Next Generation V2X – IEEE 802.11bd as fully backward compatible evolution of IEEE 802.11p

CAR 2 CAR Communication Consortium

About the C2C-CC

Enhancing road safety and traffic efficiency by means of Cooperative Intelligent Transport Systems and Services (C-ITS) is the dedicated goal of the CAR 2 CAR Communication Consortium. The industrial driven, non-commercial association was founded in 2002 by vehicle manufacturers affiliated with the idea of cooperative road traffic based on Vehicle-to-Vehicle Communications (V2V) and supported by Vehicle-to-Infrastructure Communications (V2I). The Consortium members represent worldwide major vehicle manufactures, equipment suppliers and research organisations.

Over the years, the CAR 2 CAR Communication Consortium has evolved to be one of the key players in preparing the initial deployment of C-ITS in Europe and the subsequent innovation phases. CAR 2 CAR members focus on wireless V2V communication applications based on ITS-G5 and concentrate all efforts on creating standards to ensure the interoperability of cooperative systems, spanning all vehicle classes across borders and brands. As a key contributor, the CAR 2 CAR Communication Consortium and its members work in close cooperation with the European and international standardisation organisations.

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Document information

Number:	2098	**Version:**	1.0	**Date:**	2023-02-02
Title:	Next Generation V2X – IEEE 802.11bd as fully backward compatible evolution of IEEE 802.11p			**Document Type:**	White Paper
Release:	n.a.				
Release Status:	Public				
Status:	Final				

Changes since last version

Date	Changes	Edited by	Approved
2023-02-02	Initial release	Release Management	Steering Committee

Table 1: Changes since last version

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Definitions

Existing	actively in use
Communication Cluster	A set of ITS stations in a geographic area which is relevant for the safety related communication
Similar	Something that behaves, acts and/or looks almost the same
Interoperability	IEEE 802.11p devices to be able to decode at least one mode transmission of NGV device, and NGV devices to be able to decode IEEE 802.11p transmissions
Co-existence	IEEE 802.11p devices to be able to detect NGV transmissions (and hence defer from transmissions during NGV transmissions causing collisions) and vice versa
Backward compatibility	Ability of NGV devices to operate in a mode in which they can interoperate with IEEE 802.11p devices
Fairness	Ability of all devices (both IEEE 802.11p and NGV) to have the same opportunities to access the channel
Multi-Channel operation	Process of controlling the use of several channels, technologies and frequency bands based on actual channel state information and application requirements
Ranging	Operation to determine a distance between objects by means of time measurements, e.g. to support positioning operations

Abbreviations

11p	IEEE 802.11p
11bd	IEEE 802.11bd
3GPP	3rd Generation Partnership Project (https://www.3gpp.org)
4G	fourth Generation of broadband cellular network technology
5G	fifth Generation of broadband cellular network technology
ACL	Adjacent Channel Leakage
ACLR	Adjacent Channel Leakage Ratio
ACR	Adjacent Channel Rejection
ACS	Adjacent Channel Selectivity
AWGN	Additive White Gaussian Noise
BCC	Binary Convolutional Coding
BPSK	Binary Phase-Shift Keying modulation
BSS	Basic Service Set
CAM	Cooperative Awareness Message
CBR	Channel Busy Ratio
C-ITS	Cooperative Intelligent Transport Systems
CPS	Collective Perception Service
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DCM	Dual Carrier Modulation
e.i.r.p.	Equivalent Isotropic Radiated Power
ETSI	European Telecommunications Standards Institute
FEC	Forward Error Correction
FTM	Fine Timing Measurement
GNSS	Global Navigation Satellite Systems
I2R	Ista-to-Rsta
IEEE	Institute of Electrical and Electronic Engineering
ISTA	Initiating STAtion
ITS	Intelligent Transport Systems
ITS-S	Intelligent Transport Systems Station
LDPC	Low Density Parity Check
LLR	Log-Likelihood Ratio
LMR	Location Measurement Report
LTE	Long Term Evolution (standard for wireless broadband communication)
LTF	Long Training Field
MAC	Medium Access Control
MCO	Multi-Channel Operation
MCS	Maneuver Cooperation Service
MIMO	Multiple-Input Multiple-Output
NAV	Network allocation vector
NDP	Null Data PPDU
NDPA	Null Data PPDU Announcement
NGP	Next Generation Positioning
NGV	Next Generation V2X
NLOS	Non-Line-Of Sight
Non-TB	Non-Trigger Based
OCB	Outside the Context of a BSS
PSTA	Passive (observing) STAtion
PASN	Pre-Association Security Negotiation

POTI	POsition and TIme
PPDU	Physical Protocol Data Unit
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
R2I	Rsta-to-Ista
RSTA	Responding STAtion
RTT	Round Trip Time
SIFS	Short InterFrame Spacing
SNR	Signal to Noise Ratio
STA	STAtion
TDOA	Time Difference of Arrival
TOA	Time Of Arrival
TOD	Time Of Departure
TOF	Time Of Flight
TXOP	Transmit (TX) OPportunity
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything

1 Executive summary

This White Paper describes the enhanced technical access layer features of the new IEEE 802.11bd amendment to the IEEE 802.11-2020 standard, also known as Next Generation V2X (NGV). IEEE 802.11bd is the evolutionary enhancement of the existing IEEE 802.11p amendment, which became part of the IEEE 802.11-2020 standard and is the access layer basis for the ITS-G5 set of ETSI standards. In this paper the focus will be the full access layer backward compatibility and co-channel interoperability capability of the new IEEE 802.11bd specification including the integration of the new capabilities into the set of ETSI ITS-G5 standards.

2 Introduction

This White Paper presents the key improvements of Next Generation V2X (NGV), which is standardized in the amendment IEEE 802.11bd of the Wireless LAN standard. It focuses on the physical layer enhancements, as well as on the seamless transition that it allows from IEEE 802.11p based systems like ETSI ITS-G5, thereby leveraging all the already-existing deployments and roll-outs.

Technical advances include an extended more efficient physical layer that is able to transmit IEEE 802.11p based waveforms and new “NGV” frames, improving the quality of the communication and the transmission range. For robust low data-rate applications, new forward-error-correction codes combined with midambles yields 2-3 dB of improvement, while advanced features such as multiple-input multiple-output (MIMO) or high-order modulation enable high-data-rate applications.

IEEE 802.11bd allows a smooth and gradual transition from IEEE 802.11p based systems thanks to the evolutionary nature, with coexistence and backward compatibility being key requirements for this new standard. It allows existing IEEE 802.11p and new IEEE 802.11bd (NGV) stations to interoperate. This makes it possible to benefit from innovations and at the same make full use of an installed base of existing systems.
The analysis in this whitepaper shows that

- Existing deployments in vehicles will continue operation when NGV is deployed
- Investments in ITS-G5 and DSRC road infrastructure are safeguarded
- Advanced use cases are supported without hindering or abandoning existing deployments.
- NGV will not increase the demand for more spectrum.

In addition to a comprehensive technical overview, the following topics are discussed in this white paper:

- **Coexistence:** When NGV stations communicate in NGV mode, co-channel coexistence with IEEE 802.11p devices is ensured. This is due to the use of the 10 MHz IEEE 802.11p preamble so that existing and NGV stations can detect others transmissions and defer the access to the channel in case. Even the 20 MHz NGV mode uses the 10 MHz preambles;

- **Fair coexistence:** NGV stations support fairness in channel access when sharing a channel with existing IEEE 802.11p devices. This is due to the use of “Listen Before Talk” (LBT) based on the well-known CSMA/CA medium access protocol with the same minimum sensitivities as specified in IEEE 802.11p. Even the 20 MHz NGV mode uses the same minimum sensitivity for clear channel assessment in each underlying 10 MHz sub-channel;

- **Backward compatibility:** Backwards compatibility ensures that existing deployments will not be disrupted, and that radio spectrum is used efficiently. It is realized by the following two requirements:

    - Each NGV station must be capable of transmitting with the IEEE 802.11p based 10 MHz physical layer protocol data unit (PPDU) format so that ITS-G5 devices can receive those transmissions. Each NGV station must also be capable of receiving transmissions from existing ITS-G5 stations.

    - Each NGV station will set an NGV capability indicator when it sends IEEE 802.11p based PPDUs so that neighbouring NGV stations can detect that it is an NGV station. That information can then be used by the NGV neighbours to intelligently control their transmissions so that they either use IEEE 802.11p based format or a NGV format depending on the intended recipient(s). The radio environment status report provides information to upper layers about the total number of neighbours and the subset of neighbours that are NGV stations. This information can be used for different interoperability strategies.

- **Interoperability:** Full co-channel access layer interoperability achieved thanks to the capability of the IEEE 802.11bd stations to transmit and receive IEEE 802.11p PPDUs.

In this White paper, the potential impact including the possible interoperability strategies onto the ITS-G5 set of standards in ETSI will be presented. This interoperability strategy is based on the multi-channel operation concept developed in ETSI [ER-4].

3 History of 802.11-based short range communications

3.1 Introduction

In 2010, the IEEE took an important step to enable direct, short range vehicular communication, with the publication of the Wireless Access for Vehicular Environments (WAVE) amendment of the widely deployed IEEE 802.11 wireless local area network standard. The amendment, formally IEEE Std 802.11p-2010, introduced a new ad hoc type of communication called “outside the context of a Basic Service Set” (OCB) that does not need the usual coordination by an Access Point. OCB is the key to enabling extremely low latency (< 1ms) and high reliability communication for moving vehicles.

IEEE 802.11p became the basis for the ITS-G5 access layer standard, which was developed by ETSI in response to a standardization mandate of the European Commission “to support the interoperability of co-operative systems for intelligent transport in the European Community”.
IEEE 802.11p is also the basis of DSRC in the US. Extensive testing in Europe, the U.S., and other regions, has demonstrated the ability of IEEE 802.11p-based systems to support a wide range of vehicle-to-everything (V2X) use cases for road safety, improved traffic efficiency, reduced emissions, and support of automated driving. These systems have been deployed in Europe, the U.S., and Japan.

3.2 Existing deployments

ITS-G5 based systems for road safety related applications are deployed in Europe on the vehicular and infrastructure side.

By the end of 2022, in Europe already 20’000 km of roads are covered by road-side units (RSUs) based on ITS-G5 [ER-10] and almost 1 Million vehicles [ER-11] are equipped with ITS-G5 onboard units based on the ETSI ITS-G5 set of standard.

It can be assumed that these deployment figures will further increase in the next years.

3.3 IEEE 802.11bd standards development

In March 2018, an IEEE Study Group named Next Generation V2X (NGV) was formed to work on an amendment to the IEEE standard for enhanced V2X communication technologies. In December 2018, the IEEE-SA approved this project creating a Task Group with the goal of producing IEEE 802.11bd [ER-2], a seamless evolution path for IEEE-based V2X communications.
This amendment targets higher spectral efficiency, increased reliability, and extended range, while ensuring backwards compatibility with the existing deployed systems in the 5.9 GHz ITS band. The latter is an essential element for IEEE 802.11bd[ER-2] to provide a seamless evolution path from IEEE 802.11p [ER-1]. IEEE 802.11bd based devices can receive transmissions from any IEEE 802.11p device and can transmit in a way that IEEE 802.11p devices can receive and decode. With these capabilities of IEEE 802.11bd [ER-2], today’s investments in IEEE 802.11p based technologies are fully protected. IEEE 802.11p can continue to be deployed today, since future implementations with IEEE

802.11bd based devices can be seamlessly introduced, fully benefitting from existing 802.11p deployed vehicular and infrastructure ITS stations.
IEEE has a proven track record of seamless evolution through their releases of key amendments such as IEEE 802.11a/g/n/ac/ax [ER-1]. By contrast to the IEEE evolution approach, a disruptive introduction of a technology incompatible with IEEE 802.11p would undermine and discourage the investments that are needed today for the society to realize the potential of direct V2X communication and might permanently prevent interoperability among major automotive stakeholders (vehicle manufacturers and road authorities).

A cornerstone of achieving the backward compatibility and interoperability goal is that IEEE 802.11bd will use and improve OCB communication, relying on frame formats and channel access rules that are fully compatible with IEEE 802.11p.

The goal of faster and more reliable communication recognizes that IEEE has developed even more advanced capabilities in recent years, for example in the IEEE 802.11ac (60 GHz) and IEEE 802.11ax amendments. Some of these advanced capabilities are not yet available for OCB communication or in the 10 MHz channels that have been chosen to optimize vehicular communication. IEEE 802.11bd will specify these capabilities for OCB and for 10 MHz channels.
IEEE 802.11bd will introduce additional improvements, such as specific capability for ranging (distance measurements), a 20 MHz channelization option fully backward compatible to the 10 MHz IEEE 802.11p channels and an operational mode in the 60 GHz band, which is partly allocated in Europe for the use in ITS (63.72-65.88 GHz [ER-5]), based on the DMG/EDMG OCB feature.

A future ITS system based on ETSI ITS-G5 and the addition of IEEE 802.11bd features will lead to enhancements in the ITS-G5 access layer. The new features of IEEE 802.11bd as part of ITS-G5 will be controlled and provided to the ITS applications by the multi-channel operation (MCO) specified in ETSI.

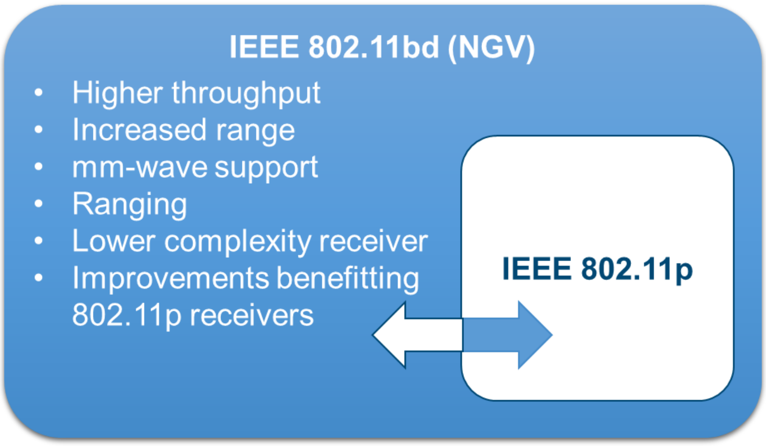

Figure 1: IEEE 802.11bd as evolution of IEEE 802.11p

3.4 Seamless evolution of IEEE 802.11p to IEEE 802.11bd

Seamless adoption and deployment will start as soon as IEEE 802.11bd is fully standardized and tested. The fundamental aspects of this gradual and smooth transition are:

- No disruption to existing systems;
- No need for dedicated spectrum resources (no fragmentation);
- Support for IEEE 802.11p and IEEE 802.11bd with a single modem.

Today's investments are fully protected.

IEEE 802.11bd allows a smooth transition from existing (IEEE 802.11p-based) systems like ETSI ITS-G5 to the newer standard that can be seen as an enhanced ETSI ITS-G5. It capitalizes on existing IEEE 802.11p deployments and infrastructure investments throughout the world by using the same frequency channel in co-channel operation without causing any disruption to existing C-ITS stations. Interoperability in IEEE 802.11bd is achieved using a compatible waveform structure as shown in Figure 2.

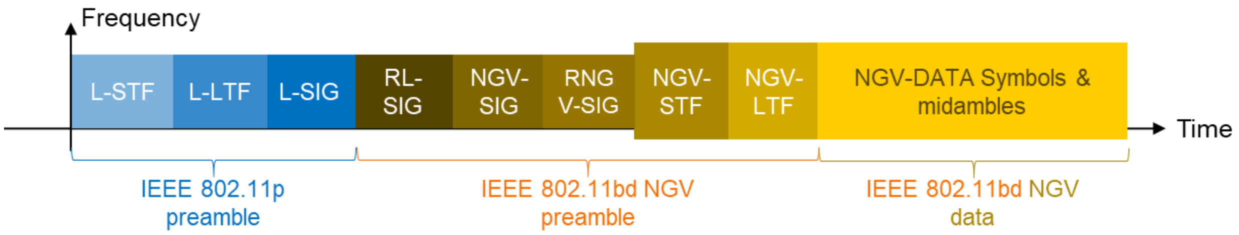

Figure 2: IEEE 802.11bd frame format with IEEE 802.11p preamble, repeated SIG and new DATA symbols

This frame format supports a common channel access mechanism across existing and enhanced systems where all messages are transmitted following the same "listen-before-talk" (LBT) principle and use the same carrier sensing mechanism. The asynchronous and non-persistent type of V2X messages fit very well to typical V2X networks, where messages (such as ITS-G5 cooperative awareness messages, CAMs) are very diverse and non-persistent in terms of message size and transmission rate, since the mechanisms triggering the message generation are tightly coupled to the dynamics of the vehicle (as change in position, speed and/or heading).

When an enhanced C-ITS station based on enhanced ETSI ITS-G5 and IEEE 802.11bd access layer detects the presence of IEEE 802.11p based stations based on ITS-G5 in its vicinity, all safety-related day one messages will be transmitted using the IEEE 802.11p based access layer, so that the existing stations can decode the content of the messages. When no IEEE 802.11p based stations are detected, transmitted messages could use the full potential of IEEE 802.11bd and its increased performance. This operation is shown in Figure 3.

In all cases the packets transmitted using the IEEE 802.11bd format will be detectable by the existing stations due to the use of the same preamble as depicted in Figure 2. An existing station can consider the enhanced packets in the CSMA/CA channel access mechanism even without the capability of decoding the content of the IEEE 802.11bd data-fields.

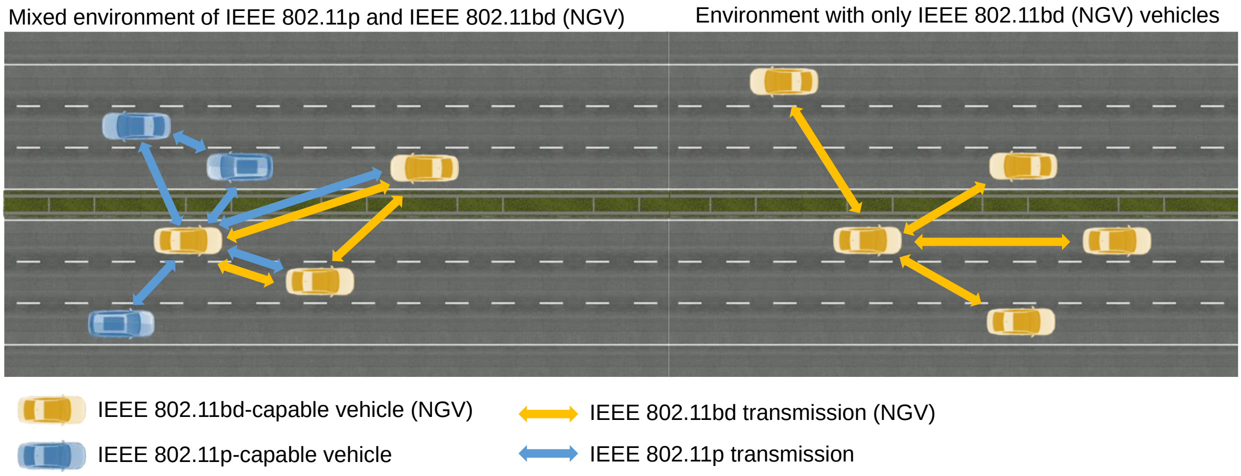

Figure 3: Interaction between existing ETSI ITS-G5 based IEEE 802.11p vehicles and enhanced ETSI ITS-G5 based on IEEE 802.11bd vehicles

In the MCO defined in ETSI [ER-4] the capabilities of an ITS-G5 access layer using IEEE 802.11bd features will be offered to the applications. The MCO facilities entity will control the usage of the corresponding access layer technology capabilities based on the request by the application, the available resources, and the technology in use by the neighbouring stations. The use of the new features can be limited to a set of applications which are specified to only use the new features in the ITS-G5 access layer or can be flexibly deployed based on the visible peer communication systems as depicted in Figure 3. The switch between the existing features and the enhanced features in a single channel can be performed on a message-by-message base by choosing the corresponding access layer instantiation (ALI).

3.5 Backwards compatibility by design

Backwards compatibility is a key requirement from the start for IEEE 802.11bd definition [ER-16]. It builds on the concepts of coexistence and interoperability which describes the ability for IEEE 802.11bd-based stations to understand the nature of the other stations in their vicinity and adapt their transmission type accordingly.

As illustrated in Figure 4 IEEE 802.11bd stations can transmit in both NGV or IEEE 802.11p format. Typically, these transitions between NGV and IEEE 802.11p formats are based on local measurements and set of rules specified by the regional regulators or standardization organizations like CEPT or ETSI.

IEEE 802.11bd defines MAC SAP interface to allow upper layer to choose between NGV and IEEE 802.11p format based on the existence or percentage of IEEE 802.11p stations in the neighbourhood.

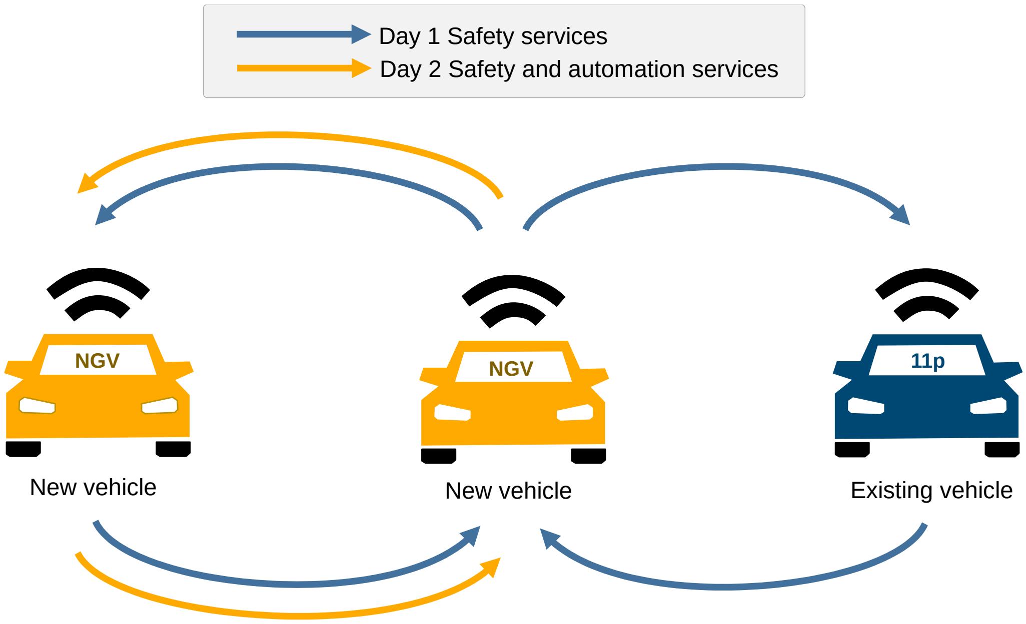

Figure 4: Backwards compatibility operation

3.6 Co-Channel coexistence by design

Coexistence between IEEE 802.11p and IEEE 802.11bd within the same frequency channel is at the heart of the IEEE 802.11 evolutionary concept and is achieved by having the newer waveforms packets starting with the same sequence as used by the existing implementations based on IEEE 802.11p. This ensures

- ✓ IEEE 802.11p devices to be able to detect IEEE 802.11bd based on IEEE 802.11p format and NGV transmissions;
- ✓ IEEE 802.11p devices can identify presence of packets, derive their duration (from L-SIG info) and defer transmission to avoid collisions.

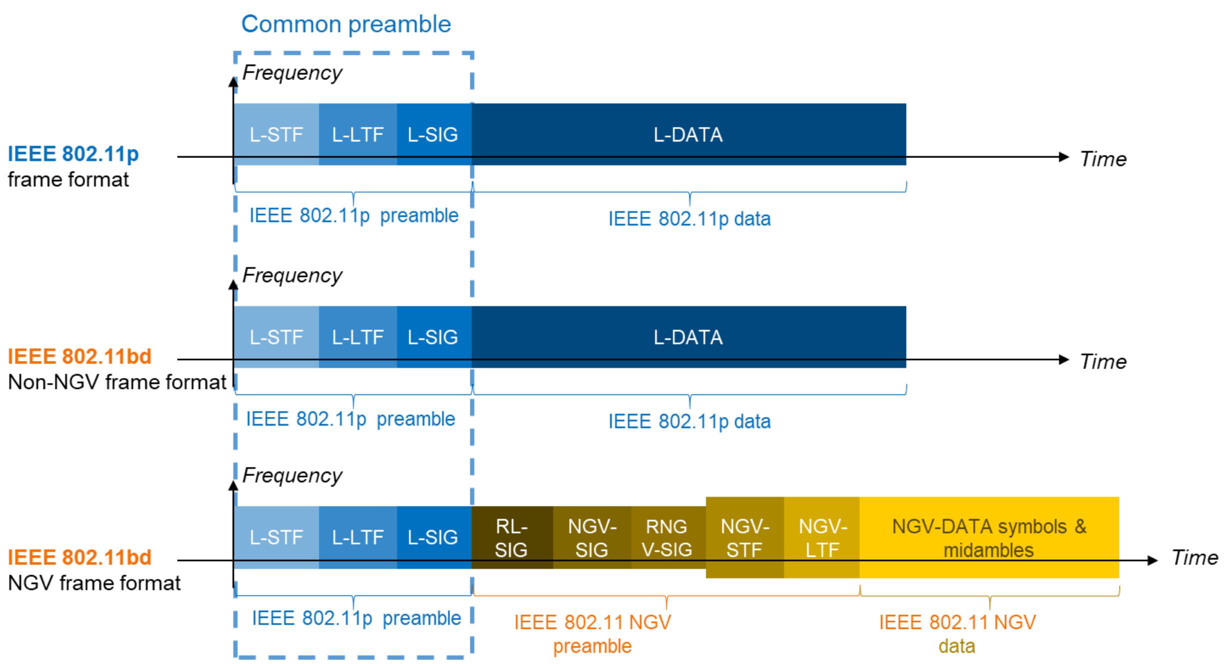

Figure 5: Coexistence by design with common preamble

IEEE 802.11bd implements the following principle for co-channel coexistence:
- Preamble insertion in conjunction with CSMA/CA
- Reservation using NAV setting in mixed 10 MHz/20 MHz operation

3.7 Fairness by design

Fairness is an important aspect of ITS communication systems. It is required that all stations should play with the same rules to get access to the channel (avoiding that NGV stations highjack the channel, rendering existing stations less efficient). This requirement is fulfilled by having the IEEE 802.11bd stations continue relying on the proven CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) procedure as defined in IEEE 802.11-2020 [ER-1]. This scheme has been deployed and validated for years and has been demonstrated to be very efficient and reliable.

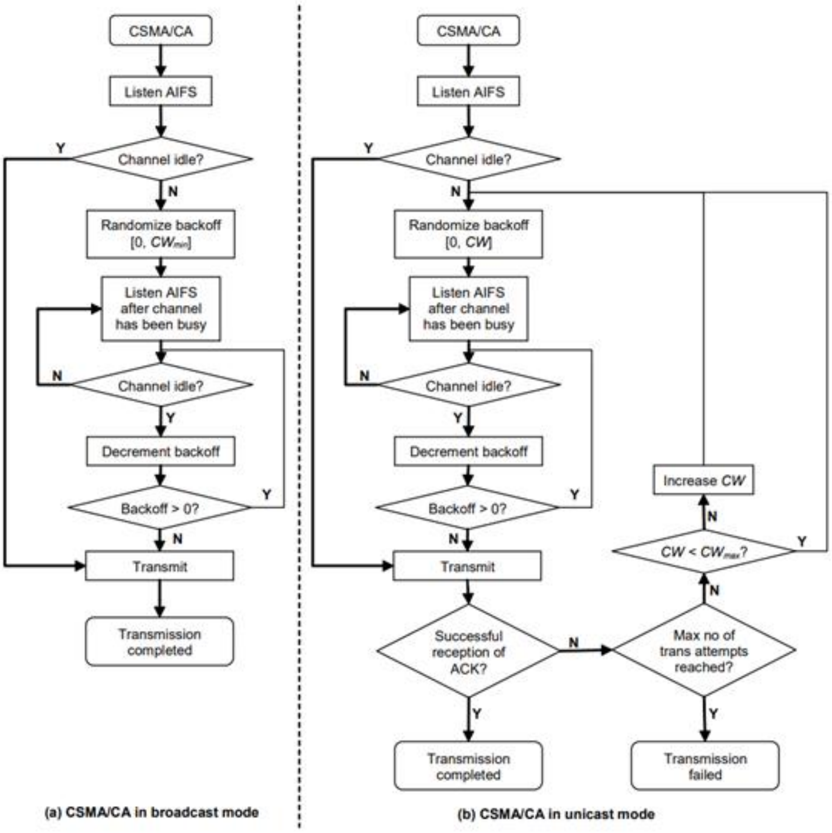

Figure 6: Fairness by design with the CSMA/CA channel access procedure

3.8 Interoperability by design

Interoperability is an important aspect of IEEE 802.11bd. Interoperability describes the fact that stations from different generations can detect each-others and exchange information. One objective of IEEE 802.11bd is to enable access layer interoperability to abstract the burden from higher layers perspective (e.g., application layer).

IEEE 802.11bd-equipped vehicles are able to:

- Decode transmissions from any IEEE 802.11p device;

- Transmit in a way that IEEE 802.11p devices can decode.

IEEE 802.11p-equipped vehicles are able to:

- Communicate with both IEEE 802.11p and IEEE 802.11bd devices using the IEEE 802.11p format;
- Decode IEEE 802.11bd relevant channel access information like packet duration from NGV packets and defer from transmission.

In addition to this access layer interoperability the higher layers of an ITS-G5 system support an interoperability up to an application level. The required integration of the enhanced features of IEEE 802.11bd capable access layer is performed by the MCO controlled in the facilities layer.

4 IEEE 802.11bd technical features

4.1 Overview

To build IEEE 802.11bd, an evolutionary approach leveraging the technical advances successfully tested and standardized in very recent IEEE 802.11n/ac/ax has been chosen. This ensures that the new features are based on solid building blocks that have been proven to be effective, and which are known and well tested already. This facilitates the development of modems and shortens the development and testing time.

Several improvements have been introduced by IEEE 802.11bd at the physical layer. Most of them pertaining to the NGV mode of transmission.
Some, however, also apply to the devices using the IEEE 802.11p format. These include more stringent requirements on selectivity, sensitivity, and out-of-band emissions for an optimized MCO, as well as the introduction of repetitions on the access layer. The enhancements are summarized in Table 2.

Table 2: Toolbox of technical advances of IEEE 802.11bd[ER-2] compared to IEEE 802.11p[ER-1]

	IEEE 802.11p	IEEE 802.11bd	Benefits of IEEE 802.11bd
Modulation	BPSK, QPSK, 16-QAM, 64-QAM	**BPSK-DCM**, BPSK, QPSK, 16-QAM, 64-QAM & **256-QAM**	Up to 44% higher throughput (27 Mb/s versus 39 Mb/s)
Error correction	BCC	BCC **& LDPC**	2-3 dB better sensitivity ⇨ Improved robustness ⇨ Range extension
Channel bandwidth	10 MHz or 20 MHz	**Interoperable** 10 MHz **and** 20 MHz	Improved interoperability
Data subcarriers	48	48 & **52**	8% higher throughput
MIMO	N/A	**2x2 MIMO**	2x higher throughput for unicast transmission Improved robustness and range
Frequency bands	5.9 GHz	5.9 GHz & **60 GHz**	New applications
Adaptive Repetitions	N/A	**1-3 repetitions, depending on CBR**	⇨ Improved robustness ⇨ Range extension
Localization	N/A	**Supported**	New applications
DCM mode	N/A	**Supported**	3 dB better sensitivity ⇨ Improved robustness ⇨ Range extension
Channel tracking	Proprietary	Proprietary & **Midamble-based**	Lower complexity receiver
Total Benefit:			
Range extension		**DCM and LDPC, repetitions**	**up to 3 times longer range**

Throughput		256 QAM and MIMO	up to 3 times higher throughput

The new IEEE 802.11bd specific access layer can increase the throughput by up to a factor of 3 or the range by up to a factor of 3 with a lower channel tracking complexity as compared to IEEE 802.11p.

4.2 Modulation

The NGV mode of IEEE 802.11bd physical layer provides additional modulation and coding scheme options compared to IEEE 802.11p.

On the low-data rate side, the “BPSK-DCM 1/2” modulation and coding scheme is intended for use cases and applications requiring very low sensitivity. On the high-data rate side, 256-QAM modulation has been added and is available with coding rates of ¾ or 5/6. The latter allows up to 39 Mbit/s in a single 10 MHz channel for very short communication links, which is a potential enhancement of up to 44% compared to the 64-QAM as defined in IEEE 802.11p.

The new IEEE 802.11bd specific access layer can support higher order modulation up to 256-QAM with coding rates down to R = 5/6 which leads to a data rate increase of 44% as compared to IEEE 802.11p.

4.3 Signal structure

The NGV mode of IEEE 802.11bd physical layer is based on the same subcarrier spacing as IEEE 802.11p (156.25 kHz) but defines 56 subcarriers compared to 52 (48 for the data and 4 for channel tracking) in IEEE 802.11p. In other words, IEEE 802.11bd uses a larger fraction of the channel (e.g., 8.75 MHz out of a 10 MHz channel, compared to the 8.125 MHz used by IEEE 802.11p).

These 4 additional subcarriers can be seen as an immediate throughput and spectrum efficiency gain of 8% without changing the MCS.

The new IEEE 802.11bd specific access layer signal structure increases the throughput and the spectrum efficiency by 8% without changing the MCS as compared to IEEE 802.11p.

4.4 Channel coding

One of the most important improvements in the physical layer of the NGV mode is the use of Low-Density Parity Check (LDPC) forward error-correction coding (FEC). LDPC has been introduced in IEEE 802.11n and offers increased spectral efficiency compared to the Binary Convolutional Code (BCC) scheme used in IEEE 802.11p. As such, LDPC has also been adopted in a wide range of wireless standards, including 3GPP 5G due to its favourable performance compared to the (power-greedy) Turbo codes employed by 3GPP 4G-based systems (e.g., LTE-V2X).

For the IEEE 802.11bd NGV mode three different codeword block lengths are defined for each available coding rate, i.e., 648, 1296, and 1944. LDPC has been demonstrated to be 2-3 dB more robust than convolutional codes, as illustrated by Figure 7.

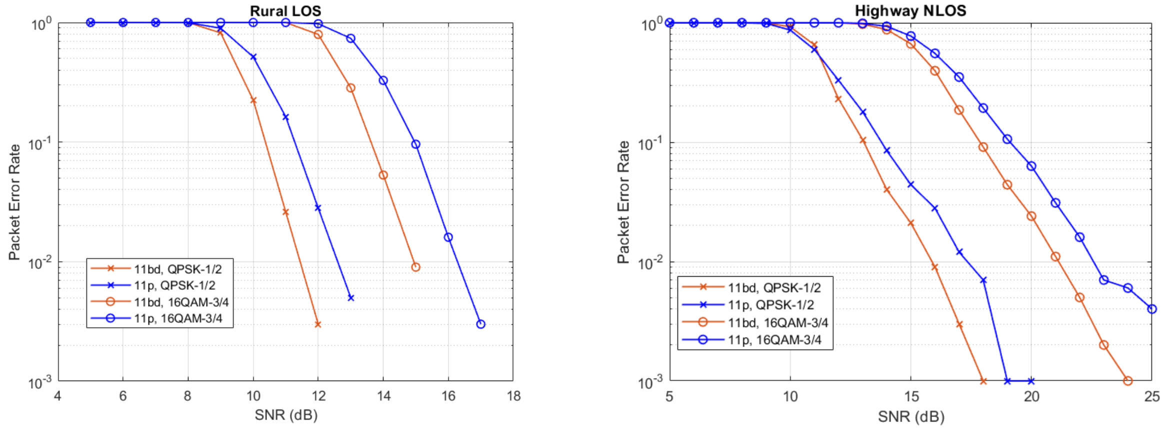

Figure 7: Channel coding enhancements of IEEE 802.11bd

> **Statement:**
> **The new IEEE 802.11bd specific access layer channel coding based on LDPC codes can provide up to 3dB SNR gain as compared to the CC used in IEEE 802.11p.**

4.5 Channel estimation and tracking

The main difference between a state-of-the-art IEEE 802.11p and a common Wi-Fi (IEEE 802.11a) receiver is the ability of the former to operate under high mobility conditions with relative speeds of 500 km/h or higher [ER-12]. This is possible using enhanced channel tracking mechanisms and involves advanced signal processing algorithms for estimating the rapidly changing wireless channel conditions in mobile environments.

In IEEE 802.11bd a new scheme is introduced for the NGV mode, which embeds known reference symbols (midambles) in-between the data symbols. The midamble symbols allow updating the estimate of the wireless channel conditions in mobile environments also during packet transmissions, simplifying the receiver design at a cost of lower efficiency. The difference between a preamble- and a midamble-based channel estimation is depicted in Figure 8.

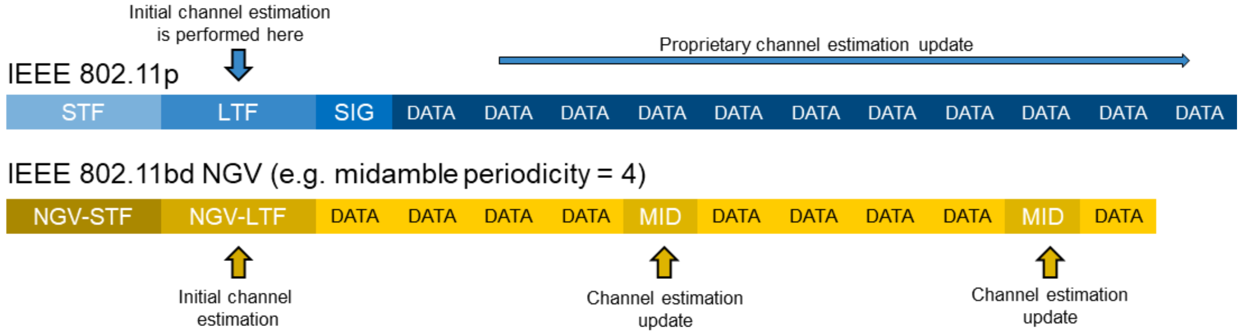

Figure 8: Preamble-based vs midamble-based channel estimation

The midamble uses the same format as the NGV-LTF and three different periodicities are possible: one midamble every 4, 8 or 16 symbols. The overall midamble parameterization is indicated in the NGV-SIG. The NGV-LTF is an enhanced version of the LTF used in IEEE 802.11p and may include 1 or 2 symbols depending on the number of MIMO spatial streams.

The new IEEE 802.11bd specific access layer supporting midamble channel estimation reduces the complexity of the channel tracking as compared to IEEE 802.11p based systems using iterative approaches.

4.6 Adaptive repetitions

Repetition of messages improves both IEEE 802.11p & NGV transmission formats of IEEE 802.11bd and provides performance gain for IEEE 802.11bd as well as for IEEE 802.11p stations.

✓ **Existing IEEE 802.11p stations see each repetition as a standalone message:**
  - Performance improvement (0.5 to 2 dB) due to time-diversity;
  - Duplicated messages naturally filtered by application (performed by higher protocol layers);
  - No software update needed.

✓ **Initial PPDU and repetitions can be combined by IEEE 802.11bd stations, either when sent in IEEE 802.11p format or new NGV format:**
  - Combining at LLR (log-likelihood ratio) level using weighted soft-values of the received symbols is the recommended technique, but others are possible.

Performance improvement has been validated in numerical simulations as well as with real hardware. Simulation results indicate:

- With 1 repetition: 0.5-0.8 dB improvement for IEEE 802.11p stations and 3-4 dB improvement for IEEE 802.11bd stations;
- With 3 repetitions: 1.0-1.7 dB improvement for IEEE 802.11p stations and 6-8 dB improvement for IEEE 802.11bd stations.

Table 2: Performance improvements results based on adaptive repetition

		Improvement for IEEE 802.11p stations	**Improvement for NGV stations**
AWGN	1 repetition	0.5 dB	3.0 dB
	2 repetitions	0.7 dB	4.7 dB
	3 repetitions	0.8 dB	6.0 dB
G5-Highway NLOS 886 Hz Doppler	1 repetition	0.8 dB	4.3 dB
	2 repetitions	1.4 dB	6.7 dB
	3 repetitions	1.7 dB	8.1 dB

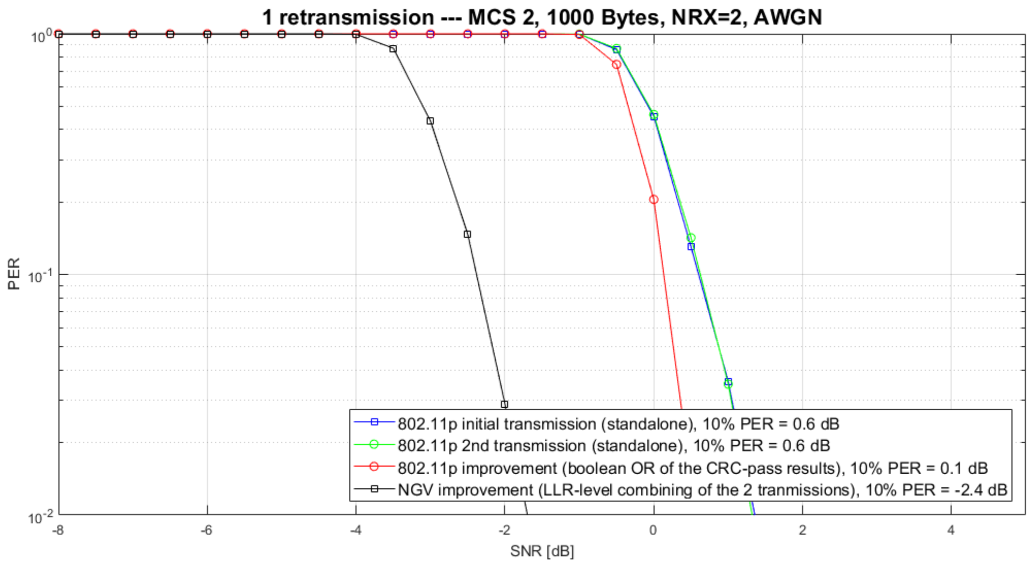

Figure 9: Adaptive repetitions: exemplary PER performance gain under AWGN with 1 repetition

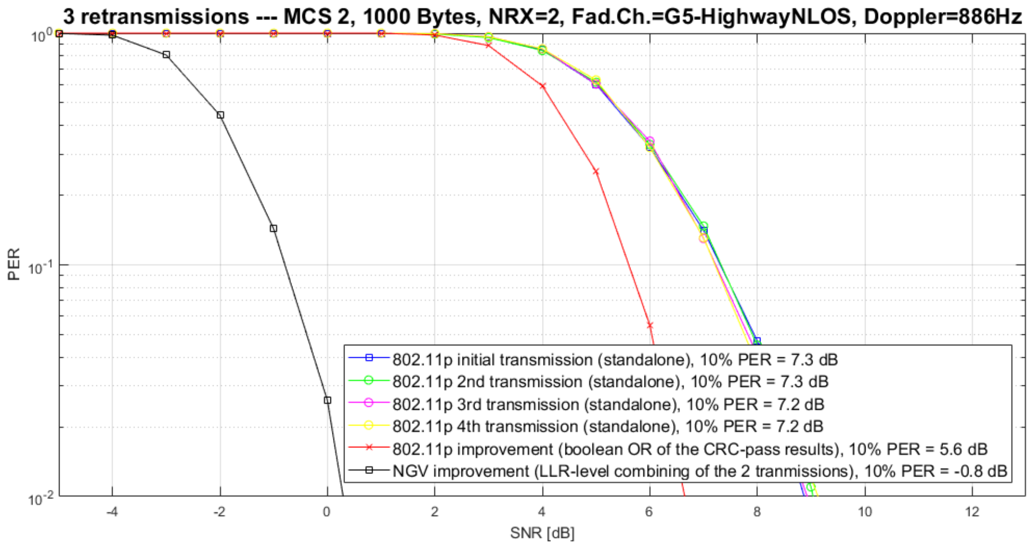

Figure 10: Adaptive repetitions: exemplary PER performance gain under HighwayNonLOS with 3 repetitions

Performance has been demonstrated on real hardware [ER-7].

The number of repetitions can be gradually increased as the occupancy of the channel goes down. In congested environment (high CBR), retransmissions are disabled. Exemplary schemes (defined at upper layers, such as in 1609 or ETSI ITS-G5 standards) for controlling the number of repetitions are hard or soft steps [ER-13] as depicted in Figure 11.

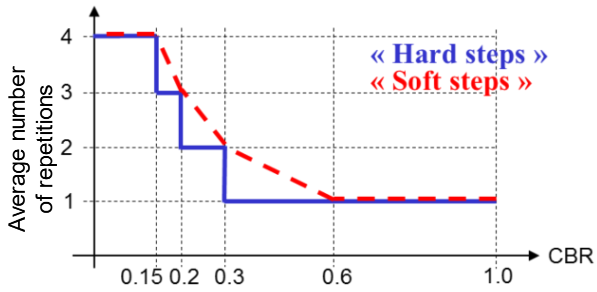

Figure 11: Adaptive repetitions: control schemes

In ETSI ITS-G5 the control of the number of repetitions can be performed by the MCO entity of the facilities layer.

The new IEEE 802.11bd specific access layer repetition scheme adds an additional flexible feature to increase the robustness and range of future ITS-G5 systems when required by the application.

4.7 MIMO

Support for MIMO technology is also specified in IEEE 802.11bd offering a potential gain in unicast transmissions of 2 times higher throughput. This operational mode is not intended for the broadcast operation.

For specific peer-to-peer operations the new IEEE 802.11bd specific access MIMO feature can increase the throughput by a factor of 2 as compared to non-MIMO systems.

4.8 Range extension and robustness

In addition to improvements in throughput, the potential need by some applications for supporting higher robustness and thus longer transmission ranges is also being addressed in IEEE 802.11bd. One of the methods chosen to achieve this goal is through the use of Dual SubCarrier Modulation (DCM) technology where each data symbol is transmitted in two subcarriers, therefore increasing the diversity gain which translates to up to 40% longer transmission range at the cost of a reduced capacity.

Another method to increase robustness and operation range on IEEE 802.11bd is by adaptive retransmissions which can improve performance for both existing and next-generation receivers as explained in clause 4.6.

Combining the available features can lead to a range improvement of more than a factor of 2, up to a factor of 3 in case of a non-congested channel where sufficient resources are available to deploy DCM and repetition.

The new IEEE 802.11bd specific access layer capabilities will increase the possible robust communication range by more than 100% as compared to IEEE 802.11p.

4.9 Fully backward compatible 20 MHz channel arrangement

The IEEE 802.11bd 20 MHz operation utilizes two adjacent 10 MHz channels to achieve higher throughput. These two adjacent 10 MHz channels can simultaneously be utilized as a 20 MHz channel, or as independent 10 MHz channels, thus maintaining backward compatibility with 10 MHz operation. This technique is sometimes referred to as 'channel bonding'.

A 20 MHz-operating device needs to check the BUSY/IDLE status on both 10 MHz subchannels with equal CCA detection sensitivity and transmit a 20 MHz PPDU if both 10 MHz subchannels are IDLE. A 20 MHz-operating device may also choose to fallback to 10 MHz transmission if only the primary 10 MHz subchannel is available. With doubled throughput, 20 MHz transmission can lead to lower duty cycle on the air or larger possible packet sizes respecting the duty cycle limit. The 20 MHz NGV PPDU contains duplicated preamble in each 10 MHz subchannel such that 10 MHz operating devices can detect the preamble for better coexistence, as depicted in Figure 12.

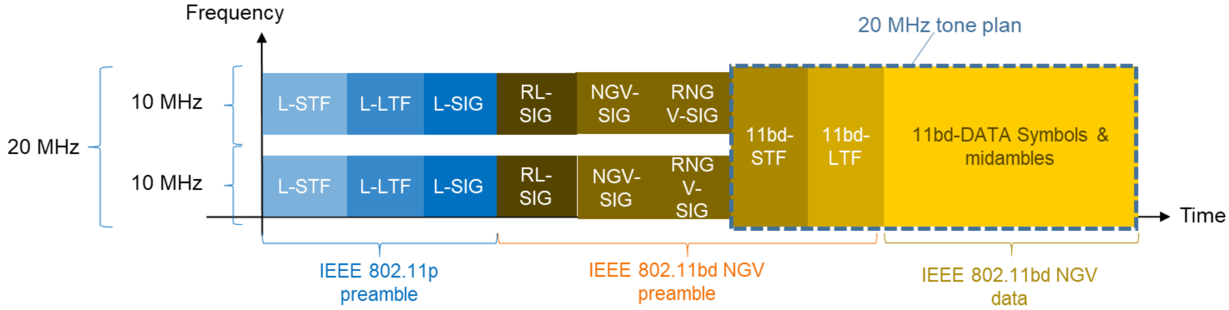

Figure 12: 20 MHz channel arrangement based on two 10 MHz channels

The new IEEE 802.11bd specific access layer capabilities will have a fully backward compatible mode where two independent 10 MHz channels are aggregated to allow a higher data rate when required by the application. This mode is fully interoperable with the 10 MHz operation.

4.10 MAC layer capabilities

IEEE 802.11bd also introduces changes at medium access control (MAC) level like the indication of next-generation capabilities (in the duration/ID field of the MAC header) and unicast communication in Outside the Context of a BSS (OCB) mode:

- Mandatory support for extended MAC service interface to provide higher layers with the ability to control NGV transmissions and receive status regarding NGV receptions and the radio environment, fully backwards compatible with 10 MHz IEEE 802.11p;
- Mandatory support for fully backward compatible 20 MHz channel access with 10 MHz primary and 10 MHz secondary channel;
- Mandatory support for NGV capability indication for non-NGV PPDUs encoded in the Duration/ID field of the MAC header;
- Mandatory support for reception of frame aggregation when communicating OCB;
- Optional support for transmission of frame aggregation when communicating OCB.

The new IEEE 802.11bd specific MAC layer extension facilitates the identification of NGV frames and unicast operation in OCB mode.

4.11 Enhanced ranging for positioning support

Today we heavily rely on global navigation satellite systems (GNSS) in road transport. Due to the large distance between transmitting satellites and GNSS receiver (approximately 20 000 km), the GNSS signals are very weak and easily disturbed by interference. Moreover, GNSS signals suffer from multipath propagation in cities due to high-rise buildings. Finally, in parking garages, underground, or in tunnels the GNSS signals cannot be received. Thus, land-based alternative position, navigation, and timing services are important to augment GNSS for safety-of-live applications. With this aim, the IEEE 802.11bd also includes the definition of procedures for at least one form of positioning in conjunction with V2X communications.

Thus, IEEE 802.11bd specified NGV ranging, which is a subset of the Fine Timing Measurement (FTM) procedures in IEEE 802.11az Enhanced Positioning. NGV ranging provides at least one of the following functions:

- Non-trigger based (non-TB) ranging, i.e., FTM procedure negotiation and termination for Non-TB ranging and Non-TB ranging exchange in the 5.9 GHz frequency band with 10 MHz or 20 MHz NGV PPDUs;
- Differential distance computation relative to two NGV STAs based on non-TB ranging in the 5.9 GHz frequency band;
- FTM measurement procedures outside the 5.9 GHz frequency band through a station co-located with an NGV station.

The benefit of NGV non-TB ranging is that an NGV equipped vehicle can determine its distance relative to another NGV equipped vehicle within 1 millisecond and its position within 3 milliseconds relative to 3 NGV RSUs. Clearly, this fast non-TB ranging exchange is crucial for the vehicular environment. For example, a car driving at 100 km/h just moves 18 cm during the position determination with three RSUs.

Another benefit of the fast, non-TB ranging exchange is that the 3 milliseconds to position a vehicle relative to three RSUs would still allow the vehicle to send one CAM message with 350 bytes length during the $T_{O\mathrm{N}}$ period in conformance to [ER-3].

Furthermore, NGV stations can use differential distance computation using the non-TB ranging frame exchange between two NGV STAs, e.g., RSUs. With this method the observing or passive station (PSTA), records the TOA t_{p1}, when it receives the NDP 1 from the ISTA, and TOA t_{p2}, when it receives the NDP 2 from the RSTA.

The differential distance between ISTA, RSTA, and PSTA can then be computed as

$$d_{IR} = c(T_{IP} - T_{RP}),$$

where $T_{IP} = t_{p1} - t_1$ denotes the time of flight (TOF) between ISTA and PSTA and $T_{RP} = t_{p2} - t_3$ denotes the TOF between RSTA and PSTA. In order to calculate the TOFs T_{IP} and T_{RP}, the PSTA needs to receive the TODs t_1 and t_3 contained in the R2I and I2R LMRs. Alternative the differential distance can be computed by

$$\begin{aligned} d_{IR} &= c\left(t_{p1} - t_1 - \left(t_{p2} - t_3\right)\right) \\ &= c\left(t_{p1} - t_{p2} - (t_1 - t_3)\right) \\ &= c\left(t_{p1} - t_{p2} - \left(t_1 - (t_4 - T_{IR})\right)\right) \\ &= c\left(t_{p1} - t_{p2} - T_{IR} - (t_1 - t_4)\right) = c\left(t_{p1} - t_{p2} - (t_1 - t_4)\right) - d, \end{aligned}$$

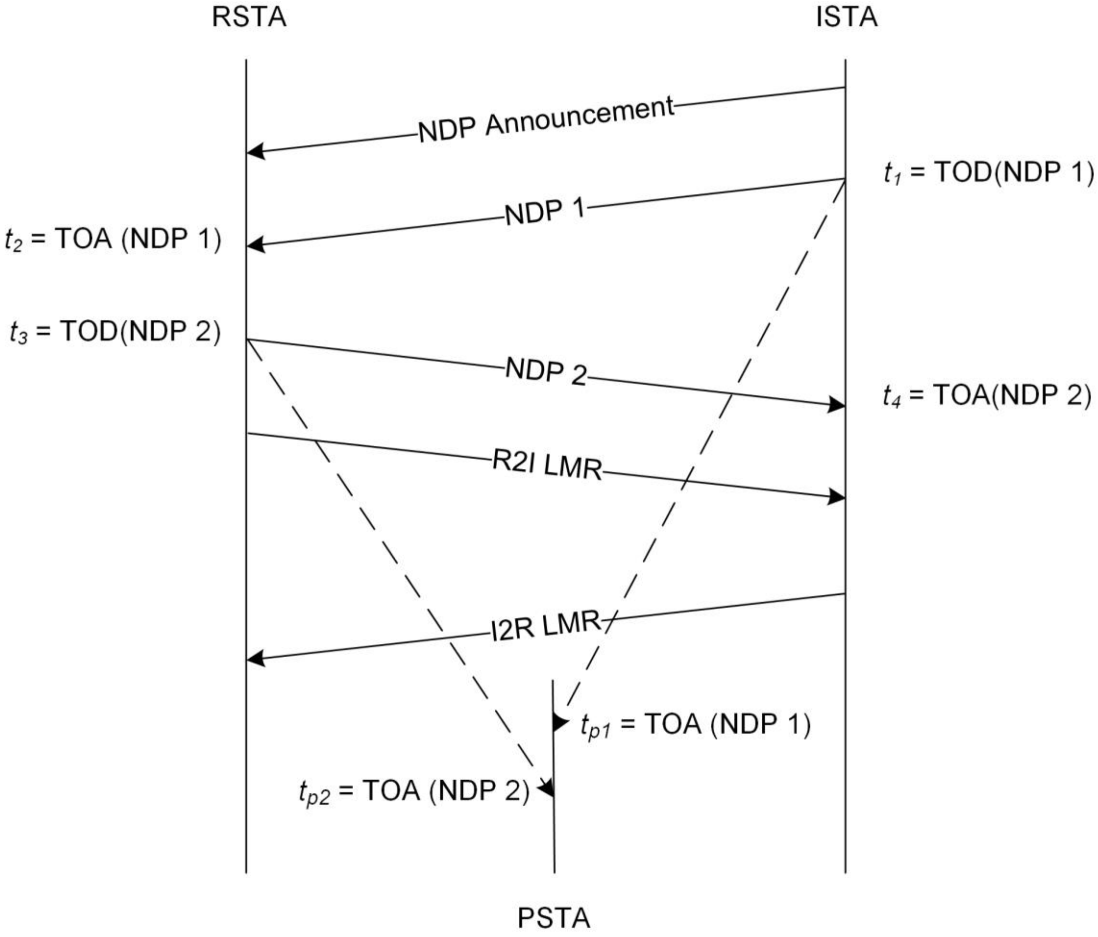

Figure 13: Differential distance computation based on non-TB measurement exchange: Observed parameters by a PSTA

where we used $d = cT_{IR} = c\frac{(t_4 - t_1) - (t_3 - t_2)}{2}$. Comparing lines 2 and 4 in the above equation, the main difference is that in line 2 the TODs t_1 and t_3 are in different clock bases compared to line 4 where the time differences $t_{p1} - t_{p2}$ and $t_1 - t_4$ are all in the same clock base. Thus line 4 can remove any constant clock biases between ISTA and RSTA compared to line 2. Further, the last line of the above equation also shows a differential distance relative to the base line distance d between ISTA and RSTA. Hence, this method has the name differential distance computation.

When comparing non-TB ranging and differential distance computation using non-TB ranging, we can make the following observations:

For each non-TB ranging exchange, we need to transmit at least 4 frames and 5 frames if the RSTA would like to compute the distance to the ISTA. If we have 3 RSUs and N an arbitrary number of vehicles can position themselves relative to three RSUs in 3 milliseconds reducing the communications overhead tremendously.

Finally, an NGV station can use FTM procedures outside the 5.9 GHz frequency band if co-located with a station that supports FTM functionalities based on 802.11 and its amendment IEEE 802.11az Enhanced Positioning. The benefit in this scenario is that the IEEE 802.11 stations will use separate unlicensed frequency bands, e.g. at 5 GHz or 6 GHz allowing for bandwidth of 80 MHz, 160 MHz, or 320 MHz. The large bandwidths compared to the 10 or 20 MHz bandwidths in the 5.9 GHz ITS frequency band will provide a significant accuracy gain for the FTM ranging procedures, e.g. by a factor of 4 to 32. At the same time, the FTM ranging exchange does not require any further spectrum resources in the 5.9 GHz ITS frequency band after initiating the FTM ranging exchange via the NGV station. Moreover, the specific FTM ranging implementation may supports security features such as pre-association security negotiation (PASN) or others that ensure that the measurement exchange is executed with the intended peer. The most likely use cases for an NGV station co-located with a station supporting an FTM procedure are localizing equipped vehicle underground or in parking garages, e.g. for automated valet parking, or transitions from indoor to outdoor.

The capability discovery and negotiation procedures for NGV ranging could be implemented through the position and time (POTI) services and the MCO capabilities.

The new IEEE 802.11bd positioning features will open up a broad range of possible application for future ITS-G5 implementations.

4.12 Summary

In this section the main technical features and capabilities of IEEE 802.11bd have been presented. These enhanced features can significantly extend the capabilities of an ITS-G5 stations and applications in a fully co-channel backwards compatible and interoperable manner. The control of the new features and capabilities will be done by the MCO operation in an ITS-G5 system considering the requirements of the applications and the actual environmental conditions in the vicinity of the ITS station.

5 IEEE 802.11bd for ITS-G5

5.1 Introduction

The IEEE 802.11bd amendment to the IEEE 802.11-2020 standard will provide a set of new features which can be integrated into the overall ETSI ITS-G5 protocol stack to result in an enhanced ETSI ITS-G5 system. Some of the envisaged enhanced applications under specification or investigation like CPS[ER-8] and cooperative manoeuvring application [ER-9] can significantly benefit from the new capabilities of an access layer based on IEEE 802.11bd.

In this clause some of the identified interrelationships and the corresponding potential implications onto upcoming releases of the ETSI ITS-G5 protocol will be depicted. Especially the co-channel access layer interoperability features fully supported by the multichannel operation specified for ITS-G5 are of utmost importance for the support of a stable C-ITS communication environment and eco-system.

5.2 Access Layer

The ITS-G5 access layer supporting IEEE 802.11bd will have some additional elements to be implemented. The main elements here are related to the modulation and coding scheme mainly the channel coding based on LDPC and the higher order modulation capability up to 256QAM. Furthermore, the MIMO operation of the IEEE 802.11bd enabled ITS-G5 system must be specified into the access layer specification.

Furthermore, the MAC layer extensions including the repetition features need to be specified.

The newITS-G5 access layer capabilities will be specified in an updated version of the EN 302 663 [ER-3]. These new capabilities can be seen as an extension of the available toolbox in support of the different requirements of the ITS applications.

The new IEEE 802.11bd specific access layer capabilities will add additional features to the existing toolbox including additional higher performance transmission formats staying fully backward compatible with existing devices.

5.3 Positioning and time (POTI)

The facilities functionality for “Position and Time” is specified in ETSI EN ETSI EN 302 890-2 [ER-14]. This functionality is mainly based on the GNSS positioning features. IEEE 802.11bd now provides some additional cooperative location and positioning features that could enhance the stability and robustness of the existing PoTi features especially in cases where GNSS is temporarily not available. Furthermore, the cooperative approach integrated into IEEE 802.11bd can be used to extend the PoTi features and will allow a cooperative time synchronization among devices where or when GNSS is unavailable. This would allow to implement an alternative positioning, navigation and timing service to GNSS.

These capabilities can be specified in an upcoming version of the PoTi EN.

With the deployment of ITS-G5 stations with IEEE 802.11bd capabilities enhanced cooperative PoTi features can be implemented leading to higher robustness and stability in cases where the GNSS services are not available or not fully available.

5.4 Multichannel operation (MCO)

5.4.1 Overview

The multichannel operation specified in ETSI is the basis for the smooth introduction of the fully backward compatible IEEE 802.11bd enhancements into the ITS-G5 Release 2 set of specifications. Especially the facilities layer MCO operations are important for the control of the channel access based on the requirements of the applications, the available transmission resources, and the conditions in the vicinity.
The MCO operation in ITS-G5 Release 2 can control the channel access technology and the related parameters on an application by application and a message-by-message basis. Depending on the application requirements and requests and the known capabilities of the ITS stations in the surrounding communication cluster the MCO facilities will provide the corresponding resources (frequency channel, technology, access parameter, TX power) to the requesting applications. This mechanism fully supports the fair co-channel interoperability between existing devices only deploying IEEE 802.11p based access layer and enhanced devices supporting the IEEE 802.11bd access layers including IEEE 802.11p and NGV features.
All information related to the deployed technologies in the communication cluster are available at the MCO facilities routing entity.

5.4.2 MCO FAC

MCO Facilities layer functionalities are essential for the operation of a fully backward compatible and interoperable ITS-G5 system deploying existing stations without NGV capabilities and stations with a full support NGV in IEEE 802.11bd. The MCO FAC will have to monitor the characteristics of the ITS stations participating in the communication and will have to take these into account in the access layer control operation. Based on the actual situation of participating stations the MCO FAC controls the usage of the different available access layers or access layer features for each of the active applications (see Figure 3).
The existing MCO FAC specified in ETSI TS 103 141 [ER-15] already provides a set of hooks to implement this functionality.
The details will have to be specified in an updated version of the TS.

The actual MCO FAC in TS 103 141 and the related MCO specifications in ETSI already provides the basic functionalities to control the backward compatible interoperability of existing ITS-G5 stations and ITS-G5 stations with NGV capabilities.

5.4.3 MCO Access

The MCO functionalities of an IEEE 802.11bd enabled access layer will provide the new capabilities to the higher layer MCO control entities in the facilities layer. From the basic operational point of view the new capabilities are an extension of the existing access layer capabilities. The use of these extensions by specific applications or set of applications will be possible in the same operational channel. Different applications can deploy the enhanced NGV capabilities, other might rely on the basic capabilities provided by the IEEE 802.11p based access layer capabilities. The choice of used capabilities can be switched from frame to frame and is controlled by the MCO Facilities entity.

In a mixed operational environment where Release 1 devices (which only support IEEE 802.11p capabilities) and Release 2 devices (also with support for IEEE 802.11bd) are operated simultaneously, the choice of the capabilities will also rely on the actual deployment scenario in the vicinity, and thus the corresponding interoperability requirements given by the used applications. In this case all applications which must interoperate with IEEE 802.11p only devices will have a limited set of access layer capabilities available. Applications with no such interoperability requirements can still use the complete set of capabilities.

More details related to the available capabilities are included in the ETSI TS 103 695 [ER-6].

The actual MCO Access specified in ETSI TS 103 695 provides the mechanisms for an easy integration and control of an IEEE 802.11bd capable access layer into the ITS-G5 protocol stack.

5.5 Summary

The new capabilities available in IEEE 802.11bd must be included into the ETSI ITS-G5 Release 2 set of specifications. The main points to be considered and updated are the access layer and the facilities layer specifications. The basic control functionality to handle the new capabilities and the co-channel interoperability between IEEE 802.11p based devices and IEEE 802.1bd devices is defined in the stet of MCO specifications [ER-4].

New application specifications should take these capabilities into account.

6 Conclusions

The IEEE 802.11bd standard is an evolutionary extension of the existing IEEE 802.11p as part of the IEEE 802.11-20 standard. It adds significant building blocks to enhance the performance and flexibility of the access layer used in European ETSI ITS-G5 and U.S. DSRC V2X systems. It is fully backward compatible and interoperable with the existing implementations of IEEE 802.11p as part of ETSI ITS-G5 or IEEE DSRC WAVE. The extension can use the same channels without penalizing the performance of existing IEEE 802.11p based devices. IEEE 802.11p communication format is already supporting all the envisaged C-ITS applications of the C2C-CC roadmap up to highly automated driving, while the IEEE 802.11bd can further improve the capabilities of existing as well as future devices and applications whilst providing some additional resources.

The newly added building blocks in IEEE 802.11bd extend the existing toolbox of IEEE 802.11p by adding features that can increase the robustness, the communication range of the access layer, and can increase the available data rates in support of upcoming applications in cooperative ITS systems like Collective Perception Service (CPS) [ER-8] and Manoeuvre Cooperation Service (MCS) [ER-9] applications.

All investments performed today in deploying IEEE 802.11p (and ITS-G5) will also be available for IEEE 802.11bd. Furthermore, some improvements can be applied directly to existing IEEE 802.11p based systems and benefit the already deployed stations.

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[ER-3] EN 302 663 V1.3.1: “Intelligent Transport Systems (ITS); ITS-G5 Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band”

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[ER-5] ECC DEC(09)01: “Harmonised use of the 63.72-65.88 GHz frequency band for Intelligent Transport Systems (ITS)”

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[ER-15] TS103 141 V1.1.1: “Intelligent Transportation Systems (ITS); Facilities layer function; Communication Congestion Control“

[ER-16] IEEE 802.11: “NGV SG Use Cases (Next Generation V2X Study Group)”

■ End of Document ■