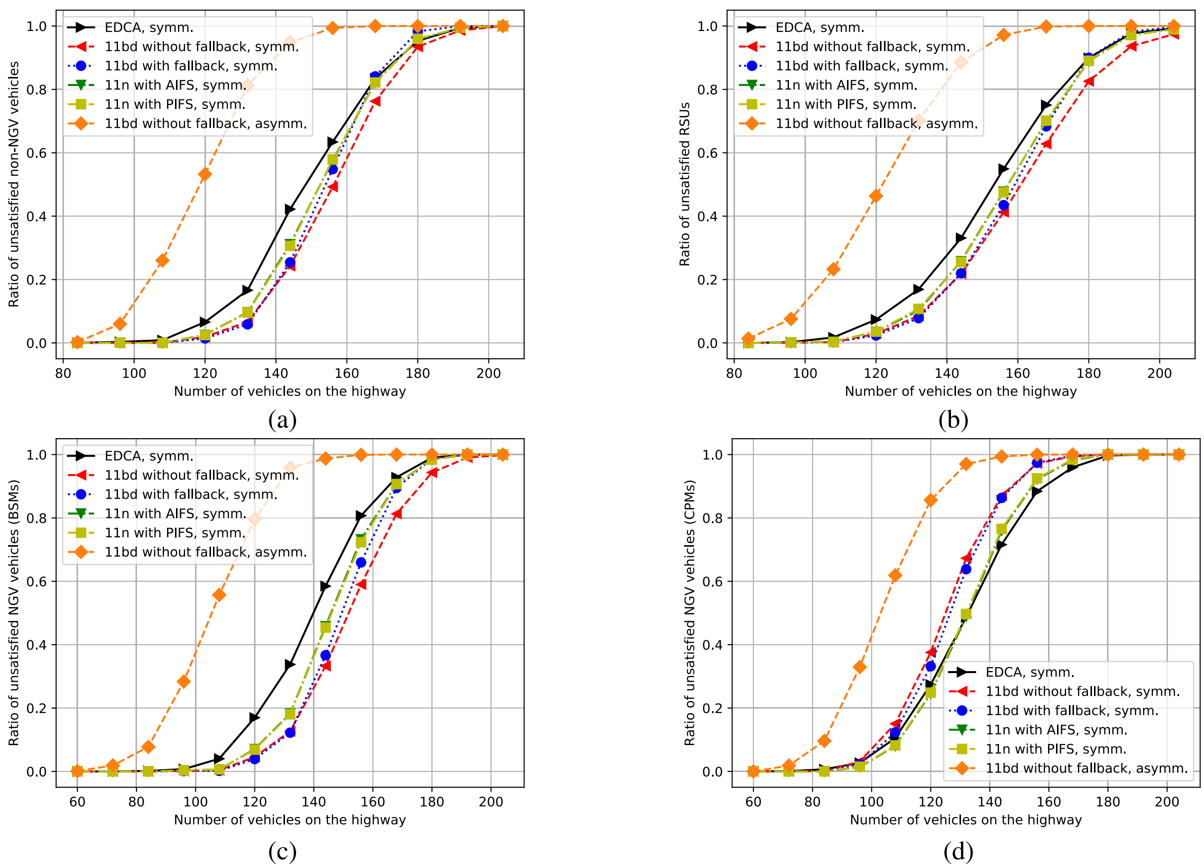


FIGURE 8. Performance comparison of the symmetric and asymmetric cases for the same number of vehicles on both sides of the highway in terms of (a) the portion of unsatisfied non-NGV vehicles; (b) the portion of unsatisfied RSUs; (c) the portion of unsatisfied NGV vehicles (BSMs); (d) the portion of unsatisfied NGV vehicles (CPMs).

C. SCENARIO WITH DIFFERENT NUMBERS OF VEHICLES ON TWO HIGHWAY SIDES

Let us consider a scenario with different numbers of vehicles on the two sides of the highway. Specifically, the number of vehicles on the top side of the highway is three times higher than on the bottom side.

Fig. 10 shows the portion of unsatisfied STAs on the top side of the highway, and Fig. 11 shows the portion of unsatisfied STAs on the bottom side. Similar to Section VI-B, we can note the following observations: the symmetric channel selection provides a noticeably lower portion of unsatisfied STAs than the asymmetric one; the channel bonding techniques from IEEE 802.11n demonstrate similar performance. The explanation of these phenomena is the same as for the equal numbers of vehicles on two sides of the highway.

We can also see that the IEEE 802.11bd channel bonding technique without fallback provides the best QoS for the top-side STAs that transmit BSMs, SPaT, and MAP messages. On the contrary, the best QoS for the STAs on the bottom side is provided by EDCA. The first phenomenon is similar to that observed in Section VI-B. In turn, the second one is explained by the fact that Channel 182 (the top side) is much more congested than Channel 180 (the bottom side), and, consequently, the performance of STAs in Channel 180 is higher when the STAs from Channel 182 do not intrude in Channel 180.

Fig. 10 and Fig. 11 also reveal that, in the symmetric case, the portion of unsatisfied STAs on the top side of the highway is always higher than on the bottom side. Since we are interested in providing a low portion of unsatisfied STAs on each side, we select the channel access method that provides the best QoS based on the numerical results for the top side. Therefore, in the rest of this section, we concentrate on the numerical results for the top side.

To begin with, in the symmetric case and for different numbers of vehicles on two sides, the portion of STAs unsatisfied with the CPMs delivery service is determined primarily by the PLR requirement. It is illustrated by Fig. 12, which corresponds to Fig. 10 (d) and shows the average frame transmission delay and the PLR for CPMs transmitted by NGV vehicles on the top side of the highway. As we can see, the average delay is almost always lower than 10 ms, which is the delay requirement for CPMs. Fig. 12 also shows that EDCA provides the highest delays and the PLR among all the considered channel access methods, whereas the channel bonding technique from IEEE 802.11bd without fallback ensures the lowest values of these metrics. The reason for it is that the usage of EDCA leads to the overload of

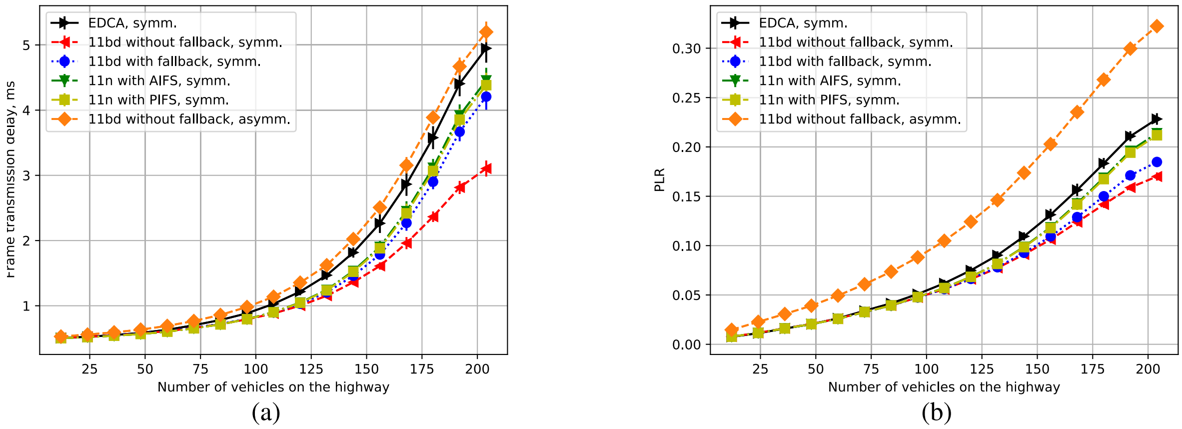


FIGURE 9. The results for the asymmetric case and the same number of vehicles on both highway sides: (a) the frame transmission delay and (b) the PLR of NGV vehicles (BSMs).

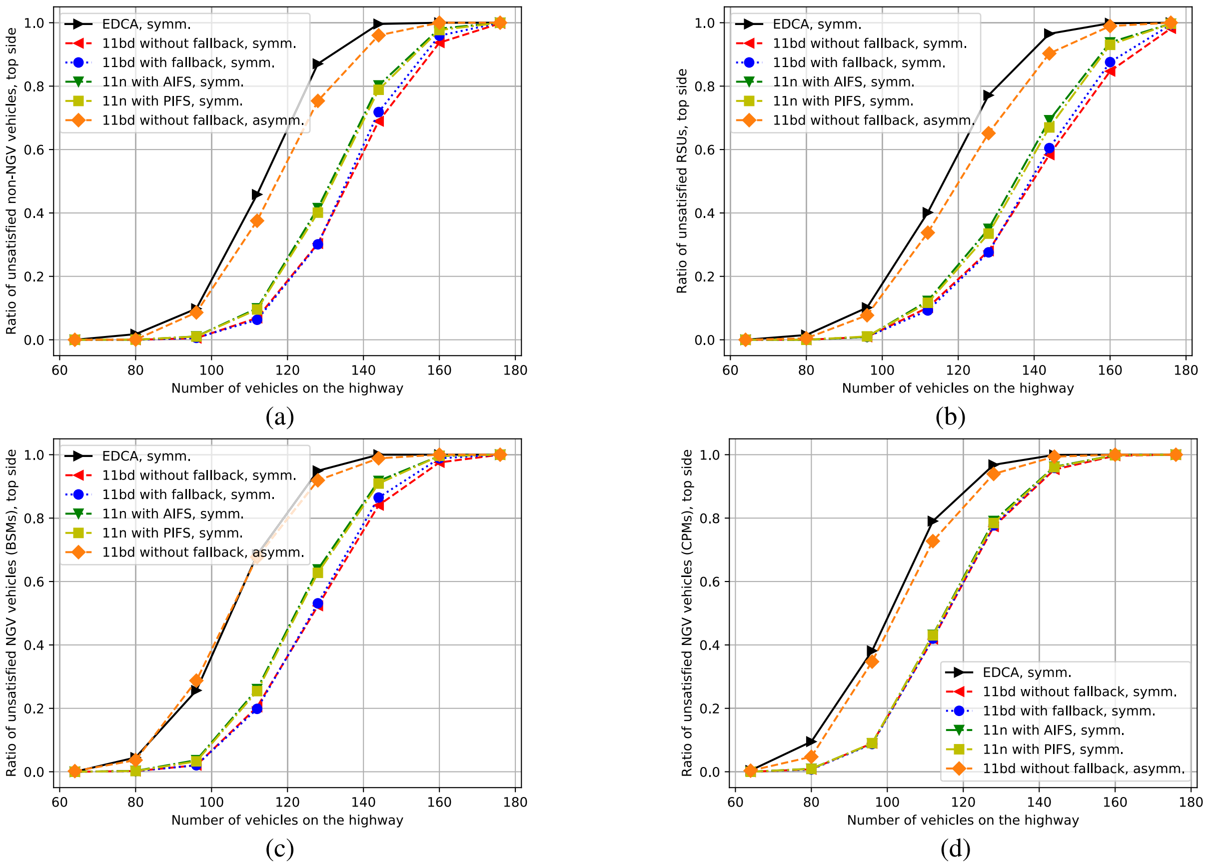


FIGURE 10. The comparison of the asymmetric and symmetric cases for different numbers of vehicles on the highway sides in terms of (a) the portion of unsatisfied non-NGV vehicles on the top side; (b) the portion of unsatisfied RSUs on the top side; (c) the portion of unsatisfied NGV vehicles (BSMs) on the top side; (d) the portion of unsatisfied NGV vehicles (CPMs) on the top side.

congested Channel 182, whereas the channel bonding technique from IEEE 802.11bd without fallback significantly alleviates the congestion in Channel 182 via 20 MHz transmissions of CPMs.

Moreover, Fig. 10 (d) shows that the IEEE 802.11bd channel bonding technique without fallback provides the lowest portion of unsatisfied STAs on the top side even for CPMs. It occurs because of two factors. Firstly, the probability of collision with a 10 MHz frame in Channel 180 is noticeably lower than in Channel 182. Secondly, 20 MHz transmissions are almost two times shorter than 10 MHz ones, which mitigates the performance degradation caused by hidden nodes.

Finally, Fig. 13 shows the results for the symmetric case where NGV vehicles on the top highway side use the

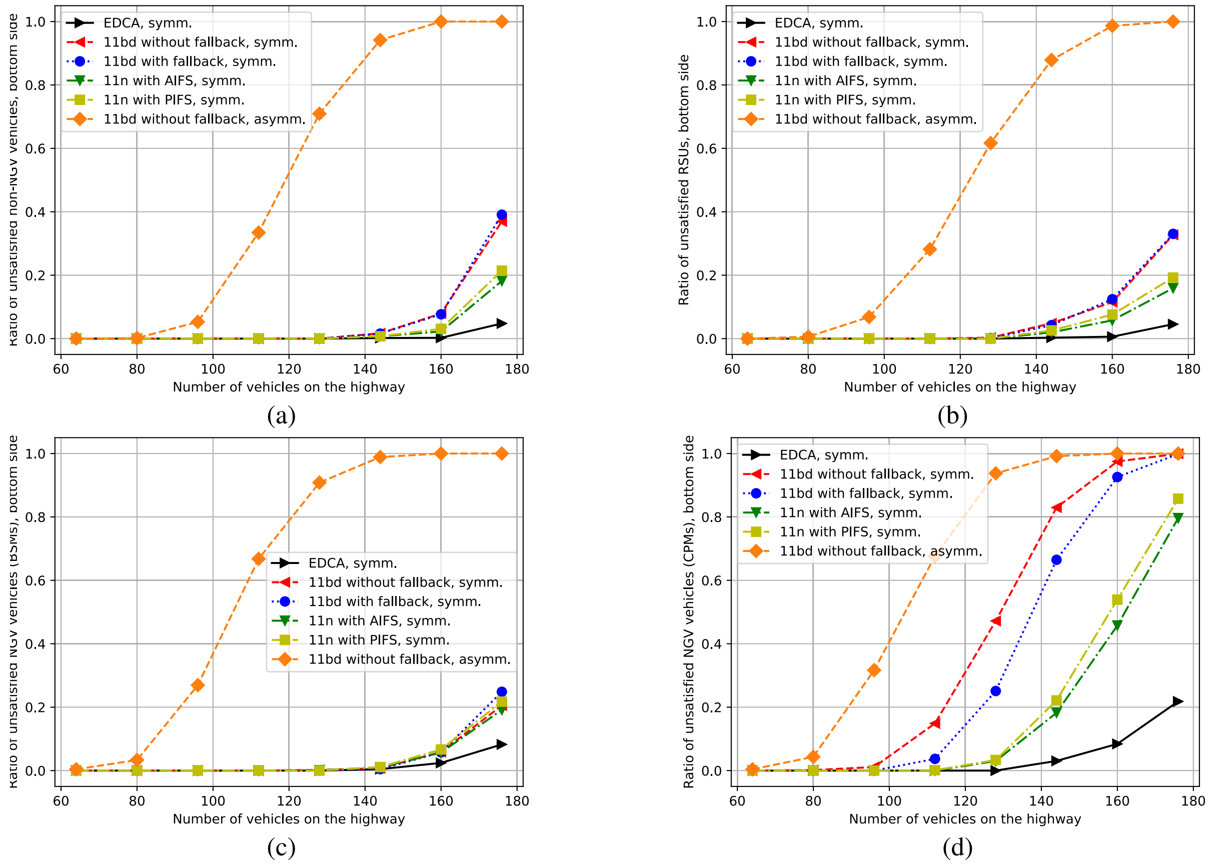


FIGURE 11. **The comparison of the asymmetric and symmetric cases for different numbers of vehicles on the highway sides in terms of (a) the portion of unsatisfied non-NGV vehicles on the bottom side; (b) the portion of unsatisfied RSUs on the bottom side; (c) the portion of unsatisfied NGV vehicles (BSMs) on the bottom side; (d) the portion of unsatisfied NGV vehicles (CPMs) on the bottom side.**

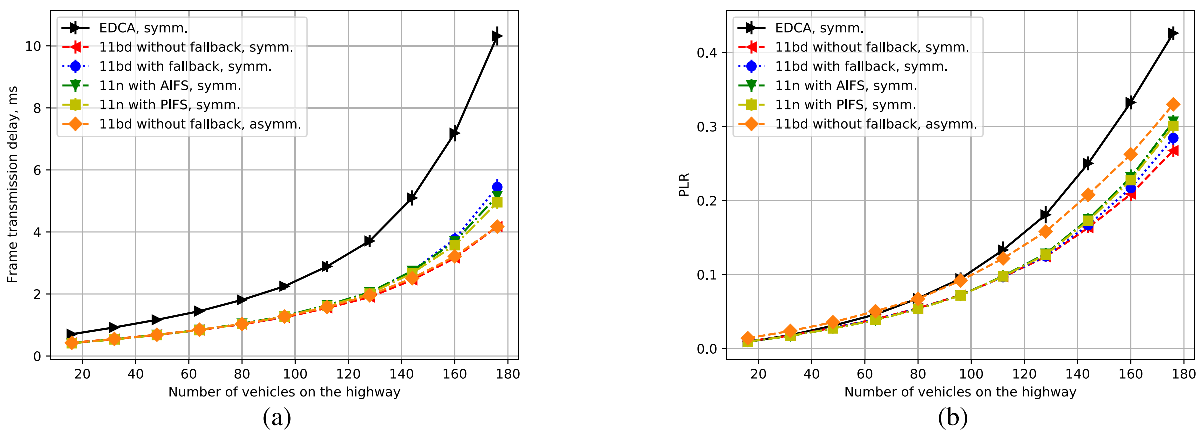


FIGURE 12. **The comparison of the asymmetric and symmetric cases for different numbers of vehicles on the highway sides in terms of (a) the frame transmission delay and (b) the PLR of NGV vehicles on the top side.**

IEEE 802.11bd channel bonding technique without fallback, and the NGV STAs on the bottom highway side use different channel access methods. Since the numbers of vehicles on the two highway sides differ, the percentage of unsatisfied STAs is always higher on the top side. Thus, we present the results only for the worst case, i.e., for the top side.

As we can see, when the NGV STAs on the top side of the highway use the IEEE 802.11bd channel bonding technique without fallback, and the bottom-side STAs use legacy EDCA, we obtain the best performance for BSMs, SPaT, and MAP messages. The reason is that PPDUs of bottom-side NGV STAs do not interfere with 10 MHz PPDUs of top-side STAs if the bottom-side STAs do not expand the channel.

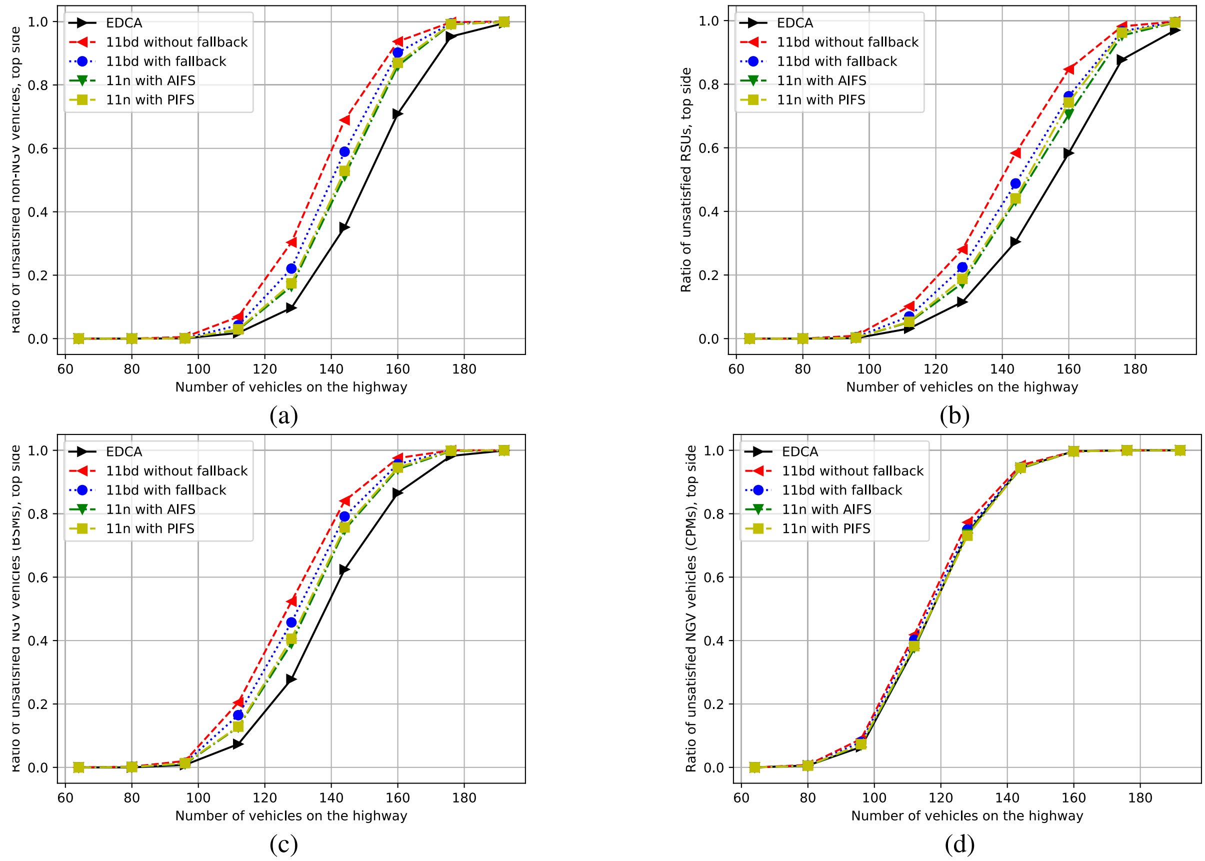


FIGURE 13. The influence of the channel access method on the bottom highway side on the network performance for the symmetric case in terms of (a) the portion of unsatisfied non-NGV vehicles on the top side; (b) the portion of unsatisfied RSUs on the top side; (c) the portion of unsatisfied NGV vehicles (BSMs) on the top side; (d) the portion of unsatisfied NGV vehicles (CPMs) on the top side.

To sum up, NGV STAs shall utilize the channel bonding technique from IEEE 802.11bd without fallback except for one case. When the number of vehicles on two sides of the highway noticeably differs in the symmetric case, NGV STAs on a less congested side shall use EDCA, whereas NGV STAs on a more congested side shall utilize the channel bonding technique from IEEE 802.11bd without fallback. From the implementation point of view, one can determine the load of a channel based on the channel busy ratio, similar to [67].

D. THE IMPACT OF CONTENTION WINDOW SIZE

Finally, we explore how the increase of W affects the performance of the network. Fig. 14 shows the dependency of the ratio of unsatisfied STAs on the W for the symmetric case when the number of vehicles on the top side of the highway is three times higher than on the bottom side, and the total number of vehicles on the highway equals 112. The W is increased only for NGV STAs, whereas non-NGV STAs have a default $W = 15$.

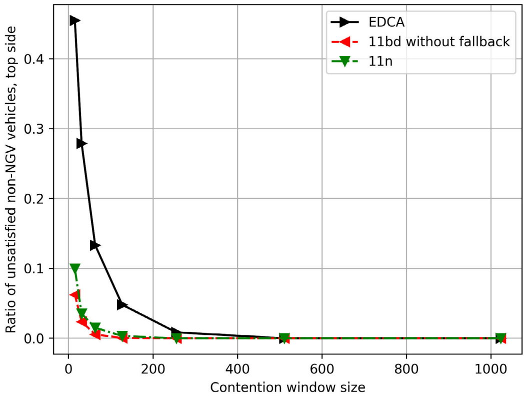
As we can see, higher values of W increase the percentage of STAs with satisfied QoS requirements for BSMs, SPaT, and MAP messages. The reason is that the delay requirements for these messages are soft and are satisfied for all considered values of W, whereas higher W decrease the congestion and, consequently, the PLR. In turn, since the delay requirement for CPMs is much stricter than for all other messages, the trade-off for CPMs exists. If W becomes lower, the number of STAs with unsatisfied PLR requirement rises, whereas high W leads to a higher number of STAs with the unfulfilled delay requirement. This trade-off determines the optimal W. We can also see that different channel bonding techniques have different optimal W because delays and PLRs induced by these techniques noticeably differ.

VII. OPEN ISSUES AND FUTURE RESEARCH DIRECTIONS

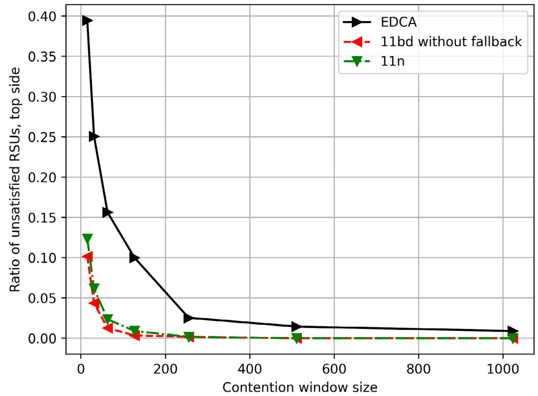
During our study, we have revealed several open problems, which may be covered in future research.

To begin with, the ETSI aims at incorporating the IEEE 802.11bd standard functionality into the ITS-G5 standard [68], [69], which is the EU analog of the IEEE 802.11p and IEEE 1609.4 standards from the WAVE group. To provide this incorporation, the ETSI started developing a new ETSI EN 303 797 standard [70], which early draft is expected to appear in January 2022.

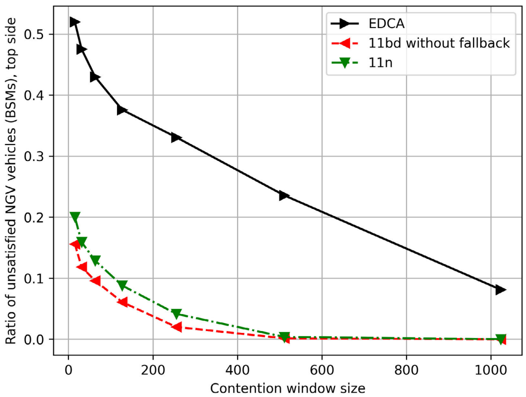
As the EU 5.9 GHz spectrum permits the usage of the channel bonding, it may be included in ETSI EN 303 797 [68]. However, there are two main reasons for channel bonding techniques to be explored separately in ITS-G5 networks.



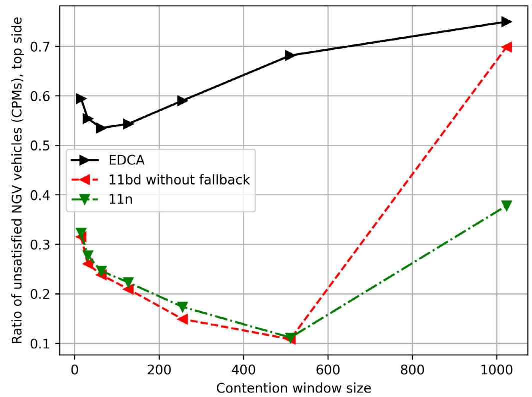
(a)



(b)



(c)



(d)

FIGURE 14. The impact of *W* on the performance for the symmetric case and different number of vehicles on two sides of the highway: (a) the portion of unsatisfied non-NGV vehicles on the top side; (b) the portion of unsatisfied RSUs on the top side; (c) the portion of unsatisfied NGV vehicles (BSMs) on the top side; (d) the portion of unsatisfied NGV vehicles (CPMs) on the top side.

Firstly, the channelization of the US 5.9 GHz frequency band significantly differs from the channelization of the EU 5.9 GHz spectrum [68], which requires a reconsideration of the scenario. Secondly, the ITS-G5 specifies a Decentralized Congestion Control (DCC) [71] that enforces STAs to dynamically regulate such MAC and PHY parameters as the transmission power, the maximum number of messages transmitted per second, the data rate, and the recipient sensitivity depending on channel conditions. Thus, one should consider the DCC while exploring the channel bonding in the ITS-G5.

Furthermore, together with the spectrum reallocation described in Section II-A, the FCC also allowed the operation of the C-V2X technology in the upper 30 MHz of the 5.9 GHz frequency band. As the coexistence of the DSRC and the C-V2X may lead to a noticeable adjacent channel interference [72], the presence of C-V2X devices may affect the performance of the IEEE 802.11bd channel bonding techniques. Thus, the exploration of the channel bonding techniques in the presence of IEEE 802.11p, IEEE 802.11bd, and C-V2X devices is another open problem.

Moreover, as the vehicular networks are highly dynamic and heterogeneous, the proportion of SPaT, MAP, BSM, and CPM traffic may vary depending on the time of day and location. Whereas in this paper, we focus only on the standardized traffic parameters, a plausible direction of future research is to study the performance of the channel bonding techniques when the considered types of traffic are mixed and have variable weights.

As follows from Section VI-D, the usage of W significantly impacts the network performance. Furthermore, an optimal W exists because of the trade-off between the delay and the PLR for CPMs. Some studies have already presented the algorithms for adaptive selection of W in IEEE 802.11p networks [73]–[75]. Nevertheless, the proposed algorithms do not take into account channel bonding and the requirements of emerging types of traffic. Thus, the development of algorithms for adaptive selection of W that consider channel bonding and the requirements of new types of traffic is another prospective area of research. However, the tuning of W shall be done at all the NGV STA.

Otherwise, NGV STA that increase their values of W will lose performance.

VIII. CONCLUSION

In this paper, we conducted a comprehensive comparative analysis of various channel bonding techniques that had been considered during the standardization of IEEE 802.11bd in the realistic highway scenario. We compared the channel access methods in terms of the ratio of stations (STAs) with the unsatisfied Quality of Service (QoS) requirement on frame transmission delays and the packet loss ratio.

Through extensive simulation in ns-3, we showed that the usage of the channel bonding techniques specified in IEEE 802.11n/bd instead of the legacy single-channel EDCA significantly increases both the portion of Next Generation V2X STAs (NGV STAs) and the portion of legacy STAs satisfied with V2X services.

We considered two primary channel selection cases: in the asymmetric one, all the STAs used the same primary channel; in the symmetric one, the STAs on two highway sides used different primary channels. The obtained results showed that the symmetric channel selection provides a much lower percentage of STAs with the unsatisfied QoS requirement on the packet loss ratio and frame transmission delays than the asymmetric one.

Moreover, we revealed that the channel bonding technique from IEEE 802.11bd without fallback gives the highest performance among all the considered channel access methods except for one case. If one 10 MHz channel is considerably more congested than the adjacent channel, the STAs in the channel with light load shall select the EDCA method, and the STAs in the congested channel shall select the IEEE 802.11bd channel bonding technique without fallback.

Besides, we also showed that the IEEE 802.11n channel bonding techniques with AIFS and PIFS on the secondary channel demonstrate very close results, i.e., the utilization of shorter interframe space on the secondary channel does not noticeably worsen the work of non-NGV STAs.

We showed that the increase of the contention window size above the standardized value could significantly boost the performance of the channel bonding techniques, and an optimal contention window can be found for a particular scenario. However, the algorithm to adaptively select the optimal value and the rules of synchronizing this value at moving vehicles are still open issues.

From the application point of view, the obtained results provide a recommendation that allows selecting the channel access method with the highest performance. Moreover, the results reveal that one can use the symmetric channel selection to enhance the performance of IEEE 802.11bd networks.

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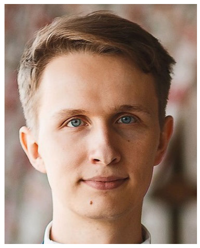

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