Vehicular Communications for ITS: Standardization and Challenges

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***Abstract*—Intelligent Transport Systems (ITS) are fast moving from connected vehicles on the road to autonomous driving. Vehicular communication is a key enabler for the deployment of advanced ITS applications such as platooning and remote vehicle control. Dedicated Short Range Spectrum (DSRC) and Cellular Vehicle-to-everything (C-V2X) are two key wireless technologies that will play a vital role in the implementation and deployment of an autonomous transport system. We review the current standardization efforts for both of these technologies with a focus on Medium Access Control (MAC) and Physical (PHY) layers. The automotive industry and research community have been working on new standards IEEE 802.11bd (for DSRC) and 5G NR V2X (for C-V2X) to meet the high reliability and low latency requirements of autonomous driving. We also highlight the major changes that have been made to previous standards such as the IEEE 802.11p and the C-V2X. Finally, we present open challenges that need to be addressed to further improve these standards for vehicular communications.**

I. INTRODUCTION

Rapid advances in sensor technologies and wireless communications are enabling the development of Intelligent Transport Systems (ITS). Applications such as cooperative collision warning, traffic management and infotainment have been made possible by wireless connectivity among vehicles. Many of these applications are now in the implementation phase and the next major goal for the automotive industry is to develop a fully autonomous vehicle system [1], [2].

Many advanced vehicular applications have been identified for autonomous vehicles [3]. These applications allow autonomous vehicles to share their trajectories and driving intentions with each other, thus enabling vehicle safety and efficient traffic management. Extended sensing is another application where vehicles have a complete view of the neighborhood with the help of data shared by neighboring vehicles. This data may include raw information captured by the cameras and the radars as well as real-time multimedia (such as images from an emergency area, videos of the accident to guide ambulances). The receipt of accurate neighborhood information provides effective situation awareness to the vehicles and assist in better mobility-related decision making.

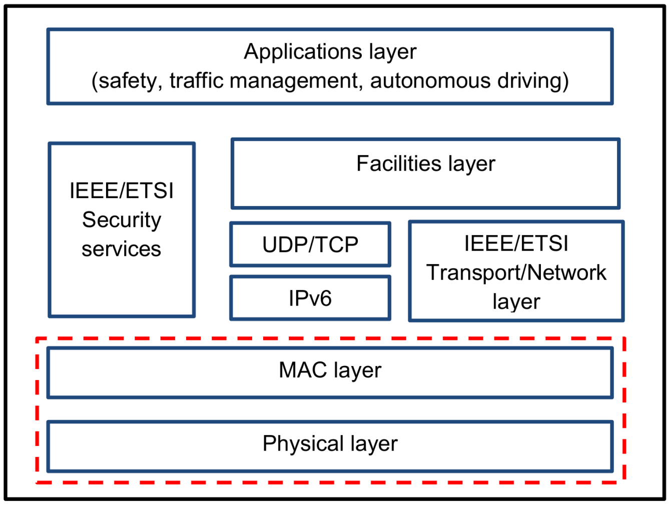
Platooning is another advanced application where vehicles form a coordinated group with low inter-vehicle spacing. This enables efficient flow of traffic on the roads, and reduces congestion as well as saves fuel consumption. Another key upcoming application allows the vehicles to be controlled remotely by using a computer application or a human operator. This facilitates cloud-based fleet control and remote public transport management. In areas where roads are uneven or slippery, such an application allows owners to remotely take control of the autonomous vehicle.

Vehicular communication is a vital component of advanced autonomous vehicles. After nearly a decade of vehicular networking research conducted by the automotive industry and academic community, various efforts have been working on the standardization of communication technologies for various applications aimed at connected vehicles. The two wireless technologies that support connected vehicles are the Dedicated Short Range Spectrum (DSRC) [1], [4] and the Cellular Vehicular-to-everything (C-V2X). However, the current standards (such as the IEEE 802.11p and the C-V2X) do not support Quality of Service (QoS) required for advanced autonomous driving applications and fail to provide consistent high data rate transmissions. To address such deficiencies, new standards are currently being developed by IEEE task group *bd* and *3rd Generation Partnership Project (3GPP)* to support future autonomous driving applications.

In this paper, we review some of the recent standardization efforts for DSRC and C-V2X technologies to support autonomous driving applications. We discuss the protocol stacks of DSRC and C-V2X for vehicular communications and the motivations behind the development of new standards for DSRC and C-V2X. We also present the MAC and PHY layers for both current standards as well as the new MAC and PHY layers that are being developed for DSRC and C-V2X. Finally, we discuss some research challenges related to the development of standards for DSRC and C-V2X, and make some concluding remarks.

II. VEHICULAR COMMUNICATION STANDARDS

The automotive industry in collaboration with research, standardization organizations and the academic community have developed various standards to support future ITS applications. For DSRC, the standardization work has been carried out by the Institute of Electrical and Electronics Engineers (IEEE) and the European Telecommunications Standards Institute (ETSI). On the other hand, 3GPP developed standards for C-V2X. In this section, we review the protocol stack for DSRC and C-V2X technologies and present the motivation for developing new MAC and PHY layer standards for them.



IEEE: Institute of Electrical and Electronics Engineers
ETSI: European Telecommunications Standards Institute
UDP: User Datagram Protocol
TCP: Transmission Control Protocol
MAC: Medium Access Control

Fig. 1: Vehicular communication protocol stack.

A. *Protocol stack for vehicular communications*

Fig. 1 shows the protocol stack used by DSRC and C-V2X for vehicular communications. The upper layers (application, facilities, transport and network) of the stack are shared by both DSRC and C-V2X whereas the MAC and the PHY layers are different for both technologies. The application layer defines various type of messages that are used by vehicles to enable ITS applications. This definition includes message formats, message coverage range and message inter-arrival times. For safety applications, periodic messages known as Cooperative Awareness Messages (CAMs) or Basic Safety Messages (BSMs) are transmitted by the vehicles [1]. For non-safety applications, event-driven Decentralized Environmental Notification Messages (DENMs) are shared by the vehicles.

The facilities layer provides various functionalities to assist ITS applications. This layer defines data structures for vehicle sensor data maintenance, filtering and aggregation of received traffic information messages and communication session management. The transport layer provides services such as end-to-end delivery, reliable data transfer and congestion mitigation. The network layer handles routing of data from the source vehicle to the destination vehicle, multi-hop broadcast communications for DENMs and data dissemination to a particular geographical area.

The only difference in the protocol stack for DSRC and C-V2X technologies lies in the MAC and PHY layers. DSRC uses Wi-Fi-based access technology whereas C-V2X adopts cellular-based access technology. This makes DSRC suitable for short range communications, but it does not provide robust connectivity when the vehicle density is high. In contrast, C-V2X can support a longer coverage range but its direct communication transmission mode does not provide the desired high reliability.

B. *Motivation for the new MAC and PHY layer standards*

The key drivers behind the development of new vehicular standards for DSRC and C-V2X include:

- While the current standards support V2X safety applications with high reliability (90%-99%) and low latency (up to 100ms), autonomous driving requires ultra-high reliability (99.999%), and ultra-low latency (up to 3ms).
- Significant advances and improvements have been made to physical layer technologies and MAC layer protocols since the last standards (i.e., IEEE 802.11p and C-V2X) have been finalized. The latest standards (i.e., IEEE 802.11bd and 5G NR V2X) use these enhancements to support advanced autonomous driving applications.

III. DSRC BASED STANDARDS

DSRC vehicular communication technology uses Wi-Fi based PHY and MAC layer protocols. The IEEE 802.11p is the default standard that defines the functionalities of the PHY and MAC layers to be used by the DSRC technology. The IEEE 802.11p standard suffers from several shortcomings which include: low data rate at high vehicle densities, and packet loss due to hidden terminals [5]. Recently, work has started on the new IEEE 802.11bd standard to overcome the shortcomings in the IEEE 802.11p standard [6]. In this section, we briefly review both of these standards.

A. *IEEE 802.11p*

IEEE 802.11p is a modified version of the IEEE 802.11 standard and works for high mobility vehicular scenarios [1]. In 2004, the IEEE task group *p* started working on this standard and it was finally approved in 2010. IEEE 802.11, also known as Wi-Fi, was selected as the base standard for the DSRC technology as it was a stable and a popular product, and was expected to provide successful market penetration. Table I shows the key parameters of IEEE 802.11p.

Overview of the PHY layer

The physical layer of IEEE 802.11p uses Orthogonal Frequency Division Multiple Access (OFDM) with a channel bandwidth that is reduced to half as compared to IEEE 802.11, thus doubling the OFDM symbol duration. This was done to handle large delay spread and inter-symbol interference in a vehicular network. The data rate of IEEE 802.11p was also halved as compared to IEEE 802.11. The peak data rate offered by the IEEE 802.11p standard is 27 Mbps.

Overview of the MAC layer

The MAC layer of the IEEE 802.11p standard is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. By using contention-based channel access, CSMA/CA protocol manages simultaneous transmissions by the vehicular sensors. Moreover, the IEEE 802.11p also implements the Enhanced Distributed Channel Access (EDCA) procedure that prioritizes access of the channel for various traffic categories. This allows emergency messages to be transmitted with a shorter contention time.

B. IEEE 802.11bd

Since the approval of the IEEE 802.11p standard in 2010, various improvements have been made to the PHY and MAC layer protocols of IEEE 802.11. These advances have been incorporated into the latest set of standards such as 802.11n, 802.11ac and 802.11ax. The improvements include the use of efficient techniques such as Low-Density Parity Check (LDPC) coding, Space Time Block Coding (STBC) and Midambles. Moreover, with the emergence of autonomous vehicular applications and contending C-V2X standards evolving at a rapid pace, there was a need to achieve higher throughput and transmission range. In December 2018, the task group *bd* was set up to investigate the changes that should be made to the IEEE 802.11p standard. Table I presents the major differences between IEEE 802.11p and IEEE 802.11bd.

Key goals: The three main goals of the IEEE 802.11bd as defined in the project Authorization Request (PAR) are:

- To define one transmission mode that can double the MAC throughput at speeds of up to 500 km/h.
- To define one transmission mode that can reduce the noise sensitivity level of the lowest data rate in IEEE 802.11p by 3dB to enable a longer communication range.
- To define a positioning technique that can work together with V2X communications.

Key requirements: The four key requirements of IEEE 802.11bd include:

- ***Interoperability:*** Since various car manufacturers have already been working on installing IEEE 802.11p devices in their future vehicles, IEEE 802.11bd needs to be fully interoperable with the legacy IEEE 802.11p standard. This means that the IEEE 802.11bd devices should be able to decode the IEEE 802.11p transmissions. In contrast, IEEE 802.11p devices should be able to decode at least one mode of the IEEE802.11bd transmissions.
- ***Co-existence:*** Both IEEE 802.11bd and IEEE 802.11p devices should be able to detect each others transmissions in order to avoid simultaneous transmissions and collisions.
- ***Backward compatibility:*** IEEE 802.11bd devices should be backward compatible with IEEE 802.11p devices with at least one mode of operation for mutual communications.
- ***Fairness:*** Both IEEE 802.11bd and IEEE 802.11p devices should have fair access to the physical transmission channel.

Key changes in the PHY layer

The IEEE 802.11bd standard [7], [8] have incorporated the following changes in its PHY layer.

1) OFDM numerology: IEEE 802.11bd aims to use the more efficient OFDM numerology of IEEE 802.11ac. With a higher number of sub-carriers and reduced sub-carrier spacing, IEEE 802.11ac OFDM numerology offers better spectral efficiency as compared to the IEEE 802.11p standard. However, the impact of channel variations on the reduced sub-carrier spacing must be evaluated.

2) LDPC Forward Error Correction coding: LDPC forward error correction codes haven been adopted by IEEE 802.11n/ac due to their higher coding gain. IEEE 802.11bd replaces the Binary Convolution Code (BCC) used in IEEE 802.11p with LDPC as the Forward Error Correction (FEC) technique.

3) Midamble: Midamble is the sequence of symbols that are inserted in-between data symbols to estimate the channel. As compared to the preamble (used in IEEE 802.11p) which is inserted at the start of the data symbol for initial channel estimation, the midamble is good for estimation of fast-varying channels. In 802.11bd, the midamble is inserted periodically every M data symbols and is an effective Doppler mitigation technique.

4) Higher modulation scheme: In 802.11ac, higher Quadrature Amplitude Modulation (QAM) schemes are used which can increase throughput. IEEE 802.11bd is currently considering to adopt 256QAM with a coding rate of $3/4$. Due to the midamble, the channel can be estimated with a higher accuracy and therefore a higher modulation and coding scheme can be used.

5) 20 *MHz channels for transmission:* Two adjacent 10 MHz channels are available for use in the 5.9 GHz spectrum (for example channel 175 and 181 in the United States). IEEE 802.11bd is considering to define a 20 MHz channel comprising these adjacent channels to double the throughput as compared to IEEE 802.11p.

6) Out of channel transmitter emissions: Out-of-channel transmitter emissions are reduced in IEEE 802.11bd to minimize the interference between adjacent channels and achieve better Signal to Interference and Noise Ratio (SINR).

7) Receiver waveform improvements: At the receiver, minimum signal sensitivity in static channels will be increased by 6 dB. To mitigate multi-path fading and consider the Doppler effect, realistic Vehicle-to-Vehicle (V2V) channel models must be considered.

8) Transmission reliability using retransmissions: To provide transmission reliability and mitigate multi-path fading, retransmission of packets (up to a maximum of 3 times) is considered as part of IEEE 802.11bd. The number of retransmissions can be adjusted depending on the channel congestion. The proposed scheme yields a 4 dB improvement in SNR for a given packet error rate.

Key changes in the MAC layer

The IEEE 802.11p MAC works well for basic safety applications. However, for new advanced user cases of autonomous driving, it is not sufficient. IEEE 802.11bd [9] will incorporate the following changes in the MAC layer.

9) Fast Basic Service Set (BSS) transition and Fast Initial Link Setup (FILS): Since vehicular communications involve high mobility and frequent disconnections, IEEE 802.11bd reuses the Outside the Context of Basic (OCB) service set based communication that is defined in IEEE 802.11p. This means that the stations that are not member of a Basic Service Set (BSS) do not require authentication and association. For certain use cases where BSS-based communication is required, the fast BSS transition feature (quick authentication with access points using security key negotiations and resource allocation to occur in parallel) of IEEE 802.11r and fast initial

TABLE I: Comparison of IEEE 802.11p and IEEE 802.11bd

Parameter	IEEE 802.11p	IEEE 802.11bd
OFDM sub-carrier spacing	156.25 KHz	39.0625 KHz, 78.125 KHz, 156.25 KHz
FEC coding	BCC	LDPC
Channel Estimation	Preamble	Midamble
Modulation Scheme	up to 64 Quadrature Amplitude Modulation (QAM)	up to 256 Quadrature Amplitude Modulation (QAM)
Channel Bandwidth	10 MHz	10 MHz, one 20 MHz channel
Retransmissions	No	up to 3
Fast BSS transition	No	Yes
Error correction	part of data packet	dedicated packet sent separately

link setup feature (reduce time for initial association of nodes with access points) of IEEE 802.11ai can be used.

10) Dedicated error correction packet: IEEE 802.11bd, a dedicated error correction packet is sent after waiting for a Short Inter Frame Spacing (SIFS) time. The transmitted packet is divided into blocks containing the data bits and Reed Solomon (RS) algorithm encoded parity bits. Byte interleaving is used to reduce the probability of burst errors and has been shown to provide a gain of 1.5 dB. The block size is defined as the sum of the data bits and the parity bits. For a fixed number of data bits, a higher block size implies more parity bits and a larger overhead by the error correction algorithm. The overhead is adjusted based on the vehicle speed and the network load. At high vehicle speeds where packet error rate can be higher, more parity bits are inserted into the transmission block resulting in a higher overhead. If the network load is high, few parity bits are used to reduce network congestion.

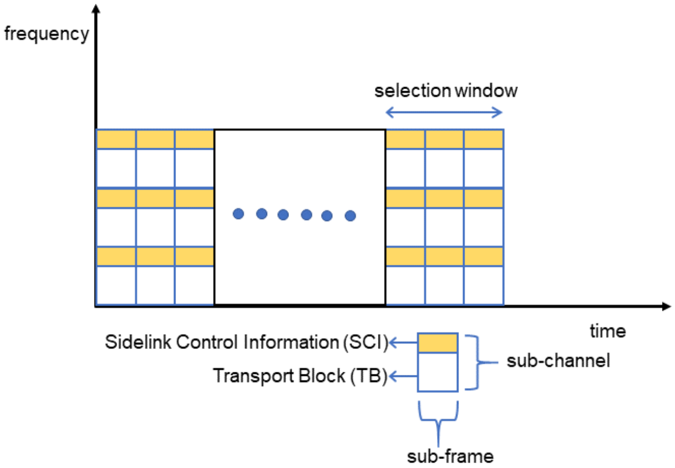


Fig. 2: C-V2X frame structure.

IV. C-V2X BASED STANDARDS

5G will provide ubiquitous cellular connectivity to a plethora of devices in the near future. It offers long range and high data rates which makes it suitable for many vehicular applications. Cellular communications emerged as a potential vehicular connectivity technology with 3GPP release 12 and 13 that support Device to Device (D2D) communications. In the past, it was perceived that cellular communications cannot support low latency vehicular safety applications because the message has to be relayed through the infrastructure. However, the advent of D2D communications enables direct communications between neighboring vehicles. This idea was further refined in 3GPP release 14 and 15. Currently, C-V2X is in implementation phase and work is in progress on the 5G New Radio (NR) standard to meet ultra-reliable and ultra-low latency requirements which will be particularly useful for autonomous driving applications. This will be part of 3GPP release 16. Next, we review C-V2X and 5G NR V2X standards.

A. C-V2X

The C-V2X standard was developed by the 3GPP (in release 14) to support vehicular applications [2]. The standard introduced two types of communications, network communications using the Uu interface (the radio interface between the user equipment and the enodeB) and direct communications using the sidelink channel over PC5 interface. Network communications operate over licensed spectrum and messages are relayed to a vehicle User equipments (UEs) using Evolved node B (enodeB). In contrast, direct communications occur in the 5.9 GHz spectrum allowing vehicles to directly exchange information. Furthermore, two new D2D transmission modes (mode 3 and mode 4) were introduced. They differ from each other in the way resources are allocated. In mode 3, enodeB collects channel quality information from the vehicles to allocate resources whereas mode 4 allows autonomous resource allocation without the need of enodeB. These modes can support low latency vehicular applications.

Overview of the PHY layer

C-V2X uses Single Carrier-Frequency Division Multiple Access (SC-FDMA) and works on both 10MHz and 20 MHz frequencies. Channels are divided into frames of 10ms and further into sub-frames of 1ms. Each sub-frame contains two time slots, where a single time slot has 7 SC-FDMA symbols. Since each sub-frame contains 14 SC-FDMA symbols, only 9 out of these 14 can be used for data transmission. The four pilot symbols are called De-Modulation Reference Symbols (DMRSs) whereas the last symbol of each sub-carrier is reserved as a guard band. In the frequency domain, each sub-carrier is 15 KHz wide [2].

A Resource Block (RB) is the smallest frequency unit that can be allocated to a vehicle. Each RB is 180 KHz wide in frequency (12 sub-carriers of 15 KHz). Data in C-V2X is

TABLE II: Comparison of C-V2X and 5G NR V2X

Parameter	**C-V2X**	**5G NR V2X**
Sidelink modes	Mode 3 and Mode 4	Mode 1 and Mode 2
Fast sidelink scheduling	No	Yes
Preemptive resource scheduling	No	Available for critical messages
OFDM sub-carrier spacing	15 KHz	15 KHz, 30 KHz, 60 KHz
PSCCH and PSSCH multiplexing	Frequency	Time
Retransmissions	Blind	Adaptive based on channel state information received on PSFCH
FEC coding	Turbo	LDPC
Modulation scheme	up to 64 QAM	Up to 256 QAM
DMRS per sub-frame	4	Flexible
Frame types	Broadcast	Unicast, Groupcast, Broadcast
Slot duration	Fixed	Min-slots and multi-slots available
Sensing window	Fixed	Adaptive

DMRS: De-modulation Reference Symbol
FEC: Forward Error Correction
LDPC: Low-Density Parity Check
OFDM: Orthogonal Frequency Division Multiple Access
PSCCH: Physical Sidelink Control CHannel
PSFCH: Physical Sidelink Feedback CHannel
PSSCH: Physical Sidelink Shared CHannel
QAM: Quadrature Amplitude Modulation

transmitted in Transport Blocks (TBs) which are groups of RBs containing the complete data packet. Sidelink Control Information (SCI) is also transmitted in 2 consecutive RBs along with the data, and contains information related to the modulation and coding scheme used, and the RBs that are used to transmit the TB. Data is transmitted on the Physical Sidelink Control CHannel (PSSCH) and SCI is transmitted on the Physical Sidelink Shared CHannel (PSCCH).

Overview of the MAC layer

The C-V2X MAC layer uses Sensing-Based Semi-Persistent Scheduling (SB-SPS) protocol which consists of two parts, sensing and semi-persistent scheduling [2].

*1) **Sensing**:* The following steps are executed during the sensing phase:

- ***Selection Window selection:*** Vehicles choose a Selection Window (SW) which is the time interval corresponding to a window of RBs from which vehicles can pick TBs for data transmission. Selection window depends on the latency requirements and its value is between 20 ms and 100 ms. A low value of selection window can reduce latency, but it can cause more collisions in a dense network.
- ***Free resource estimation:*** Vehicles estimate the available resources (i.e., sub-channels) within selection window by filtering out the busy resources. Based on the received information (in the SCI) from any other vehicle in a sensing period of the last 1000 sub-frames, the vehicle marks the busy resources. Additionally, if the Reference Signal Received Power (RSSP) over a resource is greater than the threshold, it is marked as busy. After excluding the busy resources, vehicles select the top 20% of the resources with the lowest Received Signal Strength Indicator (RSSI) values within the sensing period. If the available resources are less than 20% of the selection window, the free resource estimation procedure is repeated with an increase in the threshold by 3 dB.
- ***Random resource selection:*** A resource is randomly chosen out of available resources lists for the Reselection window counter.

*2) **Semi-persistent scheduling:**:* Semi-persistent scheduling is used to avoid selecting the same resource by a given vehicle repetitively, and also reduce collisions. This is done by selecting a *reselection counter* value which measures the number of packets a vehicle can transmit consecutively. The reselection counter is randomly selected depending on packet arrival rate. Once resources are allocated, the reselection counter decreases by one. When the counter value reaches zero, vehicles make a decision to keep the same resource with probability ρ and select a new resource with probability $1-\rho$. The value of ρ can be selected between 0 and 0.8.

C-V2X also supports a retransmission feature where a vehicle can retransmit the packet if it finds a free resource within a time interval of 15ms. This feature offers robustness but reduces spectral efficiency.

B. 5G NR V2X

The aim of the 5G NR V2X standard is to support advanced applications that require ultra-reliability and ultra-low latency. As C-V2X is already in the deployment phase, future vehicles will have both C-V2X and 5G NR V2X technologies co-existing with each other. Table I presents the major differences between C-V2X and 5G NR V2X.

Key modifications in the PHY layer

The following key changes have been considered by 5G NR V2X in the PHY layer [10]–[14].

1) Sidelink modes: 5G NR V2X defines two sidelink modes (mode 1 and mode 2) which are similar to mode 3 and mode 4 in C-V2X except with some changes. In mode 1, vehicles directly communicate with each other within the coverage range of the base station gnodeB which allocates resources. A key enhancement in mode 1 is that vehicles should send location and beam information to the gnodeB so that it can allocate resources with improved spatial reuse. The mode 2 allows D2D vehicular communications where resources are allocated autonomously. A noticeable addition in 5G NR V2X is that various sub-modes of mode 2 are also defined where vehicles can assist each other in resource allocation by sharing resource occupation and channel quality information. Such a feedback improves the autonomous resource allocation mechanism. Furthermore, for groupcast communications, a group leader vehicle can manage resource allocation on behalf of the group.

2) Fast sidelink scheduling: In C-V2X, a vehicle that needs to schedule a sideLink (SL) resource first needs to send a Scheduling Request (SR) to the gnodeB to get a single UpLink (UL) resource. After this step, the vehicle again sends a Buffer Scheduling Request (BSR) on the allocated uplink resource to the gnodeB, which then schedules multiple sidelink resources for data transmission. To reduce the latency, 5G NR V2X introduces a fast SL scheduling mechanism where sidelink resources are scheduled in a single step by using the Uplink Control Information (UCI) message containing all the sidelink resource information.

3) Preemptive Resource scheduling for critical messages: 5G NR V2X uses a preemptive indicator signal to schedule resources for critical messages efficiently. Vehicles with a critical message can send a preemptive indicator signal to other vehicles. As a result, vehicles with reserved resources for less critical messages can release them to support quick transmission of critical messages.

4) Flexible sub-carrier spacing: C-V2X supports a fixed sub-carrier spacing of 15 KHz. 5G NR V2X supports a flexible sub-carrier spacing of 15 KHz, 30 KHz, and 60 KHz. A higher sub-carrier spacing reduces latency because the slot time is reduced. Another key change is that 5G NR V2X also supports both Cyclic Prefix (CP)-OFDM and Discrete Fourier Transform Spread (DFT-s)-OFDM.

5) PSCCH and PSSCH multiplexing: Physical Sidelink Control CHannel (PSCCH) and Physical Sidelink Shared CHannel (PSSCH) are multiplexed in frequency in C-V2X which has the disadvantage of longer delays because the receiver needs to buffer the message for the entire sub-frame and then decode it. In 5G NR V2X, time domain multiplexing is considered wherein PSCCH is transmitted first followed by PSSCH.

6) Hybrid Automatic Repeat Request: While C-V2x supports blind retransmission, 5G NR V2X supports a Hybrid Automatic Repeat Request (HARQ) scheme. Based on the channel state information of the destination vehicle, adaptive retransmissions can be selected in 5G NR V2X. The Physical Sidelink Feedback CHannel (PSFCH) is used for sharing channel state information.

7) LDPC FEC coding: 5G NR V2X uses more efficient LDPC coding for FEC as compared to Turbo coding used in C-V2X.

8) Higher Modulation scheme: 5G NR V2X can support a modulation of 256 QAM as compared to the maximum modulation of 64 QAM used in C-V2X.

9) Number of DMRS per sub-frame: In C-V2X, four DMRSs per sub-frame are used to send a pilot signal. The number of DMRSs can be adjusted in 5G NR V2X.

Key changes in the MAC layer

5G NR V2X makes the following key modifications in the MAC layer.

10) Unicast and groupcast communications: While C-V2X allows only broadcast communications, 5G NR V2X enables unicast and groupcast communications. Separate frame formats are yet to be defined by 5G NR V2X to support unicast and groupcast communications.

11) Mini-slot and multi-slot allocation: In C-V2X, only fixed sized slots can be scheduled. This causes slots to be wasted if the packet size is too small. To address this issue, the concept of mini-slots (slots with no fixed start time and end time used for flexible transmissions) has been introduced in 5G NR V2X. Similarly, for large packets multi-slot is possible which aggregates several time slots resulting in better slot utilization.

12) Adaptive sensing window: 5G NR V2X adapts the sensing window based on vehicular mobility. In a highly mobile scenario, the sensing window should be reduced as resource information becomes outdated quickly. Moreover, 5G NR V2X recommends skipping the RSSI averaging procedure while selecting resources in C-V2X. By skipping the procedure, fast resource allocation is possible. For aperiodic traffic, short term sensing similar to the one used in Wi-Fi is suggested. Long term sensing does not work well because arrival of new packets cannot be predicted for aperiodic traffic.

V. OPPORTUNITIES AND CHALLENGES

A. mmWave communications

mmWave communications could bring many benefits to V2X communications. mmWaves operate in the spectrum band of 30GHz-300 GHz and are suitable for high throughput communications particularly useful for autonomous driving applications. Many non-safety applications such as video streaming and high speed Internet access can also utilize mmWaves for quick data transfer. Another key advantage of mmWave communications is that the frequencies can be reused after short distances and there is also less interference to vehicles due to the short range of mmWaves. Additionally, the antenna cost for mmWave transceivers is also lower compared to the antenna cost of normal C-V2X transceivers.

Since mmWaves have a short communication range, they will not be suitable for applications that require long range data exchange. Due to the high attenuation of mmWaves, multiple hops may be required for many vehicular applications thereby causing large transmission delays. Both IEEE 802.11bd and 5G NR V2X are considering the use of mmWave communications in the range of 60GHz. While mmWaves can be useful for V2X application, the design of MAC and PHY layer protocols in this context needs further investigation.

B. Backward compatibility with new standards

In the past few years, standards such as IEEE 802.11p and C-V2X have been defined for vehicular communications. Field experiments and tests have also been carried out using DSRC and C-V2X technologies and they are almost ready for implementation. In fact, several car manufacturers (such as Toyota, Ford and Volkswagen) have already announced to implement DSRC and C-V2X in their upcoming new cars. By the time the new standards IEEE 802.11bd and 5G NR V2X will be fully developed, there will be many vehicles with previous V2X standards already on the market. Therefore, new standards need to be backward compatible with the previous standards. Protocols that will enable seamless interoperability between new standards and previous ones must be developed.

C. Heterogeneous V2X networks

Both DSRC and C-V2X are strong wireless technologies for future V2X applications. Future vehicles are likely be equipped with both of these technologies. As both of these technologies are suited for vehicular communications, we need to develop protocols that enable seamless communications with high throughput and low latency in a heterogeneous environment using both DSRC and C-V2X.

D. Autonomous/Fog-based resource allocation

Resource allocation (time slots in IEEE 802.11bd and resource blocks in C-V2X) will be a key challenge because the number of vehicular applications will increase in the future. This will require either a robust autonomous resource allocation scheme (such as SB-SPS technique as discussed in Section IV) or the installation of fog RSUs at different locations to facilitate efficient data exchange [15]. In addition, these fog RSUs can process data (such as traffic management) closer to the vehicles enabling real-time autonomous driving.

VI. CONCLUSION

We present a review of current work in MAC and PHY standards to support autonomous driving applications for DSRC and C-V2X technologies. The enhancements in DSRC include development of IEEE 802.11bd standard that improves OFDM sub-carrier spacing, FEC coding, channel estimation and several other processes. Similarly C-V2x is moving towards 5G NR V2X with key features of fast sidelink scheduling, preemptive resource scheduling for critical messages, adaptive retransmissions and support of unicast and groupcast communications. We also highlight the important opportunities and challenges such as mmWave communications, backward compatibility of new V2X standards, and heterogeneous V2X networks.

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