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Joint use of DSRC and C-V2X for V2X communications in the 5.9 GHz ITS band

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Abstract
Vehicular communications networks form the backbone of cooperative intelligent transport systems to support road safety and infotainment applications amongst users. IEEE 802.11p of the Dedicated Short-Range Communications protocol stack has been the technology of choice for Vehicle-to-Everything communications within the United States and Japan and has been extensively trailed in other countries such as Australia. With the advent of cellular technologies, a new, competing cellular-based Device-to-Device technology, known as Cellular Vehicle-to-Everything Sidelink, has emerged. Considering both technologies suffer from performance limitations, there is a current debate as to which of these technologies will eventually dominate the cooperative intelligent transport systems landscape if they cannot coexist. To investigate mechanisms of spectrum sharing between Dedicated Short-Range Communications and Cellular Vehicle-to-Everything for deployment in a common region, this paper initially reviews the background and technicalities of both technologies. The paper subsequently sets forth Vehicle-to-Everything platform models that allow not only spectrum sharing at the ITS band but also concurrent and simultaneous propagations of Dedicated Short-Range Communications and Cellular Vehicle-to-Everything messages. The transmission and reception mechanisms of hybrid Vehicle-to-Everything platforms are verified through a describing function model.

1 | INTRODUCTION

Road safety has always been a top priority when it comes to both road design and automobile manufacture due to the considerable number of injuries and deaths caused on roads every year. According to the World Health Organisation (WHO), almost 1.25 million deaths occurred on roads globally in the year 2013 [1] along with substantially higher cases of injury. Cooperative Intelligent Transportation Systems (C-ITS) are a current trend in the road safety context, which aim to make strides in improving the safety and manageability of land transportation, and reducing road congestion, through a suite of communications and platforms for data delivery. From the business point of view, provided that the production of vehicles is in excess of 90 million per year [2], C-ITS represents an enormous opportunity for the transportation industry with an estimation of the global connected car market to exceed $225 billion by 2025 [3]. Given the expected market growth in the connected vehicles landscape, two different Device-to-Device (D2D) communications technologies, namely, Dedicated Short-Range Communications (DSRC) and Long-Term Evolution-Vehicle (LTE-V), have been standardised by international organisations and consortia. Further developments and evaluations are progressing worldwide for both technologies.

Figure 1 illustrates different types of direct communications required in the C-ITS landscape – namely, Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), Pedestrian-to-Pedestrian (P2P) and Pedestrian-to-Infrastructure (P2I). These are between On-Board Units (OBU), Road-Side Units (RSU) and Vulnerable Road Users (VRU) carrying either Hand-Held Units (HHU) or OBUs. These D2D links can support a range of road safety use cases such as blind spot warning, lane change warning, do not pass warning, VRU warning, road work warning, emergency

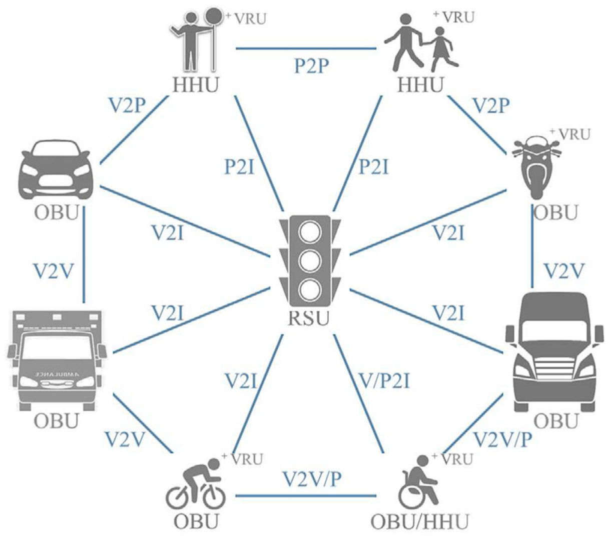

FIGURE 1 The C-ITS Landscape

electronic brake lights, intersection movement assist, and follow-me information for vehicle platooning. Requirements of C-ITS safety applications have been extensively investigated in the literature such as regarding computational complexities [4] and positioning accuracy and timeliness [5]. The consensus is that for Vehicle-to-Everything (V2X) safety applications to be effective, safety messages, that is, Cooperative Awareness Messages (CAM), must be transmitted and received in 100 ms within ranges of 150–300 m via half-duplex broadcast communications. Several studies in both white papers such as [6, 7] and peer-reviewed papers such as [8–16] have recently considered the two competing D2D V2X technologies and compared their performances from various perspectives. The evaluation results of the performance of both technologies suggest that one single technology will not be capable of meeting the requirements of various C-ITS use cases [17]. The strengths and weaknesses in the methodological and analytical approaches taken in the comparative studies of the two technologies, some of which are cited above, will be discussed in the following section after the details of the competing V2X technologies are reviewed.

IEEE 802.11p of the DSRC protocol stack is the native technology developed for V2X communications. DSRC is allocated 75 MHz of spectrum in the 5.9 GHz band by the US Federal Communications Commission (FCC) since 1999 and 30 MHz of spectrum in the same frequency band by the European Telecommunications Standards Institute (ETSI) in 2008. However, the technology has not until recently made it beyond laboratory or field trials for wide deployment. Given its technical advantages, DSRC has been the dominant V2X communications technology for the past several years [11]. The technology has undergone several large-scale field trials across the globe during a rather extended period and has just recently went into production in the US, Europe and Japan for commercial use. In the meanwhile, as the concept of permanent connectivity has evolved with the ubiquity of cellular networks, especially in densely populated areas, the prospect of C-ITS utilizing alternative technologies in place of native DSRC has come closer to reality [11]. As an alternative, LTE-V PC5 Sidelink communications that is based on the LTE cellular technology was recently introduced and is gaining momentum [18]. In this paper, we refer to V2X communications using LTE-V PC5 Sidelink as Cellular Vehicle-to-Everything (C-V2X). The direct communications link of C-V2X defined by the 3rd Generation Partnership Project (3GPP) encompasses fundamentally non-interoperable radio access layer with DSRC because of its different processing and modulation schemes. However, the use cases that can be addressed by the two technologies are identical since both are having identical application, network and security layers.

The challenge however is the need of connected vehicles to communicate with each other regardless of the type of V2X radios in use, thus the integrity of C-ITS would be undermined if a vehicle cannot decode one of the two types of CAM links in a region where both D2D V2X technologies are deployed. Operations of both DSRC and C-V2X in any one geographic area will be a likely situation given the complementary nature of the two technologies (that will be discussed in Section III). R&D projects such as Autotalks's and Unex's dual-mode system [19] have been investigating the coexistence of both technologies, that is, one communications link at a time. Although the coexistence is necessary to avoid both co-channel and adjacent-channel interferences, it is insufficient for a seamless operation in a geographical area where both technologies may be utilised concurrently or simultaneously. While both concurrent and simultaneous words mean 'occurring at the same time,' in this context 'concurrent' is used only for communications links that are propagated a short period of time apart, that is, within a few 100s of milliseconds, whereas 'simultaneous' refers to the communications links that are propagated at the same point in time, that is, within a few 10s of milliseconds.

The above classification for 'simultaneous' links necessitates the use of non-overlapping communications channels for DSRC and C-V2X given the capacity limitations of radio channels and to allow the propagation of dissimilar links simultaneously, that is, at the same point in time. Accordingly, discrete Media Access Control (MAC) mechanisms are necessary to coordinate the communications over the DSRC channel separately to those over the C-V2X channel. Unlike simultaneous links, 'concurrent' communications links allow the utilisation of a single communications channel for dissimilar links one at a time over a brief period in the presence of a common MAC mechanism that coordinates between communicating DSRC and C-V2X units. As mentioned earlier, although several countries have already allocated a range of radio frequencies for C-ITS communications, these allocations do not mandate any specific radiocommunications technology for C-ITS applications in many countries. This therefore does not put restrictions on the operation of the two competing technologies in any one region. Considering the spectrum allocations of C-ITS bands are different in every country with different channel allocations, for discussions this paper considers the ITS radiocommunications Class Licence 2017 of the Australian Communications and Media Authority (ACMA) in which the 5855–5925

TABLE 1 Channel usage in the ITS band in Australia

Frequency range [MHz]	Usage
5855–5865	Non-safety
5865–5875	Non-safety
5875–5885	Safety
5885–5895	Safety
5895–5905	Control
5905–5915	Future applications
5915–5925	Future applications

MHz spectrum (divided into seven 10 MHz wide channels) is made available for C-ITS. The ACMA's ITS Class Licence 2017 closely follows the requirements of the ETSI Standard EN 302 571. Table 1 shows the channel allocations of the ITS band in Australia.

The rest of this paper is organised as follows. Section 2 provides an overview of the current and future states of DSRC and C-V2X. Section 3 discusses the opportunities and potential issues with operations of DSRC and C-V2X in a common region. Section 4 studies hybrid V2X radio system architectures suitable for C-ITS use cases. Challenges for a V2X receiver's Physical Layer (PHY) to support simultaneous transmission of DSRC and C-V2X signals are discussed in Section 5. Section 6 concludes the study.

2 | OVERVIEW OF DSRC AND C-V2X

Today, the two main reliable and low-latency V2X radio access technologies are DSRC and C-V2X. The technology-neutral allocation of the ITS spectrum in many countries including Australia gives way to both DSRC and C-V2X to operate in the 5.9 GHz band, bounded by the relevant regulatory technical conditions. DSRC is designed to primarily operate in the ITS band while C-V2X can operate in both the ITS band and cellular licensed bands. DSRC takes a decentralised approach for the utilisation of the spectrum, while C-V2X supports both centralised and decentralised modes to control radio resources [18]. Both DSRC and C-V2X are being extensively tested and enhanced to support greater reliability, lower latency, and higher throughput.

2.1 | The current state of DSRC and C-V2X

2.1.1 | IEEE 802.11p

The underlying communications technology of DSRC's PHY and MAC layers, is IEEE 802.11p that is specified to operate in the 5.9 GHz frequency rage. In 2010 the Institute of Electrical and Electronics Engineers (IEEE) approved the 802.11p amendment to the IEEE 802.11 Wi-Fi standard, that is, based on IEEE 802.11a, to support Wireless Access in Vehicular Environments (WAVE). IEEE 802.11p supports D2D transmissions in its OCB mode (Outside the Context of a Basic Service Set) that specifies the WAVE physical layer and medium access control facilities used for direct V2X. This amendment was a response to disturbances on V2X radio signals generated by the hostile and rapidly varying radio conditions of WAVE. Comparing to IEEE 802.11a, in IEEE 802.11p the channel bandwidth and carrier spacing are halved to 10 and 0.15625 MHz respectively. This makes the technology to be more sensitive to doppler shift and hence causes carrier frequency offset because of closer narrowband sub-carriers. On the other hand, the symbol duration and all other timing parameters of orthogonal frequency division multiplexing (OFDM) are doubled. These changes have resulted in reductions in the transmission rates by half comparing to those of IEEE 802.11a that are 6–54 Mbps for 20 MHz bandwidth channels. IEEE 802.11p is however more robust to multipath propagation than IEEE 802.11a because of the doubled guard intervals that allow receivers to gather longer echoes. IEEE 802.11p utilises 52 subcarriers which are modulated using various modulation schemes, including BPSK, QPSK, 16-QAM or 64-QAM for efficient packet transmission, plus Forward Error Correction (FEC) coding with a coding rate of 1/2, 2/3, or 3/4. These support mandatory data exchange rates of 3–27 Mbps for WAVE among high-speed vehicles and roadside infrastructure in the licensed ITS band.

At the MAC layer, the IEEE 802.11p standard adopts Wi-Fi's contention-based Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) that is well-characterised and supports distributed operations. Each CSMA/CA transmitter checks if the DSRC medium is idle and waits a random back-off time before every transmission to minimise the probability of collisions. The acknowledgement mechanism and exponential back-off are not observed for V2X DSRC and thus the problem of exponential back-off times for retransmissions occurring in Wi-Fi that may lead to large Contention Window (CW) sizes and thereafter high latencies does not apply to WAVE. Given DSRC is mainly a broadcast-based radio access technology, that is, no exchange of ACK frames is provisioned, the CW parameter used in DSRC's MAC protocol remains fixed [20]. However, the CSMA/CA mechanism imposes considerable overhead on the medium that in turn impacts the overall DSRC goodput. Also, channel congestion control is a well-identified gap in DSRC when the channel occupancy increases to 50–60% or above [21] that is the root cause of the poor scalability of WAVE. This issue has been being investigated by both researchers and standardisation organisations such as IEEE, ETSI and the Society of Automotive Engineers (SAE), for example, through the IEEE 1609.4 standard.

2.1.2 | LTE PC5 Sidelink

Although the WAVE protocol stack, comprising IEEE 802.11p, the IEEE 1609 family of standards and the SAE J2735 and SAE J2945.1 standards, has defined a comprehensive set of C-ITS services, the lack of infrastructure and other limiting features of the lower layers of the stack diverted research towards other V2X technologies. For instance, as previously discussed the IEEE 802.11p standard inherited the Wi-Fi's CSMA/CA scheme for medium access, which may lead to difficulties in ensuring the scalability of Vehicular Ad-hoc Networks (VANETs) as the communications load increases [22]. The introduction of cellular D2D communications (a.k.a., LTE Sidelink) in 3GPP Rel. 12 motivated investigations into 4G LTE-based V2X communications because the advancement of Sidelink in cellular technologies improved the efficiency of spectrum utilisation and the capacity of cellular systems. LTE Sidelink relies on the Single Carrier Frequency Division Multiple (SC-FDM) access scheme used by LTE uplink and was introduced for public safety with two operation modes: Mode 1 and Mode 2. Prolonging battery lifetime of mobile devices was the design aim of both modes, which reciprocally caused the latency to increase. Considering connected vehicles require low-latency (and of course highly reliable) direct V2X communications links, none of the Sidelink modes 1 and 2 are suitable for C-ITS applications. However, an advantage of using the LTE's traditional air interface, namely, LTE-Uu, is that CAM can be sent to a local LTE base station, that is, Evolved Node B (eNB), in the uplink to be forwarded to a remote destination in the downlink by the same or a remote eNB.

The 3GPP introduced Rel. 14 in September 2016, frozen in 2017, as an alternative to DSRC, which includes support for direct V2X communications [23] and can operate within or outside of the coverage of a cellular network. To this end, the cellular communications for direct V2X commonly referred to as Cellular-V2X (a.k.a., LTE-V2X or LTE-V) defines the LTE PC5 interface that supports only broadcast communications at the PHY layer. A PC5 packet contains two components for V2X user data and Sidelink Control Information (SCI). Important details including the Modulation and Coding Scheme (MCS) and the current and future occupied resources are included in the SCI, which are necessary to decode V2X data. The PC5 interface defines the Physical Sidelink Shared Channel (PSSCH) to transmit the data component and the Physical Sidelink Control Channel (PSCCH) to carry the SCI. C-V2X multiplexes PSSCH and PSCCH in the frequency domain, that is, transmits PSSCH and PSCCH on either adjacent or non-adjacent frequency resources in the same sub-frame of the time domain.

Two new modes of communications, namely, Mode 3 (a.k.a., LTE PC5 in-coverage mode) and Mode 4 (a.k.a., LTE PC5 out-of-coverage mode), were introduced in Rel. 14 specifically for direct V2X communications. The difference between Mode 3 and Mode 4 is in the way the radio resources are selected and managed and hence they are referred to as network-controlled LTE PC5 and standalone LTE PC5 respectively. In Mode 3, the User Equipment (UE), for example, OBU/RSU/HHU, needs to access the cellular network to receive control information from the network for the management of radio resources for direct V2X. To this end, Mode 3 provides Vehicle-to-Network (V2N) services that supports V2X links via LTE-Uu. The UE utilises the LTE-Uu interface to connect to base stations (eNBs) on the core network via the uplink (SC-FDM) to receive control information for direct V2X via the downlink (OFDM). On the other hand, the LTE PC5 interface can be utilised in the absence of V2N connections for supporting low-latency and high-reliability D2D V2X services. Mode 4 defines the standalone LTE PC5 air interface for V2X between UEs without requiring them to connect to an eNB. To this end, Mode 4 includes a distributed scheduling scheme, that is, sensing-based Semi-Persistent Scheduling (SPS), that allows UEs to autonomously select radio resources for V2X without cellular coverage. LTE PC5 Sidelink supports distributed congestion control, and because its Mode 4 does not depend on the availability of cellular networks it is considered the benchmark mode of C-V2X that competes with and/or complements IEEE 802.11p.

C-V2X Mode 4 utilises SC-FDM and supports channels with 10 and 20 MHz of bandwidths with each channel divided into sub-channels in the frequency domain and sub-frames (with 1 ms transmission time intervals) in the time domain. Sub-channels are further divided into Resource Blocks (RBs). An RB with a 180 KHz frequency width is the smallest frequency resource unit that can be allocated to an LTE user (that includes 12 sub-carriers of 15 KHz bandwidth). Each sub-channel is defined as a group of a variable number of RBs in the same sub-frame of the resource grid and is used to transmit control information including MCS and user data. Safety data such as a beacon or a CAM are transmitted in Transport Blocks (TBs) using QPSK or 16-QAM with turbo coding. Each TB is transmitted in a PSSCH along with its relevant SCI transmitted in a PSCCH (occupying two RBs), which may be positioned adjacent or non-adjacent to each other in the same sub-frame. Correct receptions of TBs that may span across multiple sub-channels are vital for decoding the transmitted message. Comparing to SPS, the C-V2X dynamic scheduling algorithm permitted in Mode 3 allows for better exploitation of spatial frequency by scheduling two or more V2V transmissions on the same RBs if the frequency reuse results in a weak mutual interference over a given geographical area. The eNB saves valuable frequency resources through the frequency reuse mechanism that potentially reduces the delay before transmissions of several V2X packets. However, the frequency reuse distance is reduced as the traffic density grows that itself may produce a counterproductive result by causing interference levels among C-V2X users to increase.

2.1.3 | Technical properties and performance of IEEE 802.11p and LTE PC5

Table 2 summarizes the technical properties of the two competing D2D V2X technologies—namely, IEEE 802.11p and LTE PC5. Although LTE PC5 Mode 3 is not considered in the comparison represented in Table 2 because of its fundamental difference that includes its dependence on the coverage of the cellular network, its performance is compared with that of IEEE 802.11p and LTE PC5 Mode 4 in the literature. Figure 2 demonstrates a summary of comparative studies reported in the literature since 3GPP Rel. 14. The results of comparative studies are shown in four broad categories including highway and urban scenarios as well as high and low channel load scenarios. The consolidation of the literature survey findings shown

TABLE 2 Technical properties of IEEE 802.11p and LTE PC5

Parameters	IEEE 802.11p	LTE PC5 – Mode 4
Access technology	Wi-Fi CSMA	LTE uplink
PHY Waveform	OFDM	SC-FDM
Transmission time	0.4 ms (typical)	1 ms
Modulation mode	BPSK, QPSK, 16QAM, 64QAM	QPSK, 16QAM
Code (rate)	Convolution (1/2, 2/3, 3/4)	Turbo (QPSK - 0.13, 0.17, 0.21, 0.27, 0.33, 0.41, 0.48, 0.57, 0.65, 0.73, & 16QAM - 0.41, 0.46, 0.52, 0.59, 0.67, 0.72, 0.75, 0.84, 0.92, 1.00)
Number of subcarriers	52 (OFDM)	12 per RB (SC-FDM)
Subcarrier spacing	0.15625 MHz	0.015 MHz
Symbol duration	8 μs	71 μs

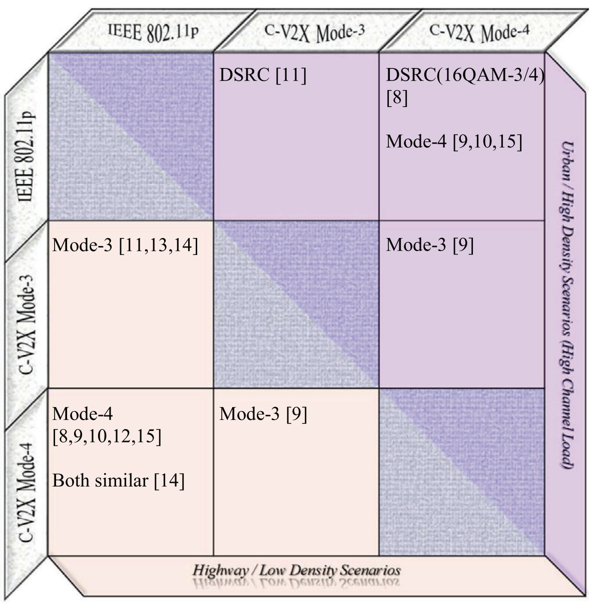

FIGURE 2 Performance of IEEE 802.11p vs. C-V2X Reported in Literature – each cell identifies the superior technology between the two associated with the cell in its respective scenario alongside the references supporting the claim.
Note: the default MCS considered for DSRC is QPSK-1/2 unless otherwise stated

in Figure 2 confirms that none of these technologies is the best single option for diverse V2X scenarios. Having said that, several limitations are prevalent in the methodological and analytical approaches adopted in most of the studies referred to in Figure 2. First and foremost is the use of simulation studies as opposed to field trials. Although simulation studies usually provide reliable results, they are often limited in scope, that is, consideration of specific use cases such as platooning [15], and are carried out under ideal conditions [11] or with non-optimal settings [14] that in turn affects the comprehensiveness of results. Secondly, although the basic consensus is that C-V2X performs better in larger areas comparing to its DSRC opponent, the contributions that potential PHY and MAC improvements of DSRC can offer are not comprehensively studied, and that many traffic scenarios are less investigated.

2.2 | The future of DSRC and C-V2X

Research shows both DSRC and C-V2X may consistently support C-ITS safety applications demanding a D2D latency of 100 ms in vehicular environments with a low to moderate density [8]. However, advanced V2X applications and ever challenging vehicular environments may demand more stringent quality of service (QoS) consistency [24] that is not serviceable by the current states of IEEE 802.11p and LTE PC5 [25]. The currently unresolved V2X challenges coupled with the limitations of IEEE 802.11p and LTE PC5 in addressing futuristic demands of the highly mobile VANETs have ignited the designs of IEEE 802.11bd and 5G New Radio (NR) C-V2X. These enhancements are vital to the efficacy of C-ITS considering a broad and growing set of V2X use cases demand for improvements in terms of data rates, latency, reliability and QoS to efficiently support hybrid connectivity (of DSRC and C-V2X) and heterogeneous services. Futuristic use cases of V2X are beyond the initial safety and collision avoidance services and include integrated autonomous services such as coordinated driving and dynamic ride sharing that require V2X discovery, remote control services, context awareness and real-time management of fleet and road transport [10]. Futuristic use cases of V2X are essentially different because of the higher degree of autonomy exerted in cooperative vehicles, which for fully autonomous driving require a link reliability of at least 99.999% (up from 90%–99% required for lower levels of autonomy) and a link latency of up to 3 ms (down from 100 ms required for lower levels of autonomy) [26].

2.2.1 | Next generation DSRC (IEEE 802.11bd)

The IEEE Task Group 802.11bd (TGbd) was formed in January 2019 out of the IEEE 802.11 Next Generation V2X Study Group formed since 2018. The aim of TGbd is to not only lessen the performance gap in areas where C-V2X outperforms DSRC but also add additional modes of operations to DSRC and increase the throughput offered by the technology [25]. Key goals of the next-gen DSRC include doubling the throughput at MAC and enabling longer communications ranges by reducing the noise sensitivity level [26]. Some key changes in the PHY layer of the next-gen DSRC may include the inclusion of OFDM numerology of IEEE 802.11ac for better efficiency, the adoption of Low-Density Parity Check (LDPC) forward error correction codes to enable higher coding, the utilisation of midambles for improved channel estimation, the adoption of higher modulation and coding schemes such as 256-QAM with

TABLE 3 Technical properties of IEEE 802.11bd and NR C-V2X

Parameters	IEEE 802.11bd	NR C-V2X
Base technology	IEEE 802.11n/ac	5G NR
PHY waveform	OFDM	OFDM (mini-slot scheduling)
MAC	CSMA	Mode 1: gNB schedulingMode 2: Flexible sub-mode
MCS	QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM
Subcarrier Spacing (Sub-6 GHz Spectrum)	78.125 KHz, 156.25 KHz, 312.5 KHz	15 KHz, 30 KHz, 60 KHz
Retransmissions	Congestion dependent	HARQ
Interoperability	Yes with 802.11p	Yes, non-co-channel with C-V2X
Backward compatibility	Co-channel with 802.11p	No

the coding rate of 3/4, and the consideration of packet retransmission to improve reliability and mitigate multipath fading [26]. Furthermore, some key changes in the MAC layer of the next-gen DSRC may include the adoptions of the fast basic service set transition feature of IEEE 802.11r and the fast-initial link setup feature of IEEE 802.11ai on top of the OCB mode, and the introduction of a dedicated packet for error correction [26].

2.2.2 | Next generation C-V2X (5G NR C-V2X)

The development of New Radio (NR) C-V2X as a part of 3GPP Rel. 16 is underway, that is, the proposed Freeze date is March 2020 and the completion date is June 2020. The NR C-V2X standard is being built based on 5G NR that was standardised in Rel.15. NR C-V2X will support more stringent QoS requirements of advanced V2X applications [24]. The advancements of C-V2X aiming at supporting ultra-high reliability that corresponds to the packet delivery ratio (PDR) of 99.999% [27] pave the way for a plethora of data intensive use cases including advanced access paradigms such as cooperative navigation, vehicular fog and cognitive radio. For instance, Mode 1 of 5G NR (that is equivalent to C-V2X Mode 3) requires vehicles to share location information with the 5G NR gNB base station (that is the equivalent of eNB of 4G-LTE), which can assist with location-based use cases. Additionally, Mode 2 of 5G NR (that is equivalent to C-V2X Mode 4) provisions the assisted resource allocation mechanism, which can assist with optimising the utilisation of spectrum for groupcasting. Some key enhancements being considered for the PHY layer of the next-gen C-V2X include the definition of various submodes to allow vehicles assist others with resource allocations in addition to autonomous resource allocations, the introduction of a mechanism for fast Sidelink scheduling and the support for flexible sub-carrier spacing to improve latency, the provision of pre-emptive resource scheduling to give way to critical messages, the inclusion of Hybrid Automatic Repeat Request (HARQ) scheme for adaptive retransmissions, and the adoption of higher modulation schemes such as 256-QAM [26]. Furthermore, some key changes in the MAC layer of the next-gen C-V2X may include the inclusion of unicast and groupcast communications, the scheduling of mini-slot and multi-slot for more efficient slot allocations, and the adaption of the sensing window according to mobility conditions for fast resource allocations [26].

2.2.3 | Technical properties of and challenges for IEEE 802.11bd and NR C-V2X

Table 3 summarises the technical properties of the two future D2D V2X technologies—namely, IEEE 802.11bd and NR C-V2X. Both evolutionary IEEE 802.11bd and NR C-V2X are being developed based on similar design objectives but rather different design methodologies. Both technologies aim at enhancing bandwidth, latency and reliability. The IEEE TGbd has specified the next generation DSRC must support interoperability, coexistence, backward compatibility, and fairness with deployed OCB devices, that is, based on IEEE 802.11p, while similar constraints are not imposed on NR C-V2X by 3GPP. This implies that DSRC devices based on 802.11p and 802.11bd will naturally be able to communicate with each other while tuned to the same channel. However, with the emergence of hybrid connectivity that will support the shift from connecting vehicles on roads to fully autonomous driving, scalability, responsiveness and security of V2X links are still among the challenging requirements needed to enable ultra-high reliability and ultra-low latency for advanced use cases.

The challenges these evolved technologies will face, to a great extent, are still dependant of situational factors such traffic density and dynamics, which are in fact different in nature. For instance, many V2X links in an urban setting are non-line-of-sight (NLOS), particularly in dense city areas where the path of propagation, to a varying degree, is obscured. Furthermore, addressing the heterogeneity of hybrid V2X networks and allocations of fog-based resources are emerging challenges related to the deployment of the next-gen DSRC and the next-gen C-V2X [26]. In fact, supporting seamless communications that maintain high throughput and low latency in the heterogeneous V2X environment requires advanced resource allocation protocols at the network level. In particular, allocations of time slots and channel estimation in IEEE 802.11bd and allocations of resource blocks in 5G NR C-V2X represent key challenges when both technologies operate in the same channel [26, 28]. Thus, further research is necessary to investigate how and to what level these evolved V2X technologies are able to support advanced use cases of connected vehicles and their emerging roles.

3 | CONCURRENT AND SIMULTANEOUS OPERATIONS OF DSRC AND C-V2X

A diverse range of studies and tools including analytical models, simulations and field trials have been used to characterise the performance of both DSRC and C-V2X. PDR that shows the percentage of the number of packets received at a target receiver (Rx) to the total number of packets transmitted from a reference transmitter (Tx) is a common performance metric being used to measure the performance of V2X links. It is proven that the performance of IEEE 802.11p DSRC is satisfactory for most safety applications requiring a latency of 100 ms in low(-to-moderate) vehicular traffic densities [20]. DSRC however suffers from poor scalability when the density of vehicles increases, that is, the PDR of DSRC declines rapidly in dense traffic because of channel congestion due to excessive simultaneous transmissions, mainly from hidden nodes [25]. Various congestion control mechanisms [29] have been proposed that typically control transmission parameters like transmission power (coverage area) and/or CAM exchange rate (packets/second) to make up for the poor scalability of DSRC. Existing literature shows LTE PC5 Mode 4 offers performance advantages compared to IEEE 802.11p DSRC because of better resilience to interference, better link budget and better NLOS reception as per the experimental findings in [30]. Having said that most C-V2X performance characterisation studies have been based on simulations which may have been influenced by limitations of simulation studies.

Figure 3(a) confirms both C-V2X PC5 Mode 4 and IEEE 802.11p (18 Mb/s data rate) deliver comparable PDR for Tx-Rx distances of less than 200 m while C-V2X PC5 Mode 4 outperforms IEEE 802.11p (18 Mb/s data rate) when the distance between Tx and Rx becomes larger than 200 m due to the performance of physical layer. Figure 3(a) is a reproduction of a simulation study conducted in [8] with minimal congested traffic, that is, lower CAM exchange rate (10 CAM per second). Figure 3(b) that is a reproduction of a second simulation study conducted in [8] further illustrates both C-V2X PC5 Mode 4 and IEEE 802.11p DSRC (18 Mb/s data rate) do not perform as well when the channel is more congested, that is, higher CAM exchange rate (50 CAM per second), because of the increase in packet collisions in such traffic scenarios. Anyhow, considering Figure 3(b) IEEE 802.11p (18 Mb/s data rate) slightly outperforms LTE PC5 Mode 4 in more congested traffic and for Tx–Rx distances of larger than 100 m despite the design advantages that C-V2X LTE PC5 have over IEEE 802.11p DSRC.

The deficiencies existing in the performance and scalability of both IEEE 802.11p DSRC and C-V2X PC5 Mode 4 have been the sources of major concerns within the C-ITS community and hence the developments of IEEE 802.11bd DSRC and C-V2×5G NR. Now that C-ITS will have more than one option for its V2X communications, its functional and technical problem domains surrounding the integrity of the available or proposed radio access technologies have become more tangled. This leads to a major research gap that is how to ensure integrity in operations of radios of competing technologies for uncompromised hybrid V2X in the 5.9 GHz spectrum. In this context, hybrid V2X refers to the use of at least one version of DSRC in conjunction with the use of at least one version of the C-V2X technology in one geographic area to increase the effect on C-ITS safety objectives. We argue such a definition mandating the requirements of interoperability, coexistence, compatibility, and fairness proposed for IEEE 802.11bd to work with IEEE 802.11p [31] should be extended to every pair of V2X radio access technologies, whether they belong to the same family of V2X technology or different families of V2X technologies. This is because many countries such as Australia consider technology neutrality in the ITS band for efficient use of the spectrum. Hence, the functional definitions of the four integrity

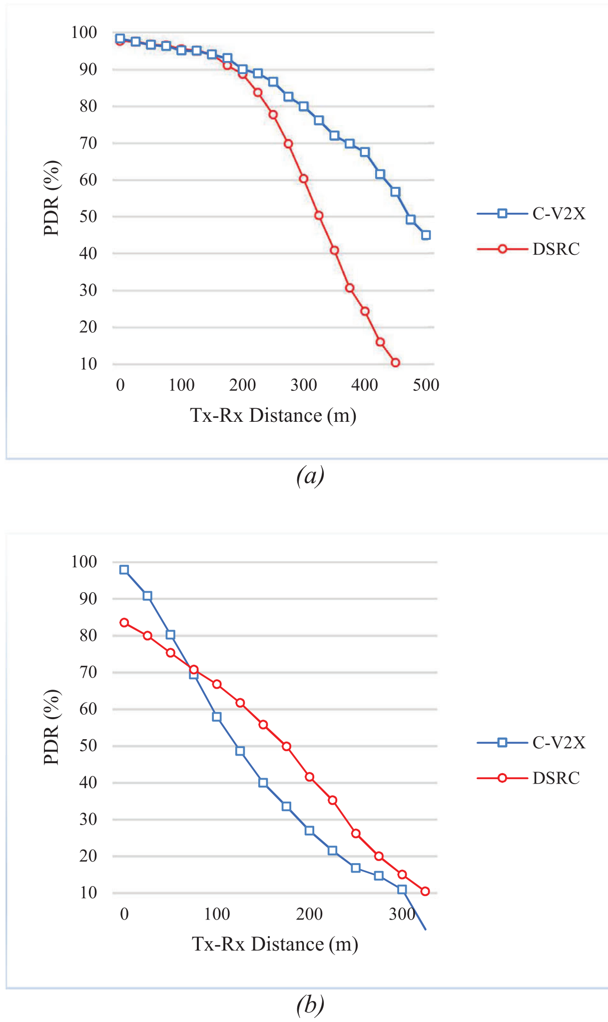

FIGURE 3 Performance of IEEE 802.11p (18 Mb/s) and LTE PC5 Mode-4 (a) CAM at 10 Hz, (b) CAM at 50 Hz

requirements for uncompromised hybrid V2X safety services can be defined as follows:

- Interoperability—the ability of devices of a V2X technology to decode at least one mode of transmission by devices of other V2X technologies, and vice versa;
- Co-existence—the ability of devices of a V2X technology to detect and defer to transmissions by devices of other V2X technologies to avoid collisions, and vice versa;
- Compatibility—the ability of devices of a V2X technology to operate in a mode that can interoperate, that is, exchange messages, with devices of other V2X technologies, and vice versa;
- Fairness—the ability of devices of a V2X technology to allow the same access opportunities for devices of other V2X technologies to use the channels of the ITS band, and vice versa.

The abovementioned integrity requirements ensure all users gain an uncompromised access to critical road safety related information whatever V2X technology used. However, enabling co-channel coexistence of DSRC and C-V2X, that is, access to the same shared channel, to increase the 'concurrent' utilisation of the ITS band imposes a different set of technical challenges than enabling adjacent-channel coexistence, what is, access to non-overlapping dedicated channels, to improve the 'simultaneous' throughput of the ITS band. Each of these sets of challenges demands distinct technical definitions for the four integrity requirements for uncompromised hybrid V2X safety services:

- Interoperability – [in both shared and dedicated channel access strategies] the prioritisation of safety critical information needs to be common to all competing, or alternative, technologies and conforms to the same scaling properties so that those message types can be decoded by all road users with the same priority;
- Co-existence –
  - [in the time-slotted shared channel access strategy] the avoidance of co-channel interference needs a common 'concurrent' transmission mechanism for all competing, or alternative, technologies that allows for identification of heterogeneous terminals operating in the same channel; and
  - [in the non-overlapping dedicated channels access strategy] the avoidance of adjacent-channel interference needs a common 'simultaneous' transmission mechanism for all competing, or alternative, technologies that allows for identification of heterogeneous terminals operating in adjacent channels;
- Compatibility – [in both shared and dedicated channel access strategies] the realisation of both heterogeneous and backward interoperability amongst all competing, or alternative, technologies requires the use of similar physical layers and medium access control protocols;
- Fairness – [in both shared and dedicated channel access strategies] the maximisation of throughput for reliable operations necessitates the use of equal spectrum bandwidth by all competing, or alternative, technologies to exchange information with the same priority.

At present, none of the families of V2X technologies proposed for use in the ITS band, that is, DSRC and C-V2X, has mechanisms in place to meet the above functional and technical integrity requirements for uncompromised V2X safety services. Hence, in the absence of an appropriate solution, that is, hybrid V2X, one family of V2X radio access technologies is unable to operate without the exclusion of the other family of V2X communications, or of co-/adjacent-channel interferences and serious impairment of safety applications. Having said that, if interoperability, coexistence, compatibility, and fairness can be provided with any type of V2X devices, whether by their nature or through add-in radio components, all V2X technologies can be utilised with no ITS band or channel fragmentation and no loss of C-ITS services.

4 | HYBRID V2X SYSTEM ARCHITECTURES

DSRC and C-V2X are derived from fundamentally different technologies that resulted in different operational characteristics. DSRC inherently supports distributed operations whereas C-V2X (mode 4 – distributed algorithms) is induced with supplementary mechanisms to enable distributed operations. When both DSRC and C-V2X are utilised in a common geographical area such as a country or a subcontinent without a practical coexistence solution they will mutually encounter harmful channel interferences. Hybrid V2X systems are a fundamental part of a comprehensive solution to the heterogeneity of the emerging environment of C-ITS as a stop-gap until interoperability, coexistence, compatibility, and fairness are embedded within all V2X communications technologies. An inclusive hybrid V2X system that is a system capable of decoding CAMs of any types would eliminate the need for a global standardisation for V2X communications as long as all technologies individually meet the technical requirements of safety use cases. A hybrid multiple-radio approach can be also considered to support redundancy for improved V2X operations.

Figure 4 illustrates all possible complementary inclusive hybrid V2X communications systems. To perform the required decoding of different types of CAMs for interoperability, inclusive hybrid V2X systems must be equipped with either dual-Rx units of appropriate types (Units i, ii and iii in Figure 4) or a translator-Rx (Units iv, v and vi in Figure 4). A translator-Rx is essentially a cognitive protocol translator capable of translating between DSRC and C-V2X packets (like the one proposed in [32]) which allows interpretation of different types of CAMs. Single-Tx hybrid V2X systems (Units i, ii, iv and v in Figure 4) allow auto manufacturers to fit only one type of Tx and go through only one certification process, which means reduced total costs of ownership for OEMs. On the other hand, dual-Tx hybrid V2X systems (Units iii and vi in Figure 4) can optimise transmission parameters of CAM signals according to specific situations, that is, it may be advantageous to send a CAM

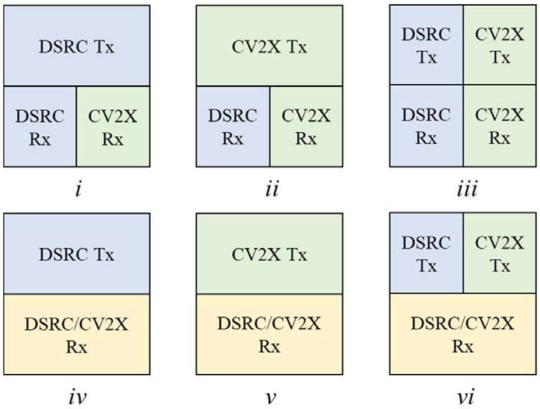

FIGURE 4 Inclusive hybrid V2X communications units enabling concurrent and simultaneous operations of DSRC and C-V2X

using DSRC rather than C-V2X in some scenarios or vice versa. Dual-Tx hybrid V2X systems would potentially provide better support for users including VRU such as cyclists carrying HHU. Figure 5 illustrates the evolution of hybrid V2X environments, including single-Tx environments (that solely consist single-Tx systems), mix-Tx environments (that consists a mixture of single-Tx systems and dual-Tx systems) and dual-Tx environments (that consist dual-Tx systems).

4.1 | Reception of CAM in hybrid V2X environments

Considering the nature of the hybrid V2X environments, two multiplexing approaches for V2X coexistence can be supported using the proposed inclusive hybrid V2X systems: (1) Frequency Division Multiplexing (FDM) where non-overlapping dedicated channels are separately allocated to 'simultaneous' DSRC and C-V2X propagations, and (2) Time Division Multiplexing (TDM) where a time-slotted shared channel is jointly assigned to 'concurrent' DSRC and C-V2X traffic, that is, alternating pattern. While FDM is the way forward for adjacent-channel coexistence, TDM is the preferred approach for co-channel coexistence in the absence of fair contention-based access methods based on equal priorities for both V2X technologies. Dual-Rx hybrid V2X systems (Units i, ii and iii in Figure 4) can support FDM by simultaneously tuning to separate channels while translator-Rx hybrid V2X systems (Units iv, v and vi in Figure 4) require a frequency hopping protocol to support FDM. On the other hand, dual-Rx hybrid V2X systems (Units i, ii and iii in Figure 4) support TDM by concurrently tuning to the same channel while translator-Rx hybrid V2X systems (Units iv, v and vi in Figure 4) support TDM by constantly tuning to the one channel allocated for co-channel coexistence.

4.2 | Propagation of CAM in Mix-Tx and Dual-Tx environments

In the interest of an increased spectrum utilisation, an optimising scheme that enables co-channel coexistence for dual-Tx hybrid V2X systems is necessary. Single-Tx hybrid V2X systems are exempt from requiring such an optimising scheme given the non-selective nature of their Tx. Decisive factors of choosing between DSRC and C-V2X are of two bases, namely situational and computational. Amongst the situational factors are the density, distance, pattern and speed of traffic, while the channel estimation and Signal-to-Noise Ratio (SNR) factors are amongst the computational measures that can be considered. While the computational factors are measured at the PHY layer, the situational factors are assessed at the MAC and higher layers. Given the multitude of combined effects of situational and computational factors, prior performance characterisation tests of combinatorial factors are required to classify the superiority of one of alternative V2X technologies in each scenario. Further research is essential to characterise the effects of situational and computational factors on performance of DSRC versus that of C-V2X. Machine and deep learning approaches are candidates for developing a fair multi-criteria recommender system that considers different situational and computational factors when selecting the right V2X technology for Tx.

5 | PHY AND MAC OF DSRC AND C-V2X FOR HYBRID V2X

Figure 6 shows the results of a preliminary simulation study on the performance of DSRC and C-V2X with 10 Hz messaging rate for both FDM and TDM operations. As discussed, the time and frequency characteristics of DSRC and C-V2X signal resource grids and their channel access methods are fundamentally different. IEEE 802.11p-based DSRC adopts CSMA/CA using the OFDM modulation scheme as its channel access technology whereas SPS using synchronised SC-FDM is the channel access approach defined in 3GPP Rel. 14 for the Mode 4 D2D C-V2X. Due to these significant differences a co-channel coexistence solution based on equal priorities does not readily exist in the current standards. If the co-channel coexistence solution requires contention for access, CSMA/CA transmitters would be significantly disadvantaged against by UEs utilizing sensing-based SPS that operate in the same channel. Even under the TDM approach as can be seen in Figure 6 that has studied a contention-less environment with alternate DSRC and C-V2X transmissions, C-V2X outperforms DSRC. An IEEE 802.11p device always operates over the entire 10 MHz spectrum of the operating channel for a duration between 0.4 and 1 ms, whereas a C-V2X (LTE PC5 Sidelink) device operates in RBs with fixed frequency and time allocations. It is however possible for a C-V2X device to also occupy the entire frequency channel by combining individual RBs if the RB allocation strategy permits.

The SC-FDM modulation scheme has accommodating time domain properties that make it easier for LTE PC5 Mode 4 C-V2X to adopt co-channel TDM hybrid mode. However, the favourable time domain properties of LTE PC5 Mode 4 are achieved at the costs of higher out-of-band emission levels in the frequency domain. Although the out-of-band emission is optimisable at UE in the absence of eNB at additional costs due to implementation complexity, SC-FDM receivers are generally

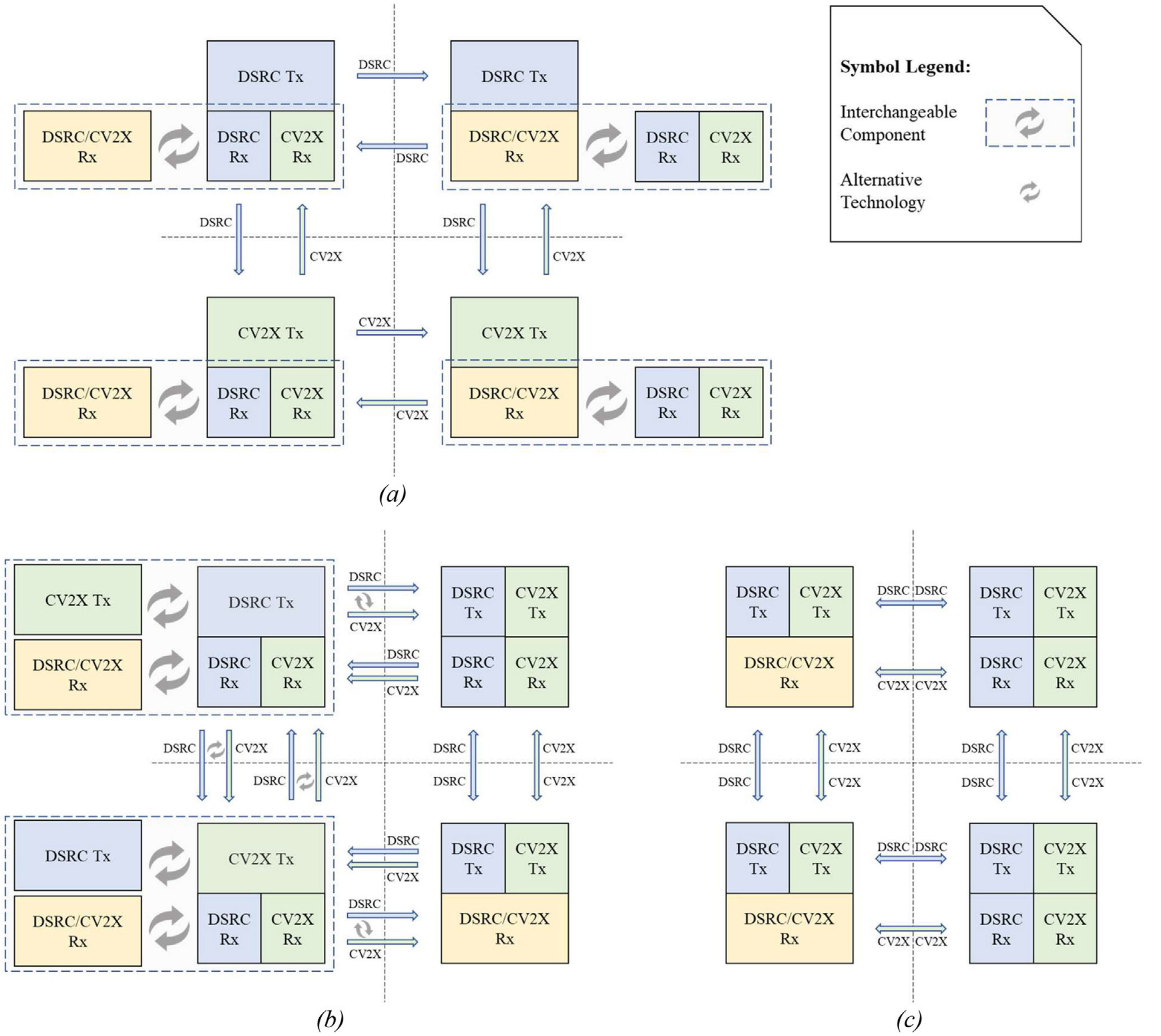

FIGURE 5 Evolution of hybrid V2X environments supporting concurrent and simultaneous operations of DSRC and C-V2X (a) single-Tx environment, (b) mixed-Tx environment, (c) dual-Tx environment

less robust against multipath fading in highly dynamic environments. On the other hand, OFDM devices do not require complex receivers to efficiently handle multipath propagation because of simple and cost-efficient Fast Fourier Transform (FFT) techniques that enable scalable OFDMA with respect to bandwidth by changing the FFT size. However, OFDM signals suffer from high Peak-to-Average-Power Ratio (PAPR), that is, high amplitude variability that necessitates larger backoffs in amplifiers to ensure linear behaviour. PAPR increases as the number of subcarriers increases and typically leads to reduced amplifier efficiency.

FDM by its nature avoids any co-channel interference between DSRC and C-V2X technologies altogether, whereas TDM requires a method of channel sharing, that is, mutual fair detect-and-vacate, to be put in place so to minimise the likelihood of harmful co-channel interference. Also, no tight synchronisation between DSRC and C-V2X is needed for FDM operations when each technology operates in a separate channel. However, the allocation of channels and allowable transmission powers must consider effects of adjacent-channel interference where FDM is the multiplexing strategy. For instance, the results of the interference test reported in [25] indicates the PDR of C-V2X may be degraded by 30% at Rx-Tx distances of up to 100 m if the frequency separation between channels being simultaneously utilised is reduced from 10 MHz (one channel gap) to 0 MHz (adjacent). Also, FDM will lead to a significant decrease in interoperability capabilities of single-Rx systems (and hence, in this study, single-Rx systems are not included in the collection of the inclusive hybrid V2X systems that ensure coexistence and compatibility between DSRC and

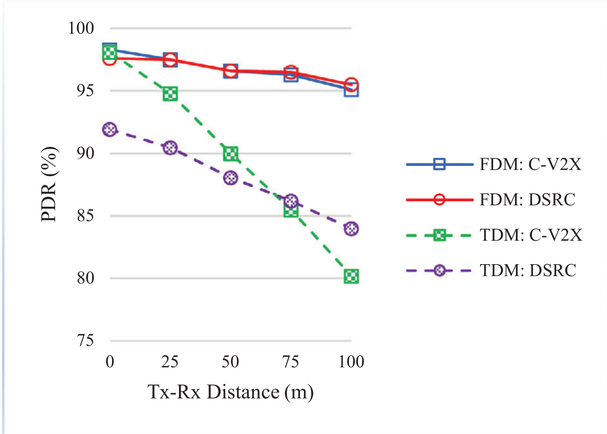

FIGURE 6 Performance of IEEE 802.11p (18 Mb/s) and LTE PC5 Mode-4: FDM and TDM (10 Hz switching rate)

C-V2X). On the other hand, tight synchronisation requirements are imposed by TDM for operations of DSRC and C-V2X in the same channel. Although this approach allows for the most efficient use of the ITS spectrum, it makes it more challenging to serve safety applications requiring low latency.

6 | CONCLUSION

The comparison between DSRC and C-V2X is multi-dimensional given their technical dissimilarities. The impact of every parameter needs a separate analysis based on the requirements and properties of V2V applications given the technology neutrality in ITS spectrum allocations in many countries. The multi-channel nature of the ITS band increases the likelihood of adjacent-channel interference in the absence of proper considerations for channel allocations and transmission powers. Adjacent-channel interference test results of various studies have demonstrated potential problems caused by simultaneous operations of DSRC and C-V2X on adjacent channels if the transmitters are in close proximity. The nature of hybrid V2X environments challenges the assumption associated with early DSRC systems that each vehicle is equipped with a single V2X radio and hence the current multi-channel operation standards such as IEEE 1609.4 may no longer be valid. Also, the operation of the two technologies in the same channel for concurrent transmissions without a mutual synchronisation solution would result in harmful co-channel interference. Both co-/adjacent-channel interferences are still open research problems in hybrid V2X systems.

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