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On the Design of Sidelink for Cellular V2X: A Literature Review and Outlook for Future

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ABSTRACT Connected and fully automated vehicles are expected to revolutionize our mobility in the near future on a global scale, by significantly improving road safety, traffic efficiency, and traveling experience. Enhanced vehicular applications, such as cooperative sensing and maneuvering or vehicle platooning, heavily rely on direct connectivity among vehicles, which is enabled by sidelink communications. In order to set the ground for the core contribution of this paper, we first analyze the main streams of the cellular-vehicle-to-everything (C-V2X) technology evolution within the Third Generation Partnership Project (3GPP), with focus on the sidelink air interface. Then, we provide a comprehensive survey of the related literature, which is classified and critically dissected, considering both the Long-Term Evolution-based solutions and the 5G New Radio-based latest advancements that promise substantial improvements in terms of latency and reliability. The wide literature review is used as a basis to finally identify further challenges and perspectives, which may shape the C-V2X sidelink developments in the next-generation vehicles beyond 5G.

INDEX TERMS 5G, cellular-vehicle-to-everything, literature review, new radio, sidelink.

I. INTRODUCTION

We are entering a new mobility era, characterized by an increasing number of vehicles which are connected to the Internet and to neighboring road elements, such as other vehicles, pedestrians, traffic lights, or roadside units. According to Strategy Analytics, about 60% of new vehicles in North America, Europe, and China, have cellular connectivity and this number is projected to grow to 85% by 2025. At the same time, noticeable advances are observed toward the deployment of vehicles with higher and higher automation levels, which let an automatic on board system take control over driving and eventually make the driver enjoy the ride as a passenger.

On the path towards a fully automated mobility, where vehicles can perform any driving function under all conditions without driver intervention, future vehicles will have to increasingly rely on more than their own sensors.

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Wireless communications will be the key to boost their perception capability of the surrounding environment and to enable exchanging manoeuvring intentions. This will allow the vehicles to cooperatively drive and build an extended (even in non-line of sight) horizon, so to promptly and accurately detect the presence of nearby cars, objects and other road users, and to react accordingly. Such a scenario introduces unprecedented challenges to the underlying vehicle-to-everything (V2X) communication technology.

The first set of radio standards enabling V2X communications was based on the IEEE 802.11 technology [1], and was referred to as dedicated short range communication (DSRC)/wireless access in vehicular environment (WAVE). This technology has long been considered, in both Europe and the US, as the only key enabler for V2X connectivity. More recently, however, the Third Generation Partnership Project (3GPP) has introduced device-to-device (D2D) communications over the PC5 interface as a new feature to enable direct connectivity through what is referred to as the *sidelink*.

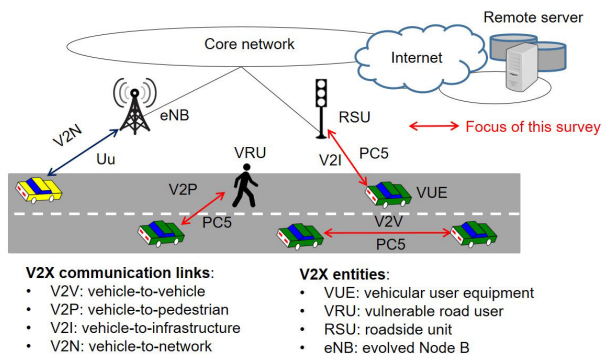


FIGURE 1. V2X communication links, entities and radio interfaces.

Within the V2X context, the sidelink refers to the direct communication between vehicles, between vehicles and vulnerable road users (VRUs), and between vehicles and road side units (RSUs). More precisely, 3GPP uses vehicular user equipments (VUEs) to denote the vehicles, and vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), vehicle-to-infrastructure (V2I), to address the different kind of links, as specified in [22] and exemplified in Figure 1. Sidelink over the PC5 interface is intended in addition to conventional uplink/downlink communication over the *Uu* interface, which has also been tailored to the specific automotive vertical's needs and can be exploited for both V2I or vehicle-to-network (V2N) interactions, i.e., to provide connectivity to the cloud. The resulting technology is often referred to as *cellular-V2X* (*C-V2X*), which is an umbrella term that includes both the long term evolution (LTE) enhancements and the fifth generation (5G) new radio (NR) latest advancements to support V2X communications using cellular technologies.

A. ROADMAP OF 3GPP C-V2X SIDELINK SPECIFICATIONS

The use of cellular networks for vehicular applications is definitely not a new concept as it dates back to at least twenty years ago [23]–[26]. With the advent of the fourth generation (4G) technology, such interest increased [27]–[31], and 4G was applied initially to V2I and, in general, to V2X applications [2], [32]–[34]. The extension of the D2D mode to V2X communications started to gain much attention with 3GPP Release 12. Some preliminary works, such as [35]–[37], attempted to apply D2D communications to the vehicular scenario.

It was only after assessing the technological feasibility and the undoubted commercial opportunities for network operators, that in the first quarter of 2015 3GPP launched a feasibility study to include C-V2X in the new Releases of the standards. Since then, the specifications evolved, Release by Release, by incorporating new features and capabilities with special attention to direct communications.

A first version of C-V2X was published in March 2017, in Release 14. At that time, the 4G LTE system was under development and thus, the specification addressing

the automotive vertical needs was named *LTE-V2X*. Since Release 15, frozen in 2018, in addition to refinements to LTE-V2X, the 3GPP started to work within the 5G framework at the specifications of the so-called *5G-V2X*. Regarding the 5G-V2X, use cases and requirements were identified in Release 15, while a first set of NR V2X specifications, including the sidelink, were defined in Release 16, frozen in June 2020. Improvements to sidelink 5G-V2X are expected in Release 17, which is still undergoing and planned to be issued by 2022.

B. MOTIVATIONS AND CONTRIBUTION OF THIS SURVEY

Since the real beginning, the sidelink interface appeared as the most revolutionary and demanding design aspect of C-V2X, and its deployment catalyzed the interest of standardization groups and fora, and research scientists worldwide. The majority of vehicular applications, ranging from the LTE-V2X use cases that support basic active safety (such as emergency braking, collision warning, intersection management, etc.) to the enhanced V2X (eV2X) use cases specified for 5G-V2X (such as vehicles platooning, advanced driving, extended sensors) consider *direct* communications as a necessary requirement. The reasons are multifold. First, most of the communication interactions are localized in the vehicle's neighborhood, so there is no need for data going through the network. Second, vehicular entities may need to reliably exchange sensor data and driving intentions even outside the coverage of the cellular network. Third, latency is a critical parameter for safety-critical applications, for which any delay introduced by the transit through a fixed communication infrastructure may be unacceptable.

Recently, a large number of surveys and tutorials addressed cellular-based V2X communications, among which [2]–[21]. In order to better remark the difference between our survey and the cited works, in Table 1 per each of the mentioned reference it is indicated: (i) if it refers to cellular systems before Release 14, LTE-V2X, or 5G-V2X; (ii) if it focuses on infrastructure-based communications (*Uu* interface) or sidelink (*PC5* interface); (iii) if it provides tutorial details on the 3GPP specifications (indicated as *Specs*); (iv) if it includes a significant review of the literature on the discussed aspects (indicated as *Review*); and (v) if it includes original results (indicated as *Results*).

As indicated in the Table, earlier works referred to standards before LTE Release 14; they explored the suitability of cellular networks to support V2X use cases [2], [3], [8] or they anticipated the novel sidelink specifications that were at that time under definition [4]–[6]. The sidelink LTE-V2X included in Release 14 was then detailed by the tutorial work of Molina-Manegosa *et al.* in [7] for the first time. Later, various other tutorial works provided details on the C-V2X sidelink specifications in the various 3GPP Releases, from Release 14 to 16, in [9]–[17], [21]. Yet, these works do not include any, or they report a very limited, discussion of the related research literature, which has instead flourished in the latest years, recognizing the pivotal role

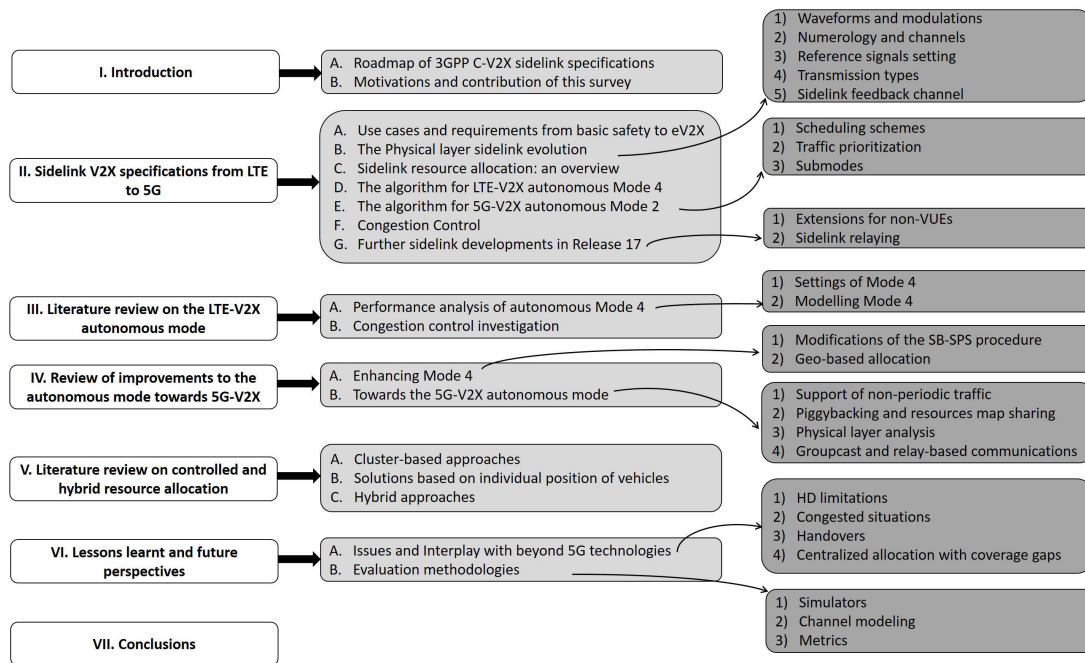


FIGURE 2. Outline of the survey.

TABLE 1. Summary of the main related survey papers. The column Specs indicates if the referenced paper focuses on the 3GPP specifications. The symbol ✓ indicates a property that is clearly present in the document. Brackets are used if a given property is only partly within the focus of the paper. R# is used instead of 3GPP release #.

Reference	LTE/5G	Uu/PC5	Specs	Review	Results	Main focus
Araniti, 2013 [2]	Pre-R14	Uu(&PC5)	(✓)			Early work on cellular systems for V2X
Tseng, 2015 [3]	Pre-R14	PC5	(✓)			Early work on PC5 interface for V2X
Seo, 2016 [4]	Pre-R14	Uu&PC5	(✓)			Early work on service and requirements for LTE-V2X
Sun, 2016 [5]	Pre-R14	PC5	✓			Early work on physical layer of PC5 in LTE-V2X
Chen, 2017 [6]	LTE	PC5	✓			Anticipations on PC5 in LTE-V2X
Molina-Masegosa, 2017 [7]	LTE	PC5	✓		✓	Performance of LTE-V2X Mode 4
MacHardy, 2018 [8]	Pre-R14	Uu(&PC5)		✓		Survey of V2X technologies, incl. cellular before R14
Fodor, 2019 [9]	LTE	PC5	✓		(✓)	Enhancements to PC5 LTE-V2X in R15
Bazzi, 2019 [10]	LTE(&5G)	PC5	✓	(✓)	✓	Performance of 802.11p and LTE-V2X Modes 3 and 4
Naik, 2019 [11]	5G	PC5	✓		(✓)	Anticipations on 802.11bd and PC5 5G-V2X
Chen, 2020 [12]	LTE&5G	Uu&PC5	(✓)			Overview of C-V2X with focus on deployment in China
Zeadally, 2020 [13]	LTE&5G	PC5	✓			Overview of 802.11p/bd, PC5 LTE-V2X, PC5 5G-V2X
Lien, 2020 [14]	5G	PC5	✓		✓	Details on 5G-V2X physical layer and control channels
Ashraf, 2020 [15]	5G	PC5	✓		(✓)	Enhancements to PC5 LTE-V2X in R16
Ganesan, 2020 [16]	5G	PC5	✓			Focus on specific aspects of PC5 5G-V2X
Garcia-Roger, 2020 [17]	LTE&5G	Uu&PC5	✓			3GPP specifications on V2X from R14 to R16
Storck, 2020 [18]	LTE&5G	Uu(&PC5)		✓		Review on 802.11p and (mostly Uu) LTE/5G-V2X
Zhou, 2020 [19]	LTE	Uu(&PC5)		✓		Review with focus on cloud-based Internet of vehicles
Gyawali, 2020 [20]	LTE&5G	Uu(&PC5)		✓		Review on research activities on cellular V2X
Garcia, 2021 [21]	LTE&5G	(Uu&)PC5	✓			3GPP PC5 LTE-V2X and 5G-V2X specifications
<i>This survey</i>	<i>LTE&5G</i>	<i>PC5</i>	<i>✓</i>	<i>✓</i>		<i>Literature review on PC5 LTE-V2X and PC5 5G-V2X</i>

of sidelink in targeting reliability and latency demands of vehicular applications. An analysis on the literature review is only provided in [18]–[20], which however address V2X in a broad scope and have a very marginal focus on the sidelink.

This work intends to fill the current gap by including, after a summary description of the sidelink evolution through the 3GPP standardization efforts (Section II), a thorough and comprehensive survey of the related research targeting the sidelink interface. In particular, we critically scan more than one hundred papers appearing in the literature and

targeting C-V2X sidelink communications, and we group them according to their scope and targeted issues. The focus is first on solutions investigating the performance of the plain autonomous resource allocation scheme in LTE-V2X (Section III) and then, moves to solutions improving it and preliminarily investigating 5G-V2X sidelink communication solutions (Section IV). Centralized and hybrid resource allocation studies conclude the review (Section V). The work is completed by a discussion of perspectives and opportunities that are still open for future research (Section VI). The whole paper organization is reported in Fig. 2.

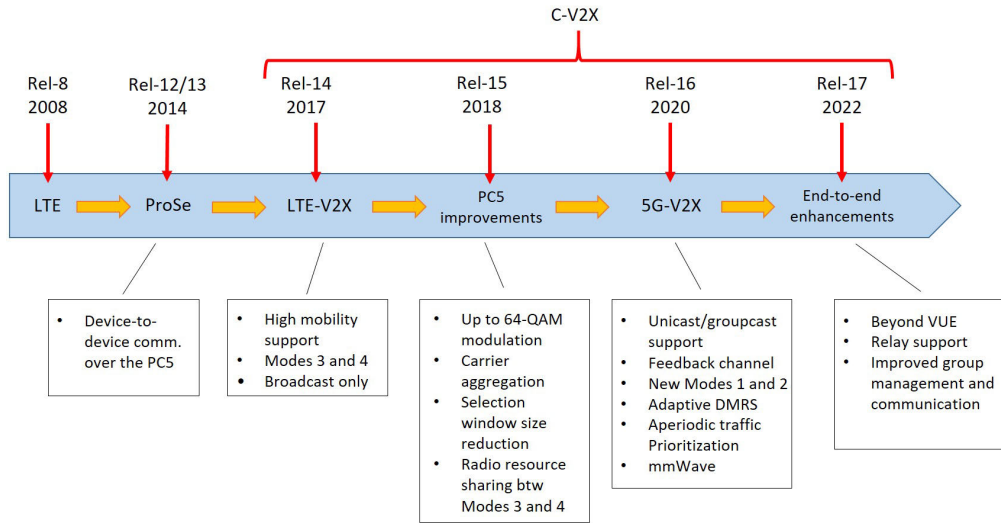


FIGURE 3. C-V2X timeline along with the main features and capabilities of sidelink in 3GPP releases.

TABLE 2. Selected 3GPP specifications covering V2X communications. LTE-related are listed before 5G-related, with technical reports (TRs) before technical specifications (TSs) per each technology.

Specification	Reference	Release	Year	Main scope
TR 22.885	[38]	14	2015	Study on use cases and requirements for LTE support of V2X services
TR 36.885	[39]	14	2016	Study on LTE enhancements for LTE-based V2X services
TS 22.185	[22]	14-16	2020	V2X service requirements to be supported by LTE
TS 23.285	[40]	14-16	2020	Architecture enhancements to the LTE system to facilitate vehicular communications for V2X services
TS 36.213	[41]	8-16	2020	Physicals layer procedures in LTE
TS 36.321	[42]	8-16	2020	LTE MAC protocol
TR 22.886	[43]	15,16	2018	Study on use cases and requirements to enhance support to V2X in 5G
TR 38.885	[44]	16	2019	Study on NR V2X
TS 23.287	[45]	16	2020	Architecture enhancements to the 5G system to facilitate vehicular communications for V2X services
TS 22.186	[46]	15,16	2019	V2X service requirements to enhance support to V2X by 5G
TS 38.213	[47]	15,16	2020	Physicals layer procedures in 5G
TS 38.321	[48]	15,16	2020	5G MAC protocol
TR 37.985	[49]	16	2020	Summary of the features introduced by 3GPP to LTE and NR in support of V2X from Rel. 14

TABLE 3. Sidelink improvements from Release 12 to Release 14 to support V2X communications.

Target	Description	Peculiarities compared to Release 12 D2D
Ubiquitous communications	Safety-critical communications require common bands, regardless of the mobile operator, under all geographies	Use of ITS unlicensed bands around 5.9 GHz
High-speed support	Relative velocity up to 500 km/h (e.g., cars in a freeway at 250 km/h in opposite direction)	Doubling of reference symbols from 2 to 4 per subframe
Low latency	Stringent delay requirements for most applications	<ul style="list-style-type: none"> Control and data transmitted during the same subframe No connection establishment and no ProSe discovery
High density support	Up to hundreds of nodes in mutual range	Channel sensing to estimate the interference level and reduce collision probability
High reliability	Need for reliability improvement and longer range	Blind retransmission
Support to periodic traffic	Support of V2X applications relying on the periodical broadcasting of awareness messages	Resources pre-allocated periodically

II. SIDELINK V2X SPECIFICATIONS FROM LTE TO 5G

Several works have already comprehensively described the C-V2X specifications in the different Releases, e.g., [7], [9], [10], [13], [17], [21]. Hence, in this Section, only the most salient features of 3GPP specifications for the sidelink are reported, which are needed to set the ground for a proper understanding of the literature surveyed in the next Sections. The C-V2X timeline and Releases are summarized in Fig. 3, while the main specifications and related scope are reported in Table 2 for the reader’s convenience.

The D2D feature designed in Release 12, as Proximity-based Services (ProSe), was early recognised as unsuitable for the vehicular scenario, thus motivating the 3GPP to add/modify specific features for V2X in Release 14, as summarized in Table 3. Successive enhancements of the (still LTE-based) sidelink in Release 15 were meant to be backward compatible with Release 14, therefore suffering from the same inherent LTE limitations that prevent the full support of the eV2X use cases of [46]. This restriction has motivated 3GPP to entail the design of a new air interface,

TABLE 4. Comparison of sidelink in LTE-V2X and 5G-V2X at 5.9 GHz.

Aspect	Sidelink LTE-V2X	Sidelink 5G-V2X
Waveform	SC-FDMA	CP-OFDM
Channel coding	Turbo	LDPC
Modulation	QPSK, 16-QAM, 64-QAM	QPSK, 16-QAM, 64-QAM, and 256-QAM
Numerology	Fixed: 1 ms subframe	Flexible: 0.25, 0.5, or 1 ms subframe
DMRS reference signals	4 fixed symbols in 1 ms	Various patterns, between 12 and 24 subcarriers
SCI	2 PRBs, adjacent or non-adjacent	Two stages SCI inside transmission slot
Feedback	-	ACK and NACK possible
Transmission type	Broadcast	Unicast, Groupcast, Broadcast
Controlled mode	Mode 3	Mode 1
Autonomous mode	Mode 4	Mode 2
HARQ	1 blind retransmission	Up to 32 retransmissions, blind or feedback-based
Sensing window	Single option: 1 s	Two options: 0.1 s and 1.1 s
Portion of CCRs passed from PHY to MAC in autonomous mode	20%	A minimum of 20%, 35%, or 50%
Resource re-evaluation and re-selection	Not possible	Possible
Pre-emption	Not possible	Possible

TABLE 5. LTE-V2X communication requirements [22].

Type of communication	Requirements					
	Latency	Reliability	Message Size	Frequency	Relative Speed	Range
V2I	100 ms	High	50-300 bytes (Periodic)	10 Hz	250 km/h	N.A.
V2V	20-100 ms				500 km/h	
V2N	1000 ms		1200 bytes (Event Triggered)		N.A.	
V2P	100 ms		250 km/h			

the so-called NR, starting from Release 15, although only in Release 16 an NR interface was fully specified for the sidelink of 5G-V2X [44], [49]. The NR sidelink is intended to complement and not to replace the LTE-V2X sidelink, with the latter dedicated to basic V2X safety and the former exploited for eV2X. Release 16 discusses options for the co-existence and cooperation between LTE and NR sidelinks [49].

The LTE-V2X sidelink considered the intelligent transport system (ITS) unlicensed band at 5.9 GHz for V2X sidelink operation. Next, to satisfy the larger bandwidth needs of the advanced V2X use cases, the NR sidelink was designed to operate in a larger frequency range: frequency range 1 (FR1), from 410 kHz to 7.125 GHz, and frequency range 2 (FR2), from 24.25 GHz to 52.6 GHz, referred to as millimeter waves (mmWaves). The maximum single user bandwidth in FR1 and FR2 is 100 MHz and 400 MHz, respectively, against maximum 20 MHz in LTE-V2X. Although the 5G-V2X sidelink supports both frequency ranges, no specific optimization has been deployed for FR2 yet and most of the sidelink design refers to FR1 [21]. Indeed, we expect the sidelink design to be re-engineered when considering the mmWave spectrum, due to its peculiarities well presented in [50]. The other major enhancements included in the 5G-V2X sidelink with regard to LTE-V2X are detailed in the following and summarized in Table 4.

Specifically, in the remainder of this Section, the driving use cases and requirements are firstly briefly discussed (Section II-A), followed by some details on the physical (PHY) and medium access control (MAC) specifications of LTE-V2X and 5G-V2X (Sections II-C to II-F), and concluded by anticipations on Release 17 (Section II-G).

A. USE CASES AND REQUIREMENTS FROM BASIC SAFETY TO eV2X

Both the design of LTE-V2X and 5G-V2X was preceded by the identification of the applications and requirements the technology needs to meet. Regarding LTE, 3GPP identified in [22], [38] a set of use cases that can be supported by a cellular transport, along with their target quality of service (QoS), as summarized in Table 5. The design of LTE-V2X was based on basic safety services relying on moderately challenging traffic, mostly based on small-to-medium sized periodical messages such as cooperative awareness messages (CAMs) defined by European Telecommunications Standards Institute (ETSI), and basic safety messages (BSMs) defined by Society of Automotive Engineers (SAE), or sporadic transmissions such as decentralized environmental notification messages (DENMs), again defined by ETSI.

As already mentioned, when the design of 5G-V2X begun it was recognized that LTE-V2X is not capable in supporting the challenging eV2X use cases, for which new messages are under definition by various standardization bodies¹ and the QoS requirements were clearly defined in [46], as summarized in Table 6. For each of the V2X scenarios, QoS requirements are distinguished in [46] by application and level of automation, demonstrating that in 5G they are not only more stringent than in 4G, but they are also very precise in terms of required reliability and communication range. Summarizing, the 5G-V2X applications need (*i*) much more stringent requirements in terms of latency (from 100 ms

¹As examples, ETSI is currently specifying various messages for advanced use cases, including collective perception messages (CPMs) [51], VRU awareness messages (VAMs) [52], platoon control messages (PCMs) [53] and maneuver coordination messages (MCMs) [54].

TABLE 6. 5G-V2X application requirements [46] (L.o.A. stands for level of automation).

Communication scenario	Application	L.o.A.	Requirements				
			Latency	Reliability	Message Size	Frequency	Range
Platooning	Cooperative Driving	Lowest	25 ms	90%	300-400 bytes	30 Hz	N.A.
		Low	20 ms	N.A.	6500 bytes	50 Hz	350 m
		High	20 ms	N.A.	N.A.	N.A.	180 m
	Information sharing	Highest	10 ms	99.99%	50-1200 bytes	30 Hz	80 m
		Lower	20 ms	N.A.	6000 bytes	50 Hz	350 m
		Higher	20 ms	N.A.	N.A.	N.A.	180 m
Advanced driving	Cooperative collision avoidance	N.A.	10 ms	99.99%	2000 bytes	100 Hz	N.A.
	Info sharing for automated driving	Lower	100 ms	N.A.	6000-6500 bytes	10 Hz	700 m
		Higher	100 ms	N.A.	N.A.	N.A.	360 m
	Emergency trajectory alignment Intersection safety	N.A.	3 ms	99.999%	2000 bytes	N.A.	500 m
		N.A.	N.A.	N.A.	N.A.	UL: 450 bytes	UL: 50 Hz
	Cooperative lane change	Lower	25 ms	90%	300-400 bytes	N.A.	N.A.
Higher		10 ms	99.99%	12000 bytes	N.A.	N.A.	
Extended sensors	Information sharing	Lower	100 ms	99%	1600 bytes	10 Hz	1000 m
		Higher	3-50 ms	95%-99.999%	N.A.	N.A.	50 m - 1000 m
	Video sharing	Lower	50 ms	90%	N.A.	N.A.	100 m
		Higher	10 ms	99.99%	N.A.	N.A.	200 m - 400 m
Remote driving	N.A.	N.A.	5 ms	99.999%	N.A.	N.A.	N.A.

to 3 ms) and reliability (from 90% to 99.999%); and (ii) more frequent (from 10 Hz to 100 Hz) exchanges and larger packets (from 50 to 16000 bytes) to accommodate richer sensor data and intended maneuvers.

B. THE PHYSICAL LAYER SIDELINK EVOLUTION

1) WAVEFORMS AND MODULATIONS

The PHY layer of LTE-V2X builds upon the following main characteristics: (i) single carrier frequency division multiple access (SC-FDMA), (ii) turbo codes [55], [56], and (iii) blind hybrid automatic repeat request (HARQ) retransmission with incremental redundancy. These three combined features contribute to a link budget improvement, which directly translates into extended coverage at fixed transmit power or enhanced reliability at fixed range. 5G-V2X sidelink transmissions use cyclic prefix orthogonal frequency-division multiplexing (CP-OFDM), which ranks best on the performance indicators that matter most, namely compatibility with multi-antenna technologies, high spectral and throughput efficiency, and low implementation complexity. CP-OFDM is well-localized in time domain, which is important for latency-critical applications and time-division duplex (TDD) deployments. It is also more robust to oscillator phase noise and frequency Doppler shift than other multi-carrier waveforms, which is crucial for mmWaves and V2X. LTE turbo codes are replaced by low-density parity-check (LDPC) codes in 5G-V2X.

In Release 15, 64-quadrature amplitude modulation (QAM) is added to the quadrature phase shift keying (QPSK) and 16-QAM modulations of LTE-V2X, while 5G-V2X also supports 256-QAM with binary reflected Gray mapping. The new modulation formats can be used when channel conditions are particularly favorable, providing gain in terms of spectral efficiency and throughput at the expense of sidelink coverage.

2) NUMEROLOGY AND CHANNELS

At the PHY layer, the LTE-V2X resource allocation granularity in the time domain is given by the transmission time

TABLE 7. 5G-V2X scalable numerology.

μ	SCS	Symbols per slot	Slot duration	Spectrum
0	15 kHz	14	1 ms	FR1
1	30 kHz	14	0.5 ms	FR1
2	60 kHz	14	0.25 ms	FR1, FR2
3	120 kHz	14	0.125 ms	FR2

interval (TTI), corresponding to one subframe of 1 ms. In the frequency domain, the *subchannel* concept has been defined. A subchannel is a multiple of the 180 kHz bandwidth² of LTE resource blocks (RBs), to be set by the operator within given options.

A scalable numerology is the major difference in 5G-V2X, where the subcarrier spacing (SCS) values for the OFDM waveform are flexible, according to the law $2^\mu \cdot 15$ kHz (with the SCS configuration factor $\mu = 0, 1, 2, 3$), hence scaling from 15 to 120 kHz, and the number of slots per subframe is equal to 2^μ (Table 7). This flexibility brings several advantages. First, larger SCS means shorter slot duration and hence, lower latencies, which is paramount for safety-critical driving applications. Second, larger SCS allows better resistance against Doppler effect and carrier frequency offset at high vehicular speeds, although the channel delay spread obviously sets a limit on the SCS value in certain deployments. To avoid inter-symbol interference (ISI) that may arise with larger SCS values, 5G-V2X introduces an extended cyclic prefix (CP) option which, in principle, reduces the OFDM efficiency. This penalty may be somehow compensated for by using fewer demodulation reference signal (DMRS) per OFDM symbol (see in the following).

LTE-V2X sidelink communications are based mainly on two channels transmitted in the same 1 ms-long TTI, at different frequencies: the Physical Sidelink Control Channel (PSCCH), carrying the control information (e.g., priority, modulation and coding scheme (MCS), frequency resource

²Corresponding to 12 subcarriers of 15 kHz each.

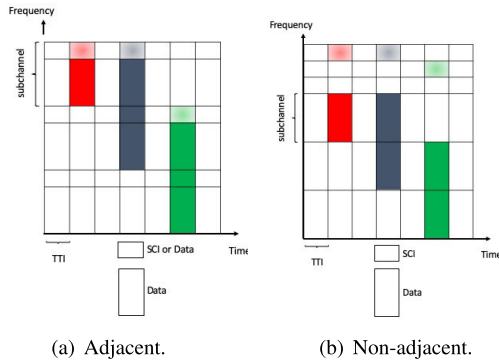


FIGURE 4. LTE-V2X sidelink: Adjacent and non-adjacent allocation of the control information (SCI) with respect to time-frequency grid of resources.

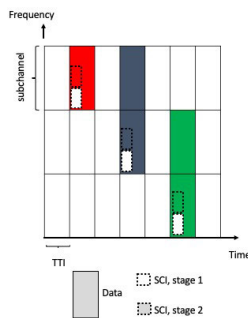


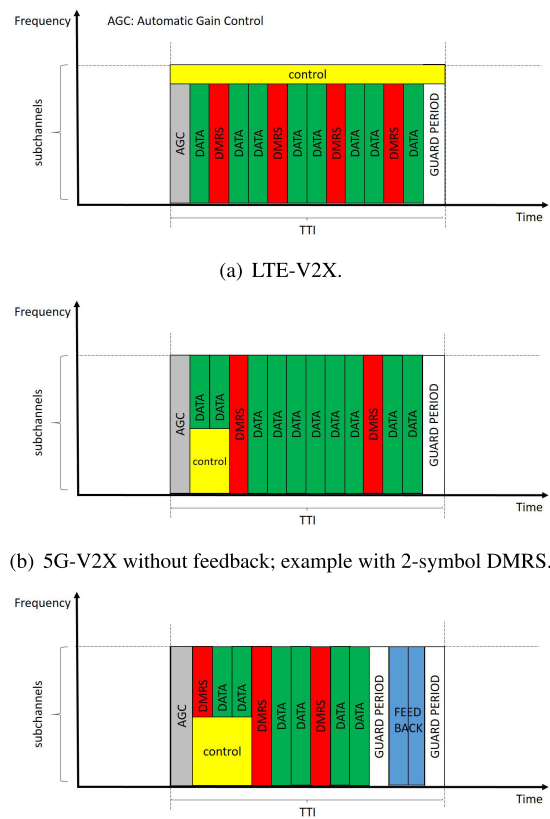
FIGURE 5. 5G-V2X sidelink: two-stage SCI allocation.

location, retransmission index) in the sidelink control information (SCI) message, and the Physical Sidelink Shared channel (PSSCH), carrying data in the transport blocks (TBs). Each data packet is allocated in one TTI and one or more subchannels. The associated SCI always occupies 360 kHz, with two possible configurations, as represented in Fig. 4: in the *adjacent* configuration, the SCI is transmitted within the subchannels, and more precisely at the beginning of the first allocated subchannel; in the *non-adjacent* configuration, dedicated resources are reserved for the SCIs, outside the subchannels.

With 5G-V2X, SCI messages are instead transmitted in two stages [14], [49], as illustrated in Fig. 5. The first stage SCI, conveyed by the PSCCH, carries information on the reserved PSCCH resources for the current TB and for its retransmissions, and information (e.g., the MCS) for decoding the second stage SCI, which is carried in the PSSCH together with the TB. It conveys additional control and scheduling information, e.g., for decoding PSSCH and for supporting HARQ feedback (see Section II-B5). The two-stage SCI transmission in 5G-V2X simplifies the SCI decoding; vehicles sensing the channel to learn about resource occupancy only need to decode the first stage SCI (see Section II-E).

3) REFERENCE SIGNALS SETTING

As shown in Fig. 6(a), the number of DMRS within a TTI is fixed to 4 in LTE-V2X; therefore the interval between adjacent DMRS symbols is still less than the coherence



(c) 5G-V2X with feedback; example with 3-symbol DMRS.

FIGURE 6. TTI structure and DMRS format.

time at relative speed of 500 km/h, which is around 0.15 ms at 6 GHz. 5G-V2X instead provides adaptive DMRS configuration options, to achieve a better trade-off between channel estimation accuracy and overhead at different vehicle speeds. At high speeds, channel variations are much faster and more reference signals are needed for better channel estimation; at low speeds, vice versa less DMRSs can keep the overhead low [57]. Scalable numerology impacts reference signal setting: with larger SCS channel variations within the slot are reduced, thereby needing fewer DMRSs per slot. Figs. 6(b) and 6(c) report examples with 2-symbol and 3-symbol DMRS which may apply, respectively, to slow and medium vehicle speed conditions.

4) TRANSMISSION TYPES

While LTE-V2X sidelink only supports broadcast communications, many eV2X applications rely on unicast or groupcast message transmissions. For instance, more conveniently a platoon leader disseminates messages to the platoon members through groupcast rather than broadcast, and exchanges data with nearby platoon leaders via unicast. Therefore, the PHY layer of the 5G-V2X sidelink flexibly supports broadcast, unicast, and groupcast operation. A point-to-multipoint channel, named Sidelink Traffic Channel (STCH), is specified in 5G-V2X for the transfer of user information from one vehicle to multiple vehicles.

5) SIDELINK FEEDBACK CHANNEL

Recognizing that sidelink LTE-V2X does not guarantee sufficient reliability for eV2X applications, in 5G-V2X the sidelink communication is improved through (i) a number of (blind) retransmissions, instead of only once or twice permitted in LTE-V2X, and (ii) a Physical Sidelink Feedback channel (PSFCH) that carries information about the HARQ success/failure in case of unicast/groupcast transmissions [44]. Every one, two, or four slots, the last two symbols excluding the guard period accommodate the PSFCH, as shown in Fig. 6(c). The HARQ feedback may be in the form of conventional Acknowledgement (ACK)/Negative ACK (NACK) for unicast, and NACK-only, with nothing transmitted in case of successful decoding, or no response for groupcast. The latter operation successfully saves sidelink resources. For example, in the extended sensors use case, sensor information must be spread to all vehicles located within a given radius³ around the sender. In this case, the NACK-only feedback can be restricted to vehicles within such a radius, and any farther vehicle does not provide any HARQ feedback [49]. The sender decides the feedback option based on e.g., the message reliability and latency requirements, the number of receivers in a group, the amount of available feedback resources, etc.

C. SIDELINK RESOURCE ALLOCATION: AN OVERVIEW

In Release 14 two sidelink resource allocation modes have been designed:

- *Mode 3 (controlled)*. Scheduling of resources and interference management over the PC5 interface are managed by the evolved NodeB (eNodeB) in a centralized manner, via control signaling over the Uu interface. It only applies to in-coverage conditions.
- *Mode 4 (autonomous)*. V2V scheduling and interference management is supported by distributed algorithms directly operating in each vehicle. Such a mode is crucial to cope with out-of-coverage scenarios.

In Mode 3 the resources can be granted for a single transmission through *dynamic scheduling* or, in case of periodic traffic, for a number of consecutive transmissions through a *semi-persistent scheduling* (SPS). With dynamic scheduling, similarly to what happens for uplink transmissions, a vehicle undergoes a handshake procedure to request sidelink resources to the eNodeB for every single TB transmission (and possible blind retransmission). With SPS, the allocated sidelink resources recur with a periodicity matching the V2X traffic pattern. However, the specific implementation of resource allocation in Mode 3 is left to the operator. Differently, a detailed algorithm is defined for Mode 4, based on SPS, which is further discussed in the next subsection.

In 5G-V2X, two new sidelink modes are identified that still correspond to a controlled (Mode 1) and an autonomous

³A minimum communication range (MCR), along with a QoS metric such as the transmitter-receiver distance, is notified by the transmitter in the SCI to maintain a given reliability of a groupcast packet.

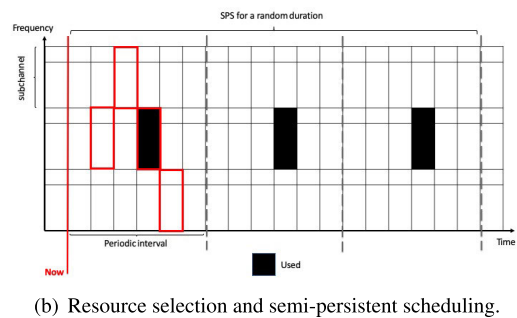
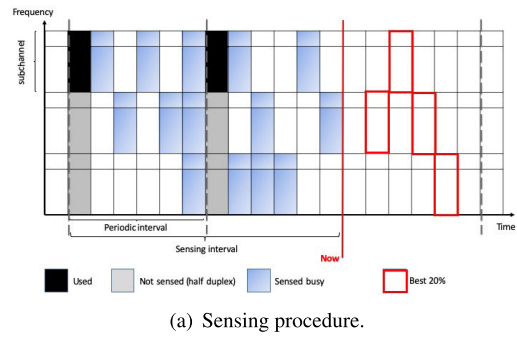


FIGURE 7. Mode 4 resource selection and allocation procedure.

(Mode 2) operation. They are, respectively, counterparts to Mode 3 and Mode 4 in LTE-V2X.

With Mode 1 (controlled), the NR base station, called gNodeB, schedules the sidelink resources using the NR (or LTE) Uu interface. This Mode only holds for in network coverage conditions. Similarly to Mode 3, Mode 1 provides *dynamic grant* scheduling of sidelink resources for a single TB (and its possible blind or HARQ retransmissions), and a *configured grant* scheduling that pre-allocates a set of sidelink resources for transmitting one or multiple (periodic) TBs in order to reduce delay. The pre-allocation is based on collected information from the vehicles regarding the expected traffic specifications (e.g., TB maximum size, periodicity) and QoS requirements (e.g., latency, reliability, priority). The grant is configured once and can be immediately used by the vehicle (Type 1 grant) or only after indication of the gNodeB that activates the grant (Type 2 grant).

In Mode 2 (autonomous) the vehicles autonomously determine the set of sidelink resources to be used among those (pre-)configured by the gNodeB/eNodeB. This Mode can be leveraged both under in-coverage and out-of-coverage conditions like for the LTE-V2X Mode 4. Modes 2 and 4 however have some differences in the scheduling scheme, as explained in the next subsections.

D. THE ALGORITHM FOR LTE-V2X AUTONOMOUS MODE 4

Sidelink LTE-V2X Mode 4 is mainly designed for periodic traffic and it is based on sensing-based semi-persistent scheduling (SB-SPS). Every vehicle is allocated the same group of subchannels periodically for a given interval,

which is the reason why the term semi-persistent is used. Hereafter, the set of subchannels required to accommodate the data transmission is denoted as candidate single-subframe resource (CSSR) and the period is called resource reservation interval (RRI). The selection of the CSSR, depicted in Fig. 7, is performed based on the status of resources monitored during the last 1 s. At the PHY layer, during that sensing interval, the node compares the received power with a given sensing threshold and attempts to decode the transmitted SCIs. Based on this information (related to the past), it selects the 20% of CSSR that are less probably occupied in the (future) selection window, i.e., they have lower reference signal received power (RSRP) levels. In order to control the access delay, the selection window can be restricted to an interval within the next T_1 (between 1 and 4) and T_2 (between 20 and 100) subframes. In Release 15, a lower bound equal to 10 is set on T_2 in order to reduce the guaranteed radio layer latency to 10 ms.

The selected set of CSSR is then passed to the MAC layer, where one CSSR is randomly selected. Once the subchannels have been reserved, the same are maintained periodically for a given number of RRIs. Such number is initially randomly chosen between given minimum and maximum values (depending on the RRI). After such time, the allocation is changed with probability $1 - p_k$ and confirmed otherwise. If confirmed, another random interval is selected with the same rules and so on. The parameter p_k , a.k.a. *keep probability*, is set by the network (within 0-0.8) and appears critical as further discussed in Section III.

Optionally, the network can configure a node to restrict its choice within a certain portion of CSSRs, called pool. Such resource pools can be also mapped to geographical zones that can be configured or pre-configured by the eNodeB. Then, the VUE selects the V2X resource pool based on the zone the VUE is located in [58].

E. THE ALGORITHM FOR 5G-V2X AUTONOMOUS MODE 2

The major adjustments implemented in Mode 2 with regard to Mode 4 refer to the need to help accommodate not only eV2X services but also basic aperiodic traffic, which was not directly considered in LTE-V2X sidelink specifications. Aperiodic traffic includes, in particular, DENMs generated asynchronously upon the detection of a road hazard event (e.g., emergency braking [59]). Moreover, CAMs themselves are not necessarily periodic, since their generation depends on the mobility of the transmitting vehicle [60].

1) SCHEDULING SCHEMES

Mode 2 implements two scheduling schemes: dynamic and SB-SPS. They operate similarly but differ in the number of selected/reserved resources: the former suits aperiodic traffic and selects new resource for each single TB, the latter for a number of consecutive TBs every RRI. LTE-V2X can reserve resources every (20, 50, 100) ms or any multiple of 100 ms up to a maximum of 1 s. With 5G-V2X, the RRI below 100 ms has higher granularity than in LTE-V2X: it

can take any integer value in the range [1:99], so to better fit the requirements of eV2X applications. In both dynamic and SB-SPS cases, Mode 2 resources can be reserved to be used for a number (up to 32) of blind or potential HARQ-feedback-based (re)transmissions of a TB within the same selection window [44]. Once a TB is positively acknowledged by using HARQ, the sending vehicle will cancel the next scheduled retransmissions. Both *long-term* sensing, spanning the typical 1s-long window, and *short-term sensing* are analysed in Release 16 [44]. Averaging over a long sensing period increases the risk of using outdated observations, as a result of fast changes in the generated interference due to mobility and traffic generation dynamics. Short-term sensing, over a shorter window, could solve this issue. Therefore, the sensing window size specified in [49] for the 5G-V2X sidelink can be either 1100 ms or 100 ms, with the latter option particularly useful for aperiodic traffic, and the former for periodic traffic.

2) TRAFFIC PRIORITIZATION

It is manifest that aperiodic messages should get higher priority than periodic messages in most cases, so the TB priority is announced in the first stage SCI, together with reserved resources and the RRI. The priority of the TB affects the following parameter settings in Mode 2 [49]:

- the lower bound on the selection window size, which is determined by the packet delay budget (T_2), depends on the TB priority and the SCS value, according to $[1, 5, 10, 20] \cdot 2^\mu$ slots, so that Mode 2 can guarantee 1 ms minimum latency compared to 10 ms of Mode 4;
- the RSRP threshold is a function of the transmitting TB's and the reserved TBs' priorities. Thus, a higher priority transmission can occupy resources which were reserved by another sender with sufficiently low RSRP and sufficiently lower-priority traffic;
- a vehicle randomly selects its resources from the CSSRs that remain available after the exclusion of those that are both reserved and have an RSRP exceeding a given threshold. The threshold is relaxed in steps of 3 dB if the remaining resources are not at least a portion $x\%$ of the total CSSRs, where x can take values of 20, 35, and 50 for each traffic priority (differently, in LTE-V2X the random selection is always performed in a group including the 20% of the CSSRs).

Two other major differences are included in Mode 2 in order to cope with aperiodic higher-priority service messages [49]:

- *re-evaluation*: just before accessing its sidelink reserved resource, a vehicle re-evaluates the resource status, considering the late-arriving SCIs due to an aperiodic higher-priority service that started to transmit after the end of the original sensing window. If the reserved resources are no longer suitable, then new resources are selected from the updated resource selection window;
- *pre-emption*: Mode 2 introduces a mechanism to prioritize traffic in accessing the sidelink resources by

configuring a resource pool with a pre-emption function designed to help accommodate aperiodic traffic. A vehicle frees its resources reserved for lower priority TBs and reselects them all if it detects that another nearby vehicle with higher priority traffic arrival is going to use any of those resources.

3) SUBMODES

The following submodes of Mode 2 were investigated during the study item phase of Release 16:

- Mode 2(a): corresponds to the described Mode 2;
- Mode 2(b): then removed as a standalone submode from Release 16 [44], where a vehicle can assist other vehicles in resource selection (e.g., by suggesting or preventing the use of certain candidate resources). Such functionality, referred to inter-UE coordination, is currently under discussion for enhancements in Release 17 [61], [62];
- Mode 2(c): for out-of-coverage operation, vehicles use pre-configured sidelink transmission patterns; this mode has been finally not adopted;
- Mode 2(d): vehicles can select sidelink resources for other vehicles. It can be useful for group-based communication such as platooning, where a group leader (in network coverage) acts as an intermediary between its serving gNodeB and the group members, and manages resource allocation on behalf of the group, without the need of direct connection between any group member and the gNodeB. Details for the implementation of this submode are left as enhancements for future Releases.

F. CONGESTION CONTROL

In order to cope with congested situations, decentralized congestion control (DCC) has been always considered a key aspect for V2X, and indeed extensively investigated on top of IEEE 802.11p [63], [64]. In Europe, a specific mechanism has been defined by ETSI in [65] for C-V2X, where the transmission of a packet over PC5 might be restricted based on its priority and two estimated parameters, called channel busy ratio (CBR) and channel occupancy ratio (CR). The CBR represents an estimation of the total occupation of the channel and is defined as the amount of subchannels in the previous 100 subframes (100 slots or $2^\mu \cdot 100$ slots in 5G-V2X [66]) that experience an average Received Signal Strength Indicator (RSSI) higher than a pre-configured threshold (a range of values is specified in Releases 14 and 16). The CR quantifies the channel occupancy generated by the transmitting vehicle and is defined as the amount of subchannels that the transmitting vehicle utilizes during a period of 1000 subframes (1000 slots or $2^\mu \cdot 1000$ slots in 5G-V2X [66]), which might include past and future subframes (slots).

The vehicle measures the CBR and, accordingly, adjusts the CR to comply with CR limit values by (i) limiting the number of packet retransmissions, (ii) dropping some

packets generated by the application, (iii) selecting a less robust MCS to reduce the number of required subchannels, and/or (iv) reducing the power to limit the interfered area. In principle, also (v) increasing the minimum interval between the generation of two consequent packets is possible, even if this solution requires the interaction with higher layers. NR V2X sets a 1 ms or 2 ms time interval for the CR and CBR calculation; this is shorter than LTE-V2X's 4 ms with the purpose of better following faster load fluctuations due to aperiodic traffic [49]. Both Release 14 and Release 16 do not specify a given DCC algorithm, but they just define the above mentioned metrics and countermeasures.

In the US, specific procedures are not yet defined and the same foreseen by SAE at the higher layers apply also to C-V2X, with a variant of J2945/1 under progress [67].

G. FURTHER SIDELINK DEVELOPMENTS IN RELEASE 17

Some concepts lying under the 5G NR umbrella but not prioritized by 3GPP in the race towards 5G-V2X, are set to follow in Release 17. Some of the main foreseen design enhancements affecting sidelink communications, at the time of writing this survey, are summarized in the following.

1) EXTENSIONS FOR NON-VUEs

The focus of initial studies in Release 17 will be on pedestrian UEs that are most likely smartphones. A high-level overview of the topic from 5GAA can be found in [68], which remarks the role of the infrastructure and the need for precise positioning. Especially critical appears anyway sidelink, which needs to be supported by battery-powered device types that have to work in a low power consumption mode. To this aim, 3GPP Release 17 will work on power and spectral efficiency optimizations [69]. In particular, discontinuous reception (DRX) has been identified in Release 16 as one of the mechanisms for power efficient sidelink communications [70]. Based on it, NR PC5 DRX has an ON- and OFF-duration, and a pedestrian UE will not send/receive V2X messages with the same periodicity as a VUE but it would only turn on its PC5 radio interface during the ON-duration. Since smartphones will support Uu as well as PC5 connections, it is therefore necessary to coordinate the device's Uu DRX operation with the PC5 DRX operation.

Release 17 will further focus on whether and how the pedestrian UE can make use of the sidelink DRX mechanism for broadcast, groupcast and unicast without degrading QoS of the PC5 communication and ensuring power efficiency can be maintained.

2) SIDELINK RELAYING

Sidelink proximity reachability is currently limited to single-hop, which is not sufficient when there is no Uu coverage. Sidelink connectivity should be further extended in NR framework to support the enhanced QoS requirements. Therefore, Release 17 will additionally study how to provide relay capabilities over the sidelink. UE-to-UE application layer relay may be used to enhance the V2V communication

TABLE 8. Main issues related to the LTE-V2X autonomous mode.

Issue	Description
◇ Half-duplex transceivers	<ul style="list-style-type: none"> • VUEs not able to simultaneously receive while transmitting, although over a different frequency • VUEs not able to sense the channel while transmitting
◇ Broadcast transmissions	<ul style="list-style-type: none"> • No feedback on the actual successful reception at the intended destinations
◇ Hidden terminals	<ul style="list-style-type: none"> • VUEs that do not hear each other may select overlapping resources
◇ Persistent collisions	<ul style="list-style-type: none"> • VUEs selecting overlapping resources may keep them for long time due to the SPS
◇ Poor support for aperiodic and variable sized packets	<ul style="list-style-type: none"> • Long reservations as per SPS may either waste resources or incur more interference

coverage; in this case one or more V2X relay UEs may be involved. It is then possible that a V2X UE may receive multiple copies of the same message that are repeatedly re-transmitted by several V2X relay UEs [71]. Thus, how to reduce the V2X message broadcast flood when using V2X relay UEs is also for further study in Release 17.

III. LITERATURE REVIEW ON THE LTE-V2X AUTONOMOUS MODE

This section provides a comprehensive literature review of scientific papers, contributed by researchers in academia as well as by experts in automotive and telecommunication industries, which address LTE-V2X sidelink in the autonomous mode. It is organized in two parts. The first part (Section III-A) reviews the literature that focuses on performance investigation of the autonomous Mode 4, when considering the parameter settings as defined by 3GPP specifications. In the second part (Section III-B), particular attention is given to sidelink congestion control mechanisms.

A. PERFORMANCE ANALYSIS OF AUTONOMOUS MODE 4

The analysis of the literature has testified huge efforts in the study of C-V2X autonomous resource allocation schemes. Given the definition of a complex algorithm with a number of parameters to be optimized, most of the attention has been dedicated to Mode 4 rather than Mode 3. The greater interest in the autonomous mode is also justified by the fact that it is the only operating mode working in out-of-coverage conditions (e.g., urban canyons, tunnels) and it overcomes the handover complexity between cells and between networks belonging to different operators. Last but not the least, the distributed nature of the algorithm, lacking a perfect coordination among vehicles, may unavoidably lead to performance degradation in the resource allocation, especially under high-density scenarios, due to the issues reported in Table 8.

Studies on Mode 4 are aimed both to analyse its performance and understand the impact of the different parameter settings as conceived in the 3GPP algorithm, as summarized in Table 9.

1) SETTINGS OF MODE 4

Several studies have investigated, mostly through simulations [72]–[77], the impact of the various parameters on the performance of Mode 4, especially in terms of packet reception ratio (PRR) and inter-packet gap (IPG).⁴

The pioneering studies in [73] and [74] showed that most parameters have a minor impact on Mode 4 performance, especially in scenarios with low to medium number of vehicles; differently the impact may become higher under congestion. A first outcome in [73] is that sensing over a long time interval increases the risk of inaccurate or outdated measurements and results in lower PRR, while reducing the sensing period below 1 s improves PRR of up to 10%, if the generated traffic has a periodicity of 100 ms. A sensing period duration, which is variable with the setting of traffic generation at the neighbours, is therefore recommended to improve performance. In [74], the suggestion for a better performance is to select the highest transmission power and the lowest threshold power to sense the resource as occupied.

More works [73]–[77] agreed on the conclusion that parameter p_k , which determines the probability to keep resources once the reservation period is expired, significantly affects Mode 4 performance and the trade-off between a higher PRR and a lower IPG. On the one hand, a small value of p_k makes vehicles changing their allocation more often, with consequent reduced effectiveness of the sensing mechanism, and an achieved lower PRR. If p_k is set to 0, results in [72] show similar performance between Mode 4 and a simple random allocation, with or without retransmissions. On the other hand, a large value of p_k may cause longer bursts of errors in case of wrong resource allocations, and thus, larger IPG on average.

The work in [78], which is not indeed limited to Mode 4 but well linked with the previous ones, discusses the rigidity of the LTE-V2X resource grid. The authors show that capacity and efficiency in LTE-V2X are very sensitive to the relation between message size and subchannel configuration, and small variations in parameters like either the packet size (even an increase of only one byte) or the MCS, can cause significant modifications in the performance. This high sensitivity implies that mobile network operators should analyse the vehicle traffic pattern in their area of service before setting LTE-V2X operating parameters.

Whereas the listed publications cover the analysis of most of the Mode 4 parameters in generic scenarios (e.g., highway, urban) when no specific application is addressed, a few works in [79]–[82] highlight that different challenges might arise when specific use cases are considered, such as platooning [79], [80], video-assisted overtaking [80] and crash warning system [82]. In particular, in [79], where the performance of LTE-V2X Mode 3 and Mode 4 is compared to that of IEEE 802.11p considering the platooning application, it is suggested to change more frequently the

⁴The IPG is typically defined as the time gap between successfully received packets (a.k.a. update delay, depending on the paper).

TABLE 9. Studies that focus on the performance of Mode 4.

Reference	Main focus	Methodology	Scenario(s)	Main observations
Molina-Menegosa, 2017 [72]	PRR of Mode 4 vs. random allocation	Veins simulator	Urban-Manhattan congested, 85 v/km	Slight improvement of Mode 4, especially with retransmissions
Bazzi, 2018 [73]	Impact of parameters on PRR and IPG	LTEV2VSim simulator	Highway, 126 v/km; Urban 270/320 v/km ²	PRR vs. IPG trade-off of keep probability, sensing interval has an impact, limited impact of the others
Molina-Menegosa, 2018 [74]	Impact of parameters on PRR and IPG	Veins simulator	Highway slow, 120 v/km	PRR vs. IPG trade-off of keep probability, sensing threshold to set low, transmission power to set high
Nabil, 2018 [75]	Impact of parameters on PRR and IPG	ns-3 NIST-D2D simulator	Highway fast/slow, 61.8/123.6 v/km	Relevance of number of subchannels and reservation interval
Toghi, 2018 [76]	Impact of parameters on PRR and IPG	ns-3 LENA simulator	Highway, 50-400 v/km	PRR vs. IPG trade-off of keep probability, synchronization of generation instants has no relevant impact
Wendland, 2019 [77]	Impact of parameters on the time with awareness	Artery + SimuLTE simulators	Urban dense, 185 v/km ²	Persistent allocations have a negative impact
Lopez, 2020 [78]	Relationship between MCS, payload, subchannels	Analytical	(Ideal)	The resource grid structure makes performance strongly varying with parameter settings
Vukadinovic, 2018 [79]	Performance with platooning	Nokia simulator	Platoon of 10 trucks + 1 v. and 0-60 v/km	Suggested to perform frequent changes of resource allocation to avoid bursts of errors
González, 2019 [80]	Performance with platooning	Analytical	Platoon, uniform inter-vehicle distance	Multiple SPS processes in parallel to cope with limitations on time granularity
Magalhaes, 2020 [81]	Performance with video-assisted overtaking	Experiments	2 vehicles	Good video quality observed but variable video traffic causing higher end-to-end latency
Hirai, 2020 [82]	Performance with a crash warning system	Proprietary simulator	Intersection with up to 500 v	Mode 4 is unable to cope with QoS requirements under the considered settings
Wang, 2018 [83]	Analytical model of simplified Mode 4	Proprietary simulator for validation	Highway, 0-200 v/km	Constraints on allocation can reduce delay with small degradation of PRR
Gonzalez-Matín, 2019 [84]	Analytical model of PRR, separating half duplexing, low received power, channel effects, interference	Veins simulator for validation	Highway, uniformly 100-300 v/km	Prevailing impact of interference at medium distance, of received power at large distance
Wijesiri, 2019-20 [85], [86]	Markov-based model	Analytical	Highway, 160 v/km	The average delay of C-V2X has a locally optimal CAM/DENM packet arrival combination

allocated resources in Mode 4, so to limit the risk of long bursts of errors in case of selection of interfered resources. In [80], attention is posed on the limitations on allocation periodicity; as a solution, it is suggested to set up multiple semi-persistent sessions in parallel, allowing a finer period granularity. Latency and video-related metrics are measured in [81] in a real-world scenario, with two vehicles equipped with C-V2X transceivers. The suitability of Mode 4 for video-assisted overtaking application is evaluated, showing its poor performance in presence of variable traffic. The ability of Mode 4 to cope with QoS requirements is questioned also in [82] with reference to a crash warning system, considering an intersection with various ideal and realistic traffic conditions.

a: SUMMARY AND OPEN ISSUES

As witnessed by the provided overview, only a few parameter settings have a major role on Mode 4 performance (e.g., sensing period, p_k). Although Mode 4 appears well investigated in general, still limiting aspects arise once a specific advanced V2X use case is addressed, confirming that new countermeasures are needed in the SB-SPS mechanism of LTE-V2X Mode 4, thus paving the way towards further enhancements in 5G-V2X sidelink. Moreover, the majority of previously scanned works focused on highway scenarios

with line-of-sight (LOS) conditions. However, the presence of buildings and other obstacles, especially at intersections, may significantly reduce the effectiveness of the sensing mechanism and deserve further investigation.

2) MODELLING MODE 4

Although the majority of works in the literature focused on simulation studies, in [83]–[86], analytical models have been proposed for a better understanding of Mode 4 performance.

In particular, in [83], collision probability and delay of SB-SPS are derived in a simplified Mode 4 with static nodes. In [84], the focus is on the PRR when varying the transmitter-receiver distance; the sources of errors are classified as: errors due to half duplexing, those due to a low received power level, those due to channel variations, and those due to interference. Results show an overall minor impact of channel variations and half duplexing, a dominant effect of interference at medium distances, and a prevalent impact of received power at high distances.

A Markov-chain based perspective is, instead, proposed in [85], [86], where performance in terms of PRR and delay of sidelink LTE-V2X Mode 4 is investigated and compared to that of IEEE 802.11p. Attention is posed on the relation between CAM and DENM generation and the periodical

TABLE 10. Studies on congestion control.

Reference	DCC parameter	DCC std.	Simulator	Main achievements
Mansouri, 2019 [87]	Packet transmission rate	ETSI	ns-3	Dropping at application level, congestion control does not improve performance
Toghi, 2019 [88], [89]	Packet transmission rate, transmission power	SAE	Not specified	Effectiveness of resource reuse in dense scenarios; effectiveness of packet generation rate control; limited impact of range control
Bazzi, 2019 [90]	Packet transmission rate, range, MCS	Generic	LTEV2VSim	Effectiveness of packet generation rate control; limited impact of range and MCS control
Shimizu, 2020 [91]	Packet transmission rate, transmission power	SAE	ns-3	LTE-V2X compared against 802.11p
Kang, 2021 [92]	Packet transmission rate, transmission power	Generic	LTEV2VSim	Adaptive adaptation of transmission rate and power improves performance in both urban and highway scenarios
Yoon, 2020 [93]	Packet transmission rate, transmission power	SAE	LTEV2VSim	Adjustment of the rate control function to react to congestion in a more relaxed manner
Kang, 2018 [94]	Transmission power	Generic	LTEV2VSim	A small improvement of PRR is shown in congested scenarios reducing the transmission power
Haider, 2019 [95] Saifuddin, 2020 [96]	Transmission power	Generic SAE	LTEV2VSim ns-3	Proposes an algorithm able to optimize the transmission power High-priority event-driven messages benefit from adaptive transmission power for BSMs
Choi, 2020 [97]	Packet transmission rate, transmission power	SAE	LTEV2Vsim	Adaptive control of transmission power/packet transmission rate under congestion according to QoS requirements of messages to be transmitted
Naik, 2020 [98]	Adaptive HARQ	Generic	ns-3	HARQ if CBR is low, deactivated if CBR is high

allocation, showing that there are local minima in the delay for optimized values.

a: SUMMARY AND OPEN ISSUES

A few works have been published on this aspect. Among them, the work in [84] provides a careful insight on Mode 4 and accounts for both propagation and collisions; despite this, some simplifications are introduced by the authors to make the problem tractable, which might be overcome by future work.

B. CONGESTION CONTROL INVESTIGATION

Given the importance of reliability in vehicular communications and the fact that a number of studies revealed that sidelink C-V2X might suffer from high interference in dense scenarios [99], congestion control is felt as one of the major points by the vehicular community in C-V2X, and it has already been the subject of several researches, including those presented in [87]–[97]. Given the particular relevance of the topic, a dedicated summary is provided in Table 10. Although some of the listed papers propose novel ideas or improvements to the specifications, the main focus is in general on the performance of sidelink C-V2X in the presence of congestion control procedures, and for this reason presented in this section.

In [87], the effect of the ETSI DCC mechanism is investigated assuming that packets are dropped at application level under congestion. With such approach, a conflict is observed between DCC and the sensing procedure, causing a degradation even worse than without any control (an issue also addressed in [100]). In [88], [89], congestion control mechanisms are, instead, considered following the American standards published by SAE and designed with DSRC in mind. The algorithms act on both packet generation and transmission power. It is shown that the variation of the packet generation interval is effective to guarantee high PRR

and limited IPG, whereas the range-control has a lower effectiveness. A similar conclusion is also reached in [90], where the impact of a variation in the packet generation rate, range, or MCS is investigated without referring to specific DCC algorithms; more specifically, results show that only a packet generation rate control is really effective to improve the PRR, at the expense of IPG. The performance of Mode 4 against IEEE 802.11p with SAE congestion control is assessed in [91].

The adaptation of the message interval and transmission power is also investigated in [92], but without considering DCC rules and metrics. Instead, the message interval is adapted according to the estimated collision probability, whereas the transmission power is dynamically set to ensure the highest expected PRR given the awareness of the surrounding neighborhood, tracked through Sidelink-RSSI (S-RSSI) statistics.

In [93] the authors propose to adjust the rate control function to react to congestion in a more relaxed manner so that the power control contributes more actively to the overall congestion control. Such a re-balancing between the control elements is shown to improve IPG performance.

Power control algorithms are also proposed in [94], [95], showing that a reduction of the transmission power in congested situations leads to some improvement. The work in [96] considers the co-existence of periodic and event-driven messages. Achieved results demonstrate that transmission power control of periodic messages can be highly beneficial for higher priority event-driven messages.

With the similar objective of differentiating performance, in [97] a QoS mechanism is added on top of SAE DCC. Two classes of QoS, one that protects information update rate at the cost of reduced range and the other that protects range at the cost of reduced update rate, are considered for which the transmission power and the packet transmission rate are respectively adapted.

TABLE 11. Studies proposing improvements to the 3GPP specifications on Mode 4.

Reference	Main focus	Simulator	Scenario(s)	Main achievements
Modification to the SB-SPS procedure Molina-Menegosa, 2017 [7]	Modified Mode 4 with packets of variable size	Not specified	Highway fast/slow, 60/120 v/km	Inefficiencies with packets of variable size and proposed modification (more frequent SPS reservation)
Wendland, 2019 [100] Bazzi, 2020 [101]	Reservations split in sub-reservations Avoiding long wireless blind spots	Artery + Veins LTEV2VSim	Urban dense, 185 v/km ² Highway 200 v/km	Using sub-reservations reduces bursts of errors and allows improved DCC Long bursts of errors avoided by limiting the number of times a resource can be maintained
Jung, 2019 [102]	Two resources used alternately	Proprietary	Highway slow, 240 v/km	Using two resources alternately reduces the probability of consecutive collisions
Abanto-Leon, 2019 [103] Yoon, 2020 [104]	Random allocation of re-transmissions Packet dropping attack due to SPS predictability	Not specified LTEV2VSim	Urban dense Highway, 42-195 v/km	Blind random allocation of retransmissions over secondary subchannels can improve PRR Mitigated impact of attacks and persistent collisions through jittering reservations
Heo, 2020 [105]	SPS periodicity optimiz. and backup on DSRC	Proprietary	Not specified, 50-300 v/km	SPS periodicity set based on collision estimation and coordination, with DSRC as backup
Abanto-Leon, 2018 [106] Sharma, 2020, [107]	Exponential weight of sensed power in time Autonomous reservation	Proprietary LTEV2VSim	Highway dense, 100 v/km; Urban dense Highway, 110 v/km	Emphasis on more recent values lets vehicles better estimate future resources status Continuous sensing and cooperative learning; Q-learning based power control
Geo-based allocation Kim, 2018 [108]	Allocation based on position and movement	Not specified	Highway and urban, fast and slow	Improvement of geo-based allocation compared to a random allocation
Yang, 2016 [109]	Sub-pools based on driving direction	Not specified	Urban-Manhattan, 24 v/km	Sub-pools dedicated to vehicles on perpendicular roads allow reducing hidden-terminal collisions
Molina-Menegosa, 2019 [110]	Geo-based allocation algorithm	Veins	Highway, fast/slow, 60/120 v/km	The proposed algorithm, based on the position, outperforms legacy Mode 4

In [98], congestion control is treated with focus on HARQ. In particular, the authors propose to adaptively issue retransmissions, noting that whereas they can improve the reliability in lightly loaded scenarios, they might increase the collisions in congested situations. The CBR is exploited to discriminate.

1) SUMMARY AND OPEN ISSUES

Already a number of studies have shown relatively small impact of power variations and suggested to mostly focus on packet generation rate. This rule appears however subject to exceptions, as shown in [96], when high-priority messages are considered. The same paper is indeed the only one among those reviewed that considers more than one class of traffic (basic safety versus event-driven messages), implying that the impact of congestion control with packets of various sizes and different priorities appears as an open issue. Additionally, only a few studies have deepened the performance of C-V2X with the ETSI DCC, which might lead to some different conclusions compared to those obtained with the SAE solution.

IV. REVIEW OF IMPROVEMENTS TO THE AUTONOMOUS MODE TOWARDS 5G-V2X

The previously surveyed literature shows that performance improvements can be achieved by properly tuning some of the parameters of the resource allocation algorithm for the autonomous mode. However, a number of modifications have been proposed compared to the legacy algorithm to further achieve higher reliability and timeliness, as detailed in the following.

A. ENHANCING MODE 4

Straightforward solutions proposed to improve Mode 4 are hereafter grouped in classes and also summarized in Table 11.

1) MODIFICATIONS TO THE SB-SPS PROCEDURE

Several improvements have been proposed to the legacy Mode 4. Most of them, including [7], [100]–[107], focus on the SB-SPS procedure. Changes in the reservation procedure are proposed in [7], where the issue of messages of variable size is addressed. In Mode 4 the management of messages of variable sizes produces a sub-optimal use of resources, which sometimes translates into a waste of resources reserved but not used, while other times causes rescheduling because the allocation is insufficient; the proposal of that paper is to alter the reservation procedure and perform more frequent re-selections.

The issue of long intervals with the same allocation which may result in persistent collisions, referred to as *wireless blind spot* in [101], is addressed in [100]–[103]. Consecutive packet losses may be particularly detrimental for V2X safety use cases because they make difficult to identify, for instance, an overtaking manoeuvre of a neighbor and other potential imminent crash scenarios. Specifically, in [102] each vehicle selects two resources, rather than one, and uses either of the two alternatively, thus significantly reducing the probability of consecutive collisions. A similar proposal is presented in [100], in the form of parallel sub-reservations; the stated objectives are both to reduce bursts of collisions and allow better management when changes in packet generation rates occur. In [103], the authors propose to use the legacy Mode 4 on primary subchannels to convey

the first transmission, but to adopt a random allocation on secondary subchannels for the retransmissions. In [101] it is proposed to revise the procedure by setting a limit to the number of times the same resource can be kept, independently to the value of p_k .

A modification to the allocation procedure is also proposed in [104], although moved by a different motivation. Due to the predictability of resource reservation in SB-SPS, it is observed by Yoon *et al.* that a vehicle may become a “ghost” for its neighbors if an attacker intentionally transmits over its reserved resources. Due to HD limitations, the victim cannot in fact be aware of occurring attack. The solution proposed in [104] is to randomize to a certain degree the actual resource locations in the time domain used in packet transmissions, while preventing the SB-SPS performance degradation. A feedback mechanism is applied to let vehicles detect an ongoing attack and change the reservation.

In [105], the authors suggest to introduce the exchange of local measurements. Based on that, the VUEs estimate the collision probability and possibly modify the packet transmission rate accordingly; a backup to the DSRC interface in a separate band is also foreseen if the required QoS cannot be granted.

The power sensing procedure is instead revised in [106], [107]. In [106], the authors propose to use an exponential weight to the measured received power levels during the sensing interval, thus giving more emphasis on the recent values, deemed more relevant due to the dynamicity of the environment. An exponential weight is used also in [107], with the addition of multiplicative factors that account for resources that are expected to be released in short; additionally, the transmission power is adjusted through a distributed Q-learning approach.

a: SUMMARY AND OPEN ISSUES

The scanned literature confirms that there is much room for enhancing the legacy SB-SPS procedure. Overall, we can state that the design of more accurate sensing procedures, coupled with a more reliable (time-bounded) reservation should be pursued.

2) GEO-BASED ALLOCATION

As recalled in Section II, an option allowed by 3GPP specifications is that the VUE selects the resource based on its position, also called geo-based allocation. Such option is investigated, in particular, in [108]–[110]. In [108], different frequency and time resources are used based on vehicle speed, density, direction, and position. Urban and highway are treated separately. In [109], sub-pools are created to separate the allocation of vehicles driving on perpendicular roads, which are subject to frequent non-line-of-sight (NLOS) conditions. In [110], a geo-based distributed allocation is proposed, based on the position exchanged by the vehicles and trying to maximize the distance of resource reuse.

a: SUMMARY AND OPEN ISSUES

A few geo-based resource allocation protocols have been proposed in the literature. Although they have already shown the potential improvement compared to the basic SB-SPS protocol, results are overall limited to few cases and thus, this topic still appears to be under-investigated.

B. TOWARDS THE 5G-V2X AUTONOMOUS MODE

Evaluation of 5G-V2X sidelink is still at its infancy, mainly due to the ongoing status of standardization activities, with specifications not yet frozen. However, some conceived enhancements in the literature somehow anticipated issues specifically addressed by 3GPP specifications in Releases 16 and 17 and a few works already provide interesting insights about the latter ones. Such works, summarized in Table 12, are discussed in the following, which will motivate further research which standardization could also benefit from.

1) SUPPORT OF NON-PERIODIC TRAFFIC

Although the majority of works focused so far on periodic message pattern, being it the one targeted by LTE-V2X, the validity of this hypothesis is not general and has been also questioned through experimental data [133] when referring to the European CAMs. For this reason, recent works started to consider sporadic transmissions or aperiodic packet generation patterns, which might conflict with the regular allocation procedures of SB-SPS. The study in [111], for example, demonstrates that IEEE 802.11p can cope better than LTE-V2X with aperiodic messages and messages of variable size. In fact, unlike 802.11p, LTE-V2X uses a predefined time-frequency structure that conditions the access to the channel as well as the size of packets that can fit in a configured sub-channel. Moreover, Mode 4 semi-persistently reserves the selected sub-channels, which might not be utilized if messages are generated aperiodically. In [112], the impact in LTE-V2X of a mismatch between the packet generation and the allocation periodicity is further investigated comparing various possible approaches and concluding that reserving resources more frequently and leaving some of them empty appears as a good trade-off in most of the cases.

The work in [113] analyzes the co-existence of aperiodic and period traffic in Mode 4 and proposes ways to handle such co-existence. In particular, Mode 4 without reservations is straightforwardly applied to serve aperiodic traffic generated at an average rate of 10 packets/s. The case of a mixed traffic with periodic CAMs and asynchronous DENMs has been investigated in a few recent works [59], [85], [86], [114], [116], [117]. In [59], a stochastic geometry-based model is proposed to derive closed form expressions for the DENM loss probability. Bounds on the DENM delivery performance are derived when considering the aggregate interference due to periodic CAMs simultaneously transmitted over the sidelink. In [114], CAM and DENM packets compete for

TABLE 12. Studies targeting sidelink communications towards 5G-V2X.

Reference	Main focus	Simulator	Scenario(s)	Main achievements
Performance of autonomous mode with non-periodic traffic Molina-Menegoza, 2020 [111]	Mode 4 vs. 802.11p in presence of realistic CAM generation	Veins	Highway, 60-400 v/km	Mode 4 outperformed by IEEE 802.11p with aperiodic messages and messages of variable size
Bartoletti, 2021 [112]	Mismatch between generation and allocation	LTEV2Vsim	Highway, 50-200 v/km	Aperiodic traffic makes configuration challenging; the use of a small RRI is a good trade-off
Lusvarghi, 2020 [113]	Co-existence of periodic and aperiodic traffic	ns-3	Highway, 60-258 v/km	Reservation-less allocation for aperiodic traffic
Campolo, 2019 [59]	Stochastic geometry-based model for DENM loss probability	Matlab	Highway, 50-200 v/km	Aggregate interference due to competing CAMs
Gibellini, 2018 [114]	Co-existence of CAMs and DENMs	ns-3	200 20m-spaced platoon vehicles	Multi-hop DENM transmissions coupled with repetitions at the first hop to improve reliability
He, 2020 [115]	Short-term sensing (a few symbols) adapted to message priority	Proprietary	Highway, 100-300 v/km	Analytical models of the performance (outage probability, PRR) of periodic and aperiodic traffic
Romeo, 2020 [116]	Performance of DENM repetitions	LTEV2VSim	Highway, 100, 200 v/km	Reservation-less DENM repetitions coupled with short-sensing for improved reliability
Romeo, 2020 [117]	Impact of Mode 4 parameters on DENM performance	LTEV2VSim	Highway, 200 v/km	Short sensing and smaller resource selection list ensure low-latency DENM delivery
Piggybacking and resources map sharing He, 2018 [118]	Piggybacking of subsequent reservations	Proprietary	Highway slow, 150-210 v/km	Piggybacking reservations reduces the impact of collisions on the control channel
Mughal, 2019 [119]	Piggybacking control information	Proprietary	Simplified scenario	Piggyback of control information is shown to improve throughput and reduce collisions
Cecchini, 2017 [120]	Piggyback of sensing	LTEV2VSim	Highway slow, 126 v/km	Awareness improved over two hops
Yi, 2020 [121]	RSU's sensing information shared in smart intersection	MATLAB	Vehicles at an intersection	Lower collision and BLER compared to the legacy SB-SPS
Maruko, 2018, [122] & Sabeeh, 2019-20 [123], [124]	Piggyback of pre-reservations	Proprietary (both)	Highway, 50-300 v/km & Highway, 126.5-275 v/km	Performing reselection in two steps reduces collision probability
Jeon, 2020 [125]	Reservation announced in advance	Not specified	Urban, 60-430 v/km ²	Piggybacking reservation in the SCI in advance improves the performance under congestion
Peng, 2021 [126]	Piggybacking of suspected collisions	Not specified	Highway, 25-125 v/km	Piggybacking reduces recurrent collisions, improving performance in terms of AoI
Gündoğan, 2020 [127]	Allocation with deep reinforcement learning	RealNes	Highway, 16-40 v/km	Improved performance compared to Mode 4 for short distances
Physical layer analysis Anwar, 2019 [128]	PER, PRR, net data rates, and IPG analysis for LTE-V2X, 5G-V2X, IEEE 802.11p and 802.11bd	MATLAB	Urban NLoS	Higher range and reliability of 5G-V2X w.r.t. IEEE 802.11bd
Lien, 2020 [14]	Analysis of two-stage SCI effectiveness	Proprietary	BLER Vs. SNR analysis	Error propagation solved by placing the two SCIs as close as possible
Campolo, 2019 [129]	Impact of NR flexible numerology on Mode 4	LTEV2VSim	Highway, 100-300 v/km	Larger subcarrier spacing reducing IBE improves CAM PRR
Groupcast and relay-based communications Leibel, 2020 [130]	HARQ optimization and relaying for groupcast	Proprietary	2-20 group members	Adaptive ACK/NACK transmissions
Noor-A-Rahim, 2019 [131]	Relaying at intersections	LTEV2VSim	Urban intersection, 60-300 v/km	NLOS conditions at intersections drastically impact on performance
Kim, 2019 [132]	Groupcast for platooning over mmwave	Proprietary	5-6 platoon members	Heuristic for optimal joint selection of retransmissions and resource allocation for improved groupcast success rate

sidelink resources, and DENMs are multi-hop transmitted. No specific workarounds are considered in the resource allocation scheme to deal with the DENM traffic pattern but the same Mode 4 parameters are used for both types of messages. DENM repetitions over the first hop are shown to be crucial for improving transmission reliability. Similar trends are observed in [116], where allocating different resources

to each DENM repetition, instead of keeping them using the standard SB-SPS, is shown to improve the PRR thanks to higher resource diversity. To the best of our knowledge, the study in [117] is among the first literature works assessing the performance of the short-term sensing (100 ms-long interval) added in 5G-V2X: reliability improvements are observed when it is applied to DENMs while keeping

long-term sensing (1s-long interval) for periodic CAMs to better capture reservation dynamics, thus confirming early intuitions in [134].

More incisive modifications of the sensing mechanism are finally proposed in [115], which significantly depart from the legacy one, both as foreseen in LTE-V2X and in 5G-V2X. A VUE willing to select resources performs short-term sensing at first. The length of the sensing period, spanning just a few symbols, is set according to the priority of the message to be transmitted. Similarly to the backoff procedure, a VUE freezes the sensing timer whenever the measurement result is above the defined short-term threshold and restarts it later.

a: SUMMARY AND OPEN ISSUES

From the surveyed literature, it clearly emerges that short-sensing, as envisioned in 5G-V2X, is promising to handle aperiodic/asynchronous traffic. What is still missing in the literature is an extensive investigation of pre-emption and prioritization mechanisms in the resource allocation required when heterogeneous traffic types (besides CAMs and DENMs) compete for the same resources, as instead foreseen for Mode 2.

2) PIGGYBACKING AND RESOURCES MAP SHARING

A relevant group of papers, including [118]–[124], propose the sharing of resources status and reservation information (either in piggybacking with control/data messages or through additional packets) to improve the resource selection process. In [118], the authors assume that multiple reservations are jointly possible and propose piggybacking the reservations in data packets to reduce collisions between control messages; since SCIs and data are not in the same TTI, it should be considered as a pre-Release 14 solution. In [119], a similar idea is applied to the legacy Mode 4; the authors prove through a Markov-chain based model that the proposal increases network throughput and reduces collision probability. In [120], it is instead proposed that each vehicle piggybacks in the transmitted packets a map with the observed state of occupation of each resource. Indeed, the interference which determines the reception quality is actually measured at the receiver side. Hence, sensing measurements at the sender side, as foreseen by SP-SPS, are an inaccurate estimation of the transmission outcome. To reduce the impact of hidden terminals at intersections where VUEs may interact with RSUs, in [121], it is proposed that the RSU periodically broadcasts an RSRP map and an S-RSSI map, so that nearby VUEs can better schedule resources and improve the reception of the RSU. Piggybacking of pre-allocations is finally suggested in [122]–[124]; in [122], it is done in the last packet before reallocation, whereas in [123], [124], the planned reallocation is piggybacked when the reselection counter reaches 5. Although conceived with Mode 4 in mind, the works [120], [122], [123] anticipate Mode 2b.

In the previous works, the reservation was for the immediate next packet as in legacy SB-SPS. In [125] the

authors propose to make the reservation much earlier, e.g., a second before, the actual use of the reserved resource. This is achieved at the expenses of an additional signaling bit to be piggybacked in the SCI. Such an approach lets neighbor vehicles make an informed decision when it is their turn to reserve or select a resource. Moreover, since the reservation announcement is spread multiple times, it can be received by neighbors with a higher reliability. Another proposal relying on piggybacking of some information is made by Peng *et al.* in [126]. The core of the proposal is to piggyback those resources where high received energy but no decoding are probably due to collisions. The improvement compared to the legacy Mode 4 is shown in terms of age of information (AoI).⁵ Finally, an alternative to the SB-SPS algorithm based on piggybacking is proposed in [127], where an allocation algorithm based on multi-agent deep reinforcement learning is proposed. The vehicles locally compute the suitability of the resources and share the local view in piggyback of CAMs. Compared to SB-SPS, improved PRR is shown for the nearer vehicles.

a: SUMMARY AND OPEN ISSUES

The sharing of additional information concerning the resources status and reservation is clearly shown as a key aspect to improve the allocation process. Indeed, more information is shared in 5G-V2X and the two stages SCI allows for more flexibility in the content of the second stage. The challenge, which still appears open, is the optimal trade-off between the introduced overhead and the effectiveness of the approach.

3) PHYSICAL LAYER ANALYSIS

Papers surveyed so far target sidelink resource allocation schemes. However, it is worth to mention works focusing on physical layer issues.

The work in [128] investigates the performance of 5G-V2X, when compared to LTE-V2X, with focus on physical layer procedures. 5G-V2X theoretically outperforms LTE-V2X in terms of transmission latency and data rates. Moreover, simulations show that 5G-V2X offers superior performance than LTE-V2X in terms of net data rates, packet error rate (PER), PRR, and IPG. Different numerologies are considered in sub-6 GHz band with 10 MHz bandwidth.

The impact of the flexible 5G numerology on Mode 4 resource allocation is investigated, instead, in [129]. Improvements are experienced in terms of reduction of interference due to in-band emission (IBE).⁶ This is achieved as a sub-product of a larger SCS, which limits the number of packets that can be simultaneously accommodated on the same TTI.

⁵The AoI is normally defined as the time difference between the generation of one message correctly received and the instant when the next correct reception is completed.

⁶The IBEs contribution is due to the simultaneous use (in the same TTI) of different but adjacent frequency resources. Such unwanted emissions result from the modulation process and non-linearity in the transmitter.

5G-V2X is also addressed, again looking at the physical layer, in [14], with particular focus on the two-stage SCI in Mode 2. The authors show with simulations that the two stages might cause propagation of errors, which can be however mitigated with a careful design. It is also noted that a short 1-st stage can improve the PER.

a: SUMMARY AND OPEN ISSUES

Such early but valuable results pave the way for a more accurate analysis of physical layer dynamics for a better understanding of resource allocation procedures at the MAC layer, especially when 5G-V2X improvements are considered.

4) GROUPCAST AND RELAY-BASED COMMUNICATIONS

Release 14 targets only broadcast communications over the sidelink interface. Some works, e.g., [130], [132], have been recently published which focus on groupcast communications, as foreseen in Release 16, and aim to improve them. In [130] HARQ feedback techniques, as foreseen by 5G-V2X over sidelink, are investigated for groupcast communications and a solution proposed to improve the trade-off between resources wasted on unnecessary retransmission and system reliability. Receivers closer to the transmitter (identified through a threshold specified by the source) feedback NACK-only if decoding fails, while the others feedback ACK/NACK. Groupcast communications for platooning are also investigated in [132], but when considering the millimeter wave spectrum.

Broadcast is known to be poorly reliable but unlike for groupcast, it was decided in 3GPP to not implement the feedback mechanism within Release 16 standard [130]. A further way to improve reliability is relaying, which is investigated in [131] to improve message dissemination at intersections. There, a vehicle close to the intersection center nominates itself as relay. The latter one rebroadcasts messages by leveraging either reserved or dynamically selected resources. Better performance is achieved in the latter case, since resources are not wasted to be pre-allocated and can be used by regular messages. In [130] relaying is also proposed to improve the range of groupcast communications.

a: SUMMARY AND OPEN ISSUES

Due to the crucial role expected to be played by groupcast in critical applications like platooning and intersection management, extensive investigations of the proper feedback mechanism are still required. Relaying is indeed one of the main features expected in Release 17. Nonetheless the inherent benefits of such a solution, the way through which relays are selected and how resources are allocated for them are clearly daunting issues, for which solutions can treasure the huge literature about relaying in vehicular networks but need to account for the peculiarities of the autonomous resource allocation.

V. LITERATURE REVIEW ON CONTROLLED AND HYBRID RESOURCE ALLOCATION

In the following we survey the literature addressing sidelink C-V2X outside the autonomous mode, including those addressing the centralized mode of operation and hybrid centralized-autonomous solutions.

Nonetheless the inherent benefits of the autonomous mode, in case of V2X services requiring high reliability combined with high data rate, the autonomous allocation of sidelink resources will not be the most appropriate choice. If a vehicle is under the coverage of the cellular infrastructure, the controlled mode should be preferred given the expected significant performance improvements w.r.t. the autonomous mode, showcased for instance in [10], [111], [153]. Indeed, thanks to the cell-wide view of resources status and by enforcing spatial reuse accordingly, the eNodeB can ideally provide interference-free transmissions.

Solutions devised for the controlled mode normally rely on the position of vehicles to assign radio resources. Some of them organize vehicles into clusters according to their proximity, others assign resources to each single vehicle. In addition to these two classes of allocation procedures, hereafter and in Table 13 also those that combine the centralized with the autonomous mode are revised.

A. CLUSTER-BASED APPROACHES

In some works, including [135]–[137], it is proposed to group the vehicles in some way and jointly manage the allocation of each group. In particular, the authors in [135] propose a centralized allocation scheme based on the use of graph theory and clustering. The authors propose two sub-optimal approaches with reduced complexity compared to an exhaustive search, which organize vehicles into overlapping clusters based on their location; only one vehicle in each cluster can transmit at a given time to avoid conflicts. Conflict-free resource allocation is targeted by the same authors also in [136], where a framework for optimized subchannel allocation is proposed which aims to satisfy the following conditions: *(i)* guaranteeing differentiated QoS; *(ii)* avoiding vehicles of the same cluster to use the same subframe, thus preventing them to be reciprocally unaware; *(iii)* avoiding vehicles belonging to adjacent clusters to use the same subframe, thus limiting hidden nodes impact; and *(iv)* preferring for each node an allocation in the same subframe rather than using sparse resources in the time domain. Since the assumption that clusters can always be perfectly defined is complicated to guarantee in practice due to the highly dynamic vehicular environments, more stable clusters are defined in [137]. More specifically, Calvo *et al.* implement in [137] a predictive scheme in order to obtain the future positions of the vehicles. Vehicles are then grouped in terms of their similar position, speed and heading. In so doing, vehicles stay longer in the same cluster, making the SB-SPS more efficient.

TABLE 13. Controlled and hybrid sidelink resource allocation studies.

Reference	Main focus	Simulator	Scenario(s)	Main aspects or achievements
Cluster-based				
Abanto-Leon, 2017-2018 [135], [136]	Resource allocation through clustering with QoS	Not specified	Static vehicles, with some overlapping clusters	Suboptimal approaches compared to exhaustive search based on graph theory
Calvo, 2017 [137]	Resource allocation through clustering based on position, direction, speed	Not specified	Real-traffic data from the TapasCologne project	Estimation of vehicles trajectory to improve scheduling performance
Based on individual position of vehicles				
Cecchini, 2017 [138]	Allocation based on reuse distance	LTEV2VSim	Highway slow, 125 v/km	Allocation based on given reuse distance for QoS at given range, with packet withdrawing possible
Fritzsche, 2018 [139]	Reuse distance from range and outage	Proprietary	Generic highway scenario	Reuse distance and rate derived from range and outage, with packet withdrawing possible
Zhang, 2020 [140]	Location-aware resource allocation also accounting for message type	ns-3	Manhattan, 200-1200 v/km ²	Improved resource utilization and more vehicle transmissions allowed
Hu, 2016 [141]	Pre-release 14 D2D allocation maximizing reuse	Not specified	Highway, 250-450 v/km	Allocation based on the maximization of reuse distance
Cecchini, 2018 [142]	Allocation maximizing reuse	LTEV2VSim	Highway slow, 120 v/km; Urban slow, 320 v/km ²	Periodic reallocation based on the maximization of reuse distance
Sempere, 2020 [143]	Adaptive spatial reuse of radio resources ensuring vehicles experience similar interference levels	Veins	Highway, slow, 120 v/km; Urban, 90 v/km	Simulations validated through an analytical model showing reduced packet collisions
Park, 2019 [144]	Resource size optimization	Proprietary	Highway, 60-720 v/km	Resource size control based on density and settings
Vukadinovic, 2018 [79]	Performance with platooning	Nokia simulator	Platoon of 10 trucks + 1 v. and 0-60 v/km	Contention-free transmissions under a single-cell scenario
Campolo, 2018 [145]	Sequential transmissions by platoon vehicles as well as simultaneous transmissions by sufficiently spaced ones	OMNeT++	Highway; up to 28 platoons	Simultaneous transmissions by platoon vehicles reduce the latency and dynamic adaptation of MCS reduces interference
Hybrid with Autonomous Mode				
Sahin, 2018-19 [146]–[148]	Pre-allocation before exiting from coverage	Not specified	Highway, single lane per direction, 10-60 v/km	Network allocation prior to moving out-of-coverage, also with reinforcement learning
Hegde, 2020 [149]	Switching between Mode 3 and 4	Artery-C	Highway, 60-180 v/km	Analysis of the latency incurred in each switching phase
Mikami, 2020 [150]	Switching between Mode 1 and 2	(Experimental)	2 vehicles	Seamless (1ms-long) switching
Hegde, 2019 [151]	Platooning in multi-cell scenario	Nokia simulator	Platoon of 10 trucks + 0-30 v/km	Leader to allocate via Mode 3 for the entire platoon
Keshavamurthy, 2018 [152]	Pool allocation to avoid hidden nodes	ns-3	Manhattan high density, 30 v/km	The network allocates pools based on location, then used applying Mode 4

1) SUMMARY AND OPEN ISSUES

Clustering techniques might have merits in improving resource allocation. However, the increased signaling and necessary countermeasures that need to be enforced to ensure their stability, appear still to be deepened.

B. SOLUTIONS BASED ON INDIVIDUAL POSITION OF VEHICLES

In sidelink LTE-V2X, the allocations are not normally based on channel measurements, both because the channel might vary too quickly and because the number of measurements to be reported would increase with the square of the average number of vehicle in reciprocal range. Since positioning systems are surely available, the allocation is rather based on the location known by the controlling entity, as proposed in [138]–[144], [154], [155].

In [138]–[140], the allocation is performed granting a minimum distance between VUEs using the same resource, with a given residual outage probability tolerated (i.e., some

nodes are temporarily not allocated) in order to cope with shortages of resources. Instead of accepting some outage, in [141] and [142] algorithms are proposed where the allocation is performed starting randomly and then maximising the minimum distance between VUEs using the same resource. These algorithms are shown to approach an optimum allocation in [153].

In [143], context conditions (e.g., the traffic density and channel load) are exploited in addition to the geographical location of vehicles with the target to make all vehicles to experience a similar level of interference. An analytical validation of the proposal is also provided. Park *et al.* in [144] focus on the cases where congestion is observed and propose an algorithm that modifies the resource size to optimize the received signal-to-interference-plus-noise ratio (SINR) level.

The performance of Mode 3 is evaluated in [79] with focus on platooning applications. The study is conducted in presence of a single-cell, hence, the centralized resource allocation guarantees transmissions without interference. The feasibility and performance of the dynamic scheduling

approach, with platoon members asking for radio resources on a per-packet basis is instead investigated in [145]. Adapting the MCS to the actually experienced channel quality, as reported by the receiver, makes more efficient the transmissions between adjacent platoon vehicles, overall reducing the interference.

1) SUMMARY AND OPEN ISSUES

A few algorithms have been proposed for Mode 3, which show near to the optimum performance in highway scenarios also when the position of the vehicles is known with some inaccuracy. However, they have been designed and investigated with simplified assumptions, including messages of a fixed and uniform size, and the same QoS requirements. In addition, they all assume a single operator providing a coordinated allocation, which is an assumption that might not be always true in a real deployment. Finally, not much attention has been devoted to the VUE-to-network signaling, which instead might cause delays and other performance degradation, or even become a bottleneck in congested scenarios.

C. HYBRID APPROACHES

So far, we have investigated the autonomous and centralized resource allocation as stand-alone sidelink solutions. However, in more practical scenarios, the two approaches can work together. For instance, if resources are allocated with a centralized approach in situations with imperfect and/or intermittent network coverage, e.g., when approaching a tunnel scenario, a vehicle may be forced to switch from the controlled to the autonomous mode.

In [146]–[148] the authors address what they call delimited out-of-coverage areas (DOCAs), and propose algorithms performed on the network side to perform pre-allocations of resources before a vehicle exists from coverage. In [147], [148], a reinforcement learning approach is used to train the centralized scheduler to provide non-interfering resources to vehicles before they enter the out-of-coverage area.

The work in [149] analyzes the different phases of the mode switching procedure and studies the latency involved in each phase for both switching directions, i.e., from Mode 3 to Mode 4 and vice versa. Results show that a considerable amount of overhead is incurred because the switching requires the re-establishment of a connection as well as the synchronization and re-allocation of radio resources.

Some small-scale field experimental trials are reported in [150], where the switching in 5G-V2X between Mode 1 and Mode 2 is analyzed and a new dynamic switching function is proposed to ensure seamless V2V communications from in-coverage to out-of-coverage scenarios. The study applies to truck platooning, at a real express highway area in Japan. Mode 1 is selected when all VUEs of the group is in-coverage status, and Mode 2 is selected when a VUE of the group detects out-of-coverage status. The same authors also empirically investigate Mode 2 performance in [156], when considering a 0.25 ms-long TTI, but with 20 MHz

TABLE 14. Future perspectives.

Issue	Suggested solutions and possible improvements
Interplay with beyond 5G technologies	
◊ HD limitations	• FD transceivers [160], [161]
◊ Congested situations	• NOMA [162]–[165] • Network coding [166], [167] • Coded Slotted ALOHA [168], [169] • ML-aided approaches [170] • Cell-free communications [170]
◊ Handovers	• RISs [171] • UAVs [172]
◊ Centralized allocation with coverage gaps	
Evaluation methodologies	
◊ Simulators	• Extensions for 5G-V2X
◊ Channel modeling	• Accurate physical layer abstractions embedded in system-level simulators • Impact of vehicles as obstacles • 3GPP evaluation assumptions
◊ Metrics	• Evaluation at the application layer

allocated at 4.5 GHz band. Under such settings, latency below 1 ms and high reliability of above 99.999% are measured.

A further hybrid approach can be found in [157] to match platooning scenarios. There, the platoon leader interacts with the eNodeB to reserve sidelink resources on behalf of the other platoon members and then, distributes such resources to them. Although not referring to Modes 3 and 4, it somehow anticipates Mode 2d by letting the platoon leader act, as a scheduling UE (S-UE). A similar approach is followed in [151]. This is particularly relevant since platoon members may belong to different cells at any given time, which could complicate handover procedures. Things might even be more complicated in border areas where different operators may be involved and, as such, captured the interest of the research community, as testified by several ongoing EU projects, e.g., 5GMobix [158], 5GCroCo [159].

In [152], the authors assume that the network knows the position of all nodes and the estimated path loss of each link, including fading; based on this information, the cloud optimises the resource pool that each vehicle can use and its power level. Then each vehicle exploits Mode 4 for the final allocation, making it an hybrid controlled/autonomous approach.

1) SUMMARY AND OPEN ISSUES

Taking the best of centralized and autonomous resource allocation, hybrid approaches appear particularly promising. However, switching procedures between the two modes still need to be carefully designed and extensively evaluated, with mobility prediction schemes expected to boost such operations.

VI. LESSONS LEARNT AND FUTURE PERSPECTIVES

In Sections III, IV, V, a detailed scanning of the literature is provided with a classification and our view on open issues per each identified category of contributions. In the following, instead, the main findings of the conducted analysis are debated by clearly stating the still open challenges at a wider extent. Possible solutions, for what concern technological

and methodological foundations, are highlighted to boost future contributions in the research field of sidelink resource allocation and are summarized in Table 14.

A. ISSUES AND INTERPLAY WITH BEYOND 5G TECHNOLOGIES

The surveyed improvements of the sidelink resource allocation algorithms follow straightforward approaches, mainly targeting fully compatibility with existing specifications. However, recently, early germs of more disruptive solutions laying their foundations on emerging 5G and beyond technologies [170], [173], have been published. Some of them⁷ are detailed below as prominent solutions to address the still unsolved issues.

1) HD LIMITATIONS

A recurrent issue in the scanned literature focusing on the autonomous mode is the usage of half-duplex (HD) transceivers. In [160] the sensing-while-transmitting property of the in-band full-duplex (FD) technology is leveraged. This property is to improve the collision detection/avoidance mechanisms of the distributed resource allocation. It is demonstrated through simulations that the performance of the autonomous mode dramatically improves, by letting vehicles adapt the probability of keeping a given resource according to the level of interference detected while transmitting. Although FD transceivers are far from being commercially available, the practicality of a such prominent technology, even in vehicular environments, has been recently argued in [161], making us confident it can be effectively leveraged.

2) CONGESTED SITUATIONS

The poor scalability is one of the main impairments of the autonomous resource allocation highlighted by the scanned literature. Due to the lack of acknowledgments and hidden terminals, high reliability can barely be ensured as congestion increases, unless to reduce the up-to-dateness of exchanged packets, as foreseen by DCC mechanisms. Instead, the adaptation of the generation rate needs to trade off the accuracy of conveyed information with the channel utilization, as early investigated in [174], [175], in case of CPMs. Notwithstanding, the improvements of DCC mechanisms to the legacy Mode 4, as well as to Mode 2, still need to be fully disclosed.

By relaxing the orthogonality constraint, i.e., letting users interfere on the same resources, non-orthogonal multiple access (NOMA) can improve spectral efficiency, reliability and throughput, support massive and heterogeneous connectivity, and decrease the amount of channel feedback whenever available. The possibility to leverage NOMA for V2V autonomous scheduling towards sixth generation (6G) is acknowledged in [170] and, recently, a very few works have been published [162]–[165].

⁷The analysis is not intended to be exhaustive, but aimed to provide some hints to the reader for further investigation.

In [162], [163] an extension of Mode 4 with uplink NOMA is proposed. There, nodes broadcast their data frames at a time-frequency resource selected by the standard Mode 4 SB-SPS; the signals that are superposed at the receiver side are decoded applying successive interference cancellation (SIC), which allows increasing the PRR by almost 40%. Both NOMA receivers based on SIC and joint decoding (JD) are proposed in [164]; assuming an ideal scenario and without specifying the resource allocation procedure, both receivers are shown to offer significant improvements compared to the conventional orthogonal multiple access (OMA) approaches, with JD providing better performance at the cost of higher complexity. In [165] a grant-free NOMA solution is proposed, meaning that transmissions are performed without any reservation and access control, with the aim to resolve collisions of vehicles broadcasting in their surroundings by means of specially designed transmit signatures, combined with an advanced receiver that performs SIC.

Repetitions and soft-combining are included in the HARQ mechanism of both LTE-V2X and 5G-V2X. Network coding can be adopted instead of simple repetitions to improve the reliability as proposed in [166], [167]. More sophisticated solutions exploiting the combination of messages, such as adopting uncoordinated coded-slotted ALOHA (CSA) [176], can be applied to the V2X sidelink interface with similar purposes. CSA uses the idea of the original slotted ALOHA together with SIC. The contending users introduce redundancy by encoding their messages into multiple packets, which are transmitted in randomly chosen slots. The receiver buffers the received signal, decodes the packets from the slots with no collision and attempts to reconstruct the packets in collision exploiting the introduced redundancy. Unlike the sensing-based mechanism of Mode 4 which tries to avoid collisions, CSA tries to exploit them. It is applied in vehicular scenarios for the broadcasting of periodic traffic in [168], [169], on top of the carrier sense multiple access with collision avoidance (CSMA/CA) protocol. Its suitability for the sidelink interface deserves further investigations.

3) HANDOVERS

The majority of the surveyed literature, with the exception of a few works, e.g., [149], [150], neglects handover issues. This is because they either focus on autonomous resource allocation, or consider single-cell scenarios, in case of centralized resource assignment.

However, the mobility of vehicles may lead to fast handovers resulting in frequent resource allocation for conventional approaches, potentially incurring huge overhead. Such issues are even more exacerbated for platoons. Machine learning (ML)-aided approaches can help to predict vehicle trajectory and to allocate resources accordingly. Among them, it is indicated in [173] that those which do not require prior knowledge of vehicular environment, as reinforcement learning (RL), have to be preferred.

TABLE 15. Main open-source C-V2X sidelink simulators.

Reference	Simulation platform	Mobility scenarios	Targets	Availability
Cecchini, 2017 [177]	<i>LTEV2VSim</i> , in Matlab	Models or traffic traces	Mode 3 and Mode 4; includes ITS-G5; focus on cooperative awareness	At [178]
Eckermann, 2019 [179]	Extension to ns-3	Scenarios of ns-3	Based on the ns-3 D2D model in [180], Mode 4	At [181]
McCarthy, 2019 [182]	<i>OpenCV2X</i> , based on OMNeT++	Scenarios of OMNeT++	Extension to SimuLTE [183], with Artery or Veins, Mode 4	At [184]
Hegde, 2020 [185]	<i>Artery-C</i> , based on OMNeT++	Scenarios of OMNeT++, SUMO	Extension to SimuLTE, Modes 3 and 4, flexible numerologies	Planned
Feron Tech [186]	<i>lte-sidelink</i> , in Matlab	Models	Link simulations, applicable to both D2D and V2X use-cases	At [186]

As a further option, cell-free communications, with no cell boundaries, can allow seamless mobility of vehicles, as argued in [170]. There, this is advocated in presence of mmWave and terahertz (THz) communications, required to satisfy the need of higher rates.

4) CENTRALIZED ALLOCATION WITH COVERAGE GAPS

Local out-of-coverage conditions may largely degrade the performance of centralized resource allocations. Switching schemes from centralized to autonomous mode do not come without side effects, e.g., in terms of latency.

In coverage-limited scenarios also due to harsh propagation conditions, e.g., at an obstructed intersection, the exploitation of reconfigurable intelligent surfaces (RISs) can improve packet reception [171], for both V2V and V2I links. With specific reference to the sidelink interface, we can expect such improvements also to benefit the sensing-based approach of the autonomous mode, poorly behaving at intersections, as demonstrated in the surveyed literature.

Lack of connectivity may also become an issue in case of V2V links, like in the case of small penetration ratio of the technology on board the vehicles. Although poorly investigated in the literature studies, scenarios far from 100% penetration may be likely in the short-term. The usage of unmanned aerial vehicles (UAVs) can be helpful to address them and overall boost connectivity [173]. UAVs equipped with C-V2X capabilities can be even considered as vehicles themselves, employing short-range communications [172]. Sidelink extensions accounting for UAVs peculiarities should be envisioned. Similarly to VRUs, the design of power saving techniques would entail the major efforts.

B. EVALUATION METHODOLOGIES

Simulations represent the most suitable methodology to evaluate the performance of the sidelink C-V2X technology. Only a few works have provided field-trials for realistic performance assessment, e.g., [81], [150], [156], and in all cases they consider only pairs of vehicles in the evaluation. However, although much simpler, mature and cheaper w.r.t. field-trials, simulators still entail contributions from the research community to improve their effectiveness and realism in evaluating C-V2X sidelink communications.

1) SIMULATORS

Much work has been done in the development of simulation platforms for the investigation of sidelink LTE-V2X, with special attention to Mode 4. However, in most cases, the implementations are proprietary and not shared publicly (see most of the works in Tables 9, 11, 10, 13). Such a trend hinders easy reproducibility of results and valuable comparisons. A few solutions have also been (or are planned to be) made available as open-source, as summarized in Table 15. The first example is LTEV2Vsim [177], which is a simulator written in Matlab with the aim to allow investigation of resource allocation in sidelink LTE-V2X, both Mode 3 and Mode 4. It focuses on cooperative awareness at the application layer and also includes ITS-G5. Many of the surveyed literature works have used this platform for their evaluation study. Another Matlab implementation is available at [186]. There, the focus was mainly on the simulation of a sidelink air-interface compliant with the D2D specifications on Releases 12 and 13, although D2D tweaks for V2X communications based on Release 14 are also provided. The simulator presented in [179], focusing on Mode 4, is, instead, an extension of ns-3 and it is based on the D2D model presented in [180]. The solution presented in [182], also focusing on Mode 4, is a modification and extension of the SimuLTE [183] within OMNeT++; it is implemented in two versions, one integrating with the Artery⁸ framework to provide full ITS-G5 standardisation across the entire communication stack and the second one integrating with Veins [187] only. In [185], the authors present Artery-C, a simulation framework for the performance evaluation of C-V2X protocols, encompassing V2V and V2I communications via the sidelink interface, and V2X applications.

It is worth observing that, at the time of writing, no open-source simulator exists for 5G-V2X, with the exception of Artery-C, which however, only supports 5G flexible numerologies. Hence, efforts are required in this direction.

2) CHANNEL MODELING

The surveyed literature models channel access dynamics through system-level simulators. However, the latter ones poorly capture physical layer phenomena, by mainly relying

⁸<https://github.com/riehl/artery/>

on simple physical layer abstractions (PLAs) to ensure bounded computation latency and complexity. More accurate PLAs are needed, as early provided in [188] for LTE-V2X and, more recently, for 5G-V2X [189]. Proven the viability and accuracy of such approaches, simulation studies should be overhauled to include PLAs.

As a further suggestion, a thorough understanding of the communication channel, would also encompass to model the presence of vehicles (especially trucks) as obstacles. This option early investigated in [190] for 802.11-based V2V communications, has been poorly considered in the literature targeting sidelink communications, although considered in 3GPP specifications [39].

Furthermore, it is highly recommended for researchers working in the field to refer to the guidelines provided by 3GPP for the evaluation of both LTE-V2X and 5G-V2X, which have been followed during the standardization work [21]. Alignment to channel models as well as to link level simulation settings and assumptions provided by 3GPP will allow an easier and fairer comparison among different literature solutions.

3) METRICS

The surveyed literature contributions mainly focused on link-layer metrics, i.e., PRR, IPG. However, they barely capture the behaviour of the sidelink resource allocation in light of the specific V2X application. Even the works specifically analyzing platooning, e.g., [79], considered them, with a few exceptions [80], [81]. Hence, the assessment of application-specific performance metrics is highly advocated.

VII. CONCLUSION

In this paper, we first discussed the evolutionary path of cellular V2X communications over the sidelink interface. The analysis spans from the early specifications of LTE-V2X in Releases 14 and 15 to the currently specified and underway workarounds in 5G-V2X supporting V2X advanced use cases in Releases 16 and 17. After presenting specifications for the sidelink interface, deemed particularly critical for the low-latency and highly reliable delivery of V2X application messages, focus of the work is the critical and comprehensive review of the recent relevant literature. Solutions aimed to unveil the weaknesses of the 3GPP specifications, through simulations and analytical models, as well as to tackle impairments of sidelink communications are extensively discussed. To the best of our knowledge, this is the first work providing a literature survey of C-V2X sidelink communications.

Hints about the interplay with emerging 5G and beyond technologies to address the identified issues are also provided to boost future research directions in this exciting and challenging field, also expected to fuel ongoing standardization activities.

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