IEEE 802.11bd for Next-Generation V2X Communications: From Protocol to Services

Journal:	*IEEE Communications Standards Magazine*
Manuscript ID	COMSTD-24-00050
Manuscript Type:	Vehicular Networking
Date Submitted by the Author:	06-Jul-2024
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Key Words:	

IEEE 802.11bd for Next-Generation V2X Communications: From Protocol to Services

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Keywords: IEEE 802.11bd, Vehicle-to-Everything (V2X), vehicular communication, IEEE 802.11p, Next Generation Vehicle-to-everything (NGV) station (NGV STA), use cases

IEEE 802.11bd is a modern standard in the Vehicle-to-Everything (V2X) domain, designed to address the evolving demands of vehicular communications. Building on its predecessor IEEE 802.11p and considering today's stringent communication requirements, IEEE has crafted a robust communication tool introducing the next-generation vehicle-to-everything (NGV) station. This involves significant modifications in the physical (PHY) and the medium access control (MAC) layers. This paper explores the new IEEE 802.11bd standard highlighting its predecessor's limitations. The major PHY and MAC layer characteristics are elucidated to aid newcomers and facilitate a comprehensive comparison between the two standards. Finally, the paper underscores the impact of IEEE 802.11bd on contemporary V2X use cases and scenarios, offering concise explanations of its role in each case.

Introduction

The IEEE 802.11bd amendment, entitled "Enhancements for Next-Generation Vehicle-to-Everything (V2X)" is a significant advancement in the context of wireless local area network (WLAN) specifications, primarily designed to cater for the unique and demanding requirements of vehicular networks. This standard is crucial in enabling enhanced connectivity and safety for vehicles towards future intelligent transportation systems (ITS) [1]. It defines the physical (PHY) and medium access control (MAC) layers, while the upper layers are governed by the IEEE 1609 family of standards, also known as wireless access in vehicular environments (WAVE). WAVE plays a pivotal role by defining interfaces for various aspects of vehicular communications, including security, networking services, multi-channel operations, management services, and more [2, 3].

IEEE 802.11bd serves as a logical enhancement of its predecessor, IEEE 802.11p. The latter marked the initial venture of IEEE into vehicular communications in 2010. The advent of IEEE 802.11p also led to the development of dedicated short-range communications (DSRC), a technology tailored for short to medium-range communication between vehicles and infrastructure. While DSRC builds upon IEEE 802.11p, its relevance extends seamlessly to IEEE 802.11bd [4].

Over the years, the research community diligently scrutinized the capabilities of IEEE 802.11p, pinpointing limitations in throughput, reliability, transmission range, etc [5]. To address these shortcomings, IEEE 802.11bd amendment was proposed in alignment with the requirements of autonomous driving [6].

In this context, this paper explores the factors driving the evolution of IEEE 802.11p, followed by an analysis of its successor. It begins with IEEE 802.11bd PHY, elucidating some of its most paramount characteristics. A concise description is next provided for the MAC layer, emphasizing its pivotal features in orchestrating efficient and reliable communications for vehicular networks. Additionally, this paper investigates the anticipated impact of IEEE 802.11bd on current V2X use cases, exploring the significance of its new characteristics. Overall, this paper aims to provide a comprehensive understanding of the nuanced enhancements that characterize the evolution from IEEE 802.11p to the advanced capabilities of IEEE 802.11bd.

IEEE 802.11p: Need for Evolution

The transition from IEEE 802.11p to IEEE 802.11bd is justified by the evolving landscape of vehicular communications and the rising need for connected and autonomous vehicles. IEEE 802.11p, published over a decade ago, encounters latency, coverage, and capacity limitations, along with its inability to support advanced technologies like beamforming or single-user multiple-input multiple-output (SU-MIMO) [2].

One of the main limitations of IEEE 802.11p is the low signal quality and poor resource allocation for emerging services. In particular, IEEE 802.11p cannot effectively handle high Doppler shifts arising in fast-moving stations, thus, impacting communication stability in high-speed scenarios. Moreover, even though IEEE 802.11p provides several choices of modulation and coding schemes (MCS), they are proven to be inadequate for demanding applications in vehicular environments [5]. On the other hand, IEEE 802.11bd introduces midambles to support frequent channel estimation to mitigate signal detection issues, along with new MCSs, including higher-order modulation and low-density parity check (LDPC) coding in place of binary convolutional coding (BCC) as well as dual subcarrier modulation (DCM). These, complemented with adaptive packet repetition and SU-MIMO, offer better coverage, higher rates, and enhanced resiliency.

Another set of limitations encompasses issues related to frequency and bandwidth constraints. IEEE 802.11p operates in the 5.9 GHz band utilizing 10 MHz channels. IEEE 802.11bd introduces, in addition, unlicensed frequencies in the mmWave band. It also supports 10 or 20 MHz channels with a dynamic channel switching mechanism that allows the devices to switch between them according to the traffic conditions and application requirements.

On the other hand, IEEE 802.11p uses simple carrier sense multiple access with collision avoidance (CSMA/CA) to allocate resources. However, CSMA/CA can lead to channel congestion in high-load scenarios by causing intensive collisions. IEEE 802.11bd engages enhanced distributed channel access (EDCA) to allocate the resources according to data load in congested areas [1].

It becomes evident that IEEE 802.11p encounters challenges in effectively supporting emerging applications, e.g., applications supporting event-driven messages or geospatial services with stringent criteria such as a maximum latency of 3 ms, a 0.001 percent maximum packet loss rate (PLR), and high data rates [5, 6]. Therefore, the evolution to IEEE 802.11bd signified a strategic move to keep pace with automotive industry transformation and contribute to safer, more efficient, and intelligent transportation networks. The key enhancements introduced in IEEE 802.11bd in the PHY and MAC layers are further explored in the next two sections, shedding light on distinctive features compared to IEEE 802.11p.

IEEE 802.11bd Physical Layer

Certain mechanisms integrated into IEEE 802.11bd have been pre-established in IEEE 802.11-2020 that provides a valuable repository of information, with insights into the foundational principles and protocols that underpin IEEE 802.11bd. Beyond this continuity, IEEE 802.11bd introduces the next generation V2X station (NGV STA), i.e., an STA equipped with newly added capabilities to transmit NGV PHY protocol data units (PPDUs). Stations not supporting NGV PPDUs, also known as non-NGV stations, can coexist with NGV ones [1]. The most important features of the physical layer are concisely described below.

Frequency Allocation

IEEE 802.11bd has made progress in this field by revising the licensed spectrum and integrating the capability of the unlicensed spectrum framework. In particular, the predominant licensed frequency band lies in the 5.9 GHz range (5.850-5.925 GHz in the United States and 5.855-5.925 GHz in Europe), segmented into 10 or 20 MHz width channels. Each 10 MHz channel comprises 64 orthogonal frequency division multiplexing (OFDM) sub-carriers, with 52 dedicated to data transmission while a 20 MHz channel uses 128 sub-carriers, with 108 allocated for data. All sub-carriers are spaced by 156.25 kHz [5]. Because of the large 20 MHz channels, the standard also introduces improved spectral mask, significantly reducing energy radiation into adjacent spectrum channels.

IEEE 802.11bd extends its operation to the unlicensed mmWave band [4, 7]. The standard outlines the utilization of the 60 GHz (57 GHz to 71 GHz) frequency band for directional multi-gigabit (DMG) discovery, specifically between NGV stations in “outside the context of a BSS” (OCB)[†] mode. OCB mode was previously unavailable for DMG STAs in prior amendments, such as IEEE 802.11ad. Utilizing the OCB mode of IEEE 802.11bd, peer DMG NGV STAs may apply DMG discovery by exchanging higher-layer information [8]. Furthermore, the standard introduces the transmission of DMG beacon frames in OCB mode; crucial information such as channel number, discovery beacons, DMG parameters, capabilities, and beam link status [1] is conveyed, supporting DMG operation.

Modulation and Coding Schemes

Comparing to its predecessor, several new MCSs have been introduced in IEEE 802.11bd. NGV stations can utilize up to 256-QAM and 5/6 coding rate schemes, achieving data rates of 90 Mbps with a single spatial stream [1]. This represents a notable improvement compared to IEEE 802.11p, where the highest data rate is limited to 27 Mbps for 64-QAM modulation and 3/4 coding rate. The available MCSs and their rate-dependent parameters are provided in Table 1 [1]. A notable enhancement in IEEE 802.11bd modulation schemes is the incorporation of DCM, a feature derived from IEEE 802.11ax, that allows NGV stations to modulate and transmit each data symbol across two subcarriers. This offers significant range extension (up to three times) and enhanced diversity gain for low-rate services. The inclusion of DCM in IEEE 802.11bd is noteworthy, particularly considering its absence in IEEE 802.11p [4, 9, 10].

Given the introduction of higher-order modulation schemes in IEEE 802.11bd, the forwarded error correction (FEC) mechanism is critical for successful transmissions. In response, the standard has introduced LDPC channel coding, recognized for its ability to enhance spectral efficiency [4, 10].

[†] An STA in OCB mode can exchange data and control frames with other STAs in coverage any time without setting up a service set. This allows low-latency communication but removes authentication, association, and data confidentiality services from the MAC layer – see next section.

Modulation	R (code rate)	NGV Data Rate (Mb/s)				Non-NGV Data Rate (Mb/s)
		10MHz		20MHz		
		Nss=1	Nss=2	Nss=1	Nss=2	10MHz Repetitive Tx
BPSK	1/2	3.3	6.5	6.8	13.5	3.0
BPSK	3/4	-	-	-	-	4.5
QPSK	1/2	6.5	13.0	13.5	27.0	6.0
QPSK	3/4	9.8	19.5	20.3	40.5	9.0
16-QAM	1/2	13.0	26.0	27.0	54.0	12.0
16-QAM	3/4	19.5	39.0	40.5	81.0	18.0
64-QAM	2/3	26.0	52.0	54.0	106.0	24.0
64-QAM	3/4	29.3	58.5	60.8	121.5	27.0
64-QAM	5/6	32.5	65.0	67.5	135.0	-
256-QAM	3/4	39.0	78.0	81.0	162.0	-
256-QAM	5/6	-	-	90.0	180.0	-
BPSK-DCM	1/2	1.6	-	3.4	-	-

Table 1 *Rate dependent parameters and MCS*

In comparison to BCC employed in IEEE 802.11p, LDPC coding elevates the error correction capabilities of the standard significantly, and combined with midambles, offers enhanced throughput in high SNRs, providing almost triple data rates [5]. Furthermore, a minimum of 3 dB better receiver input sensitivity is supported by IEEE 802.11bd in 5.9 GHz band mainly in high mobility channel environments [1, 3, 4].

IEEE 802.11bd further introduces adaptive packet repetition that has been shown to offer gains in the order of 3 to 8 dB (at block error rates of 0.1); comparatively, IEEE 802.11p repetition may improve performance by 0.5-1.7 dB only [5, 10].

Midambles

Since the inception of IEEE 802.11p and vehicle communications, the dynamic radio environment introduced by moving terminals has been a crucial consideration. Preambles at the beginning of a frame may be inadequate to provide valid channel estimation due to high Doppler shifts. In this context, midambles, named after their position in the frame, play a pivotal role in obtaining the most current information for channel estimation. Midambles are placed periodically every 4, 8, or 16 OFDM symbols depending on the variability of the channel and the modulation scheme. While midambles offer better channel estimation and lower packet error rate (PER), they lead, at first glance, to higher transmission overhead, especially for small packets. This is mitigated by the effectiveness of LDPC and higher-order MCS which combined with midambles result in much higher throughputs than IEEE 802.11p in both low and high Doppler channels [11]. Midambles share a similar format with the NGV long training field (NGV-LTF), a component of the NGV packet preamble.

SU-MIMO

MIMO antenna systems have been used for almost three decades to increase throughput or enhance the reliability of wireless communication, by spatially multiplexing different data streams or introducing spatial diversity of a single data stream, over different (ideally independent) transmitter-receiver propagation paths, respectively. Depending on the specific channel characteristics, a proper combination of them maximizes spectral efficiency when channel state information (CSI) is available. This is important in vehicular environments, especially in non-line-of-sight (NLOS) cases where obstacles block the direct link between the transmitter and receiver. NGV STAs in IEEE 802.11bd support MIMO (absent in IEEE 802.11p) with two spatial streams doubling the achievable rate (Table I) with at least two transmitting and receiving antennas.

Recent simulation results [4] in NLOS urban and highway environments with one or two antennas at the transmitter and receiver have shown that multi-antenna configurations improve the quality of communication in all aspects. Besides coverage enhancement, lower packet error rates and inter-arrival times, higher packet reception and effective data rates have been reported, especially at longer distances.

PPDU Formats

To ensure backward compatibility with non-NGV STAs, IEEE 802.11bd delineates two principal formats for PPDUs: NGV and non-NGV [1]. The NGV format was designed to address the challenges of dynamic and fast-varying vehicular environments by supporting MIMO technology. Further, it boasts the flexibility to operate in 10 or 20 MHz channels, which are formed by pairing two adjacent 10 MHz channels. Within this pairing, one channel is designated as the primary channel, while the other assumes the role of the secondary channel. This adaptability allows bandwidth assignment flexibility and optimization of communication performance based on specific operational needs.

The structure of the NGV-PPDU is shown in Fig. 1. The typical NGV preamble exhibits a meticulously structured composition, encompassing key components essential for efficient wireless transmissions in vehicular environments. The non-HT legacy short training field (L-STF) and the non-HT legacy long training field (L-LTF) allow the receiver to detect the existence of a signal, perform frequency offset estimation, timing synchronization, etc. The non-HT legacy signal field (L-SIG) follows, incorporating information about the data length or transmission time while the repeated L-SIG field (RL-SIG) separates NGV PPDUs from non-NGV ones. The NGV signal field (NGV-SIG) introduces crucial parameters like MCS, bandwidth, number of spatial streams, and midamble periodicity, further tailoring the communication for vehicular requirements. The repeated NGV-SIG (RNGV-SIG) echoes NGV-SIG for redundancy. The NGV short training field (NGV-STF) is used for automatic gain control estimation in

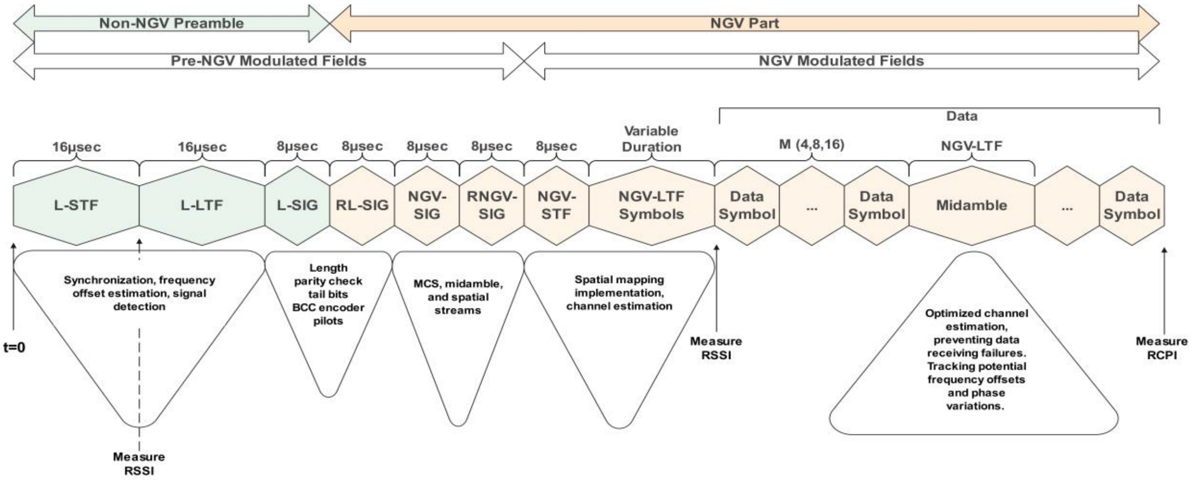

Figure 1 *NGV-PPDU Format.*

MIMO transmission while the NGV-LTF is used for channel estimation, either in the preamble or in the midambles. Finally, the Data field carries the payload of the PHY Service Data Unit (PSDU), completing the NGV format structure.

The non-NGV format retains the fundamental preamble for synchronization and signal acquisition of IEEE 802.11p. In particular, the trio L-STF, L-LTF, and L-SIG define its core structure, while the L-SIG, NGV-SIG, RNGV-SIG, NGV-STF, and NGV-LTF fields are excluded so that the packet can be decoded by non-NGV stations (Fig. 1). The non-NGV format is categorized into two classes: non-NGV transmission for 10 MHz bandwidth, and non-NGV duplicate transmission across adjacent 10 MHz channels. Stations tuned to any of these adjacent channels may receive the non-NGV duplicate signal. This approach enhances the reach and accessibility of the communication, enabling a broader audience of stations within the vicinity to effectively “listen” to the transmitted data.

IEEE 802.11bd MAC Layer

The MAC layer of IEEE 802.11bd demonstrates continuity with IEEE 802.11-2020, ensuring a seamless integration of established mechanisms. It also introduces novel MAC mechanisms to keep up with the ITS requirements. This section presents the most important ones, emphasizing their significance in advancing V2X communications by enhancing network coverage, reducing latency, and upgrading throughput. Although defined in IEEE 802.11p, OCB is a valuable source of knowledge for the standard, so we begin with this.

Outside the Context of Basic Service Set

OCB is an extension of the IEEE 802.11 standard, specifically tailored for vehicular communication scenarios. It addresses the challenges posed by high-speed mobility, frequent channel switching, and the need for low-latency communication in ITS [9]. Similarly to IEEE 802.11p, NGV stations operate exclusively in OCB mode.

OCB in IEEE 802.11bd utilizes the EDCA for its channel access mechanism and introduces additional elements such as tight timing synchronization. In this mode, there is no authentication or association. The former eliminates the need for time-consuming verification steps while the latter allows stations to communicate without prior setup. However, OCB lacks inherent data confidentiality mechanisms, making it imperative for users to implement supplementary security measures if necessary. Overall, OCB excels in reducing connection establishment delays and prioritizing swift and efficient communication, which is particularly beneficial in dynamic vehicular environments where rapid data exchange is of paramount importance.

Compared to the BSS context and traditional Wi-Fi networks certain procedures are strategically omitted in OCB mode (e.g., synchronization procedures, timing definitions with the specified BSS, failure timeout limits) for the sake of streamlined communication. Other parameters are considered predefined or defined by higher layers such as station capabilities, supported channels, Quality of Service (QoS) parameters, EDCA parameters [8], etc. For example, transmission opportunity (TXOP) which designates a specific time interval wherein a station enjoys the exclusive right to transmit multiple frames consecutively, is predefined as zero for each access category (AC), allowing transmission of only one frame at a time [1].

MAC Service Interface

Significant improvements have been implemented in the MAC service interface and the MAC sublayer management entity (MLME) service access point (SAP) interface. NGV stations now excel in efficiently monitoring and managing their radio environment through MAC service primitives. These

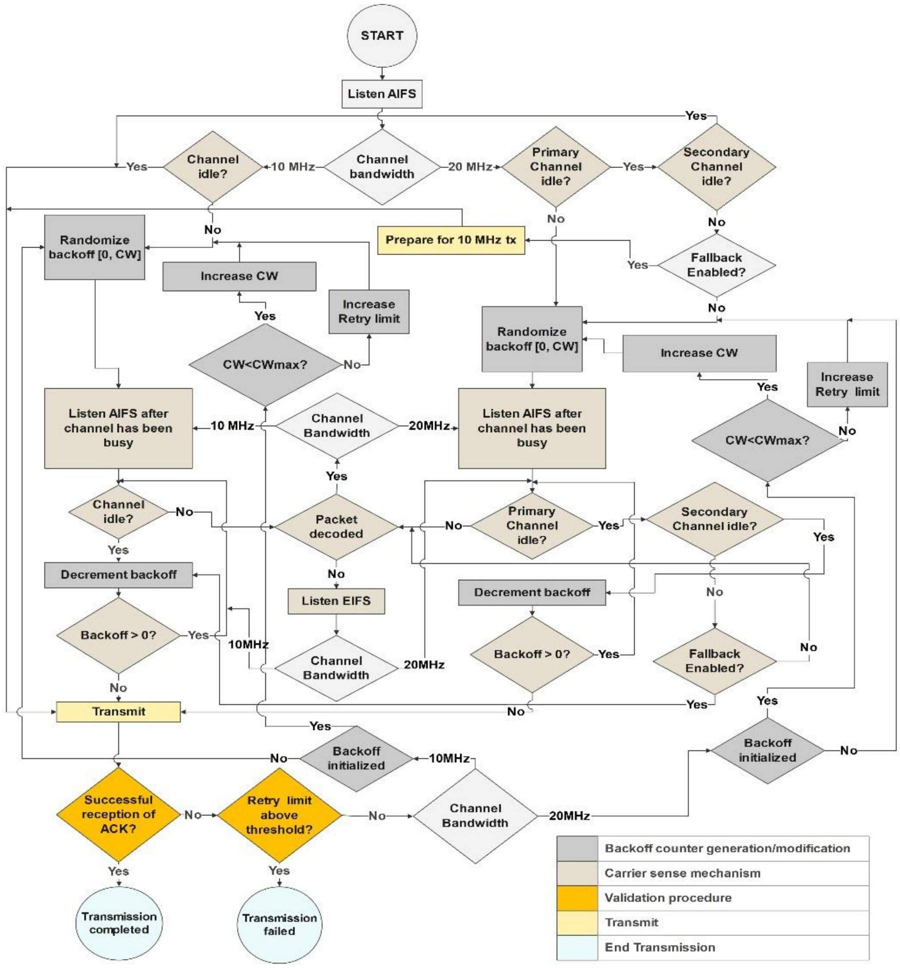

Figure 2 *EDCA NGV PPDU Unicast.*

include essential data on the environment, current radio status, recent receptions, and measurements of parameters influencing potential channel disorders. A brief description of these aspects is provided below [1].

A significant concept in the context of V2X communications is the expiry time. This new parameter is specifically associated with an enhanced distributed channel access function (EDCAF). When the expiry time elapses, the corresponding MAC service data unit (MSDU) is discarded without altering the contention window (CW) state variable.

Another novel parameter, aptly named “fallback enabled”, introduces a valuable feature specifically tailored for NGV PPDUs. It is utilized in scenarios in which the 20 MHz channel is occupied, by seamlessly facilitating the transition to a 10 MHz transmission. This capability ensures optimal adaptability and uninterrupted communication efficiency in NGV environments [5].

Repetitive transmission is another valuable capability within the MAC service interface, allowing for the broadcast transmission of the same frame up to three times [5, 10, 12]. This feature is limited to non-NGV 10 PPDUs, which adhere to the IEEE 802.11p. The time interval between repetitions is governed by the short interframe space (SIFS), ensuring seamless delivery and precluding contention for the medium during this period. Possible factors for determining the number of repetitions may include considerations from higher layers, channel busy percentage, the quality of recent transmissions, received signal strength indicator (RSSI), and the criticality of the transmitted data. This multifaceted approach ensures adaptability in tailoring repetition strategies based on a comprehensive evaluation of diverse factors.

Similar to the MAC service interface, the MLME SAP interface undergoes significant enhancements through the inclusion of various parameters. Among them is the channel busy percentage, a metric reflecting the percentage of time the channel is occupied. The measurement period may vary from 100 to 1000 ms or zero, allowing precise customization. This metric empowers users to adapt to dynamic channel occupancy effectively. The station measurement parameter, on the other hand, indicates the number of unique MAC addresses detected during the measurement period. Additionally, the NGV capability percentage is derived from the Duration/ID field in the MAC header and reveals the percentage of NGV-capable STAs in the network. This insight into the diversity of active

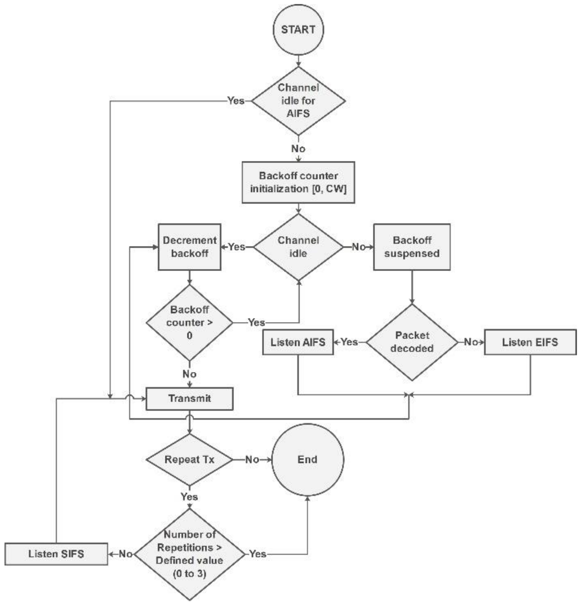

Figure 3 *EDCA non-NGV PPDU Broadcast.*

stations aids in comprehending network dynamics and informs strategic decisions for efficient channel management (e.g., PPDU format choice, bandwidth).

The final noteworthy parameter, “cancel Tx”, introduces the ability to annul the transmission of MSDUs belonging to a specific AC of EDCAF. These are MSDUs that were previously sent to the STA and are still in the transmit queue of the MAC entity. Cancel Tx provides a mechanism for controlled cancellation of transmissions, enhancing operational flexibility and efficiency.

Enhanced Distributed Channel Access

EDCA is a feature first introduced in the IEEE 802.11e, an amendment to the IEEE 802.11 standard for QoS support. The incorporation of a 20 MHz channel bandwidth in the IEEE 802.11bd standard not only introduces advanced clear channel assessment (CCA) processes but also intersects with the impact of the “fallback enabled” capability as well as it is further influenced by the consideration of the OCB mode [6, 9]. This dual influence emphasizes the need for corresponding CCA mechanisms capable of seamlessly assessing channel availability in dynamic environments distinct from those already defined for 20/40 MHz BSS channels in the IEEE 802.11-2020 standard [1]. The wider bandwidth necessitates nuanced strategies for sensing the wireless medium while the fallback-enabled feature ensures a smooth transition to an alternative channel configuration if the secondary 10 MHz channel is congested.

What sets IEEE 802.11bd apart is the consideration of both the primary and secondary 10 MHz channels, emphasizing the need for a comprehensive assessment of channel conditions. During the CCA process, devices operating in IEEE 802.11bd must conduct channel sensing both on the primary 10 MHz channel and the associated secondary 10 MHz channel. This dual-channel CCA approach ensures evaluation of the entire 20 MHz bandwidth, providing a more accurate depiction of the wireless medium status as depicted in Fig. 2.

The CCA criteria in the IEEE 802.11bd standard are defined based on received power thresholds, corresponding to physical sensing. In the primary channel, the CCA sensitivity dictates that a detection event occurs within a period of *aCCAtime* if the received power surpasses −85 dBm for decoded packets or −65 dBm for any undecoded signal. Similarly, in the secondary channel, a detection event is registered firstly if the conditions for the primary channel are not present and secondly for any signal exceeding −65 dBm within *aCCAtime* or if a detected PPDU is greater than −85 dBm within *aCCAMidTime* (predefined equal to 45 μs). In this way, the CCA mechanism evaluates the energy levels on the non-primary channel to ascertain if there is any ongoing wireless activity [1].

In the virtual carrier sense (CS) case, which involves estimating channel status based on network-derived information, specific mechanisms are employed to convey essential details, especially in scenarios where no traditional flow control exists, i.e., Request to Send (RTS)/Clear to Send (CTS) frames. In particular, for broadcast or group-addressed transmissions, crucial information, such as packet length, transmission time, or other relevant details, is embedded in the PSDUs for OCB mode [2]. This ensures that devices can make informed decisions regarding channel access and transmission in OCB mode, without explicit flow control, contributing to efficient and reliable V2X communications. Representative flow paradigms for unicast and broadcast transmissions in IEEE 802.11bd standard are given in Fig. 2, and Fig. 3 [6, 9, 10].

Frame Aggregation and Block Acknowledgment in OCB

Frame aggregation is used to enhance data transmission efficiency in IEEE 802.11 networks. It involves combining multiple smaller data frames into a single, larger frame before transmission. This process reduces the overhead associated with frame headers and interframe gaps, improving overall throughput and efficiency [8]. Opposed to IEEE 802.11p in which this mechanism was not supported, the new standard defines specific conditions for this process. It specifies a maximum NGV MAC protocol data unit (MPDU) length of 7991 octets with a corresponding PPDU duration of 10968 μs. Additionally, it mandates a minimum time interval of 2 μs between adjacent MPDUs within an Aggregated MPDU (A-MPDU) to ensure proper separation and decoding [1].

The standard also incorporates add block acknowledgment (ADDBA) with distinctive features, including the absence of a timeout mechanism and the provision of 32 buffers capable of holding 7935 octets. ADDBA request/response frames

Feature	IEEE 802.11p	IEEE 802.11bd	Description - Benefits of IEEE 802.11bd
PHY			
Modulation	BPSK, QPSK, 16/64-QAM	BPSK-DCM, BPSK, QPSK, 16/64/256-QAM	Improved throughput
Error correction	BCC	BCC and LDPC	Improved sensitivity, robustness, range extension
Channel bandwidth (MHz)	10	Interoperable 10 and 20	Improved interoperability
Data subcarriers	48	48 and 52	Improved throughput, additional channel transmissions, spectrum efficiency
Subcarrier spacing (kHz)	156.25	312.5, 156.25, 78.125	-
MIMO	N/A	2x2	Improved throughput for unicast transmission, improved robustness and range
Licensed Frequency bands	5.9 GHz	5.9 GHz	-
mmWave	N/A	Yes (unlicensed 60 GHz)	Only for DMG discovery, new applications perspective
DCM mode	N/A	BPSK, QPSK, 16-QAM	Improved sensitivity, robustness, range extension
Coding Rate	1/2, 3/4, 2/3	1/2, 3/4, 2/3, 5/6	Data flexibility, enhanced data rates
MAC			
Frame aggregation	N/A	Yes	Only for unicast, overhead reduction, tx efficiency
Adaptive Repetitions	N/A	1-3 repetitions (only broadcast)	Improved robustness, reliability, range extension
Localization	N/A	Supported (FTM)	Improved spatial and location awareness
Fallback enabled	N/A	Yes	Adaptability, uninterrupted and efficient communication
Block ACK	N/A	Yes	Improved OCB mode
Cancel Tx	N/A	Yes	Resource release
Station measurement	N/A	Yes	Situation awareness, efficient channel management
Identity information	N/A	Yes	-
Channel busy percentage	N/A	Yes	Improved adaption
Secondary channel detection	N/A	Yes	Time period defined in MAC
RSSI feed	Only in Tx mode	Available for last received packet	Improved environment estimation and resource allocation
Expiry time	N/A	Yes	Withdraw obsolete data, resource release
Performance Metrics			
Supported relative speeds	250 km/h	500 km/h	
Channel tracking (estimation)	Proprietary	Proprietary and midamble-based, lower complexity receiver, face Doppler shift	
Data rates (Mbps)	Up to 27Mbps	Up to 180 Mbps for two spatial streams and unicast mode, improved throughput	
Communication range	100m	Range extension up to 3 times longer through DCM, LDPC, repetitions	
AWGN and Doppler effect gain	0.5 − 1.7 dB	3 − 8 dB	
Packet Error Ratio (PER)	< 10% (for PSDU 1000 octets)	< 10% for 2048 octets for BPSK-DCM or 4096 octets for all other modulations	

Table 2 *IEEE 802.11bd vs IEEE 802.111p*

(agreement mechanism) eliminate the need for capability exchange limits. However, frame aggregation and block acknowledgment mechanisms are not supported for group-addressed transmissions, indicating a targeted application toward unicast communication for optimal performance [1].

NGV Ranging

In rapidly changed communication scenarios, tracking the location of nodes plays a pivotal role in system performance. In such environments synchronization procedures are challenging, so IEEE emphasized advancing the capability of NGV ranging that enables stations to determine distances among them. Derived from the fine timing measurement (FTM) procedure outlined in IEEE 802.11-2020 for V2X scenarios, NGV ranging incorporates significant modifications. It introduces the capacity for differential distance computation, reliant on knowledge from two nearby NGV stations [10]. Furthermore, the non-trigger-based (non-TB) ranging mechanism allows an NGV station to swiftly compute its position (approximately within 1 ms with NGV station assistance and 3 ms via road-side units). Moreover, NGV ranging extends its capabilities beyond the 5.9 GHz frequency band, as highlighted in [10].

Figure 4 *IEEE 802.11bd V2X use cases*

This enhancement ensures that NGVs can reliably and rapidly ascertain their position in the area of interest (AoI), establishing robust connectivity with other nearby nodes [5].

Coexistence with IEEE 802.11p

Coexistence with IEEE 802.11p is supported by sharing the same CCA requirements and incorporating NGV capability identification in corresponding PPDUs, as already mentioned. By aligning CCA requirements, transmissions are conducted efficiently without causing interference, promoting smooth coexistence [5]. Therefore, a non-NGV station monitors an NGV PPDU (without decoding) to adjust its transmission, while an NGV station detects the presence of non-NGV stations to adapt its transmission strategy accordingly. Thus, IEEE 802.11bd devices can communicate with non-NGV devices fostering a transition that accommodates new and existing technologies in vehicular communication networks [1].

A concise comparison of the most significant differences of the two standards is provided in Table 2 [1, 3-5, 8, 10].

Future Outlook and Use Cases

V2X applications and use cases have substantially evolved over the past decade. In response to the dynamic landscape, IEEE 802.11bd confronts several impactful factors inherent in the V2X environment, guiding the development of its new capabilities. Noteworthy challenges encompass scalability concerns, heightened by the rapid time-varying nature and complexity of the environments involved [13]. Addressing transmission ranges and managing broadcast storms, crucial for safety data dissemination, pose additional hurdles. Furthermore, the V2X environment is marked by stringent demands, including extremely low-latency applications, high reliability, and adherence to stringent QoS parameters amid congestion scenarios. Lastly, emergency circumstances necessitate stations to understand their radio environment proactively, enabling optimal transmission of aperiodic safety data when needed [5].

V2X scenarios and use cases, encompassing diverse factors and assumptions, find useful references in documents of SAE or ETSI, who provide valuable guides and specifications in this domain. Categorization and analysis of these use cases are beyond the scope of this paper; our focus lies in examining IEEE 802.11bd utilization and effectiveness within some of the main safety use cases.

Collective Perception

Collective perception has long been essential in transportation systems emphasizing the need to share and obtain environmental information. This not only fosters personal situational awareness but also extends to cooperative awareness on a broader scale. Examples range from pedestrians and cyclists to various vehicles and relevant objects. Typically, according to SAE and ETSI, entities share or sense periodic data like position, speed, heading, sensor-derived information such as light detection and ranging (LiDAR), cameras, and proximity sensors [6]. Take the example of a blind spot, a potential risk that many drivers may overlook. Yet, information exchange among surrounding vehicles can proactively prevent undesirable situations. Collision warnings, a forefront area in ITS, involve exchanging location, dynamics, velocity, acceleration, and even the geospatial context of nearby vehicles to optimize collision avoidance.

The variety of the necessary technologies and diverse information types inherent in this use case renders the performance values of IEEE 802.11p incapable of supporting the required low latency and capacity. IEEE 802.11bd could facilitate such communication through repetitive transmissions and broadcasting, addressing coexistence and backward compatibility with non-NGV stations. New MAC capabilities such as channel busy percentage and station measurements aid in making more informed choices regarding format parameters for transmitted data, thereby avoiding interference with other vehicles. Advanced techniques like frame aggregation and block-ack mechanisms streamline data exchange, enhancing the efficacy of collective perception and collision warning scenarios. SU-MIMO technology could also support the desired high data rates between stations in close proximity.

Cooperative Maneuvering

Cooperative maneuvering stands out as a quintessential use case in contemporary ITS. NGV stations can seamlessly exchange trajectory information and dynamics of their lead vehicles, contributing to advanced cooperative adaptive cruise control (C-ACC) [14]. This enhances safety by mitigating collision risks during lane changes and traffic mergers but also allows stopped vehicle detection, cut-in vehicle detection, shorter headway distances, etc. The feasibility of traffic flow scenarios and platooning is markedly improved, reducing traffic collisions and potential accidents.

A major weakness of IEEE 802.11p in these scenarios lies in its inability to effectively support densely populated cases in terms of latency and interference issues. On the contrary, IEEE 802.11bd with NGV ranging, enhanced spectrum mask, new MCSs, MIMO, and fallback enabling, could play a central role in facilitating these coordinated scenarios. These result in improved data flow, and reduced packet loss, and allow a more stable communication environment conducive to safe and efficient maneuvering in ITS contexts.

Hazard Warning and Event-Driven Messages

Supporting critical hazard warnings and event-driven messages is indispensable in a cutting-edge ITS. Scenarios in this context involve notification of perilous road conditions, stationary vehicles, pedestrians, etc., that require prompt driver reactions, such as sudden braking. Furthermore, these scenarios extend to emergency vehicles, ensuring a safer and uninterrupted route in challenging scenes. Event-driven actions are intelligibly communicated, encompassing parameters for electronic emergency brake light (EEBL), control loss, sudden changes in the steering wheel, or anti-lock braking System (ABS), as defined from SAE [13, 14].

These scenarios are characterized by stringent QoS parameters and communication requirements. NGV stations can effectively support them by canceling transmissions from vehicles not involved in the scene and enabling resource allocation release via the EDCA mechanism. Advanced error correction coding, broadcast transmissions, and beamforming reiterated as needed, further optimize communication efficiency in these event-driven contexts. None of these features are supported by IEEE 802.11p deteriorating communication reliability.

Cooperative Automated Driving

The overarching objective of the abovementioned cases is to pave the way for an integrated ITS. Advanced V2X services, particularly in the cooperative automated driving (CAD) realm, amalgamate diverse technologies combining all the previous use cases. Central concepts are automation, coordination, maneuvering, radio environment awareness, and spatial/location awareness. In this integrated framework, planned trajectories, sensor information, routes, and the status of vehicles harmoniously converge and are collectively evaluated [6, 14, 15]. IEEE 802.11bd aligns with this trajectory by introducing a range of features to enhance radio environment comprehension introducing novel PHY and MAC mechanisms in comparison to its predecessor, IEEE 802.11p.

Vehicles, leveraging timely channel measurements, busy channel percentages, and the number of nearby stations, whether NGVs or not, can decide how to utilize the medium effectively and determine the suitable PPDU format. On top of this, SU-MIMO enables higher throughput and reliability. The EDCA mechanism empowers further efficient communication with tailored transmission opportunities and access categories, canceling transmissions when necessary. The expiry time feature ensures the rejection of obsolete information, allowing stations to stay synchronized with the rapidly changing V2X parameters (Fig. 4).

Conclusion

Being a pivotal branch within ITS, the V2X domain has been recognized by IEEE since the origin of IEEE 802.11p standard. IEEE 802.11p encountered substantial challenges adapting to new V2X use cases and communication needs. The PHY and MAC modifications introduced by IEEE 802.11bd appear promising in addressing these limitations, providing robust communications for enhanced and safe transportation. It is essential to note that IEEE 802.11bd has not yet been fully assessed, particularly regarding simulation assessments and field trials. Nevertheless, the path toward next-generation vehicle communications has been widely opened for further exploration.

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Acknowledgements

This work was partly sponsored by Horizon 2020 Marie Skłodowska-Curie Actions under the project SwiftV2X (grant agreement ID 101008085).

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