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A Comparative Study of IEEE 802.11bd and IEEE 802.11p on the Data Dissemination Properties in Dynamic Traffic Scenarios

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Abstract: With the rapid deployment of intelligent transportation systems in real-life applications, both dedicated short-range communications (DSRC) and cellular Vehicle-to-Everything (C-V2X), utilized to enable V2X communication, are undergoing extensive development to meet the quality of service (QoS) demands of advanced vehicular applications and scenarios. Compared to C-V2X, which lacks fully validated effective reliability, DSRC has undergone extensive field testing worldwide, ensuring its practicality. IEEE 802.11bd, as the next-generation V2X (NGV) standard within DSRC, is expected to greatly exceed the performance of its predecessor, 802.11p. However, existing studies mention that the ambient traffic environment will influence the performance of V2X due to the cyber-physical properties of V2X. To fully assess the advancements of NGV, this study presents a comparative analysis of IEEE 802.11bd and IEEE 802.11p, focusing on dynamic traffic conditions. Specifically, the technical advancements of the IEEE 802.11bd standard are first theoretically examined, emphasizing significant enhancements in aspects like modulation and coding schemes, coding rates, and channel coding. Subsequently, these critical technical enhancements are implemented in Veins, a simulation framework for the Internet of Vehicles (IoV), encompassing large-scale dynamic traffic scenarios. The simulation results indicate that the IEEE 802.11bd standard significantly enhances the data transfer rate compared to IEEE 802.11p, achieving a stable twofold increase. Furthermore, the data transmission latency is reduced by over half compared to IEEE 802.11p, while the data transmission reliability experiences a noteworthy 20% enhancement. Notably, the enhanced data transmission mode of the IEEE 802.11bd standard requires an increased signal-to-noise ratio (SNR). Additionally, this research evaluates the data dissemination properties in the IoV and finds that the traffic volume has a limited impact on the data propagation speed.

Keywords: Internet of Vehicles; IEEE 802.11bd; IEEE 802.11p; data transfer rate; transmission reliability

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1. Introduction

By leveraging the real-time information-sharing capability with the surrounding traffic environment, the Vehicle-to-Everything (V2X) communication technology enables a range of applications in improving traffic safety and efficiency [1–4]. Additionally, supporting various related services and information sharing will significantly enhance the travel experience [5]. IEEE 802.11p was released in 2010 [6], marking the first V2X communication standard. The standard defines the protocols required for dedicated short-range communication (DSRC) to facilitate highly efficient and low-latency information exchange in V2X [7]. It is specifically designed to enhance the efficiency and robustness of data transmission in the Internet of Vehicles (IoV). Communication devices based on this standard have been widely deployed [8], such as the electronic toll collection (ETC) system in China and the ETC 2.0 system in Japan [9].

Although [10] stated that the IEEE 802.11p standard could reliably support safety applications with end-to-end latency requirements of approximately 100 ms when the vehicle density is not very high, the IEEE 802.11p standard is now struggling to satisfy the increasing quality of service (QoS) requirements due to its limitations in bandwidth, antenna modes, frequency bands, etc. [11]. In response to the urgent need for standard updates to meet the escalating QoS requirements, including faster data transfer speeds, greater data throughput, and higher transmission reliability, a research group has been established. This group aims to develop the next-generation V2X (NGV) standard, 802.11bd, by integrating the mature and advanced technologies developed within the IEEE 802.11 standard family over the past decade. After eight versions of draft revisions, the official version of the IEEE 802.11bd standard [12] was formally released on 10 March 2023 .

Due to the rapid advancement of intelligent transportation systems (ITS), there is a growing demand for a unified standard for advanced vehicular communication. The IEEE 802.11bd standard, as a strong competitor to NR-V2X for the NGV universal communication standard, has garnered widespread attention from both academia and industry. As the standard for C-V2X, NR-V2X has the potential to interact with 5G-and-beyond cellular technologies, extending vehicular communication beyond V2V and V2I communications [13–15]. However, due to the extensive safety-related field trials performed worldwide, DSRC still holds an advantage compared with C-V2X, whose effective reliability and scalability are still to be completely verified [16–18]. To investigate the potential improvement of the NGV standards, several researchers have compared the communication performance of 802.11bd with that of its predecessor, IEEE 802.11p, and its competitor, NR-V2X [19–24]. Refs. [19,20] provided pioneering and preliminary comparative evaluations of the advantages and disadvantages based on the technical characteristics of different standards, which provide some crucial insights from the analytical aspect. To obtain more detailed and realistic comparison results, researchers have utilized simulation tools such as MATLAB (https://ww2.mathworks.cn/products/matlab.html) [21–23] and OMNeT++ (https://omnetpp.org/) [24] to simulate the performance of the IEEE 802.11bd standard. The results demonstrate that 802.11bd outperformed its predecessor, 802.11p, in multiple V2X performance metrics and provide valuable observations and experience in operating the NGV standard. However, as a typical cyber-physical system, the existing study [25] has already verified that the performance of V2X will be affected by traffic scenarios. Most prior simulation-based studies have overly simplified the test scenarios to one-to-one or one-to-many linear arrays, thus overlooking the influence of intricate and dynamic large-scale traffic environments on the communication performance of the IEEE 802.11bd standard. This oversight has resulted in inaccuracies in the assessment of the practical communication performance of IEEE 802.11bd. Moreover, not all the key technical improvements are integrated into the prior studies. The impact of some novel technologies applied in IEEE 802.11bd, such as the 256-QAM modulation and coding scheme (MCS) and Low-Density Parity Check (LDPC) coding, still needs to be simulated and tested.

Motivated by the research gaps mentioned above, this research proposes a comparative study of IEEE 802.11bd and IEEE 802.11p within dynamic traffic environments. This paper first investigates the technical improvements of 802.11bd and analyzes their impact on V2X performance, which helps to refine the technical evolutions that highly correlate with the data transmission performance. These key technical improvements of 802.11bd are implemented in an IoV simulation framework, Veins [26]. Simulation tests are conducted to evaluate the communication performance in two large-scale dynamic traffic scenarios. Meanwhile, we conduct a series of simulations to investigate the factors influencing the data dissemination effectiveness in IoV. Compared to prior research, this work is one of the first efforts to provide an analytical and simulation-based hybrid approach in investigating the improvements of the novel 802.11bd in large-scale and complex traffic environments. The improved Internet of Vehicles simulation framework integrates new MCS and LDPC mechanisms, and large-scale dynamic traffic simulations based on it can more accurately represent the communication performance of 802.11bd in reality than prior research. Moreover, our analysis of the properties of data dissemination reveals the limited impact of the traffic volume on the data propagation speed. The proposed research contributes to a better understanding of the technical characteristics of this newly released standard. Hence, it will contribute to both the literature and practical applications.

The remaining sections are organized as follows. Section 2 introduces the technical improvements that we analyze from the two aspects of the data transfer rate and transmission reliability, including newly introduced enhanced data transmission modes, new antenna modes, new coding schemes, etc. Section 3 focuses on the implementation process of these key technical improvements, including a partial theoretical validation. Section 4 presents the design of the experiment for the V2X performance comparison and the properties of data dissemination, with an analysis and further evaluation of the simulation results. Conclusions and a discussion follow in Section 5.

2. Improvements and Comparative Analysis of IEEE 802.11bd

2.1. Background of IEEE 802.11p and IEEE 802.11bd

IEEE 802.11p stands as the world's first V2X communication standard, serving as the underlying protocol for DSRC and garnering extensive deployment and application over the past decade. Operating within the 5.9 GHz frequency band reserved specifically for vehicular communication, it utilizes a 10 MHz channel width. This standard is an improvement and extension of the 802.11 standard to suit the vehicular communication environment. At the physical layer, it employs Orthogonal Frequency-Division Multiplexing (OFDM) modulation, capable of delivering higher data transmission rates and enhanced resistance to multipath propagation. Through techniques such as power control adjustment and antenna design optimization, it refines the communication range and coverage, ensuring robust vehicular communication performance. At the MAC layer, the standard incorporates rapid channel-switching technology and priority management mechanisms, enhancing the communication efficiency and safeguarding the reliability of safety-critical communications.

After more than a decade of testing and application, 802.11p has amassed a broad user base, with its effective reliability and scalability fully validated. However, with the rapid advancement of intelligent vehicles, 802.11p falls short of meeting the rapidly increasing quality of service demands, such as faster data transfer rates, greater data throughput, and higher data transmission reliability. The official release of the C-V2X technology in 2017 also challenged the status of 802.11p [27]. In response to these challenges, 802.11bd [12] was officially introduced in 2023, incorporating and enhancing wireless communication technologies that have matured over the past decade. Due to the maturity of high-frequency communication technology, 802.11bd can stably operate in the 60 GHz frequency band, thereby obtaining a 20 MHz communication bandwidth. At the physical layer, 802.11bd still adopts OFDM modulation, but introduces LDPC coding to enhance the data transmission reliability. Improvements in data frame formats, such as variable Long Training Field (LTF) formats and midamble, facilitate the better estimation of rapidly changing communication channels by vehicles, further stabilizing the data transmission reliability. Advancements in data transmission modes also enable 802.11bd to utilize denser MCS and higher coding rates to increase the data transfer rates. In terms of antennas, 802.11bd improves the beamforming technology and introduces Multiple-Input Multiple-Output (MIMO) antenna modes to greatly enhance the data throughput. At the MAC layer, 802.11bd also introduces many new mechanisms to adapt to the rapid development of vehicular communication, including adaptive MCS and intelligent spectrum sensing, improving the system scalability. In the following subsections, we will delve into these technical improvements in detail and evaluate the gains in V2X performance from the key improvements.

2.2. Improvements of IEEE 802.11bd to IEEE 802.11p

The analysis in this section is based on our research of the original texts of the IEEE 802.11bd [12], 802.11p [6], and 802.11 [28] standards. The IEEE 802.11bd standard serves as a supplement and enhancement to the existing IEEE 802.11p standard, rather than a replacement, like the NR-V2X standard. The supplement and enhancement part in the

802.11bd standard is exclusively utilized for communication between NGV stations (STAs) or between NGV STAs and non-NGV STAs. For communication between non-NGV STAs, most specifications in 802.11bd are still based on the 802.11p standard. In light of the well-established adoption of the 802.11p standard, the 802.11bd standard was designed to encompass the following fundamental attributes: interoperability, coexistence, compatibility, and fairness. Indeed, a significant portion of the 802.11bd standard is devoted to realizing the four mentioned characteristics. The remainder of the standard emphasizes the technical improvements and other relevant aspects of 802.11bd. In summary, 802.11bd differs significantly from 802.11p, doubling the available bandwidth and introducing changes in frame format, leading to modifications in processing procedures and numerous parameters. From the user viewpoint in the transportation area, this paper focuses on the key technical improvements that can significantly impact the communication performance. The essential technical improvements that NGV STA supports include the following:

- Integration of enhanced modes for data transmission, specifically 64-QAM 5/6, 256-QAM 3/4, and 256-QAM 5/6;
- Adoption of three LTF formats, NGV-LTF-1x, NGV-LTF-2x, and NGV-LTF-2x-Repeat;
- Implementation of LDPC coding for both transmission and reception;
- Introduction of midamble with periodicities of 4, 8, or 16 OFDM symbols;
- Introduction of the 10 MHz NGV Physical Layer Protocol Data Unit (PPDU);
- Inclusion of NON NGV_10_PPDU and its repetitive variant, the repetitive NON_NGV_10 PPDU.

The technical improvements that NGV STA may support are as follows:

- Enabling transmission and reception of Single-User (SU) MIMO with two spatial streams;
- Utilizing the NGV ranging Null Data PPDU (NDP) for NGV ranging;
- Employing 20 MHz NGV PPDU or 20 MHz non-NGV duplicate PPDU.

In the following two subsections, we will delve into the primary technical improvements of the IEEE 802.11bd standard. Various V2X performance metrics will guide this exploration. We will also conduct a comparative analysis with the IEEE 802.11p standard to preliminarily evaluate the influence of these improvements on the V2X performance.

2.3. Key Improvements in Data Transfer Rate

Compared with the IEEE 802.11p standard, the significant increase in the data transfer rate of the IEEE 802.11bd standard mainly stems from the wider bandwidth allocation. Alongside continuing the use of the 5.9 GHz frequency band as in the 802.11p standard, the 802.11bd standard has been allocated channels in the 60 GHz frequency band with a bandwidth of 20 MHz, which is double that of the 802.11p standard. As indicated in Table 1, the impact of doubling the bandwidth on the data transfer rate is evident. When using the same modulation and coding scheme (MCS) and coding rate (R), the 802.11bd standard achieves an approximate 125% increase in the data transfer rate on the NGV channel with a 20 MHz bandwidth. Even on a compatible communication channel with a 10 MHz bandwidth, an improvement of 8-10% in the data transfer rate can still be achieved due to the advancements in the coding scheme and other fundamental technologies.

From Table 1, it is evident that the 802.11bd standard introduces three enhanced data transmission modes (i.e., 64-QAM 5/6, 256-QAM 3/4, and 256-QAM 5/6), providing a wider range of data transfer rate options. This enhancement empowers the 802.11bd standard to substantially improve the data transfer rate, with a maximum potential increase of up to 3.3 times compared to the 802.11p standard. Additionally, the introduction of MIMO technology provides the option for dual spatial streams (N_{SS} = 2), resulting in nearly a twofold increase in data transfer rates.

Regarding the length of a single data packet, the wireless channel's data packet length is limited by the maximum allowable duration of the data packet. In specific fields, regulators impose a limit of 10,968 µs or less on the maximum transmission duration of a single data packet. This implies that higher data transfer rates also raise the maximum packet length. A single data packet transmitted by the IEEE 802.11p standard cannot exceed 4095 bytes, whereas the IEEE 802.11bd standard increases it to nearly twice this size, at 7991 bytes. The advancements in the single data packet length can lead to significant performance gains, particularly in small-security-class packet applications.

Table 1. Available data transmission modes and rates of IEEE 802.11bd and IEEE 802.11p.

MCS	R	Data Transfer Rate/Mbps		
		IEEE 802.11p	IEEE 802.11bd	
		10 MHz	10 MHz	20 MHz
BPSK	1/2	3.0	3.3	6.8
QPSK	1/2	6.0	6.5	13.5
QPSK	3/4	9.0	9.8	20.3
16-QAM	1/2	12.0	13.0	27.0
16-QAM	3/4	18.0	19.5	40.5
64-QAM	2/3	24.0	26.0	54.0
64-QAM	3/4	27.0	29.3	60.8
64-QAM	5/6	N/A	32.5	67.5
256-QAM	3/4	N/A	39.0	81.0
256-QAM	5/6	N/A	N/A	90.0

2.4. Key Improvements in Data Transmission Reliability

The high-speed movement of vehicles introduces challenges such as high dynamics and spatiotemporal complexity, resulting in a significant Doppler shift and a rapidly varying wireless propagation environment [29,30]. Other factors, such as high density, resource collisions, proximity effects, and intricate interference conditions, further impact the reliability of data transmission. Therefore, data transmission reliability has become a critical performance metric in evaluating V2X standards. To address these challenges, the IEEE 802.11bd standard adopts a variety of new technologies and services to provide gains in SNR, including LDPC coding, midambles, and improved beamforming technology.

IEEE 802.11bd implements LDPC coding to replace the Binary Convolutional Coding (BCC) used in 802.11p. Compared to BCC, LDPC coding presents lower encoding and decoding complexity and a more uniform check code distribution. This quality enables LDPC coding to resist various channel interferences better and provides superior error correction, particularly in high-SNR situations. According to [31], substituting BCC with LDPC coding could lead to a 1–4 dB SNR gain in multiple scenarios. Moreover, ref. [24] estimates that this SNR gain can be translated into a Packet Reception Rate (PRR) gain of approximately 20%.

Regarding the data frame format, 802.11bd maintains the 40 µs preamble from 802.11p and introduces an NGV preamble of at least 36.8 µs, as shown in Figure 1. Notably, the NGV preamble includes a flexible NGV-LTF field strategically designed to enhance the data transmission reliability in real-world communication scenarios.

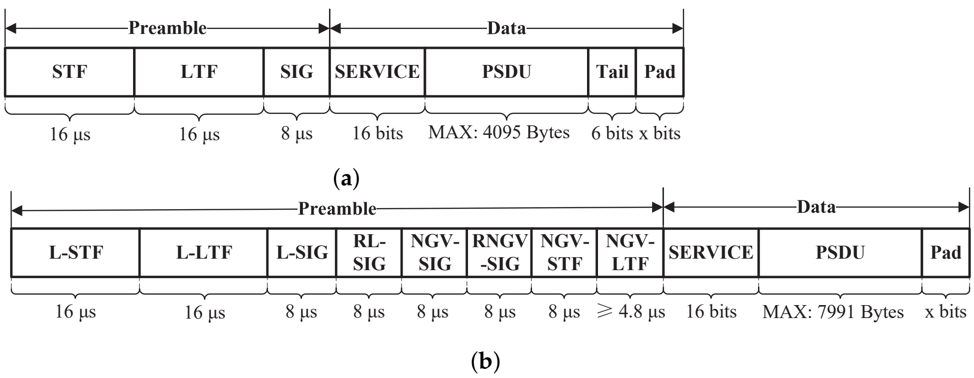


Figure 1. IEEE 802.11p (**a**) and 802.11bd (**b**) PPDU format comparison.

The IEEE 802.11bd standard introduces a midamble to the data frame format, selectively placed after a specified number of OFDM symbols (e.g., 4, 8, or 16, per upper layer instructions) in the NGV PPDU data field. The content of the midamble should be the same as that of the NGV-LTF field in the preamble. To avoid spectral line generation in the NGV PPDU spectrum, randomization is applied to both the midamble and subsequent data field OFDM symbols. Midambles convey vital information about the data transfer rate, MCS, and transmission parameters, aiding the receiver in precisely determining suitable transmission parameters. This enhances the data transmission efficiency and reliability, particularly in high-density communication environments, mitigating errors and losses due to incorrect parameter settings.

In addition to new technologies, 802.11bd introduces advanced IoV services to improve the data transmission reliability, such as NON_NGV_10 repetition transmission and non-NGV duplication operation. In the NON_NGV_10 repetition transmission mode, the physical layer transmits (1+N_PPDU_REP) NON_NGV_10 PPDUs in sequence. The time interval between every two PPDU repetition transmissions is indicated by the aSIFSTime parameter, while the higher layer indicates the N_PPDU_REP parameter. An example of repeated transmission is shown in Figure 2.

Figure 2. Example of NON_NGV_10 repetition transmission.

The NON_NGV_10 repetition transmission mode supports broadcast services for both NGV STAs and non-NGV STAs, enhancing the frame reception reliability and facilitating the transmission of crucial security warnings. Incorporating a radio environment measurement mechanism can further enhance this mode through an adaptive repetition transmission scheme. The decision and quantity of repeated transmissions are contingent on the measured radio environment congestion levels. Ref. [23] have shown that this adaptive packet repetition scheme can provide approximately a 3 dB gain in SNR.

Furthermore, the non-NGV duplication operation enables NGV STAs to transmit the Request To Send (RTS) frame in a non-NGV duplicate PPDU to safeguard an NGV PPDU with a 20 MHz bandwidth. This approach enhances the stability and reliability of the RTS/CTS mechanism, providing better assurance for data transmission.

3. Implementation and Validation

3.1. Implementation of Enhanced Data Transmission Mode and Validation

Compared to the IEEE 802.11p standard, the IEEE 802.11bd standard demonstrates remarkable advancements in communication performance, particularly in the data transfer rate, where the modulation and coding scheme (MCS) and coding rate (R) are pivotal factors. While the MCS and R combinations used in 802.11p have been integrated into Veins, this research introduces three new modes from 802.11bd, i.e., 64-QAM 5/6, 256-QAM 3/4, and 256-QAM 5/6.

To implement these three new MCS and R combinations in Veins, it is essential to comprehend their functioning in fusion simulations. As data packets are transmitted, the MCS and R combination directly influences the data transfer rate, which, in turn, determines the number of data bits per OFDM symbol (N_{DBPS}). See Table 2 for specific correspondences.

In the simulation implementation of Veins, the N_{DBPS} and the length of the data packet (L_{Data}) will largely determine the sending time of the data packet ($T_{FrameDuration}$), as shown in Equation (1). Since the preamble of the PPDU uses the data transmission mode (BPSK 1/2) with the lowest data transfer rate (6.8 Mbps) and the format/length of the preamble field is fixed, the sending time of the preamble field ($T_{Preamble}$ and T_{Signal}) is fixed. By adjusting the parameters, e.g., $T_{Preamble}$, T_{Signal}, and N_{DBPS}, we can replicate the NGV PPDU frame format and data transfer rate of the IEEE 802.11bd standard.

$$T_{FrameDuration} = T_{Preamble} + T_{Signal} + T_{Symbol} \times \left\lceil \frac{16 + L_{Data}}{N_{DBPS}} \right\rceil \quad (1)$$

The enhanced data transmission mode not only involves increasing the data transfer rate of the sending STA but also raises greater challenges in receiving STAs by requiring an increased transmission SNR. In the data packet reception simulation conducted in Veins, the data transmission mode (MCS and R) determines the theoretical Bit Error Rate (BER) calculation. Initially, the basic BER is determined based on the SNR and MCS, and then it is adjusted according to R to derive the theoretical BER. Subsequently, the probability of the entire data packet being successfully received is computed based on the data packet length. This probability is then cross-verified with a random number to ascertain successful decoding and reception. Thus, implementing the three newly introduced enhanced data transmission modes of 802.11bd involves the incorporation of the newly introduced MCS 256-QAM and the newly introduced R 5/6.

Table 2. Data transmission modes and corresponding N_{DBPS}.

MCS	**R**	N_{DBPS}	
		IEEE 802.11p	**IEEE 802.11bd**
		10 Mhz	**20 MHz**
BPSK	1/2	24	54
QPSK	1/2	48	108
QPSK	3/4	72	162
16-QAM	1/2	96	216
16-QAM	3/4	144	324
64-QAM	2/3	192	432
64-QAM	3/4	216	486
64-QAM	5/6	N/A	540
256-QAM	3/4	N/A	648
256-QAM	5/6	N/A	730

The calculation formula for MCS in Veins is based on the Additive White Gaussian Noise (AWGN) channel, an idealized model widely used in communication evaluation. This model aptly approximates the statistical attributes of noise and interference in the real world. We can derive Equation (2) for the theoretical BER of 256-QAM based on the BER calculation formula for Quadrature Amplitude Modulation (QAM) in the AWGN channel. This formula and its related code can then be implemented in Veins.

$$BER_{256-QAM} = \frac{15}{64} erfc\left(\sqrt{\frac{SNR}{170}}\right) \quad (2)$$

The polynomial parameters used to calculate the theoretical BER correction based on the coding rate in Veins are obtained from [32] on high-rate punctured convolutional codes. These parameters specifically come from the free distance of the punctured code and the coefficients of the series expansions of the corresponding weight spectra of short-memory punctured codes with different coding rates. To obtain the desired parameters for the 5/6 coding rate, we refer to the generators of the original code and the perforation matrix of the 2/3 and 3/4 coding rates and convert them into Equation (3).

$$P_{E_{\frac{5}{6}}} = \frac{1}{10}\Big(92D^4 + 528D^5 + 8694D^6 + 79453D^7 + 792114D^8 + 7375573D^9 + 67884974D^{10} + 610875423D^{11} + 5427275376D^{12} + 47664215639D^{13}\Big) \quad (3)$$

Based on Equation (3), the correction code and associated codes for the 5/6 coding rate are incorporated into Veins. Together with the previously mentioned 256-QAM BER calculation code and related codes, the three newly introduced enhanced data transmission modes are implemented, as shown by the three dotted lines on the far right in Figure 3.

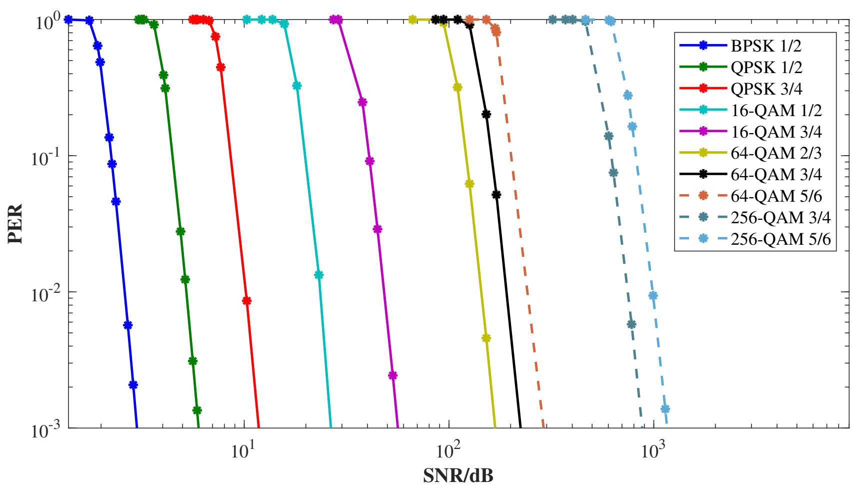


Figure 3. The simulation curve of PER with respect to SNR of IEEE 802.11bd data transmission modes in Veins.

The solid line on the left in Figure 3 represents the original data transmission modes in 802.11p. It is evident that the three newly introduced enhanced data transmission modes achieve significantly higher data transfer rates. However, concurrently, the demands for the SNR during data transmission are also escalating rapidly (experiencing almost exponential growth), consistent with the theoretical traits of QAM. As the types of OFDM symbols increase (the number of data bits carried by each OFDM symbol increases), the reduction in symbol spacing and the reduction in energy efficiency make the OFDM symbols more susceptible to noise and interference, resulting in a higher BER. Additionally, the blurring of adjacent symbol decision boundaries raises the probability of incorrect demodulation at the receiver. These factors contribute to an exponential rise in the required SNR for data transmission.

3.2. Implementation of Transmission Reliability Gains and Validation

The IEEE 802.11bd standard introduces many innovative technologies to improve the data transmission reliability. These include using LDPC coding instead of BCC, introducing midambles, and enhanced beamforming, among others. However, simulations face limitations in accurately replicating physical behaviors that are heavily reliant on real-world environments, e.g., signal modulation and coding, wireless signal transmission and reception, and beamforming. Consequently, directly implementing technical improvements such as LDPC coding via programming is impractical. Instead, these enhancements can only be indirectly realized by simulating the effects (SNR gains) of these technologies on the data transmission reliability.

Considering the significant impact of real-world wireless environments on wireless signal transmission, the reliability improvement aspect is based on the findings of [24], who concluded that the replacement of BCC with LDPC coding can result in a 1–4 dB SNR gain across multiple scenarios.

Based on these gains, certain adjustments have been made to the Packet Error Rate (PER) calculation formulas concerning the SNR in Veins. Specifically, under different data transmission modes, higher data transfer rates result in greater SNR gains, while, under the same data transmission mode, higher SNR values lead to increased SNR gains. The corrected calculation formulas for some data transmission modes are given in Equations (4)–(6).

$$SNR'_{BPSK\ 1/2} = SNR_{BPSK\ 1/2} + \min\left(1.0,\ 5^{(SNR_{BPSK\ 1/2}-2.0)/20}\right) \tag{4}$$

$$SNR'_{QPSK\ 1/2} = SNR_{QPSK\ 1/2} + \min\left(1.5,\ 10^{(SNR_{QPSK\ 1/2} - 3.3)/10}\right) \tag{5}$$

$$SNR'_{QPSK\ 3/4} = SNR_{QPSK\ 3/4} + \min\left(2.0,\ 20^{(SNR_{QPSK\ 3/4} - 6.5)/20}\right) \tag{6}$$

Figure 4 illustrates a comparison between the simulation curve of the PER with respect to the SNR for selected data transmission modes. This comparison includes a curve corrected based on the SNR gain and the original, uncorrected simulation curve.

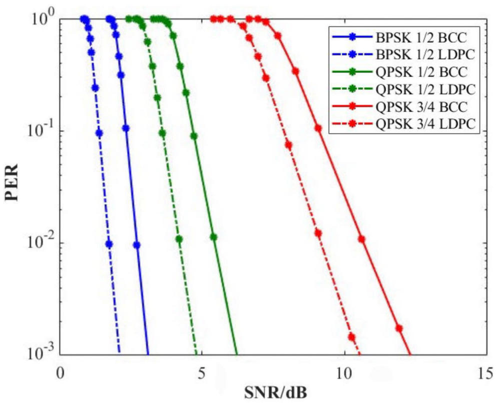


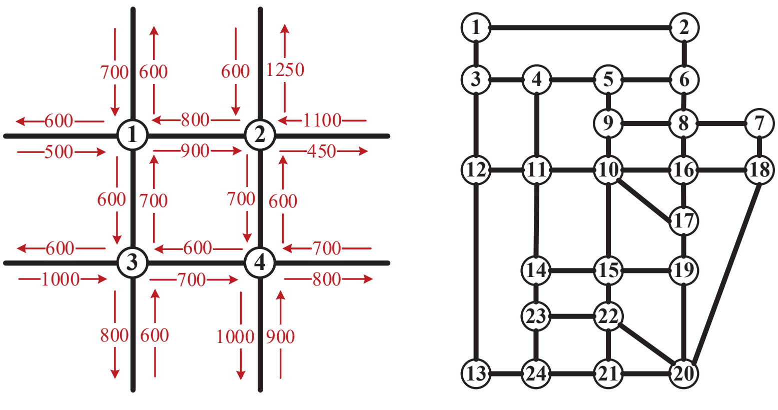
Figure 4. Correction effect of partial data transmission modes.

Based on Figure 4, it is evident that the modified (LDPC) simulation curve achieves a noticeable SNR gain compared to the unmodified (BCC) simulation curve. The modified curve exhibits a similar PER at a lower SNR, typically within a range of 1–2 dB, thereby enhancing the data transmission reliability in the simulation. This demonstrates the successful implementation of the new technologies in terms of their effectiveness in improving the data transmission reliability.

4. Simulation Experiment Design

4.1. Construction of Large-Scale Dynamic Traffic Scenario

The simulation, which was conducted using large-scale dynamic traffic scenarios that closely resembled real-world traffic environments, can effectively reflect the performance of V2X standards. Constructing such scenarios is crucial in ensuring the simulation accuracy of such research. The first simulation scenario that we constructed was the grid road scenario. The parameters of road networks and traffic flows used to construct this scenario are derived from [33], where the hourly traffic flow data are as shown in Figure 5a. Each section of the road in this scenario measures 5000 m .



(**a**) Grid road (**b**) Adjusted geometric road

Figure 5. Road network and traffic flow of large-scale dynamic traffic scenarios.

To observe the performance of V2X standards in more complex traffic environments, we also created a geometric road scenario adjusted to replicate the city of Sioux Falls. This scenario, proposed in [34], is widely utilized across traffic demand prediction, traffic flow distribution, and traffic network optimization, making it a standard benchmark in assessing traffic algorithms. The parameters of the road network node coordinates and OD demands used to construct this scenario come from [35]. The serial numbers of nodes in the road network are shown in Figure 5b, and each lane is set as a 4-lane dual carriageway.

4.2. Data Transmission Mechanism of Roadside Units (RSUs) and On-Board Units (OBUs)

The simulation scenario involves two key components: RSUs and OBUs on vehicles. RSUs follow a simple data transmission pattern. At 950 s, an RSU broadcasts a data packet, entering a dormant state afterward, refraining from sending or receiving additional data packets. This configuration ensures that the scenario's simulated traffic flow aligns with the traffic flow demands. The processing mechanism of OBUs on vehicles after receiving a data packet is depicted in Figure 6.

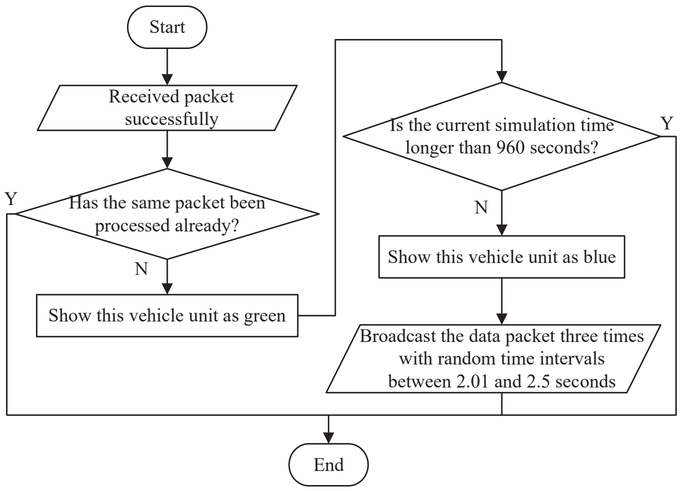


Figure 6. Flowchart of the processing of OBUs receiving data packets.

The first decision in Figure 6 is to avoid the invalid behavior of repeatedly receiving the same data packet, and the second decision is to limit the packet lifecycle. The design of the random interval time for the broadcasting of data packets aims to circumvent a scenario wherein a high volume of vehicles simultaneously transmits data packets in a brief time span. Such a situation could lead to severe degradation in the SNR, thereby reducing the number of vehicles that can successfully receive the data packets.

4.3. Simulation Parameter Configurations and Analysis Criteria

4.3.1. V2X Performance Comparison

This study primarily aims to investigate how 802.11bd enhances the key V2X performance metrics compared to 802.11p. These metrics encompass the data transfer rate, transmission delay, data throughput, and reliability. Notably, improvements in the data transfer rate and the corresponding transmission delay can be directly computed through theoretical analysis, eliminating the need for simulation experiments. From Table 1, it is evident that 802.11bd achieves over a 125% higher data transfer rate than 802.11p, using the same MCS and R on the 20 MHz NGV channel compared to the 10 MHz channel. This substantial increase in the data transfer rate results in a reduction of over 56% in the transmission delay. To compare the data throughput and transmission reliability, this research utilizes the two scenarios constructed in the previous section. The simulation parameters of this research are shown in Table 3.

Table 3 indicates that all RSUs are deployed at or near intersections. This is because intelligent traffic management targeting this area can significantly improve the traffic efficiency [36–38], and this deployment also helps to increase the sample size and enhance the simulation's credibility.

In the simulation related to data throughput, it is evident that the adjusted geometric road scenario is significantly more complex in its configuration compared to the grid road scenario. To evaluate the improvements in data throughput, we employ the macroscopic data dissemination effectiveness as the primary metric in these scenarios.

In the simulation regarding transmission reliability, we set the OBU broadcast times to 0, i.e., the OBUs only attempt to receive packets without sending any. This design aims to assess the number of vehicles that successfully receive data packets following a single broadcast from the RSUs, thereby mitigating the impact of the asynchronous wireless environment caused by the higher data transfer rate of 802.11bd. This ensures a performance comparison specific to the transmission reliability while compensating for the loss in data volume in a single broadcast through the strategic placement of dual RSUs (the adequate wireless signal coverages of the dual RSUs in these scenarios do not overlap). In this simulation, we adopt the number of vehicles that successfully receive data packets as the analysis criterion to evaluate the improvement in transmission reliability.

Table 3. Simulation parameters of V2X performance comparison.

Comparison Metric	Scenario	RSU	OBU Broadcast Times (α)	Transmission Mode
Data throughput	grid road	node 3	3	QPSK 1/2
	geometric road	Figure 13a in [33]	5	
Transmission reliability	grid road	nodes 2 and 3	0	BPSK 1/2 and QPSK 1/2
	geometric road	nodes 10 and 22	0	QPSK 3/4 and 16-QAM 1/2

In each comparison, the data packet length transmitted by IEEE 802.11bd is 600 bytes, while that of IEEE 802.11p is 300 bytes.

4.3.2. Research on Properties of Data Dissemination

We also researched the properties of data dissemination by investigating three key factors influencing the data dissemination effectiveness, i.e., the V2X standard, traffic volume, and radio signal transmission power. The simulation parameters of this research are shown in Table 4.

Table 4. Simulation parameters of the research on properties of data dissemination.

Influencing Factor	Simulation Value	Scenario	RSU	OBU Broadcast Times (α)	Transmission Mode
V2X standard	IEEE 802.11bd/p	grid road	node 3	3	BPSK 1/2, QPSK 1/2, QPSK 3/4 and 16-QAM 1/2
Traffic volume	0.25×, 0.5×, 1×, 2× [1]				QPSK 1/2
Transmission power	1×, 2×, 3×, 4× [2]				16-QAM 1/2

In the simulation regarding the traffic volume and transmission power, the V2X standard utilized is IEEE 802.11bd. [1] The traffic volume simulation multiplier is relative to the base traffic flow rate shown in Figure 5a. [2] The radio signal transmission power simulation multiplier is relative to the base power of 30 mW.

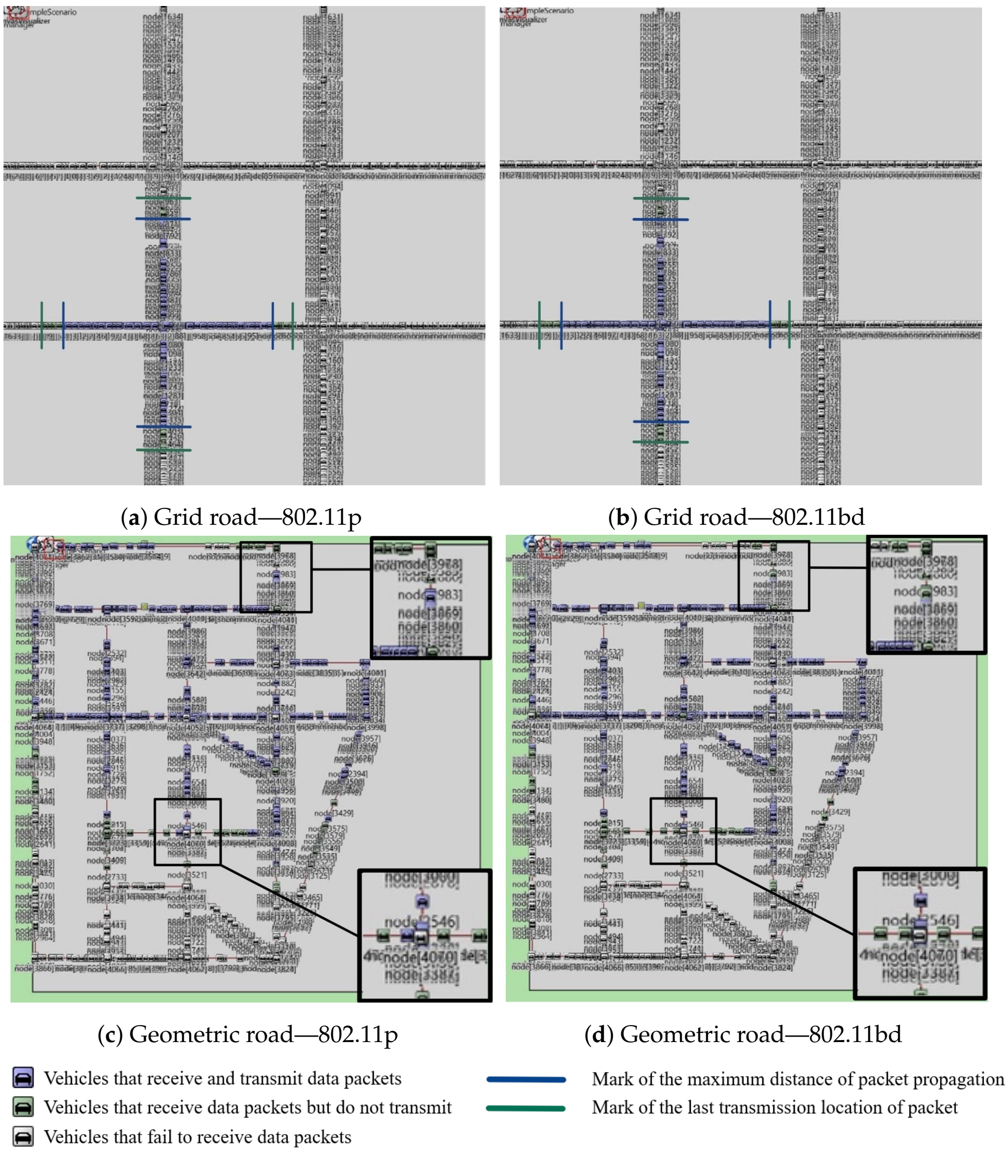
This study's evaluation is based on two key metrics: the count of vehicles that successfully receive data packets and the distance over which data are disseminated. Only one RSU is placed in the grid road scenario for the purpose of calculating the data dissemination distance. This distance is calculated as the average distance of vehicles farthest from node 3 in all four directions at the 964-s mark of the simulation, which coincides with the moment that the data packet reaches the end of its lifecycle. To increase the volume of the simulation data and enhance the accuracy of the research without altering the overall scenario architecture and the behavior of the OBUs and RSUs, we generated multiple routing files with the same traffic volume demand but different specific vehicle routes using random numbers for simulation, to create different degrees of data dissemination effectiveness for reference.

5. Performance Analysis and Numerical Results

5.1. Results of V2X Performance Comparison

5.1.1. Data Throughput

The macroscopic results of the grid road scenario and the adjusted geometric road scenario are illustrated in Figure 7, respectively. By analyzing the macroscopic data dissemination distances in the grid road scenarios depicted in Figure 7a,b, we can evaluate and compare the data throughput of 802.11bd and 802.11p. In this set of experiments, data packets are emitted simultaneously from the same location, with all vehicles following an identical data packet processing mechanism (see Figure 6), while the data packet size transmitted by 802.11bd is twice that of 802.11p (detailed settings in Table 3). After the same duration, it can be observed that the packet transmission distances of both standards are very close in all four directions (as indicated by the green line marks), with a statistical difference of only 3% in the number of vehicles that receive data packets. This substantiates the claim that 802.11bd achieves nearly double the data throughput of 802.11p.



(**a**) Grid road—802.11p (**b**) Grid road—802.11bd

(**c**) Geometric road—802.11p (**d**) Geometric road—802.11bd

Figure 7. Macroscopic results of throughput comparison simulation.

In the simulation experiments conducted in the adjusted geometric road scenarios depicted in Figure 7a,b (detailed settings in Table 3), the performance is found to be consistent with that in the grid road scenarios: with 802.11bd transmitting data packets twice the size of those in 802.11p, the dissemination effects are remarkably similar, as evidenced by the zoomed-in views in the two subfigures. The differences between the two are also minimal regarding the microscopic statistics, further confirming the significant data throughput advantage of 802.11bd over 802.11p.

5.1.2. Data Transmission Reliability

The simulation results regarding the data transmission reliability in the grid road scenario and the adjusted geometric road scenario are shown in Figure 8. The comparative simulation results include four data transmission modes with the lowest data transfer rate (the lowest requirement for SNR): BPSK 1/2, QPSK 1/2, QPSK 3/4, and 16-QAM 1/2.

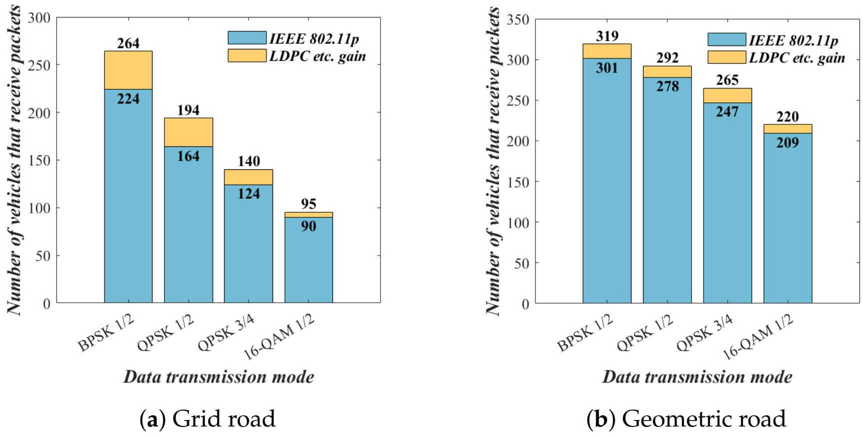


Figure 8. Simulation result of transmission reliability comparison.

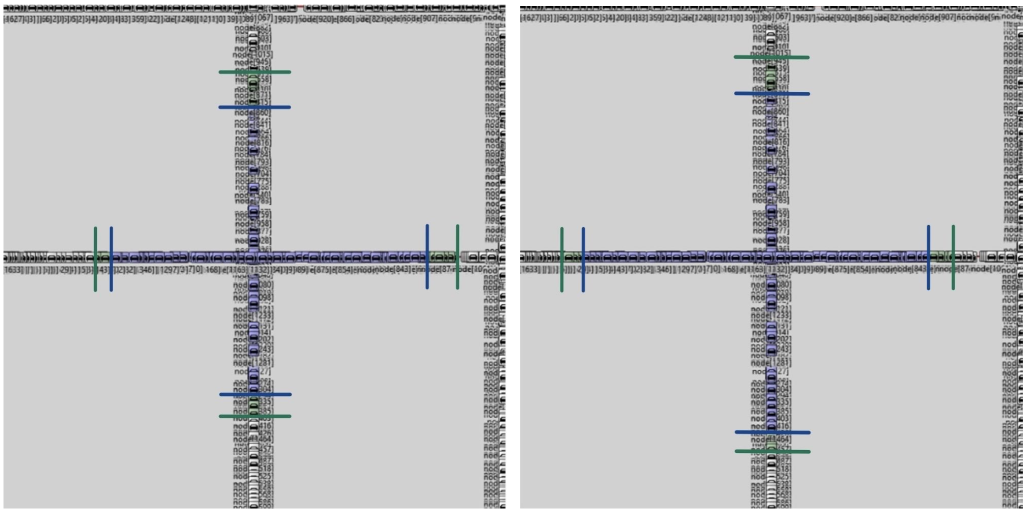
Based on Figure 8a, it can be observed that in this scenario, 802.11bd achieves an approximately 18% transmission reliability gain over 802.11p for both the BPSK 1/2 and QPSK 1/2 data transmission modes. The transmission reliability gain decreases to 13% for QPSK 3/4 and further decreases to 5.5% for 16-QAM 1/2. For more enhanced data transmission modes, the transmission reliability gain in this scenario is extremely marginal. The reason for this simulation result is that the reference data for the improvement in the transmission reliability in this paper are the SNR gains of 2-4 dB. The transmission reliability improvement of different data transmission modes can only be reasonably obtained within this range during implementation. However, the SNR requirements for different data transmission modes exhibit almost exponential growth in the simulation (see Figure 3), rapidly reducing the positive impact generated by the SNR gain as the data transfer rate increases. Derived from Figure 8b, the beneficial effects of the SNR gain wane within the intricate scenario, primarily attributed to the heightened complexity of the traffic environment. However, the transmission reliability gain remains stable (around 6%) across different data transmission modes. It does not decrease significantly with the increase in data transfer rate, as observed in the straightforward scenario.

5.2. Results of the Sensitivity Analysis on Properties of Data Dissemination

5.2.1. V2X Standard

This experiment employed four data transmission modes with favorable data dissemination effectiveness: BPSK 1/2, QPSK 1/2, QPSK 3/4, and 16-QAM 1/2. Ten different random number seeds were selected, completing 80 (10 groups) dynamic simulations. The macroscopic results of one simulation (No. 4 random number seed, QPSK 3/4) are shown in Figure 9, while the comprehensive statistical results are summarized in Figure 10.

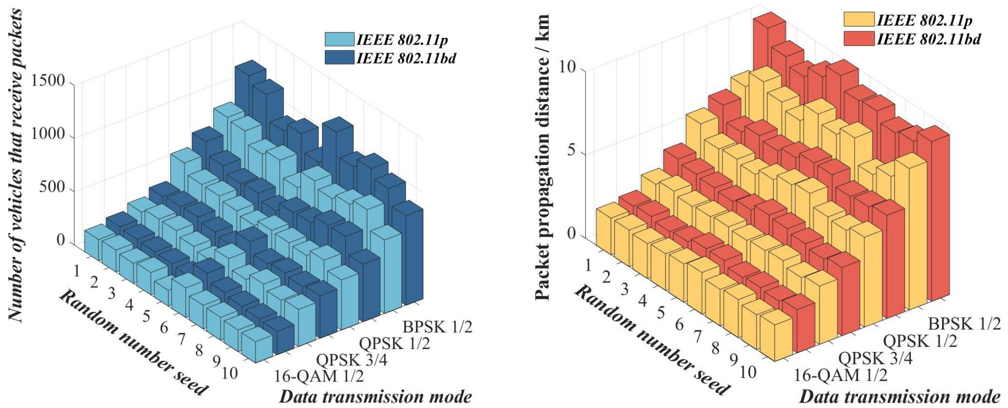
In the specific pairwise simulations conducted under different V2X standards and identical conditions, as shown in Figure 9, a distinct improvement in the data dissemination distances is evident along the roads to the west and south of the intersection, as indicated by the green line marks. In specific numerical terms, the data dissemination distance on the western road increased from 3.1 to 4.0 km, representing a 29% improvement. Similarly, on the southern road, the data dissemination distance increased from 3.1 to 3.8 km, marking a 23% enhancement. We attribute this improvement to the enhanced transmission reliability of 802.11bd. However, on the northern road, the data dissemination distance increased only slightly from 3.6 to 3.8 km. Conversely, on the eastern road, the data dissemination distance even decreased from 3.9 to 3.7 km. We believe that this outcome is attributable to the excessive traffic volume on these roads.



(**a**) IEEE 802.11p (**b**) IEEE 802.11bd

Vertical List:
- Vehicles that receive and transmit data packets
- Vehicles that receive data packets but do not transmit
- Vehicles that fail to receive data packets
- Mark of the maximum distance of packet propagation
- Mark of the last transmission location of packet

Figure 9. Macroscopic results of one group (No. 4 random number seed, QPSK 3/4).



(**a**) Number of vehicles that receive data packets (**b**) Data dissemination distance

Figure 10. Summary of the impact of V2X standards on data dissemination effectiveness.

As illustrated in Figure 10, despite some variations in the experimental results across different groups, it can be inferred overall that 802.11bd has enabled advancements in the data dissemination effectiveness compared to 802.11p. According to the statistical data, it can be observed that under the same data transmission mode and random number seed, 802.11bd outperforms 802.11p in terms of the number of vehicles that receive data packets and the data dissemination distance, with an improvement of approximately 10–20%. Taking the experimental group illustrated in Figure 9 as an example, 802.11bd exhibits a 12% increase in the average data dissemination distance (from 3.4 to 3.8 km) and a 19% increase in the number of vehicles that receive data packets (from 300 to 357 vehicles). However, the gains from the two metrics diminish with the progression of the data transmission modes (corresponding with an increased data transfer rate). Concurrently, multiple transmissions exhibit an amplifying effect on the transmission reliability. In the specific simulation scenarios, especially with BPSK 1/2, the two metrics achieve an improvement of approximately 25–30%.

5.2.2. Traffic Volume

This experiment employed a data transmission mode with favorable data dissemination effectiveness: QPSK 1/2. A total of 40 (10 groups) simulations were completed. The macroscopic results of one group (No. 4 random number seed) are shown in Figure 11, while the comprehensive statistical results are summarized in Figure 12.

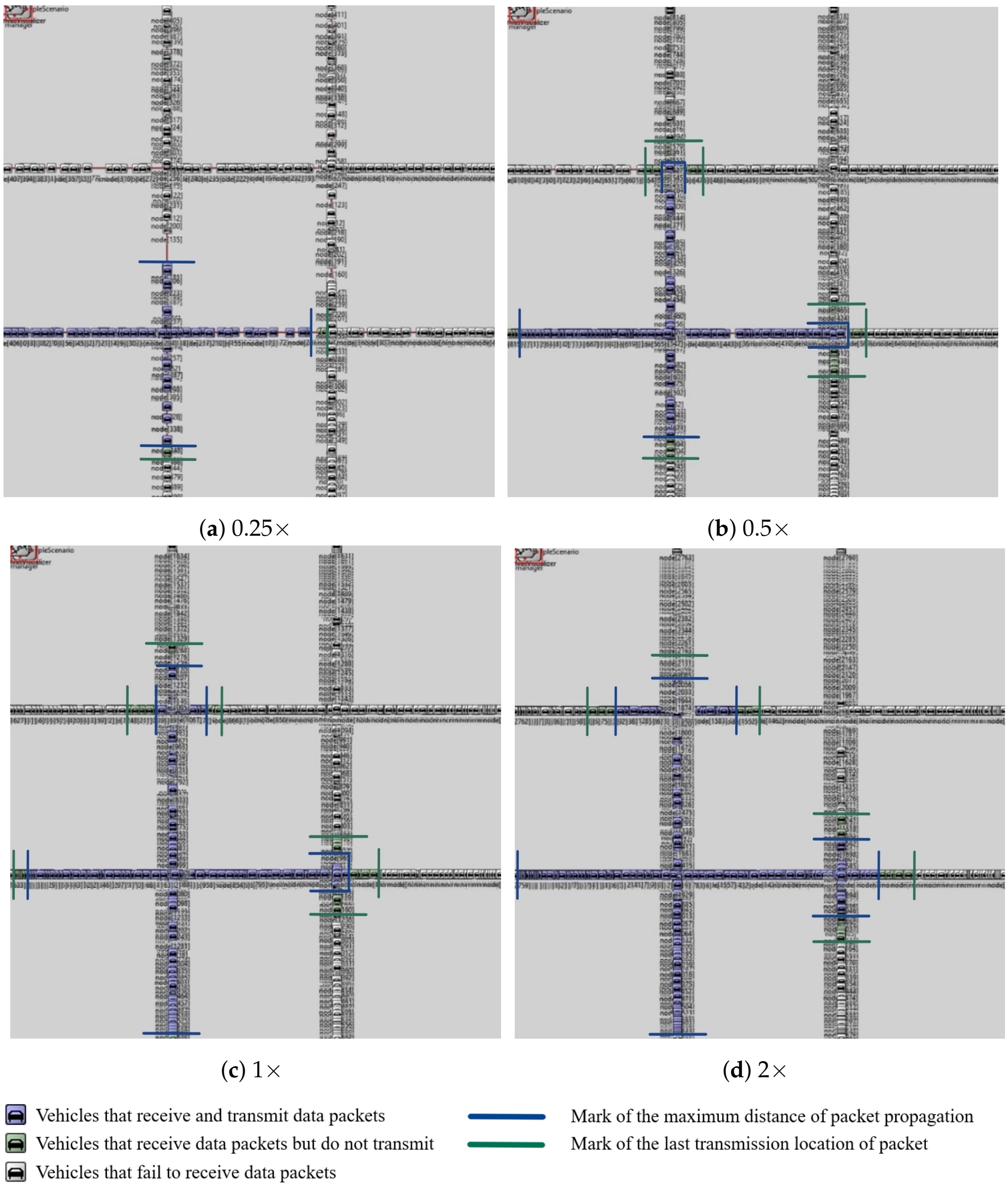
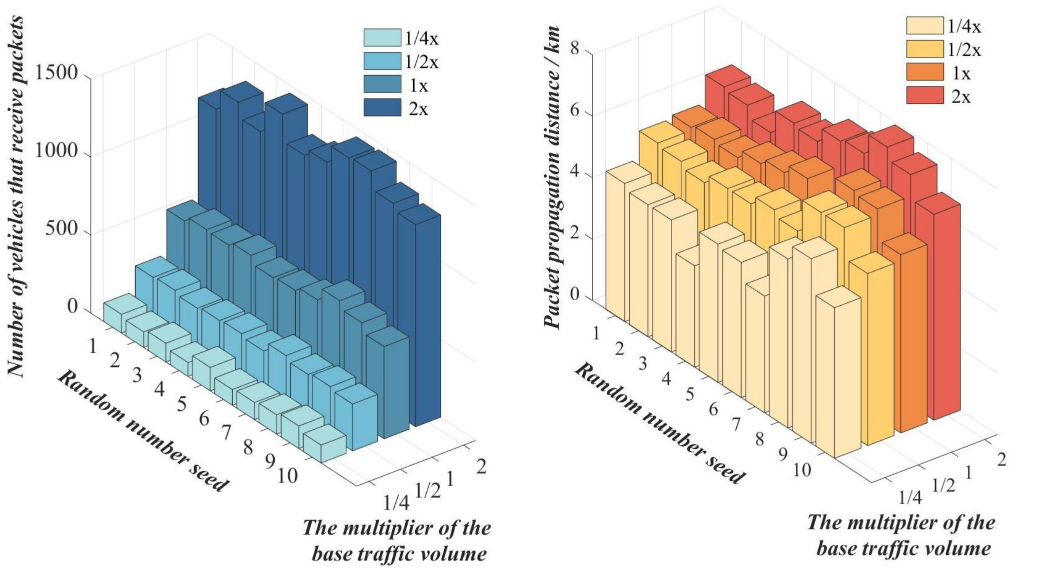


Figure 11. Macroscopic results of one group (No. 4 random number seed).

Based on the furthest data dissemination distances observed on different roads in Figure 11, as indicated by the green line marks, it can be observed that the impact of an increased traffic volume on the macroscopic data packet dissemination speed is relatively limited. This observation is further corroborated by the aggregated statistical data presented in Figure 12, which reveal a similar trend: while the number of vehicles that receive data packets doubles with the doubling of the vehicular traffic volume, the increase in the data dissemination distance is not significant, showing approximately 10% growth under 0.5×, 1×, and 2× traffic volume conditions. Taking the experimental group depicted in Figure 11 as an example, under 1× traffic volume conditions, the number of vehicles that receive data packets increases by 94% compared to 0.5× conditions, while the data dissemination distance only increases by 7%. Under 2× traffic volume conditions, the number of vehicles that receive data packets increases by 110% compared to 1× conditions, while the data dissemination distance only increases by 13%. From a communication perspective, an increasing traffic volume leads to more vehicles successfully receiving data packets. However, it also decreases the SNR, reducing the probability of successful data packet reception. When considering the joint impact of these two factors, it becomes apparent that the influence of the traffic volume on the data dissemination distance is somewhat limited.



(**a**) Number of vehicles that receive data packets (**b**) Data dissemination distance

Figure 12. Summary of the impact of traffic volume on data dissemination effectiveness.

There is a notable contrast in the data dissemination distance between 0.25× and 0.5× traffic volumes. This disparity is because the 0.25× traffic volume is exceptionally low, leading to a sparse vehicle presence on the road. In specific locations, the significant distance between adjacent vehicles increases the likelihood of data dissemination failure, as illustrated in Figure 11a, particularly observed in the middle section of the west-side north-south road. In general, when there is a certain baseline and continuous traffic flow, the overall impact of the total traffic volume on the data dissemination distance remains limited (around 10%). Interestingly, in specific scenarios, the data dissemination distance may even increase after a reduction in traffic volume in specific directions.

5.2.3. Radio Signal Transmission Power

This experiment employed a widely used data transmission mode: 16-QAM 1/2. A total of 40 (10 groups) simulations were completed. The macroscopic results of one group (No. 8 random number seed) are shown in Figure 13, while the comprehensive statistical results are summarized in Figure 14.

Based on Figure 14, it can be observed that increasing the radio signal transmission power provides an approximately 30% improvement in the number of vehicles that receive data packets and the data dissemination distance. The gain varies depending on different traffic scenarios and transmission power levels; generally speaking, the higher the radio signal transmission power, the lower the gain relative to it. Taking the experimental group illustrated in Figure 13 as an example, using the number of vehicles that receive data packets as a metric, the signal transmission power of 60 W surpasses that of 30 W by 41%, while 90 W exceeds 60 W by 28%, and 120 W surpasses 90 W by 21%. The same conclusion is drawn when using the data dissemination distance as the metric.

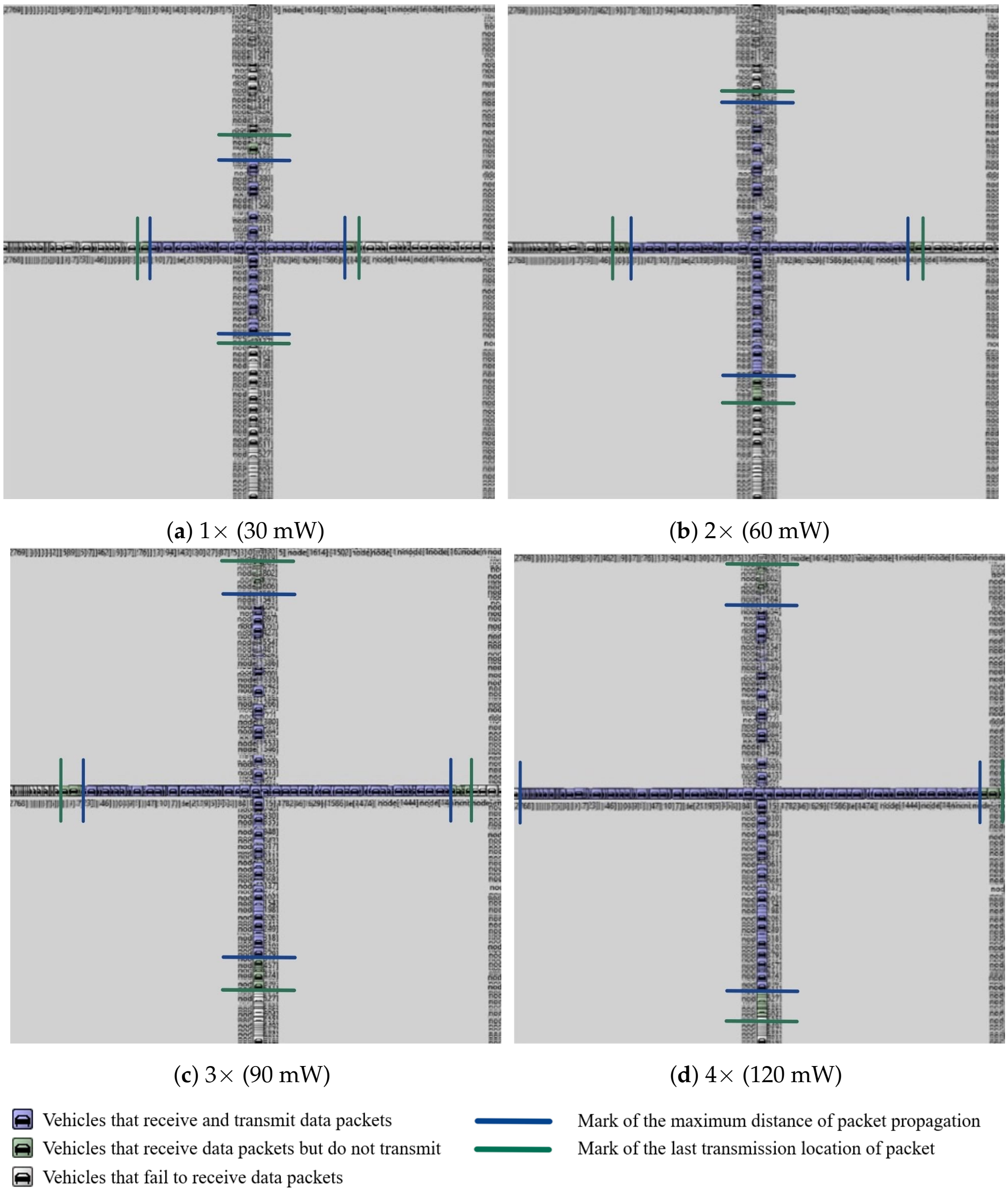
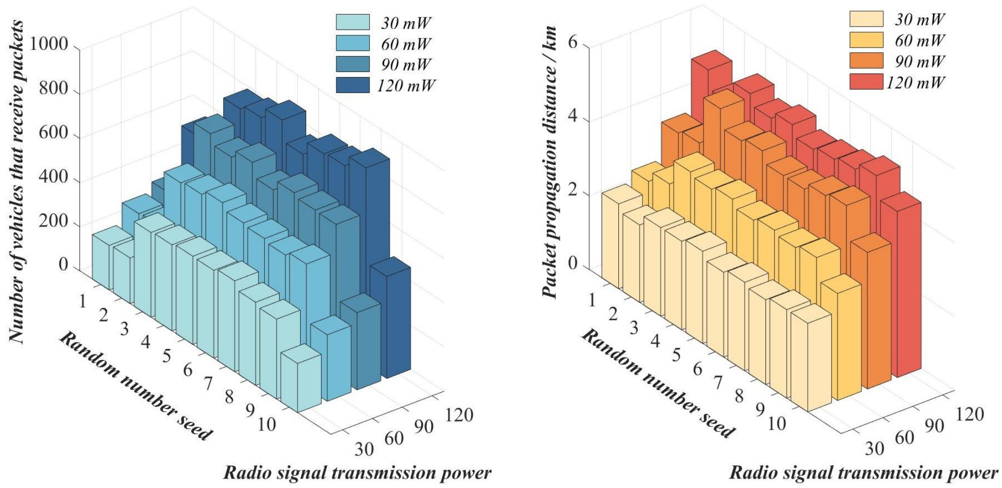


Figure 13. Macroscopic results of one group (No. 8 random number seed).



(**a**) Number of vehicles that receive data packets (**b**) Data dissemination distance

Figure 14. Summary of the impact of transmission power on data dissemination effectiveness.

6. Conclusions and Discussion

This paper first researches and analyzes the technical improvements of the IEEE 802.11bd standard and evaluates their possible impacts on V2X performance. Then, we implement key technological improvements in Veins, such as 256-QAM MCS, a 5/6 coding rate, and LDPC coding, to construct a V2X communication simulation module based on the IEEE 802.11bd standard.

Compared to its predecessor, the IEEE 802.11p standard, the IEEE 802.11bd standard exhibits significant advancements (more than twice) in data transfer rates. In order to evaluate the progress in two other V2X performance metrics, i.e., data throughput and transmission reliability, we utilized the aforementioned module to construct simulations in large-scale dynamic traffic scenarios. The following conclusions were drawn from our simulation results:

- In large-scale dynamic traffic scenarios, under identical conditions, 802.11bd achieves nearly equivalent data dissemination results to IEEE 802.11p when sending packets twice as large, demonstrating that 802.11bd can achieve approximately twice the data throughput of 802.11p;
- In large-scale dynamic simulations under identical conditions, 802.11bd achieves up to a 20% improvement in data transmission reliability compared to IEEE 802.11p in terms of the data dissemination distance and the number of vehicles that receive data packets. However, this gain rapidly diminishes with increasing data transmission rates and is limited in complex scenarios, as evidenced by the comparison between the two scenarios.

We have also researched the properties of data dissemination in IoV and found that the optimization of the V2X standards and the increase in radio signal transmission power and traffic volume positively impact the data dissemination effectiveness. Regarding the V2X standards, under the same simulation scenarios and data transmission modes, 802.11bd outperforms 802.11p by approximately 10–20% in terms of the number of vehicles that receive data packets and the data dissemination distance. Within the range of 30 to 120 mW of radio signal transmission power, an increase of approximately 30% in the gain can be observed. However, this gain diminishes with higher levels of radio signal transmission power. Simultaneously, the conclusions drawn from traffic volume simulations are even more significant: while the number of vehicles receiving data packets approaches a proportional increase due to the doubling of the traffic volume, the relative increase in the data dissemination distance is rather limited, at approximately 10%. This finding is highly thought-provoking, indicating that as long as there is a certain baseline and continuous traffic flow, the overall traffic volume has a limited impact on the data dissemination distance.

In conclusion, this research demonstrates the significant advancements of the IEEE 802.11bd standard in several key V2X performance metrics at the physical layer, while also revealing the properties of data dissemination in realistic traffic scenarios. Moving forward, our focus will shift to exploring the newly introduced communication mechanisms of IEEE 802.11bd, such as NON_NGV_10 repetition transmission and non-NGV duplicate PPDU. By designing strategies at the application layer in Veins to refine these mechanisms, we hope to guide higher-level standard architectures and unleash the full potential of IEEE 802.11bd. The implementation of another NGV standard, NR-V2X, is also planned, and we expect to compare it with IEEE 802.11bd to provide a reference for the comprehensive application of NGV.

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