Challenges and Solutions for Cellular Based V2X Communications

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***Abstract*—A wide variety of works have been conducted in vehicle-to-everything (V2X) communications to enable a variety of applications for road safety, traffic efficiency and passenger infotainment. Although dedicated short-range communications (DSRC) based V2X is already in the deployment phase, cellular based V2X is gaining more interest in academia and industry most recently. This article surveys the existing work and challenges on LTE and 5G to support efficient V2X communications. First, we present the motivations for cellular based V2X communications. Second, we summarize the LTE V2X architecture and operating scenarios being considered. Third, we discuss the challenges in existing LTE for supporting V2X communications such as physical layer structure, synchronization, multimedia broadcast multicast services (MBMS), resource allocation, security and survey the recent solutions to these challenges. We further discuss the challenges and possible solutions for 5G based vehicular communications. Finally, we discuss the open research issues and possible research directions in cellular based vehicular communications.**

***Index Terms*—Cellular V2X, LTE vehicular communications, 5G vehicular communications, vehicle-to-vehicle communications, V2X communication infrastructure, V2X security, V2X resource allocations.**

I. Introduction

THERE has been massive research from industry and other organizations to address communication capabilities in vehicles and transportation infrastructures which mainly include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P) and vehicle-to-network (V2N) communications collectively termed as V2X communications. V2X communications can enhance the safety and efficiency of transportation systems. The V2X communications along with existing vehicle-sensing capabilities provide support for enhanced safety applications, passenger infotainment, and vehicle traffic optimization. In addition, V2X communications should support a variety of use cases like do not pass warning, forward collision warning, queue warning, parking discovery, optimal speed advisory and curve speed warning [1]. The V2X communications support various use cases by exchanging messages among infrastructure, vehicles and pedestrian using various wireless communication technologies such as DSRC and cellular network technologies.

DSRC technology supports a short exchange of information among DSRC devices. DSRC devices are equipped with 802.11p chip and mainly include onboard units (OBU), roadside units (RSU) and mobile devices carried by pedestrians. To enable this technology, 75 MHz of the spectrum have been allocated in a 5.9 GHz frequency band by U.S. Federal Communications Commission (FCC). Moreover, a set of services and interfaces have already been defined by IEEE 802.11p and IEEE 1609 standards for Wireless Access for Vehicular Environment (WAVE) to be used in DSRC based applications [2]. In addition, the U.S. National Highway Traffic Safety Administration (NHTSA) worked with the U.S. Department of Transportation to enable vehicular communications capabilities in new light vehicles based on DSRC technology [3]. DSRC based V2X communications provide a number of benefits such as low end-to-end latency, ad-hoc communications and standardized protocols. However, it still faces a number of issues such as short-range, large channel access delay and huge capital investments. Thus, despite the deployment of DSRC based V2X prototype in the U.S., [4], the inherent issues of DSRC and the recent growth in cellular technologies have encouraged research and industry communities to investigate cellular technology based V2X communications.

Cellular communications such as LTE provide ubiquitous coverage, support very high mobility as well as the high number of vehicles in a cell. Moreover, the introduction of device-to-device (D2D) communications further improved spectrum utilization efficiency and system capacity of cellular systems [5], [6]. This motivated organizations like the 3rd Generation Partnership Project (3GPP) to study the feasibility of LTE support for V2X communications [7]. 3GPP is currently working on cellular technology based V2X services and aims to provide a variety of V2X services [8]. Moreover, 3GPP has completed Releases 14 and 15 with LTE based V2X services as one of the main features including other features like license assisted access, machine type communications, massive multiple input multiple output (MIMO) [9]. The Releases 14 and 15 specify highly reliable and real-time

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communications for automotive safety use cases and will continue to evolve to 5G to provide complementary and new capabilities like sensor sharing while maintaining backward compatibility [10]. In addition, there is also active research being conducted in interworking between DSRC and cellular technology to support efficient V2X communications [11].

Although LTE based V2X communications have gained a lot of interest recently, there exist several challenges before the LTE network can be massively exploited for V2X communications. Physical layer structure, synchronization, MBMS, resource allocations and security are the main challenges for LTE V2X communications. Existing physical layer design of LTE cannot support high carrier frequency and vehicular UE velocity due to Doppler effects, so there is a need for a new physical layer structure for LTE V2X communications. Similarly, high vehicular UE speed causes frequent topology change and may cause the problem in the synchronization between the vehicle user equipment and base station. In addition, large and overlapped broadcast areas cause the problem of deploying MBMS for broadcast communications. Moreover, resource allocation is one of the main challenges where resources used by the vehicular users should not conflict with the resources being used by the cellular users. Security is another main challenge in LTE V2X due to the broadcast and un-encrypted nature of communications. Many projects that have addressed these challenges are explained in detail in the rest of this article.

Along with the above-mentioned projects in LTE V2X, technology organizations like 3GPP and Qualcomm have prepared the roadmap towards 5G based V2X services. 3GPP is currently working towards the completion of Release 16 which specifies various new services such as sharing of high throughput sensor data, path planning, real-time location updates, and coordinated driving [12]. The 5G wireless system is an excellent candidate to enable high data rate applications in vehicular environment [13]. The 5G wireless system is expected to incorporate various emerging technologies such as device-to-device communications, massive MIMO, full-duplex radios, multi-radio access technology, cloud technologies, millimeter waves and software-defined networking (SDN) [14]. Each of these technologies will bring various solutions and challenges to 5G based vehicular communications. Deployment of heterogeneous and small cell networks might cause frequent handover and increase the signal load in V2X communications. Moreover, there might be issues of short communication range and high path loss in millimeter wave communications, pilot contamination in massive MIMO, and resource utilization in vehicular fog computing. In addition, there might be issues such as control plane design in SDNs, content prefetching and distribution in mobile edge computing, the configuration of multiple slices in network slicing and spectrum efficiency in dynamic spectrum sharing. There are several other challenges in each of the above mentioned 5G technologies which are discussed in detail in Section V.

TABLE I
ACRONYMS AND CORRESPONDING FULL FORMS

Acronyms	Full Form
V2X	vehicle-to-everything
V2V	vehicle-to-vehicle
V2P	vehicle-to-pedestrian
V2N	vehicle-to-network
V2I	vehicle-to-infrastructure
DSRC	dedicated short-rang communications
MBMS	multimedia broadcast multicast services
OBU	onboard units
RSU	road-side units
FCC	federal communications commission
WAVE	wireless access for vehicular environment
NHTSA	national highway traffic safety administration
D2D	device-to-device
3GPP	3rd generation partnership project
MIMO	massive multiple input multiple output
SDN	software-defined networking
CSMA/CA	carrier-sense multiple access with collision avoidance
NLOS	non-line-of-sight
eNB	evolved node-B
UE	user equipment
EPC	evolved packet core
PLMN	public land mobile network
HSS	home subscriber server
E-UTRAN	evolved universal terrestrial radio access network
MME	mobility management entity
S-GW	service gateway
P-GW	packet gateway
PCRF	policy and charging rules function
eMBMS	evolved MBMS
MBMS-GW	MBMS gateway
BM-SC	broadcast multicast service center
QoS	quality-of-service
NR	new radio
OFDM	orthogonal frequency division multiplexing
SCS	subcarrier spacing
CP	cyclic prefix
NCP	normal CP
ECP	extended CP
TTI	transmission time interval
GNSS	global navigation satellite system
TMGI	temporary mobile group identity
Geo-RNTI	geographic radio network temporary identifiers
SMDP	semi-Markov decision process
NOMA	non-orthogonal multiple access
SPS	semi-persistent scheduling
MB-SFN	multicast-broadcast single frequency network
SC-PTM	single cell point to multipoint
IBE	in-band emissions
T-RPTs	time resource patterns
CSI	channel state information
VCF	V2X control function
TIMF	temporary ID management functions
CA	certificate authority
V-UE	vehicular UE
PSS	primary synchronization signal
SSS	secondary synchronization signal
MIB	master information block
MNO	mobile network operator
IMSI	international mobile subscriber identity
OEM	original equipment manufacturer
TTA	trusted traffic authority
VFC	vehicular fog computing
VNF	virtualized network functions
NFV	network function virtualization

Only a very few surveys have been published discussing LTE and 5G based V2X communications [15], [16]. Reference [15] provides a general overview of V2X access technologies with discussion on V2X applications and requirements, and different V2X access technologies. Whereas [16] highlights the security requirements of V2X and mainly discusses the authentication issues of V2X entities.

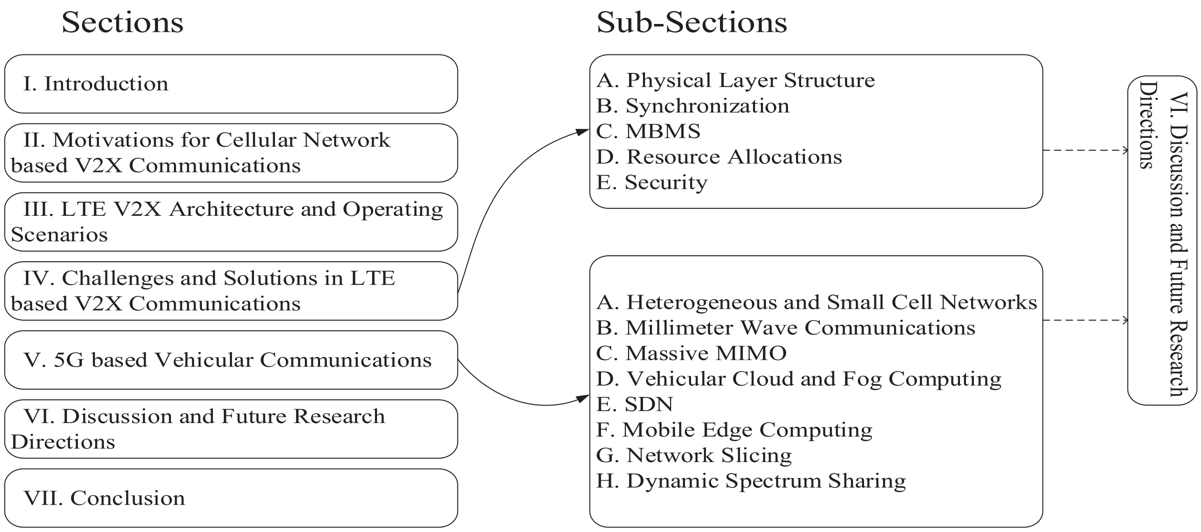

Fig. 1. Outline of this article.

This survey is different from the above two in several ways. This survey highlights the major challenges in the physical layer structure, synchronization, MBMS, resource allocations and security of LTE V2X communications and discusses in detail the prospective solutions for each of these challenges. Moreover, benefits, challenges, and solutions for several key technologies of 5G V2X communications are discussed in detail along with the possible future work. Reference [15] provides a survey only on V2X access technologies and [16] provides a survey only on the authentication issues of cellular V2X communication. Whereas, our survey covers the wide area of V2X communications and provides comprehensive information regarding major challenges, possible solutions and future research work in various areas and technologies of evolving cellular based V2X communications.

The major contributions of this survey article can be summarized as follows.

- Discussion on motivations for cellular based V2X communications and detailed comparison of cellular and DSRC based V2X communications.
- Examination of LTE V2X architecture including both general LTE V2X communication model and LTE V2X architecture from 3GPP.
- Discussion on several operating scenarios of LTE V2X communications.
- Description of several main challenges in LTE based V2X communications with prospective solutions.
- Discussion on benefits, challenges and solutions of various technologies of 5G in V2X communications.
- Discussion on future research directions on cellular based V2X communications.

The rest of this article is organized as follows. Section II provides motivations for adopting cellular based V2X communications. Section III presents the existing LTE based V2X architecture and different operating scenarios for LTE based V2X communications. Section IV presents various challenges and potential solutions for LTE based V2X communications. Section V discusses the open issues and solutions related to 5G based V2X communications. Section VI presents discussion and future research directions. Finally, Section VII concludes this article. For the readability, the outline of this article is shown in Fig. 1 and most used acronyms and their full forms are shown in Table I.

II. Motivations for Cellular Network Based V2X Communications

The latest improvements in cellular technologies have inspired industry and research communities to explore cellular network based V2X communications. This section mainly highlights the advantages and disadvantages of DSRC based V2X communications and motivations for cellular network based V2X communications.

A. DSRC Based V2X Communications

DSRC based V2X communications have been the subject of extensive standardization, field trial and product development for almost two decades. Although a lot of projects have already been studied in DSRC, it still has some limitations from technical and business perspectives. From technical perspectives, DSRC suffers from short range characteristics of around 200 to 400 meters and is limited to line of sight communications [17]. Due to which vehicles will have intermittent connectivity when moving with a high-speed [11]. Moreover, carrier-sense multiple access with collision avoidance (CSMA/CA) is used as a channel access mechanism in DSRC. This mechanism results in large channel access delay in a high vehicular traffic scenario due to the large intensity of channel conflict [18]. In addition, there is a presence of a hidden node problem due to the absence of a handshake and acknowledgment mechanism. This hidden node problem results in packet collisions, poor link performance and unreliable broadcast service in high vehicle density scenarios. From business perspectives, huge investment is required for the deployment of DSRC based

TABLE II
COMPARISON OF IEEE 802.11P BASED DSRC AND LTE V2X COMMUNICATIONS [21], [22], [23]

Features	**IEEE 802.11p based DSRC**	**LTE V2X**
Frequency band	5.86 - 5.92 GHz	450 MHz - 4.99 GHz
Modulation	Orthogonal Frequency Division Multiplexing (OFDM)	Single-carrier Frequency Division Multiplexing (SC-FDM)
Channel access mechanism	CSMA/CA	Sensing based semi-persistent transmission
Retransmission mechanism	No Hybrid Automatic Repeat Request (HARQ)	HARQ
Synchronization requirements	Asynchronous	Synchronous
Resource multiplexing across vehicles	Time division multiplexing only	Frequency and time division multiplexing possible
Channel coding	Convolution code	Turbo code
Data rate	Up to 27 Mb/s	Up to 1 Gb/s
Capacity	Medium	High
Coverage	Intermittent	Ubiquitous
Mobility Support	Up to 60 km/hr	Up to 350 km/hr
Quality-of-Service Support	Enhanced Distributed Channel Access (EDCA)	QCI and bearer selection
Broadcast/multicast support	Native broadcast	Through eMBMS
CAPEX/OPEX	High	Relatively low

V2X communications due to network backbone infrastructure like RSUs [19]. Capital expenditure and operating expenses (CAPEX/OPEX) will be very high as the large number of RSUs needs to be deployed along the roads.

B. Cellular Network Based V2X Communications

Cellular network based V2X communications such as LTE has several advantages as compared to DSRC based V2X communications from both technical and business perspectives. From technical perspectives, the LTE network provides ubiquitous coverage for V2I/V2N services and also supports very high mobility of vehicles up to 350 km/hr [19]. Moreover, the hidden node problem is prevented in LTE with the enhancement of slotted MAC. In addition, MBMS of LTE technology can be used for efficient safety message dissemination [11]. Likewise, LTE provides much better performance in the non-line-of-sight (NLOS) environment and supports a high data rate of up to 1 Gbps and a high number of vehicles in a cell [20]. From business perspectives, LTE based V2X communications can reduce the cost of mass production by utilizing the common hardware platform of LTE. A brief comparison of IEEE 802.11p based DSRC and LTE V2X communications is shown in Table II.

Although there are many advantages of using LTE for V2X, there are also some challenges for LTE V2X. LTE has a centralized nature due to which vehicular data needs to be passed through the base station which can raise the issue of latency. It has also been shown that existing beaconing capabilities of LTE to support vehicular safety application is poorer as compared to 802.11p/WAVE [23]. Moreover, LTE base station coverage is much larger than a zone of the relevance of safety messages due to which many vehicles can receive irrelevant messages [11]. These irrelevant messages can be reduced with the help of multicast service by broadcasting messages to the multicast group only. However, control signaling overhead and latency will be high for multicast service due to the join and leave process of evolved MBMS [24]. In addition, the performance evaluation of cellular network traffic should be considered while using LTE for V2X.

These various challenges of LTE or cellular V2X should be addressed to gain full advantages of cellular V2X. This article mainly surveys and discusses solutions to various challenges of cellular V2X which are presented in detail in Sections IV and V.

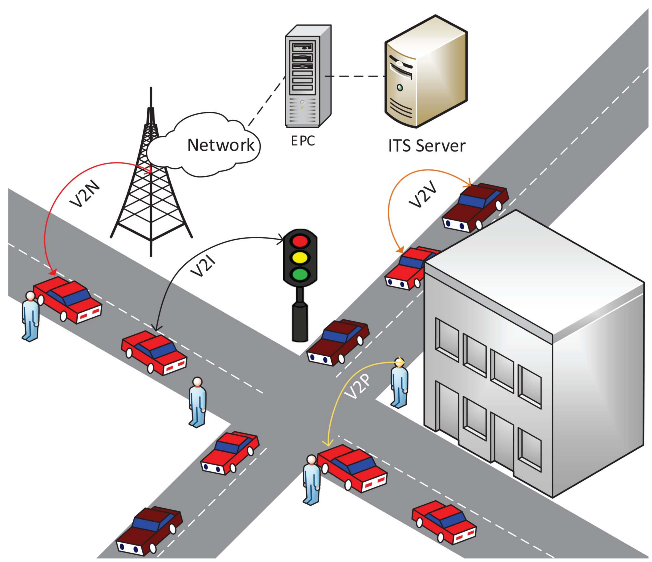

Fig. 2. General LTE V2X communication model.

III. LTE V2X ARCHITECTURE AND OPERATING SCENARIOS

Recently, various LTE V2X architectures and operating scenarios have been proposed by 3GPP and non-3GPP organizations. This section highlights the general LTE V2X communication model, LTE V2X architecture and LTE V2X operating scenarios.

A. General LTE V2X Communication Model

LTE V2X communications mainly involve V2V, V2I, V2N and V2P communications, as shown in Fig. 2. Vehicles within proximity of each other can exchange safety or infotainment related information either directly or with the help of infrastructures like evolved node-B (eNB) or RSUs. RSUs can exchange unicast information with vehicles using a V2I application. Moreover, RSUs can broadcast information related to

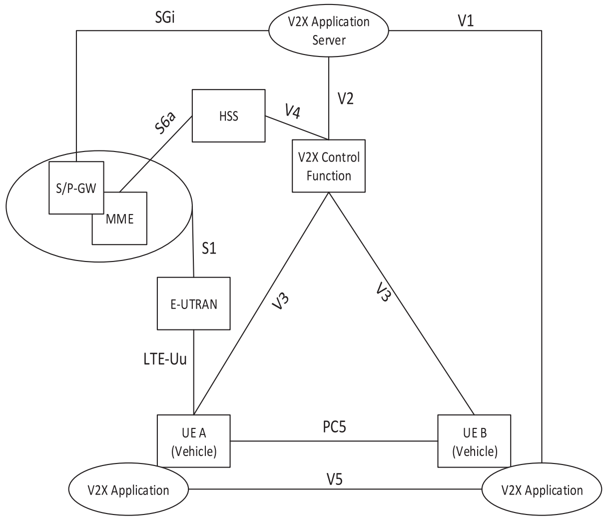

Fig. 3. PC5 and LTE-Uu based reference architecture for V2X, described by [25].

an emergency scenario or traffic condition to a group of user equipment (UE). V2N communications are also introduced in which both parties - vehicular UE and serving entity, support V2N applications and communicate with the help of the LTE network. In addition, the evolved packet core (EPC) of the LTE network may connect to an intelligent transportation system (ITS) server for various vehicular services. V2P supports the exchange of messages between vehicles and pedestrians. These messages are transmitted by vehicular UE to pedestrian UE or by pedestrian UE to vehicle UE.

B. LTE V2X Architecture From 3GPP

3GPP document [25] describes PC5 and LTE Uu based, and evolved MBMS (eMBMS) and LTE-Uu based V2X architecture.

1) PC5 and LTE-Uu Based V2X Architecture: In PC5 and LTE-Uu based architecture, as shown in Fig. 3, there are 8 reference points. The reference point between the V2X application server and the V2X application is V1 while the reference point between the V2X control function in the operator's network and the V2X application server is V2. The reference point between the V2X enabled UE and the V2X control function in UE's home public land mobile network (PLMN) is V3. Similarly, the reference point between the home subscriber server (HSS) and the V2X control function in the operator's network is V4. The reference point between the V2X applications is V5 while the reference point between the V2X control functions is V6. The reference point between the V2X enabled UE and the evolved universal terrestrial radio access network (E-UTRAN) is LTE-Uu and the reference point between the V2X enabled UE for V2V, V2I and V2P services is V8.

In LTE V2X, functional entities include V2X control function, mobility management entity (MME), V2X application server, service gateway (S-GW) and packet gateway (P-GW). The V2X control function provision the UE with necessary parameters required for V2X communications when served or not served by e-UTRAN. MME obtains subscription

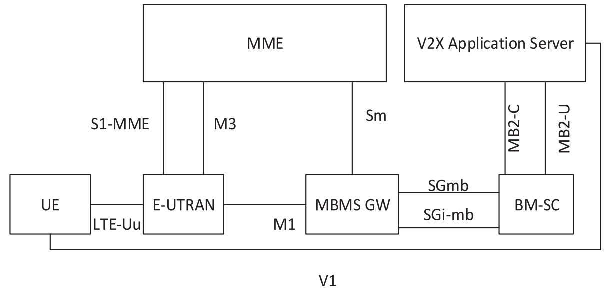

Fig. 4. eMBMS and LTE-Uu based LTE V2X architecture, described by [25].

information related to V2X and provides UE authorization status to e-UTRAN. The V2X application server is used for both collecting the uplink data from UE and delivering data to UE in a destination area. S-GW routes and forwards the data as well as perform charging with the help from policy and charging rules function (PCRF). P-GW is responsible for providing communications between IP and circuit-switched networks.

2) eMBMS and LTE-Uu Based V2X Architecture: In an evolved MBMS (eMBMS) and LTE-Uu based V2X architecture, as shown in Fig. 4, there are two additional functional entities broadcast multicast service center (BM-SC) and MBMS gateway (MBMS-GW). BM-SC receives local MBMS information from the V2X application server and sends local MBMS information to the MBMS-GW. If MBMS-GW receives local MBMS information from BM-SC, it skips the allocation procedure for IP multicast distribution.

C. Operating Scenarios

There are several operating scenarios in spectrum usage for LTE V2X. In [27], the authors presented four different operating scenarios, as shown in Fig. 5. In scenario 1, there is no dedicated spectrum for V2V and each UE, i.e., cellular and V2V UE, utilizes the spectrum of their own operator. In this scenario, if required, the same spectrum can be used for both links. However, there might be an issue of providing appropriate quality-of-service (QoS) for inter-operator operation. In scenario 2, the dedicated spectrum is allocated to V2V. In this scenario, due to the dedicated spectrum for V2V operation, the inter-operator issue is restricted only to cellular operation. In scenario 3, a single operator manages LTE V2X operation for certain areas. Due to the dedicated spectrum for an entire area, capacity and QoS for V2X operations can be greatly improved. In scenario 4, V2V links operate without any help from eNB. This scenario is applicable to the areas without any network coverage.

There are also other scenarios being discussed. In 3GPP document [7], three different scenarios are considered. In the scenario I, only one operator has eNBs in a specific area and other operators share these eNBs for all services including V2X. In scenario II, only one operator owns the dedicated V2X spectrum in a specific area and other operators share this spectrum for V2X service. In scenario III, both operators have eNBs in a specific area and a V2X server distributes the V2X message to both operator's networks.

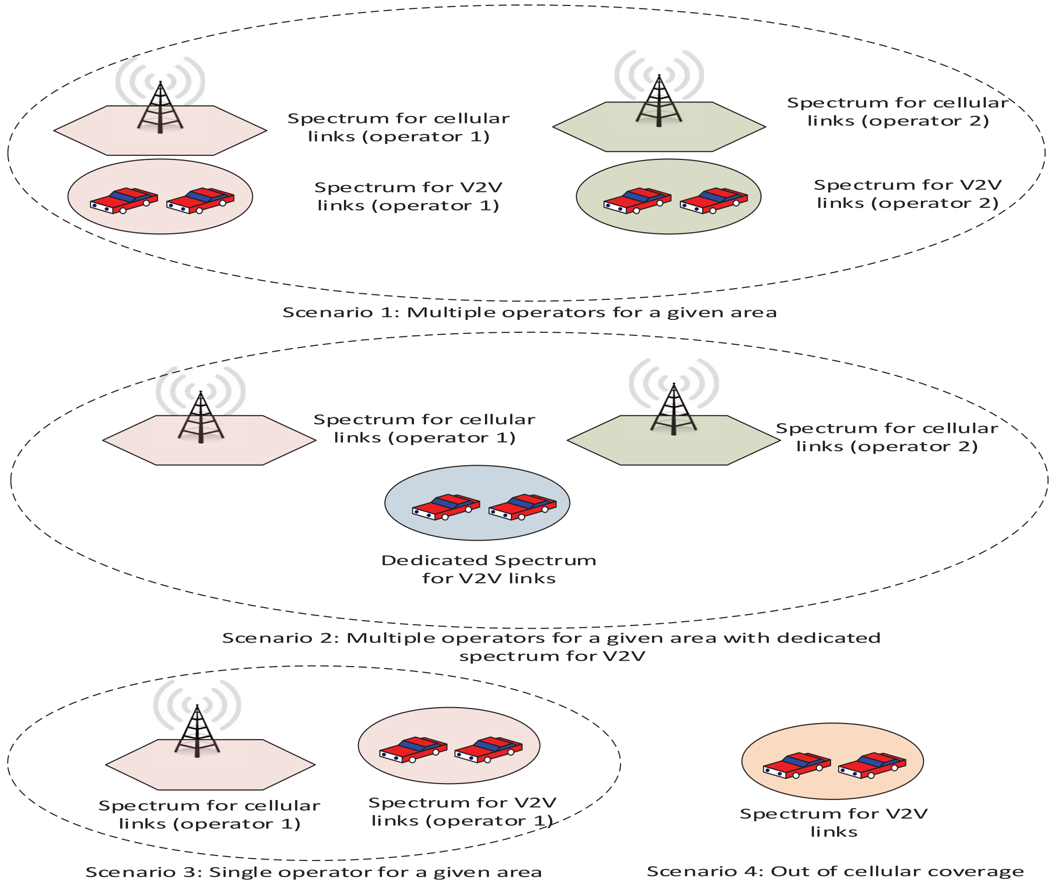

Fig. 5. Operating scenarios for LTE V2X, described by [27].

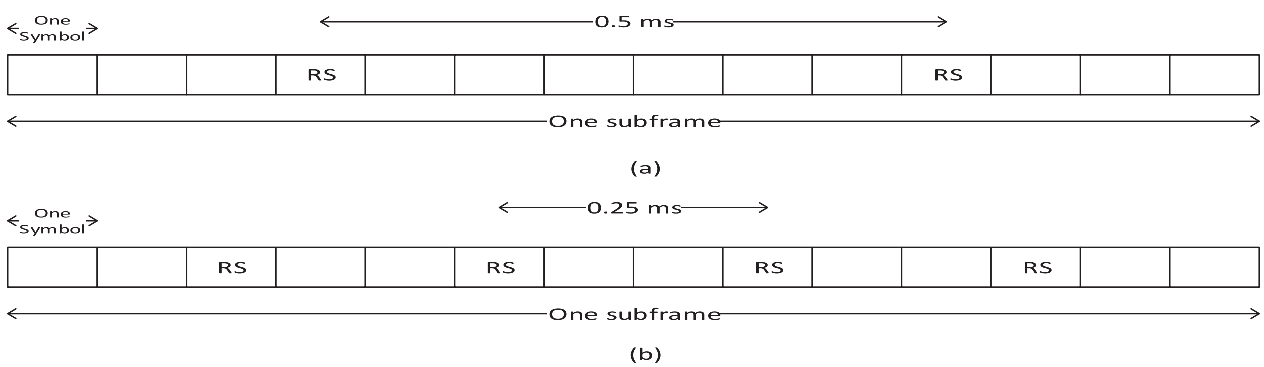

Fig. 6. Illustration of (a) existing LTE physical layer structure and (b) physical layer enhancement to track Doppler case.

IV. Challenges and Solutions in LTE Based V2X Communications

There are several challenges before LTE can be massively exploited for vehicular communications. Standards organizations including 3GPP have actively carried out research to address these challenges. This section explores some of the major challenges and possible solutions in LTE based V2X communications.

A. Physical Layer Structure

1) Challenges: Existing LTE physical layer design cannot support high carrier frequency as well as high UE velocity. However, for wider frequency allocation range, the LTE V2X system may be required to support very high carrier frequency up to 6 GHz. Moreover, vehicles may achieve high relative velocity when driving at high speed in the opposite direction causing Doppler effects. Doppler effects can introduce interference among carriers. In addition, short coherence time due to Doppler effects results in an inaccurate channel estimation [27]. If the existing physical layer design of LTE is used for LTE V2X, then the time interval of reference signal will be higher than the coherence time, as a result, the performance for demodulation of data will strongly fall [32]. In current LTE physical layer design, at max 1 kHz frequency offset can be corrected. However, the maximum frequency error between

UE in the neighboring cell can be more than 2.2 kHz [32]. Thus, there should be some enhancement in the physical layer structure of LTE for V2X communications.

2) Solutions: 3GPP is considering enhancing the reference signal structure by reducing the time interval between reference signals. To reduce this time interval, they are considering a sub-frame of 1 ms in which the four reference signal symbols are consistently located [7], [26], as shown in Fig. 6. Other techniques are also being considered in which for a single reference signal symbol, the high-frequency offset is estimated by comparing the phase of the first and second half of each reference signal [27].

In [28], the authors proposed a frame structure for LTE-V2V and compared the performance of LTE-V2V with IEEE 802.11p. In the proposed scheme, a frame of length 10 ms is considered with 10 subframes of each length of 1 ms. A slot of 0.5 ms is considered, i.e., each subframe consist of 2 slots. The subcarrier spacing of 15 kHz is considered with a variable number of subcarriers in a signal. In the time domain, the smallest unit that can be scheduled is 0.5 ms and in the frequency domain, the smallest unit is 12 subcarriers. The structure of frame and subframes affects the coding rate as well as the equivalent data rate in LTE-V2V as well as IEEE 802.11 p. The authors have done simulations and have shown that the QoS setting impacts slightly in LTE-V2V whereas heavily in IEEE 802.11p, LTE-V2V is better at longer distances communications and IEEE 802.11p is robust at limited or shorter distances.

In [29], the authors discuss the physical layer structure for 3GPP new radio (NR) based side link transmissions. As different countries have different bandwidth allocation policies, orthogonal frequency division multiplexing (OFDM) with different subcarrier spacing (SCR) is desired. To combat with different levels of inter-symbol interference, different cyclic prefix (CP) lengths are associated with different inter symbol interference levels in NR such as normal CP (NCP) and extended CP (ECP). For side link transmission in NR which is mainly used for V2V communications, CP-OFDM is supported. In 3GPP NR side link transmission based V2X communications, the length of the frame is 10 ms and the single frame contains 10 subframes. A slot contains a varying number of OFDM symbols which is equal to 12 OFDM symbols in case of ECP and 14 OFDM symbols in case of NCP. The length of the slot is based on the value of SCS and for 15 kHz SCS, the length of a slot is 1 ms. In addition, for uplink and downlink transmission in 3GPP based NR, mini-slot is used to further reduce the latency. However, mini-slots are not supported for NR side link transmissions. In this work, the authors have done simulations and have considered 4 different cases with different numbers of symbols per side - link control information (SCI), the different moving speed of vehicles and different payload sizes per SCI. Authors have shown that the impact of error propagation is limited when the 1st-stage and 2nd-stage SCI are correlated and there is 0.5 dB performance loss in case of high speed.

Transmission time interval (TTI), i.e., physical layer structure affects the end-to-end latency of LTE V2X communications. In [30], the authors discuss the frame structure to meet the strict latency requirements of LTE V2X communications. In LTE V2X, the TTI can be reduced by using two approaches: lowering the number of symbols in a frame with fixed subcarrier spacing or by increasing the subcarrier spacing and reducing the symbol duration. For these two approaches, the authors have considered a symbol-wise frame structure and a self-contained frame structure. In a symbol-wise frame structure, 3 OFDM symbols are used and the subcarrier spacing is fixed to 15 kHz. In a self-contained frame structure, subcarrier spacing is set to 60 kHz, the guard period is set to 20.33 μs with 1 symbol for uplink and 12 symbols for downlink. The symbol-wise frame structure has a scattered pilot pattern and a self-contained frame structure uses a preamble pilot pattern. Authors have done simulations and have shown that the symbol-wise frame structure is more robust compared to a self-contained frame structure in terms of the Doppler shift. The authors also discuss that faster feedback is possible in a self-contained frame structure compared to symbol-wise as channel estimation can only be done at the end of the frame in case of a symbol-wise frame structure.

In [31], the authors discuss the agile frame structure based on NR Release 16 [12] and compares the new frame structure with the LTE frame structure. For latency and in-band interference reductions in V2X communications, shorter TTI and larger SCS are desired. In LTE, fixed 1 ms length TTI and static SCS are used whereas in NR scalable SCS and TTI are used for growing V2X use cases. NR Release 16 supports TTI duration of 1 ms to 31.25 μs, i.e., in frequency domain SCS settings from 15 to 480 kHz. Release 16 NR C-V2X provides enhancements in both Uu and PC5 interfaces of LTE V2X. NR C-V2X supports variable subcarriers spacing for various V2X applications. In addition, in NR C-V2X transmissions are not bound to the entire subframe duration due to the use of mini-slots. For a small amount of data, NR C-V2X supports less than 14 OFDM symbols to occupy only the required number of symbols called mini-slots. In NR C-V2X, 5.9 GHz spectrum supports SCS of 15, 30 and 60 kHz whereas spectrum higher than 6 GHz supports higher frequency bands up to 480 kHz. In NR C-V2X, due to the allocation of wider SCS, frequency offset and Doppler Shift are handled better compared to existing LTE V2X. Similarly, due to shorter TTI, channel variation within TTI is smaller needing fewer DMRS signals compared to LTE V2X. Authors have done extensive simulations and have compared the existing LTE-V2X of 1 ms TTI and SCS of 15 kHz with NR C-V2X of flexible numerology in 5.9 GHz band. In terms of packet reception probability (PRR), the NR scheme achieves better performances compared to the LTE-V2X as a single cooperative awareness message can be accommodated in a shorter TTI of 0.5 ms instead of 1 ms in LTE-V2X. Similarly, in terms of update delay, the NR C-V2X schemes outperform the legacy LTE due to a longer burst of errors in existing LTE.

Table III shows the qualitative comparison of the different schemes regarding the physical layer structure of V2X communications.

B. Synchronization

1) Challenges: High vehicular UE speed causes a frequent topology change due to which UE needs to continuously

TABLE III
COMPARISON OF PHYSICAL LAYER STRUCTURE FOR V2X COMMUNICATIONS

Scheme	References	Symbols per slot	TTI	SCS	Mini slot	Latency	Inter Symbol Interference	Handling of Doppler Shift
LTE-V2V	[28]	14	0.5 ms	15 kHz	No	High	Moderate	Poor
NR- V2V	[29]	12 for ECP 14 for NCP	1 ms for side link transmission	15 kHz	Yes	Very High	Moderate	Poor
Symbol-wise	[30]	3	213 μs	15 to 60 kHz	No	Low	High	Good
Self-contained	[30]	1 for uplink 12 for downlink	250 μs	60 kHz	No	Low	High	Good
NR - C-V2X	[31]	14	1 ms to 31.25 μs	15 to 480 kHz	Yes	Very Low	Very High	Excellent

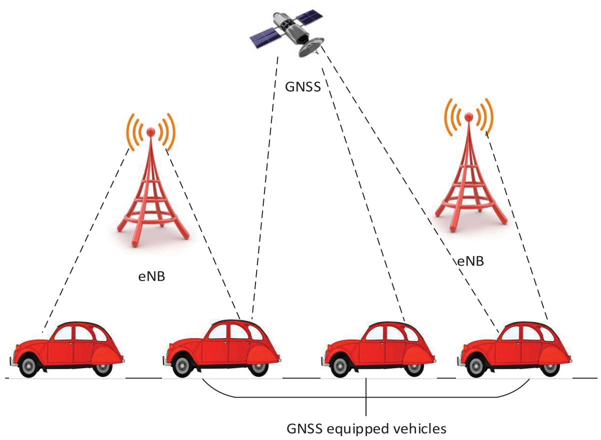

Fig. 7. Time Synchronization using GNSS and eNB.

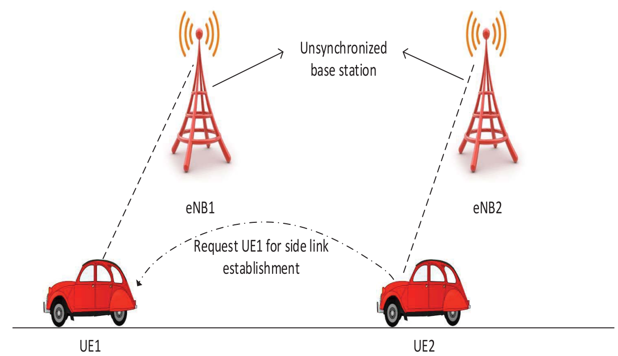

Fig. 8. Side link establishment for synchronization, described by [34].

update the reference point for synchronization. However, V2X communications need to be robust to this synchronization source change as a result of frequent topology change. Moreover, in the legacy LTE system, the neighboring vehicle's relative timing offset cannot be assumed to be within a cyclic prefix, if cellular coverage is not present or if eNBs are not synchronized [32].

2) Solutions: To address this synchronization problem, the synchronization source can be chosen as a global navigation satellite system (GNSS) [33]. Accurate timing and frequency reference can be provided by utilizing the GNSS. As shown in Fig. 7, both GNSS and eNB signal may be available within cellular coverage. Thus, in the cellular coverage region, prioritization among these two systems should be considered [32].

In [34], the authors proposed a different synchronization solution so that the cellular links and inter-cellular side link can co-exist without any interference. In LTE V2X communications, if side link and uplink transmission are not synchronized then inter-symbol and inter-carrier interference may arise due to the relative timing offset of uplink and side link transmission. This synchronization issue can be addressed using GNSS as an external synchronization source. There should be a synchronization within out of coverage mobile users equipped or not equipped with GNSS and cellular network. In the proposed scheme, synchronization signals are exchanged among out of coverage users in the side link. Other side link users detect these synchronization signals and adjust their time difference on the basis of other users weighted mean timing. In the case when more than one synchronization source is available, mobile users can prioritize the synchronization source as eNB signals, GNSS signals followed by side link (SL) signals. In addition, in this article, the authors have presented the method for synchronization between side link users attached to unsynchronized BS. In the proposed algorithm, UE2 attached to eNB2 sends a request to UE1 attached to eNB1, as shown in Fig. 8.

If UE1 rejects the request, no side link is established. If UE1 accepts the request, the side link is established only if a relative timing offset lies below a certain level. However, if this offset exceeds the label, side link establishment and synchronization procedure depend on whether UE2 is out of coverage or attached to eNB2. If the UE2 is out of the network coverage, UE2 uses the time reference of UE1 for side link establishment and then UE1 informs eNB1. If UE2 is attached to eNB2, then UE1 should request its serving eNB1 for the synchronization procedure. If eNB1 approves the request of UE1, UE1 receives one of the following synchronization instructions from eNB1. The first instruction is to connect to UE2 via side link after disconnecting from eNB1 and to utilize the time reference of UE2. The second instruction is to be handed over to eNB2 and to use side link under the control of eNB2. The third instruction is to utilize GNSS for side links and to request UE2 to use GNSS as well.

In [29], the authors discuss synchronization procedure for 3GPP NR based side link communications. If eNB or next-generation Node B (gNB) is present then, vehicle, eNB or gNB all follows the same timing reference. However if there is a lack of coverage or if eNB or gNB is not deployed, the timing

TABLE IV
COMPARISON OF SYNCHRONIZATION PRIORITY AND ERROR IN V2X COMMUNICATIONS

	eNB based Synchronization Priority	**GNSS based Synchronization Priority**	**Multi-Link Synchronization Priority**	**Absolute Time offset error**
Reference	[29]	[29]	[34]	[30]
Full Network Coverage	1. eNB 2. UE directly synchronized to eNB. 3. UE indirectly synchronized to eNB. 4. GNSS. 5. UE directly synchronized to GNSS. 6. UE indirectly synchronized to GNSS. 7. Remaining UEs.	1. GNSS. 2. UE directly synchronized to GNSS. 3. UE indirectly synchronized to GNSS. 4. eNB. 5. UE directly synchronized to eNB. 6. UE indirectly synchronized to eNB. 7. Remaining UEs.	1.eNB 2. Side link signals	Low in eNB based Synchronization Very high in GNSS based Synchronization
Partial Network Coverage	1. UE indirectly synchronized to eNB. 2. GNSS. 3. UE directly synchronized to GNSS. 4. UE indirectly synchronized to GNSS. 5. Remaining UEs.	1. GNSS. 2. UE directly synchronized to GNSS. 3. UE indirectly synchronized to GNSS. 4. UE indirectly synchronized to eNB. 5. Remaining UEs.	1. eNB 2. GNSS 3. Side link signals	High
Out of coverage	1. UE directly synchronized to GNSS. 2. UE indirectly synchronized to GNSS. 3. Remaining UEs.	1. UE directly synchronized to GNSS. 2. UE indirectly synchronized to GNSS. 3. Remaining UEs.	1. GNSS	Very High

reference of all vehicles should be aligned with each other. GNSS can be used for synchronization of out of coverage vehicles. Thus, GNSS based synchronization and eNB/gNB based synchronization can be used for NR based vehicular communications.

a) eNB/gNB based synchronization: When the eNB or gNB is present, vehicles receive synchronization signal block (SSB) from eNB or gNB. The vehicle onboard unit continues to receive SSB and remains synchronized with eNB or gNB. If eNB or gNB synchronization signals are not present, vehicle UE synchronizes to SSB based on the priority. The first priority is given to vehicle UE directly synchronized to eNB or gNB, the second priority is given to UE indirectly synchronized to eNB or gNB, the third priority is given to GNSS, fourth priority is given to UE directly synchronized to GNSS followed by UE indirectly synchronized to GNSS and last priority is given to remaining UEs. UE acts as a synchronization source for other UEs whose synchronization signals are derived from the source with low priority. If a vehicle UE cannot receive any synchronization signal from any source then UE uses its local source as the synchronization source.

b) GNSS based synchronization: In GNSS based synchronization, vehicle UE searches for GNSS signal as soon as it is powered on. UE becomes a synchronization source by transmitting SSB for other vehicle UE whose timing reference is derived from an eNB or gNB. Similarly, UE becomes a synchronization source for other vehicle UE whose timing reference is derived neither from eNB nor GNSS. If GNSS synchronization signals are not present, vehicle UE synchronizes to SSB based on the priority. The first priority is given to vehicle UE directly synchronized to GNSS, the second priority is given to UE indirectly synchronized to GNSS, the third priority is given to eNB or gNB, fourth priority is given to UE directly synchronized to eNB or gNB followed by UE indirectly synchronized to eNB or gNB and last priority is given to remaining UEs. Similarly, UE acts as a synchronization source for other UEs whose synchronization signals are derived from the source with low priority. If a vehicle UE cannot receive any synchronization signal from any source then UE uses its local source as the synchronization source.

In [30], the authors discuss the multi-link synchronization in cellular-based V2X communications. Multiple synchronization sources are available in vehicular communications due to which different vehicular UE may be driven by different synchronization source. In case of partial and out of coverage scenarios, mutual user time synchronization can be used similar to [34]. In [30], the authors have used the concept similar to [34] and have done simulations to analyze mutual and mean absolute time offset in out-of-coverage and partial coverage scenario. With simulations, the authors have shown that with some out-of-coverage users equipped with GNSS and some in-coverage cellular users, the relative time error for partial coverage is below 0.2 μs. Similarly, the authors have shown that the absolute time error for partial coverage is $0.3\mu s$. Moreover, the authors have shown that absolute time offset error for out of coverage is high due to the time drift from radio wave propagation time. This shows that the scheme similar to [34] works perfectly in a partial coverage scenario.

Table IV compares the synchronization priority and error in V2X communications.

C. MBMS

Due to the broadcast nature of MBMS, it can be utilized for safety-related applications. In addition, the signal strength of the message can be reinforced by utilizing a multi-cell broadcast of MBMS [27]. However, there exist several issues with MBMS. This section highlights some of the key issues and solutions related to MBMS service for vehicular communications.

1) Challenges:

a) Large broadcast areas: For a specific V2X message, the broadcast area may cover one or more cells. However, with the use of MBMS, information may be broadcast on more than required cells. Thus, existing LTE based MBMS can decrease the efficiency of traffic flow information and is not directly applicable in V2X communications.

b) Small, variable and overlapped broadcast areas: There are various discussions on 3GPP document [7] to support small and variable areas in V2X using MBMS. 3GPP has identified two main issues to support small and variable areas in V2X. The first issue is to determine the V2X broadcast area and the second issue is to broadcast different V2X messages in different areas, especially in overlapping areas.

c) Latency: In the existing system, MME, BM-SC, MBMS, and MBMS-GW are placed in the core network to reduce the backhaul delay between BM-SC and the eNB while delivering V2X messages. Latency will be one of the important factors while using MBMS for LTE V2X services.

2) Solutions:

a) Large broadcast areas: To solve the issue of large broadcast areas, geo-casting can be used with the help of a special purpose back-end server. This back-end server can intercept and process traffic before redistributing it to concerned vehicles in a given geographical area [35].

b) Small, variable and overlapped broadcast areas: For the first issue of determining the V2X broadcast area, a special purpose V2X server can be used which can broadcast the information based on the V2X UE location. For the second issue of broadcasting different V2X messages in different areas, 3GPP has identified two solutions based on a single temporary mobile group identity (TMGI) and multiple TMGI.

Single TMGI Based: There are several options based on single TMGI:

- *New ID to Differentiate the Flows:* In existing MBMS, flow id doesn't allow different data in overlapping areas but allow the network to provide different data in different areas. To transfer different data in overlapping areas, a new id named 'x' is invented. V2X server provides data for each 'x' id of the network and MBMS-GW transfers the corresponding data of different 'x' id bearer to the different multicast IP address. In this scenario, eNB identifies multiple 'x' ids for the same TMGI. Moreover, it combines the data of different 'x' ids and provides in the Uu interface utilizing the same TMGI.
- *Use Non-Overlapped MBMS Service Areas:* An operator can arrange small non-overlapped MBMS service areas for V2X.
- *User Plane Enhancement Solution:* In this solution, the MBMS bearer is pre-established by the V2X server with a specific TMGI for a V2X service in large broadcast areas. Broadcast area information is added to the SYNC header by BM-SC after decoding the V2X message. Generated MBMS packets are then sent by BM-SC to MBMS-GW and eNB through the pre-established MBMS bearer. The eNB decodes the new SYNC header in the arrived MBMS packets, to identify the V2X broadcast area and then determine whether to broadcast the MBMS packet or not. This solution affects eNB, BM-SC and SYNC packet.

Multiple TMGI Based: In this solution, to transmit different V2X messages in different overlapped areas, different TMGI can be applied to overlapped MBMS service areas.

3) Latency: There are two options to reduce latency while using MBMS to deliver V2X messages. The first option is that MBMS core network functions can be moved closer to eNB or even collocated in the eNB. The second option is to move the user plane of MBMS core network functions close to eNB or even collocated in the eNB. There are still some issues with localized MBMS based implementation. An operator can deploy localized MBMS in the radio access network for V2X service whereas non-V2X MBMS service may still use MBMS-GW and BM-SC in the core network. The current standard does not support the UE to use the local BM-SC for V2X MBMS service, and macro BM-SC for non-V2X MBMS services at the same time.

In addition, in [36], the authors evaluated the efficiency of MBMS and showed that performance can be significantly enhanced by using a MIMO system. Mainly, the authors proposed and analyzed the use of diversity-oriented schemes as well as multiple stream schemes to enhance the spectral efficiency of MBMS. The authors advocate the use of multiple antennas both at the base station and the UE to reduce the latency.

In [37], the authors proposed a scheme to reduce the end-to-end latency in V2X MBMS broadcasting by performing the processing at the layer-2 of the base station and the use of geographic radio network temporary identifiers (Geo-RNTI). In Geo-RNTI, different RNTI values are assigned for different geographical regions. These Geo-RNTIs values are pre-configured per service and per area and avoid the need for communication with application servers. Geo-RNTIs are managed by the mobility engine and session manager. Mobility engine updates Geo-RNTIs based on UE position and the session manager allocates TMGIs and stores a mapping information betweens associated Geo-RNTIs and TMGIs. Moreover, the authors performed the simulations and have shown that the proposed layer-2 based technique reduces the latency of the existing LTE MBMS system and satisfies the cooperative collision avoidance (CCA) latency requirements.

Table V lists the challenges, solutions, limitations, and feasibility of MBMS in V2X communications. Feasibility indicates the suitability for deployment which is decided based on the complexity of the proposed solution and changes in the existing architecture. The term very high in the feasibility column means very high suitability for deployment followed by the term high, whereas the term low means the low suitability for deployment.

D. Resource Allocations

1) Challenges: Due to a large number of concurrent transmission in dense vehicular traffic scenario, it is essential to efficiently utilize the available resources. In LTE D2D, for centralized scheme downlink control information is used for resource management whereas, for the distributed scheme, the random resource selection method is used [32]. In LTE D2D, a number of concurrent transmissions are low compared to vehicular traffic scenarios so LTE D2D resource allocation may not be applicable for V2X traffic. Further, due to highly mobile and dense vehicular users in LTE V2X communications, D2D centralized resource allocation may result in extra signaling overhead as UE needs to frequently connect to eNB whereas random resource allocation may result in resource collision due to unilateral bad decisions of vehicular UE [32].

2) Solutions: 3GPP has proposed several schemes to improve D2D resource allocation that can be used in the vehicular scenario. Improvements include a semi-persistent resource allocation scheme for centralized resource allocation

TABLE V
CHALLENGES AND SOLUTIONS OF MBMS IN V2X COMMUNICATIONS

Challenges	Solutions	Limitation	Feasibility
Large broadcast areas: Information broadcast on more than required cells.	Geo-casting with special purpose back end server [35].	Delay due to interception and re-distribution.	High
Small, variable and overlapped broadcast areas: Determine V2X broadcast area and broadcast different V2X messages in different areas.	Single TMGI: New ID to differentiate flows [7].	May cause interference if huge number of x ids are related to same TMGI.	Very High
	Single TMGI: Arrange Non-overlapped MBMS service areas [7].	Hard to find non-overlapped MBMS service areas.	Low
	Single TMGI: User Plane Enhancement [7].	eNB, BM-SC and SYNC packet are affected. Require a lot of modification in existing system.	Very Low
	Multiple TMGI: Use of different TMGI [7].	Huge number of unique TMGI are required	Very High
Latency: MBMS is placed in the core network.	Localized MBMS [7].	Current standard does not support use of localized MBMS for V2X services and macro MBMS for non-V2X services at the same time.	Very Low
	MIMO based MBMS [36].	Require huge number of antennas for MBMS service.	High
	Geo-RNTI [37].	Pre-configuration of Geo-RNTIs requires periodic information of the geographical areas.	High

and techniques such as sensing or detecting other UE transmission for distributed resource allocation. Enhancement of MBMS for communications in high traffic demand is also being considered [27].

Resource allocation can be broadly divided into centralized resource allocation and distributed/autonomous resource allocation. In centralized resource allocation, eNB sends the control signal for resource allocation whereas, in distributed resource allocation, resource allocation is conducted independently without any help from eNB.

a) Centralized resource allocations: In literature, there are several schemes proposed to efficiently utilize resources with the help of eNB. Most of the proposed schemes exploit the uplink band as of cellular users for V2X traffic. For the reader convenience, we have categorized centralized resource allocations based on the application domain and technique employed. Each of the categories is explained in detail below.

General Schemes: This category includes the schemes that employ a general system model for resource management in vehicular communications.

In [38], the authors proposed a resource allocation scheme for vehicular communications utilizing slow and large scale fading information of wireless channels. In the proposed scheme, a high information rate is desired for V2I links whereas high reliability is desired for V2V links. In this article, the authors have proposed two algorithms. In the first algorithm, the authors formulated the objective function to maximize the sum information rate of all V2I links. Whereas, in the second algorithm, the authors formulated the objective function to maximize the minimum information rate of V2I links so that the uniform performance can be achieved across all V2I links. The authors have only considered slow and large scale fading information instead of instantaneous channel state information for resource management. The authors have considered that the resource of one cellular user equipment can only be shared with a single device user equipment which is one of the main limitations of this article as it leads to poor spectrum utilization.

In [39], the authors designed a scheme to maximize the minimum capacity of cellular users while guaranteeing the reliability of vehicular users. In addition to the reliability requirement of vehicular users, i.e., block error rate, the authors have considered the latency of vehicular users. Due to the difficulty in the computation of the latency for vehicular users, the authors transformed the latency constraint into data rate constraints. The authors have proposed an algorithm based on Lagrange dual decomposition and binary search method for radio resource management. Similar to [38], the authors have considered that the resource of one cellular user can only be shared with a single vehicular user which leads to poor spectrum utilization.

In [40], the authors proposed a method for joint channel and power allocation in which channel state information of vehicular links are reported to the base station on a periodic basis. The main goal of this scheme is to maximize the capacity of the V2I link. In this scheme, at first, the power allocation is performed considering only single V2I and V2V pairs. Based on the optimum power allocation for single V2I links and V2V pairs, optimum V2I capacity is obtained. The authors have used the Hungarian algorithm to solve the proposed scheme. As in this scheme, multiple vehicular users can share the same V2I link, it leads to better spectrum utilization compared to [38] and [39].

In [41], the authors transformed the reliability and latency requirements of vehicular networks into optimization constraints. In this scheme, the authors proposed a SOLEN algorithm. In the first stage of the SOLEN algorithm, the channel allocation problem is considered as the maximum weight matching problem for a bipartite graph to allocate channels to both V2V and cellular user equipment. Second, based on channel allocation results from the first stage, power control is performed for each vehicular and cellular user equipment. Similar to [38] and [39], the proposed scheme leads to the poor spectrum utilization as a spectrum of one cellular user equipment can be shared with the only single device user equipment.

In [42], the authors proposed graph theory based resource allocations for the connectivity optimization problem. In the proposed scheme, multiple vehicular user equipment shares a single cellular user resource leading to network interference. In this scheme, the authors utilized the interference graph to obtain the number of resources that guarantee the connectivity of the network. The minimum spanning tree method is used to model and solve the proposed resource allocation scheme. Moreover, the authors have performed simulation and shown that the proposed algorithm improves network connectivity.

Heterogeneous and Cognitive Radio Based Schemes: This category discusses the resource allocation schemes for vehicular communications based on heterogeneous and cognitive radio based systems.

In [20], the authors proposed a cognitive radio based resource allocation policy. This article assumes that resources are centrally managed by eNB with the cellular user as a primary user and V2X network as a secondary user. Moreover, this article assumes that the maximum allowable transmit power for vehicles is computed by eNB. In the proposed scheme, the V2V network utilizes the most appropriate LTE-A uplink band for V2X traffic. When vehicular UE utilizes the same frequency band as of cellular users, it should not interfere with the cellular user while maintaining the required power for QoS. Due to the correlation of average path loss between uplink and downlink signals, the proposed scheme senses the path loss in the downlink signal. In this article, sensing algorithm is proposed which has two stages, cognitive sensing stage, and resource allocation stage. In cognitive sensing stage, interfering and non-interfering list is obtained by comparing the V2V nodes transmitting power with the non-interfering rule. In resource allocation stage, eNB utilizes a non-interfering V2V list to allocate resources to V2V nodes and cellular users. In addition, eNB allocates unutilized white space in the uplink band to V2V nodes in the interfering list.

In [43], the authors considered resource allocations to facilitate video streaming in cellular and cognitive radio enabled vehicular communications. The main goal of the proposed scheme is to improve the video quality of vehicular users without affecting cellular users. The authors have used a semi-Markov decision process (SMDP) for resource allocations. In this scheme, the state space is defined on the basis of the number of admitted background cellular users and the spatial distribution of admitted vehicle users. The action of RSU or base station is to accept or reject the vehicle video request based on the available spectrum. After adopting the action, the new state is defined by state transition probability. Moreover, the reward between two decision epochs is described as the product of the number of admitted vehicle users and the expected time duration between two epochs. In the proposed scheme, an optimization problem is designed to maximize the expected reward so that more video requests of the vehicles can be admitted while assuring QoS for cellular users.

In [44], the authors have considered resource allocations in heterogeneous vehicular networks with cognitive radio technology. In the proposed scheme, the available spectrum is identified by cognitive radio enabled RSUs by performing spectrum sensing in surrounding environments. Incentive mechanism is used to encourage base stations for sharing the available spectrum resource with RSUs. In addition, the authors have formulated the problem of resource allocation as the n-person game with regret matching based strategy selection. Moreover, the authors derived an equilibrium solution for the proposed non-cooperative game and used graph coloring to form the strategy set.

Clustering or Group Based Schemes: This category discusses the schemes that use clusters or groups of V2V links for resource allocations.

In [45], the authors proposed a dynamic resource allocation algorithm for vehicular scenarios based on traffic flow. In the proposed scheme, V2V nodes and cellular UE share the same resource block in one LTE cell. A physical resource block is shared by multiple V2V links without lowering the communication quality of cellular users. In addition, in this article, the authors have analyzed the connection between capacity utility value and the number of V2V grouping. They showed that the number of V2V grouping should increase with the increase in the number of V2V links. Further, based on vehicle speed, appropriate traffic flow is identified and then the number of V2V links for that traffic flow is selected. Once the V2V links are selected, suitable resources are assigned to each group of V2V communication links. The authors further presented the simulation results showing better performance than greedy and random resource allocation algorithms in terms of runtime and spectrum efficiency.

In [46], the authors transformed the reliability and latency requirements of V2V communications into outage probability. In the proposed scheme, multiple vehicular user equipment is allowed to share the common resource block. In addition, the authors proposed a three-stage radio resource management algorithm called CROWN. In the first stage, the vehicular user equipment is grouped in the cluster and in the second stage resource block sharing strategy is performed. Vehicles belonging to different clusters can share the same resource block whereas vehicles in the same cluster cannot share the same resource block. After the resource block assignment, the feasibility of the resource assignment is studied. If resource management is feasible then power allocation is performed in the third stage.

In [47], the authors presented a graph theory based resource allocations. In the proposed scheme, multiple V2V links can share the same V2I link. The authors have used a max n-cut algorithm to partition interfering V2V links into different clusters. The authors only considered large scale fading information to partition V2V links and form a cluster. After forming the cluster, the resource allocation problem is designed as a weighted three-dimensional matching problem with vertices as V2I links, resource block and

V2V clusters. To solve a weighted three-dimensional matching problem, the authors have adapted the high-performance approximation algorithm. In addition, the proposed scheme results in a higher spectrum utilization as a single cellular user equipment resource is shared by multiple device user equipment.

In [48], the authors used dynamic programming techniques and greedy techniques for resource allocations. The dynamic programming technique solves the resource allocations using optimal clustering whereas the greedy technique solves the resource allocations with low computing complexity. In the proposed method, vehicles in a cluster can reuse the same uplink frequency resource to communicate directly via a D2D mode. SINR criteria are used to compute the maximum transmission range for vehicles while sharing the resources of cellular users. The maximum transmission range is determined by the traffic density and distribution of cellular users. In addition, different transmission directions may induce different D2D transmission distances. In each cluster, vehicles share the same resource so the objective of the resource allocation algorithm is to minimize the number of clusters. In the proposed algorithm, if a current vehicle uses resources different from that of a former vehicle, then the number of resources is added by one and traditional cellular resources can be used by vehicle only when formerly allocated resources are not used by the vehicle. Moreover, the authors have shown with simulation results that when vehicle density increases, a few numbers of clusters are needed in D2D mode and the unidirectional transmission has fewer clusters as compared to bidirectional transmissions.

Cloud Computing Based Schemes: This category includes the schemes that consider resource management in a centralized vehicular cloud platform.

In [49], the authors designed a scheme to maximize the revenue of the vehicular cloud computing (VCC) system. In the proposed scheme, moving vehicles constitute a dynamic vehicular cloud. Each vehicle has one basic computation resource unit and can save the processing speed and energy by sending the task request to VCC. Whenever a request arrives, the vehicular cloud either accepts it or transfers it to the remote cloud. In this scheme, the system state is defined by several parameters like vehicles, the number of resource units, the unoccupied resource in the vehicular cloud and the event of requests. Whereas, the action reflects whether to accept the request or to transfer it to the remote cloud and reward is the revenue of the system which is calculated based on the income and the cost of the VCC system. Moreover, the authors have performed a simulation to compare the proposed scheme with other schemes and found a significant reward gain compared to other schemes.

In [50], the authors have considered enhanced cloud radio access network (C-RAN), D2D communications and SDN technologies to provide large bandwidth and high computing capability for vehicular communications. The authors have proposed a matrix game approach for resource allocation and management of cloudlets. The authors formulated resource management to enhance the resource utilization of each cloudlet. The authors have obtained a Nash equilibrium for the proposed game by employing the Karush-Kuhn-Tucker (KKT) condition into non-linear optimization. In addition, the authors have exploited the software-defined network to address the complex and heterogeneous vehicular network. Moreover, they achieve global optimization result with the help of the software-defined network.

NOMA Based Schemes: NOMA based schemes include schemes that employ non-orthogonal multiple access techniques for resource management.

Non-orthogonal multiple access (NOMA) technique can be used in LTE based vehicular network to reduce the resource collisions between different V2X applications and to support massive connectivity by using code domain or power domain multiplexing. In [51], the authors proposed resource allocation for NOMA based vehicular system, in which channel allocation is performed by the base station and power control is performed by V2V users. At the beginning of each semi-persistent scheduling (SPS) period, the base station allocates the channel on the basis of position information of each vehicle. After channel allocations, dynamic power control is performed by the transmitter or V2V users in each SPS period. Due to the use of the NOMA technique, a lot of interference is produced at the receiver side. Thus, for distributed power control and for successive interference cancellation at the receiver side, information is exchanged between transmitter and receiver users.

Similar to [51], the authors in [52] designed a scheme in which the base station performs channel allocations in a semi-persistent manner and vehicles perform distributed power control. In the proposed scheme, the transmitter-receiver is selected by base-station in a centralized manner and packet reception probability maximization problem is considered for resource allocations. The authors considered vehicular users and channels as two disjoint sets of objects to be matched together. For this matching problem, the authors have employed a multi-dimensional stable roommate matching technique. In addition, the authors proposed their own rotation matching algorithm which after a limited number of iterations converges to stable matching.

In [53], the authors proposed NOMA based resource allocations to maximize the minimum capacity of the cellulars. In addition, they imposed minimum SINR for V2V users as the constraints while formulating the problem. The authors solve the proposed resource allocation problem by decoupling the optimization problem into three stages. In the first stage, power is allocated for cellular user equipment whereas in the second stage power allocation and sub-carrier assignment is performed for the vehicular user equipment. In the final stage, the cellular user equipment is clustered and the subcarrier is assigned for the cellular user equipment. Moreover, the authors have presented an algorithm that integrates these three stages to obtain a joint solution. The authors have shown with simulation results that the cellular user equipment with diverse channel gains occupies the same cluster. In addition, they have shown that minimum cellular capacity decreases with the increase in the minimum SINR threshold and the number of V2V links.

TABLE VI
COMPARISON OF CENTRALIZED RESOURCE ALLOCATIONS FOR V2X COMMUNICATIONS

Ref.	Spectrum Sharing	Objective	Approach	Performance metric	Spectrum Utilization	Performance comparison/evaluation
[38]	Spectrum of one V2I link is shared with a single vehicle UE.	Maximize the sum rate of V2I link capacity.	Bipartite graph and Hungarian algorithm.	Capacity of cellular UE.	Poor	Instantaneous sum of cellular UE capacity better compared to [41].
[39]	Spectrum of one cellular UE is shared with a single device UE.	Maximize the minimum SINR of cellular UE.	Lagrange dual decomposition and binary search method.	SINR of cellular UE and latency of vehicle UE.	Poor	Average packet latency of 15.1 ms compared to 46.9 ms of [41].
[40]	Spectrum of one V2I link is shared with a multiple device UE.	Maximize the sum rate of V2I link capacity.	Bipartite graph and Hungarian method.	Sum capacity of cellular UE and SINR of vehicle UE.	Very High (Multiple vehicles can share same)	Outage probability in terms of vehicle UE is satisfied for threshold of 5 dB.
[41]	Spectrum of one cellular UE is shared with a single device UE.	Maximize the sum rate of cellular UE.	Bipartite graph and SOLEN algorithm.	Sum capacity of cellular UE and transmit power of cellular and vehicle UE.	Poor	High sum rate of cellular UE for 2 to 10 number of resource blocks per vehicle UE.
[42]	Spectrum of one cellular UE is shared with a multiple device UE.	Maximize the network connectivity.	Minimum spanning tree method.	Connectivity index and number of full connectivity components.	Very High	Improves connectivity compared to random and greedy algorithm discussed in the paper.
[43]	Each channel is allocated to only one user (vehicle user or cellular user).	Attain the optimal video quality.	Semi Markov decision process.	Admission ratio and channel utilization ratio of vehicle users.	Very Poor	Channel utilization of the proposed scheme is better compared to benchmark scheme.
[44]	Macro cell and RSUs reuse the spectrum.	Improve spectrum utilization and mitigate the inter-RSU interference.	N-person game and regret matching.	Achievable data rate.	High	Achievable data rate is in optimal condition at 35 km/h and data rate converges in 7 iterations.
[45]	Physical resource block is multiplexed by more than one V2V links.	Multiplex the cellular user resource with largest reuse utility value.	Traffic flow and dynamic grouping.	V2V capacity value and spectrum efficiency value.	Very High	Spectrum efficiency value is greater compared to Stochastic and Greedy algorithm.
[46]	Spectrum of one cellular UE is shared with a multiple device UE.	Maximize the sum rate of cellular UE.	Bipartite graph and Hungarian algorithm.	Sum rate of cellular UE and probability of availability.	Very High	Better cellular user sum rate and better availability compared to previous scheme.
[47]	Spectrum of one cellular UE is shared with a multiple device UE.	Maximize the sum rate of V2I links.	Bipartite graph and weighted three dimensional matching problem.	Sum V2I capacity.	Very High	Higher instantaneous sum V2I capacity compared to [46].
[52]	Spectrum of one cellular UE is shared with a multiple device UE.	Maximize the packet reception probability of the network.	Multi dimensional stable roomate matching.	Package reception probability and latency satisfaction ratio.	Super High	Higher package reception probability in dense vehicle scenario compared to orthogonal based scheme.
[53]	Spectrum of one cellular UE is shared with a multiple device UE.	Maximize the minimum weighted rate of cellular UE.	Bipartite graph matching.	Optimal control rate (cellular user data rate) and transmit power.	Super High	High spectral efficiency comparable to exhaustive search method.

3GPP Based Solutions: This category discusses ongoing discussions and projects in 3GPP for centralized resource allocations.

3GPP document [7] discusses the downlink and uplink enhancement of the Uu interface for centralized resource allocation. For downlink enhancement, 3GPP is currently considering the use of both multicast-broadcast single frequency network (MBSFN) and single-cell point to multipoint (SC-PTM). Improving MBSFN/SC-PTM on the basis of UE geographical location is being considered so that the information can be broadcast only on the target area. Moreover, the need and solutions to reduce MBSFN/SC-PTM latency are being considered. Supporting inter-operator deployment is also being discussed so that UE is allowed to receive the downlink broadcast of another operator. Similarly, 3GPP is also considering uplink enhancement for LTE V2X communications. For uplink enhancement, semi-persistent scheduling (SPS) can be used to reduce the uplink overhead. For the SPS method, it is desirable to use a long SPS period between 100 ms and 1 s. In addition, UE assistance on periodicity and timing can be provided to eNB and also UE can inform the network when SPS resources are not used.

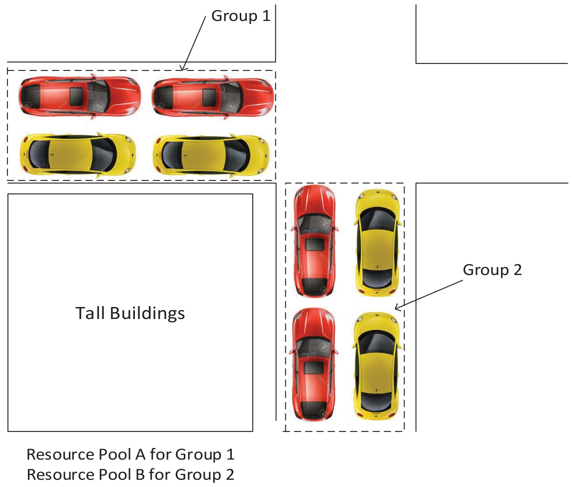

Fig. 9. Resource pool partition in intersection area, described by [55].

Table VI compares the above discussed centralized resource allocations on the basis of spectrum/channel sharing, objective, the approach employed, performance metric, spectrum utilization, and performance comparison/evaluation.

b) Distributed resource allocations: In distributed resource allocation, vehicular UE allocates the resource independently without any help from eNB. In D2D mode 2 resource allocation, UE arbitrarily selects the resource for data transmission but for V2X, a random resource selection scheme is not sufficient. Distributed resource allocation algorithm has to deal with three types of effects: interference between UE due to the utilization of the same resource, interference due to in-band emissions (IBE) by other UE transmitting in the neighboring band and packet loss due to half-duplex constraints [54]. The best way to increase the efficiency of distributed resource utilization is to make sure that nearby transmitters are co-scheduled for transmission at the same time resources. In addition, there are various methods to efficiently allocate the resources in a distributed scenario which is described with various categories of distributed resource allocations in the following paragraphs.

Location Based Distributed Resource Allocations: 3GPP document [55] discusses resource allocation based on geographic partitioning. Geographic partitioning is crucial for distributed resource allocations as various parameters of V2V communications such as transmitter power, carrier sensing threshold are location dependent. In V2V communications, different interference levels may arise across different directions and lanes if the vehicle speed is different across different directions and lanes. If vehicles approaching the intersection in the perpendicular road section are using the same resource pool, then a significant reception power difference will be observed between vehicles. Due to the large difference in reception power, the weak signals coming from different group UE can suffer from in-band emission interference of the strong signals coming from the same group UE. To address this issue, time division multiplexed resource pool partitioning between different UE groups approaching the intersection can be considered, as shown in Fig. 9.

If vehicle densities are different for vehicles moving in opposite directions, service quality can be relaxed in the direction of high vehicle density and high service quality can be applied in the direction of low vehicle density. Thus, different resource pools can be assigned to vehicles moving in opposite directions to provide different QoS.

In addition, the 3GPP document [56] explains resource allocation based on position and heading. By assigning a set of resources to a geographical zone, the effect of hidden node problem and the near-far effect caused by in-band emissions can be reduced. Two approaches used for defining geographical zones are:

- *Position Based Geographical Partitioning:* The performance of this scheme relies on having actual location information of each UE and an appropriate dividing of the geographical region into a set of zones/grids. But this scheme results in a large amount of signaling between eNBs and UE as a new set of zones has to be formed each time a UE leaves the previous zone. Position based zoning mechanism can be more useful in rural or highway scenarios however a great amount of tasks has to be conducted to optimize zones for complex urban areas.
- *Heading Based Geographical Partitioning:* In most of the urban scenarios, only two zones, each corresponding to one direction, i.e., East-West and North-South are required. Significant performance gain can be achieved by using heading based resource allocation as compared to random resource allocation. In addition, heading based partitioning can greatly simplify the signaling and provisioning in complex urban areas and can be more beneficial compared to the position based partitioning. Thus, the combination of both position and heading based geographic partitioning can be used where position based partitioning can be used for rural areas and heading based partitioning can be used for urban areas.

Sensing Based Distributed Resource Allocations: 3GPP document [54] discusses sensing based resource allocations. Sensing based resource allocations can reduce the possibility of resource collision. UE can identify the occupied resource by energy-sensing or reading other UE scheduling assignment (SA) broadcasting. In an energy-sensing method, a UE senses the received signal on the resource block to detect whether a resource block is occupied or not. In this method, a threshold value can be used to determine whether the resource block is occupied or not. Energy sensing helps to determine how much severe interference is on each resource block but this scheme cannot provide information on UE resource occupation period and duration. Whereas, in reading other UE SA/data broadcasting method, resource block usage of UE is broadcast by the scheduling assignment or together with data broadcasting. UE can obtain additional information like period, frequency domain resource usage but UE may not have the information on the interference level on each occupied resource. Therefore, it is beneficial to use a combination of both energy sensing and reading other UE SA/data broadcasting method.

In addition, the 3GPP document [57] discusses several conditions that should be met in order for collision avoidance or sensing-based scheme to work efficiently. The first condition is that the channel conditions and interference environment should vary slowly so that the sensing method can precisely predict the propagation environment during actual transmissions. The second condition is that the sensing based collision scheme should be preserved with low to medium system loading to properly handle the collision. The final condition is that the target communication range should not be larger than the sensing range. In addition, a sensing based collision avoidance scheme should address different challenges like mobility, hidden node, in-band emission and half-duplex constraint and latency.

Enhanced Resource Randomization Based Distributed Resource Allocations: 3GPP document [55] discusses enhanced resource randomization technique. In Release 12, time and frequency resources are randomly selected by UE which is not applicable for V2V communications. In addition, for mode 2, there are 108 time resource patterns (T-RPTs) in frequency division duplexing but these resources are not enough for PC5 based V2V as there is a large number of UE and packet size is also large in case of V2V. It is possible to increase the number of T-RPTS but this will cause signaling overhead for each UE and also new T-RPT design needs to be created. Thus, a more appealing solution is the use of randomized T-RPT.

Moreover, 3GPP document [58] discusses randomization technique. This document explains how the data pool structure of Release 12 D2D can be reused with some modifications like SA pool frequency division multiplexed with the data pool. For enhanced randomization, T-RPT hoping can also be used. If a T-RPT index is randomly hoped then more patterns can be created which provide enhanced randomization.

Hybrid Distributed Resource Allocations: There is a discussion going on in 3GPP whether operating a combination of these principals provide more gain then operating individual principle. For example, a combination of location based scheme and sensing based scheme can be used in which subsets of resources are associated with sets of UE location and the UE can perform sensing based schemes on these subsets associated with UE's current location. Inspired by these discussions, the authors in [59] proposed a scheme in which resource partitioning is studied based on the heading direction of vehicle UE and sensing based collision avoidance mechanism. In this scheme, a set of resources is reserved only for V2V communications. In the resource pool, one subset is for transmission of side-link control information whereas another subset is for associated data. In urban areas due to the presence of the building and other large structures, sensing based approach will not perform perfectly. To address this issue, the authors proposed a two-stage resource allocation scheme. In the first stage, time-orthogonal resources are allocated to UE moving along orthogonal directions in intersections and in the second stage in-band emission aware sensing approach is used. In sensing based stage, interfering vehicular UE is identified by decoding side-link control information. After detecting interfering vehicular UE, they are classified as a nearby and distant vehicular UE. Nearby interfering vehicular UE is arranged into the same subframe in a frequency division multiplexing manner to prevent IBE interference. After grouping, resource prioritization is conducted in which UE selects resources from the subset of free resources. If there is not an adequate resource, then UE selects a resource from decoded side-link control information and if that is also not sufficient then UE randomly selects the resource from the resource pool.

c) Hybrid centralized-distributed resource allocations: Hybrid schemes address resource allocations in both centralized and distributed scenarios. In [60], the authors presented a hybrid resource allocation and considered ad-hoc and assisted D2D mode. Outside the network coverage, devices can operate only in ad-hoc mode whereas inside the network coverage devices can operate in both ad-hoc and assisted mode. The authors proposed a unified radio frame structure which includes sub-frames for supporting both ad-hoc and assisted D2D mode. In unified radio frame, control and data channels of ad-hoc and assisted D2D mode are separated in the time domain. In the assisted control channel, only an assisted device can transmit and in the ad-hoc control channel, only an ad-hoc device can transmit. However, both ad-hoc and assisted D2D mode device can transmit in the same data channel resource. Moreover, the authors proposed a unified D2D MAC protocol in which location-aware reservation Aloha is used. The authors have performed simulations and have shown that the proposed protocol can achieve high reliability and low latency, and can be applied for both in and out of coverage scenarios.

In [61], the authors have proposed hybrid centralized-distributed resource allocations in which channel is allocated by the base station in a centralized manner whereas power is allocated by vehicular UE in a distributed manner. The authors have considered a bipartite graph for channel allocation and multi-agent learning for power control. Channel assignment is performed in two stages, channel assignment for the cellular user and channel assignment for vehicular users. For channel assignment of cellular users, the bipartite graph is designed with two groups as a set of cellular users and a set of channels. Hungarian algorithm is used to solve the designed weighted bipartite graph. For channel assignment for vehicular users, the estimated network graph is constructed. For power control, a multi-agent game with incomplete information is considered. The authors have used Q-learning to obtain the power selection strategy in a distributed manner.

Hybrid schemes discussed above are more applicable in the vehicular scenario than the individual centralized and distributed resource allocations. In centralized resource allocations, the base station collects CSI of all links in a system. However, in vehicular communications, it is very difficult to accurately measure the CSI of all links in a system due to the high mobility. For accurate CSI estimation, channel states can be frequently fed back from the vehicle to the base station. However, such schemes incur a lot of signaling overhead. Whereas distributed resource allocations are more applicable in out of network coverage scenarios and are not efficient for in coverage scenarios. Thus, an elegant way of resource allocations is Hybrid schemes which take advantage of both centralized and distributed resource allocations.

E. Security

Security is one of the main challenges in LTE based V2X communications due to the broadcast nature of wireless communications. The traffic-related and safety-critical information transferred in the V2X network may be reproduced, falsify or modified by an attacker causing a disastrous effect. Moreover, an attacker may mimic an authorized entity such as RSU or eNB and may distribute wrong information to nearby vehicles causing a traffic jam and accidents [62]. Thus, LTE V2X communications must satisfy the fundamental security requirements and requirements specific to LTE V2X in order to provide defense against various attacks.

1) LTE V2X Security Requirements: The basic security service requirements of LTE V2X are discussed in this section, as outlined in [16], [63] and [64].

a) Authentication: Authentication in LTE V2X helps to differentiate the legitimate entities with the malicious ones. Authentication in LTE V2X includes both user authentication and message authentication. User authentication helps to guarantees the authenticity of the vehicles whereas message authentication guarantees the authenticity of the messages. By using both user and message authentications, each vehicle can confirm whether the message was sent by authorized vehicles or not and also find out whether the message was modified unexpectedly or not during the transit.

b) Authorization: In LTE V2X, different entities such as vehicles, RSUs, eNB and certificate authority can have different levels of access. There should be a provision of rules and policies so that each legitimate entity gets the right level of access without getting access to unauthorized content.

c) Data confidentiality: In LTE V2X, data confidentiality is not that of concern for basic public safety messages as they are not encrypted. However, there exist several other V2X messages such as private vehicle-to-vehicle messages where data confidentiality is required. In addition, the privacy of a vehicular user is of utmost importance and is one of the main security concern in LTE V2X.

d) Availability: Availability in LTE V2X ensures that the vehicular messages are processed and made available in a timely manner to all V2X entities. Enforcing a heavy and strong cryptographic algorithm may delay the availability of the vehicular messages. Thus, lightweight and low-cost cryptographic algorithms are required so that vehicular messages can be processed in a timely manner and are available to most of the V2X entities.

e) Data integrity: Data integrity ensures that the vehicular messages are not modified or deleted by malicious users during the transit. A digital signature can be utilized to provide the integrity of the messages. In addition, the freshness of the messages can be used to ensure that messages are not been replayed by malicious users.

2) LTE V2X Security Architecture: 3GPP document [64] has described the LTE V2X security architecture, as shown in Fig. 10. Main functional entities of LTE V2X security architecture include V2X control function (VCF), Temporary ID Management Functions (TIMF) and V2X Key Management Server (KMS) or V2X Certificate Authority (CA).

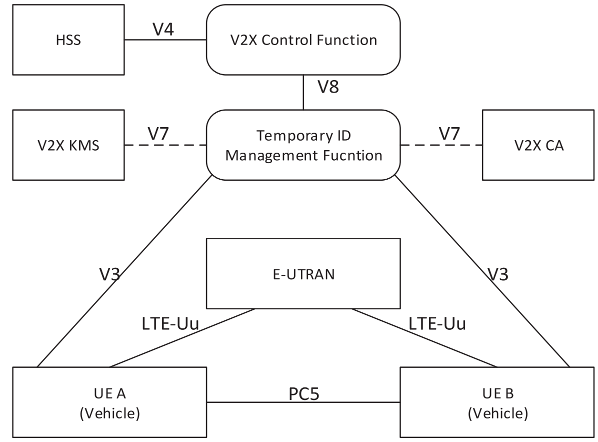

Fig. 10. PC5 and LTE-Uu based security architecture for V2X, described by [64].

VCF is mainly responsible for authentication and authorization of vehicular UE (V-UE). Temporary ID Management Function (TIMF) is mainly responsible for distributing temporary IDs and credentials to V-UE and V2X data source accountability. V2X service operator may either choose V2X KMS or V2X CA and the interface between TIMF and V2X CA/V2X KMS is referred to as V7. V8 is a reference point between TIMF and VCF and this reference point is used by TIMF to forward the authentication request to VCF.

Some of the key security challenges and their potential solutions in LTE V2X communications, mainly mentioned in the 3GPP document [64], [65], are described below.

3) Challenges:

a) Authentication: In V2X communications, an attacker may modify, reply, or forge the broadcast messages causing traffic jams and road accidents. Thus, authentication is essential to identify the authenticity of the sender's vehicle. LTE V2X communications can adopt the existing LTE security mechanism for authentication. However, there exist security vulnerabilities related to pre-authentication, authentication, and re-authentication of LTE which are described below.

- *Pre-Authentication:* In LTE, user equipment arbitrarily accesses the cell during the initial cell selection process. This arbitrary access may lead to a control channel spoofing attack. The control channel spoofing attack can restrict the vehicles to associate with authorized eNB and receive V2X services [16]. In the cell selection process, UE selects the strongest signal cell and obtains timing and frequency synchronization through the primary synchronization signal (PSS) and secondary synchronization signal (SSS) [66]. However, attackers may setup fake eNB and transmit signals at higher power levels. In addition, attackers may spoof PSS and SSS and perform PHY layer signaling attack. When UE receives spoofed PSS and SSS, UE reports to the radio resource control (RRC) layer and then RRC will expect to receive a master information block (MIB) message. As the fake cell cannot transmit MIB, the RRC will be in idle mode. When RRC is in idle mode, UE treats this cell as barred and performs barring.

- *Authentication:* Lightweight authentication schemes are desired for LTE V2X so that the messages can be processed in a timely manner. Public key based authentication scheme has heavy computation whereas symmetric-based solutions don't provide non-repudiation.
- *Re-Authentication:* High speed of vehicles causes frequent handover between MMEs or eNBs [16]. In handover between two eNBs or MMEs, the current key is used to extract a new key between UE as well as the new key for source eNB and target eNB. This key-management process can be exploited to perform a de-synchronization attack which halts the forward key separation employing the fake eNB [68].

b) V2X one-to-many communications security: Existing LTE security system provides credentials only for point-to-point communications and is not suitable for LTE V2X broadcast communications. D2D proximity services (ProSe) security for group communications is also not suitable as a group of vehicle UE cannot easily be defined. Moreover, in ProSe group communications, as any member can deduce any other member's traffic key, it does not provide any traceability of UE.

c) Vehicular UE privacy: Privacy is one of the most important requirements in the LTE V2X system. Privacy will ensure the high participation rate of the vehicular UE. There are many security threats concerning the privacy of vehicular UE. In a PC5 mode, some identifiable information is included in the periodic message which may reveal the private information of the user. Whenever the vehicular UE attaches to the network, a mobile network operator (MNO) has the ability to track the UE. In addition, whenever V2X data is sent across the network in the Uu interface, the V2X application can track the UE by linking together V2X data such as IP address. Hence in both PC5 and Uu mode, there is a threat that identity will be revealed based on data transmitted by vehicular UE.

d) Authorization and accountability: There exist different levels of access for different entities such as a vehicle, RSU, certificate authority in V2X communications. Rules and policies should be clearly defined so that each legitimate entity gets the right level of access without getting access to unauthorized content. In addition, LTE V2X messages should be processed and made available in a timely manner to all V2X entities. Heavy and strong cryptographic algorithms will introduce delay and affect accountability due to the dynamic nature of vehicular communications. Moreover, if many UEs try to request radio resources at the same time, it would cause the exhaustion of radio resources.

e) UE to V2X control function interface: An attacker can pretend to be a V2X control function and may maliciously manipulate or modify the data. As there is no shared channel between V2X control function and V-UE, V-UE will not be able to differentiate legitimate and malicious V2X control functions.

4) 3GPP Based Solutions:

a) Authentication: Various schemes have been proposed to tackle the authentication issues in cellular V2X communications. To prevent the control channel spoofing attack, the authors in [66] have proposed modifications to the LTE cell selection process. In this modification, UE should be allowed to select the second strongest cell within the same frequency if the strongest cell is considered as barred. In this modification, there will not be any uplink interference as no UE will be attached to the strongest cell considered as barred. This modification is effective in some kind of channel spoofing attack.

Lightweight authentication is desired for LTE V2X communications. Identity-based authentication can be used which can lower the communication overhead as they do not use any certificates. But identity based encryption schemes are public key based and still slower compared to the symmetric key. A hybrid authentication scheme can be used that can lower the computation overhead and provide secure authentication in the meantime. However, existing hybrid authentication schemes are complex and are not directly applicable to V2X communications.

Root key can be periodically updated during re-authentication to avert from the de-synchronization attack. During periodic root key updates, additional signaling overhead may occur due to additional key updates. In [67], the authors proposed a scheme to jointly minimize two functions: the expected volume of exposed packets after the de-synchronization attack and the expected signaling overhead due to key updates. The authors considered objective functions as a linear weighted sum of two functions in which network operators can select the suitable value of weight to balance the tradeoff of two functions regarding computational complexity. Moreover, the authors have done simulations results and have shown that their simulation results match with their analytical results.

b) V2X one-to-many communications security: Security requirements applicable to V2X communications for one-to-many communications can be satisfied by employing application layer security from other software-defined organizations (SDO) such as IEEE 1609.2 standard, which is an open standard for IEEE 802.11p based communications. In addition, the security guidelines of DSRC based scheme [69] can be analyzed and applied in LTE V2X one-to-many communications security.

c) Vehicular UE privacy: There are several security requirements currently being discussed in 3GPP such as vehicular UE pseudonymity, untraceability of a user by a single entity. Some of the proposed solutions are described below.

- *Attach Identifier Obfuscation:* In order to prevent MNO from tracking the vehicular UE, UE identities used for V2X communications can be managed separately by a third-party server such as original equipment manufacturer (OEM). In the proposed scheme in [64], [70], vehicular UE obtains temporary key K_{period} by requesting to MNO. MNO will send a mega-pool of pseudonym mobile subscriber identity (PMSI) pairs, each encrypted with a key K_{period}, to pseudonym CA or OEM. Vehicular UE establishes a secure link with OEM and requests PMSI pairs by sending its international mobile subscriber identity (IMSI). OEM sends sub pool of (PMSI, K_{PMSI}) pairs to vehicular UE. Vehicular UE decrypts each received (PMSI, K_{PMSI}) pairs with K_{period}. After vehicular UE has several (PMSI, K_{PMSI}) pairs, it can use them to attach with MNO. MNO will know that PMSI was authorized but will not be able to recognize the IMSI of UE. Both OEM and MNO should collude with each other in order to track the user equipment.

- *Privacy From MNO Based on Attached Data:* LTE network should be prevented from tracking the UE by using data of UE attached to it. There are several solutions being discussed to prevent this tracking as simultaneous re-attach with new identities. All UEs under an eNB should detach completely and then re-attach simultaneously at the same time. To spread the load, all UE can attach simultaneously at each eNBs but at different times from neighboring eNB. For this, UE needs to know the re-attach period and next re-attach boundary time which can be obtained from eNB or can be obtained as a system parameter during authorization time. Detach and re-attach is triggered in UE whenever current time value matches a boundary time instance for that eNB and UE reattach timer has a large enough value less than reattach period or current UE reattach timer has exceeded a certain maximum value.
- *Privacy Based on Data Traversing the Network:* In order to prevent MNO from tracking V-UE, it is proposed that when UE changes its application layer identifier, it also re-attaches to the network to refresh all the lower layer identities that will be visible to the V2X application server.
- *Encrypted International Mobile Subscriber Identity (IMSI):* Encrypted IMSI is being considered for LTE V2X communications. The proposed solution for LTE V2X communications mainly addresses three changes from the existing LTE attachment procedure. The first change is to encrypt IMSI used at attaching, in which IMSI is encrypted with a key that is itself encrypted with the public key of HSS. The second change is to encrypt an authentication vector (AV) in which UE sends an encryption key along with encrypted IMSI to HSS in the attach procedure and HSS will encrypt AV using this key. The final change is to provide an IMSI from the HSS to use during the attach procedure. This scheme can provide some sort of privacy of UE from MNO.
- *Hiding UE Identity From Other V2X UE and the Serving Network:* A pseudonym can be used to hide the UE identity from all network elements except HSS. Pseudonym called P-IMSI can be generated following the standard IMSI format with a mobile station identification number (MSIN) part replaced by a mobile station pseudonym (MSPN). Since mobile country code (MCC) and mobile network code (MNC) are the same in both P-IMSI and IMSI, P-IMSI is processed by all the network nodes like IMSI. So there is no impact on the legacy LTE network. On the user side, V2X capable USIM should be installed for generating the MSPN part for the pseudonym and on the network side, HSS needs to be prepared for maintaining records for V2X enabled UE and generating pseudonyms.
- *V2X UE Tracking Based on PC5 Autonomous Mode:* In the region where strong privacy rules apply, it is proposed to operate V2V/V2I communications solely over PC5 Interface in autonomous mode.
- *Homomorphic Encryption:* In the proposed scheme, MNO generates the PMSI pair pool and sends it to the pseudonym certificate authority (PCA). V-UE sends an identity request to PCA and asks for PMSI pair. PCA chooses encrypted PMSI pairs from the pool and sends an identity response message together with this pool. V-UE chooses blinding parameters and blind encrypted PMSI pairs. V-UE sends a decryption request to MNO for decryption. MNO decrypts the ciphertext and gets the blinded PMSI pairs and MNO sends it to V-UE. V-UE recovers the plaintext using the blind parameters.

d) Authorization and accountability: For authorization and accountability, MNO can check authorization information of the vehicular UE before allocating radio resources. In the proposed scheme, V-UE establishes a secure channel to the relevant trusted traffic authority (TTA) and runs an authorization or enrollment procedure and then V-UE obtains evidence from TTA upon successful authorization. During V-UE authorization with the V2X control function, the evidence from TTA is presented. In order to transmit revocation information from the TTA domain to the MNO domain, some form of additional communications would be required between the TTA domain and the V2X control function. In addition, TTA authorization evidence could be required to be unique per V-UE. The evidence binds the V-UE to a specific long-term certificate in the TTA domain and specific subscription in the MNO domain and can be used to identify malicious V-UE and thus confirming accountability.

e) UE to V2X control function interface: To solve the problem, the V2X control function (VCF) and V-UE can use a shared key for mutual authentication and establish a secure channel based on the pre-shared key. The pre-shared key could be derived using the AKA procedure when V-UE attaches to the network through the Uu interface. Here, a new branch of key derivation is that V-UE and HSS derive a root key K_{V2X} and then V-UE and VCF derive a pre-shared key K_{PSK} from K_{V2X}. V-UE and VCF could utilize the K_{PSK} and PSK Transport Layer Security (TLS) protocol to perform mutual authentication and establish a secure channel.

Table VII presents challenges, solutions, mechanisms, and limitations of security in V2X communication networks.

5) Non-3GPP Based Solutions: In addition to 3GPP projects in security, there are a few other papers address the security issues related to cellular V2X communications and they are discussed below.

The authors in [71] proposed a privacy-preserving LTE V2X security scheme. In the proposed scheme, transport authority (TA) is considered fully trusted and is responsible for the management of V2X security services. In addition, vehicle pseudonym distributors (VPD) are considered as another trusted entity that is responsible to distributes pseudonyms to vehicles. In the proposed scheme, at first, there is a domain initialization phase. In this phase, the domain parameters and master secret are created by TA. Moreover, long-term and

TABLE VII
CHALLENGES, SOLUTIONS, MECHANISMS, AND LIMITATIONS OF SECURITY IN V2X COMMUNICATION NETWORKS

V2X Security Services	Challenges	Solutions	Mechanisms	Limitations
Authentication	Pre-authentication: Control channel spoofing attack.	Modification of LTE cell selection [66].	Selection of second strongest cell if strongest cell is barred.	Effective against only some control channel spoofing attack.
	Authentication: Heavy computation in public key scheme and non-repudiation in symmetric key scheme.	Lightweight authentication scheme [16].	Hybrid authentication scheme	Existing hybrid authentication scheme are complex and not directly applicable to V2X communications.
	Re-authentication: De-synchronization attack.	Periodic root key update [67].	Joint minimization of exposed packets and signaling overhead due to key updates after de-synchronization attack.	Hard to decide the suitable value for weight.
V2X one-to-many communications security.	Existing LTE and D2D proximity services security are not suitable for V2X one-to-many communications security.	Application layer security from IEEE 1609.2.	Adoption of security guidelines defined for DSRC based communications [64].	Several protocols should be analyzed and re-defined before adopting DSRC based communications.
Vehicular UE privacy	In PC5 mode, identifiable information is included in the periodic message. In Uu mode, V2X application can track UE by linking together V2X data such as an IP address.	Attach identifier obfuscation.	UE identities managed separately by OEM.	Extra OEM entity may complicate V2X system.
		Privacy from MNO based on attach data.	Simultaneous re-attach with new identities.	Need to know re-attach period and next re-attach boundary time.
		Privacy based on data traversing the network.	Change of application layer identity.	Need synchronization time to change identities at same time.
		Encrypted IMSI.	Encrypt IMSI, AV and proivide IMSI from HSS.	Encryption increases the delay and may not be applicable for V2X communications.
		Hiding UE identity from other V2X UE and the serving network.	Use of PMSI.	Additional record should be maintained by HSS for V2X enabled UE. .
		V2X UE tracking based on PC5 autonomous mode.	Operate V2V/V2I over PC5 mode.	Problem with non-repudiation.
		Homomorphic Encryption.	Use of blind parameters and blind encrypted PMSI pairs.	Additional delay due to homomorphic encryption.
Authorization and accountability	Exhaustion of radio resources due to several radios requests at the same time.	Establish a secure channel to relevant TTA and run authorization procedure.	Use of TTA evidence for authorizing V-UE with V2X control function.	Additional communications required between TTA and V2X control function causing additional delay.
UE to V2X control function interface	Attacker pretending to be V2X control function may maliciously modify the data.	Shared keys between V2X control function and V-UE for mutual authentication.	New branch of key derivation for root and pre-shared key.	Additional delay due to new branch of key derivation

short-term keys are created by TA by using VPD id and master secret. Public keys and domain parameters of VPD is then provided to VCF. The second phase is the V2X domain registration phase, in which long-term keys and signature are loaded by TA into OBU of the vehicle. The third phase is the V2X service registration phase, in which a V-UE performs service registration with VCF. The final phase is the pseudonym requesting phase in which pseudonym seed is requested from VPD by V-UE. In addition, the authors discussed privacy and revocation procedure. Privacy is addressed by the frequent change of short-term keys. The revocation procedure is initiated by the vehicle by reporting the rogue V-UE to VPD. TA with the help of VPD compares the revocation parameter with a certain threshold value and revokes the vehicle if it is greater than a certain value. The authors also performed a security analysis of the proposed scheme which is described below.

- *Privacy Attack:* For privacy protection, short term keys are frequently changed by V-UE. Even in the worst case when VPD is compromised, the attacker can only get long term public key and cannot get V-UE real identity and actual IMSI by listening to V2X service registration.
- *Traceability:* A UE may use other's identity to hide their own trace. However, in this scheme, if an attacker captures another vehicle's short term public key and attaches to its message, then message verification will fail.

- *Frameability:* Legit V-UE might get revoked due to a lot of fake reports from malicious V-UE. However, in this scheme, fake reports from the malicious vehicle using the same short-term key are treated as a single report lowering the probability for false frameability.
- *Attack From Compromised User:* Compromised V-UE may retrieve pseudonyms by sending pseudonym requests to VPD. However, they cannot extract the seed from an encrypted message. In addition, it is difficult to find long term private key of V-UE which are stored in the tamper-resistant OBU of the vehicle.
- *Attack From Compromised VPD:* A VPD may be compromised to create pseudonyms from long term public keys to mimic V-UE. However, compromised VPD cannot mimic V-UE due to the unavailability of the short-term private key which can only be extracted from the long-term private key.

In [72], the authors proposed and analyzed security scheme for V2X networks in crowdsensing applications. In the crowdsensing applications, vehicles share information from the surrounding environment and local sensors to improve road traffic safety. In this article, the authors have evaluated two specific attacks, platoon disruption attack, and perception data falsification attack. In platoon disruption attack, an attacker repeats the information such as to accelerate or decelerate from the lead vehicle to deviate the following vehicles from the platoon. In perception data falsification attack, an attacker or selfish vehicle inserts or maliciously modify video frames to deceive the other vehicles to make a wrong decision. To prevent these two attacks, the authors advocate non-cryptographic methods in which a vehicle frequently collects the information from other vehicles in the same platoon in addition to the information from the lead vehicle. The collected data from lead and other vehicles in the same platoon provide the receiving vehicle with the capability to identify whether the received information is coherent with the next step operation of the whole platoon. However, there might be larger communication overhead and detection delay which are the main limitations of this article.

In [73], the authors proposed a model where the vehicles can immediately send the videos of a traffic accident to the nearest official vehicles. The proposed protocol takes advantage of 5G technology such as D2D communications, mmWave communications, and cloud platforms for high-speed communications and low latency. In the proposed protocol, the traffic accident video is encrypted and sent by the participating vehicles to the cloud and the cloud send the obtained video to nearby law enforcement agency or traffic authority. The proposed scheme achieves both conditional anonymity and privacy, and traceability. For conditional anonymity and privacy, the pseudonyms authentication scheme is used. For traceability, cooperation between different entities is allowed to trace the actual identity of the vehicle. In the proposed scheme, only TA can identify the relationships between pseudonyms certificate and 5G ID of the vehicle. After identifying the 5G ID, TA can send the 5G ID of the vehicle to find the actual identity of the vehicle. In addition, the authors have shown with simulation results that the proposed method can report the traffic information in less than 1 minute without violating the privacy of V-UE.

In [74], the authors have evaluated and proposed a security scheme related to resource allocation. In LTE V2X, PC5 communications with semi-persistent resource allocations may leak the location privacy of vehicular users. In this article, the authors have addressed this location privacy issues considering four different message types and have employed different resource allocation procedure related to different message types. In the proposed scheme, the type 1 message is related to periodic information from vehicles such as location, speed, and direction. This message can be sent to vehicular application servers that disseminate messages to the target area through MBMS. Network supported LTE-Uu links can be used for location privacy. Type 3 message is related to global event information such as road construction and lane closure and is sent through LTE-Uu link and location privacy is provided by the LTE-Uu link. Type 4 message is related to a message from fire-truck, ambulance, and other road signal modules. As in type-4 message, location privacy of special entity is not that of a concern, semi-persistent resource allocation can be used. Thus, type 1, type 2, and type 3 messages do not violate privacy if used according to 3GPP Rel. 14 standard policy. However, type 2 message is related to localized event-triggered information sent through the PC5 link and it reveals the location information if semi-persistent resource allocation is used. The authors have proposed random access with status feedback for type 2 messages which will provide location privacy. In the proposed scheme, all vehicular user equipment allocates data resource block in a random fashion for every sidelink control period due to which the position of allocated resource will not leak the privacy information.

In [75], the authors have investigated group based vehicular communications in the next-generation wireless system. The authors have addressed two major security challenges. The first challenge is the secure and dynamic management for distributed networks and the second challenge is the mobility and secure group access management for the centralized network. The authors have proposed software-defined network management protocol and have enforced simple network management protocol (SNMP)and OpenFlow in base stations. The authors have presented asymmetric and symmetric key based group handover authentication scheme. Moreover, the authors have proposed an efficient and secure group mobility management framework. The authors have applied the group handover authentication protocols to the group mobility management framework for fast key agreement and access to the Internet while moving across heterogeneous networks.

V. 5G Based Vehicular Communications

5G wireless networks will incorporate various emerging technologies such as massive MIMO, device-to-device communications, multi-radio access technology, full-duplex radios, millimeter waves, cloud technologies and SDN, as shown in Fig. 11. Each of these technologies will bring various solutions and challenges to 5G based vehicular communications.

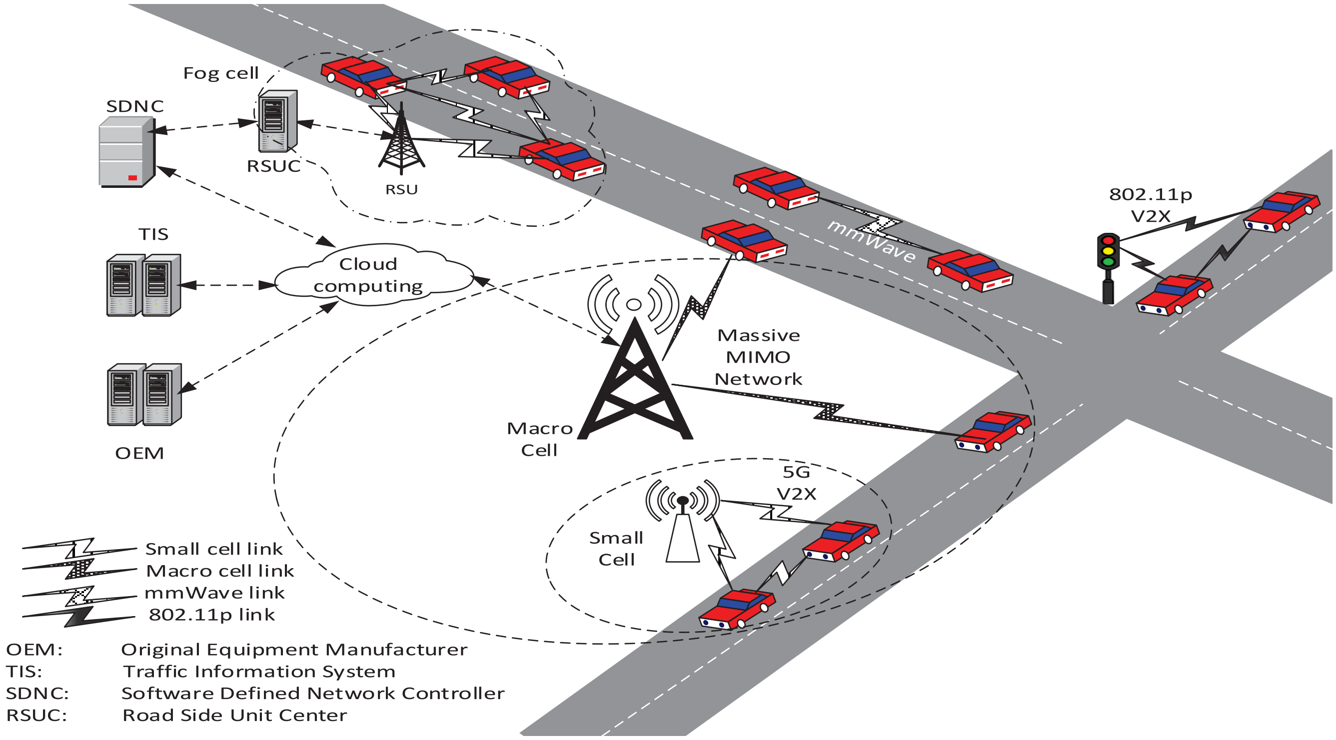

Fig. 11. 5G based vehicular communication model.

This section analyzes these key technologies and techniques of 5G and their associated challenges and solutions in vehicular communications.

A. Heterogeneous and Small Cell Networks

1) Challenges: 5G is expected to be composed of heterogeneous networks with macro, micro, and nano cell along with other access technologies. In addition, 5G is envisioned to adopt small cells to increase network capacity. However, such schemes face difficulties in providing user mobility due to frequent handovers and increased signal load on the network. Most of the existing handover schemes are applicable for centralized architecture and are not suitable for distributed and heterogeneous vehicular architecture. Moreover, the handover decision is mainly determined by a single threshold value. This threshold value depends on various parameters such as network load, channel conditions and received signal strength [76]. However, it is very difficult to map all of these parameters into a single threshold value due to the lack of a suitable model.

2) Solutions: Efficient vehicular handover scheme is needed for the envisioned ultra-dense distribution of small cells in 5G communications. Handover performance can be enhanced by implementing macro assisted small cells network and dividing the user and control plane of the network among small and macro cells. Moreover, dual connectivity can be used to reduce the handover complexity where vehicles are allowed to be concurrently associated with macro and small base stations [78]. Cooperative transmissions are also recommended for vehicles in cooperative small cell networks. The cooperative transmission scheme increases the vehicular communications capacity and handoff rate in cooperative small cell network [79]. Thus, there exists a tradeoff between vehicular handoff rate and communications capacity and should be balanced in cooperative transmissions.

In addition, for a smooth handover, content can be cached at candidate cells using mobility and handover predictions [80]. Self-sustaining caching stations can be used to realize this mobility and handover aware caching where the content can be pre-cached in the next station before a vehicle conducts handover [81]. Frequent content caching is required for mobility aware caching which introduces a lot of communication overhead. In addition, popular content and cache size should be identified for designing mobility aware caching schemes.

Cell association optimization technique can also be used to reduce the handover rate [82] in which serving stations are selected among all available base stations. Existing cell association techniques rely on the transmit power, channel and traffic-load, and cause excessive handovers in the vehicular scenario. New cell associations are required that perform cell handover accounting mobility issues, handover frequency, handover delays, backhaul variation, and network dynamics [83].

5G-enabled smart collaborative network can be used to improve handover issues in heterogeneous vehicular communications [76]. In such networks, the handover decision is performed by an onboard multi-access manager. The multi-access manager observes vehicular links and predicts the handover among cells. In addition, the multi-access manager with the help of a ground network can allow communications between wireless heterogeneous networks.

B. Millimeter Wave Communications

1) Challenges: Millimeter wave communications have been envisioned for 5G V2X to provide high data rate connections between vehicles and nearby roadside infrastructures. However, the millimeter wave faces several challenges. On the physical layer, the millimeter wave is vulnerable to shadowing. This shadowing effect limits millimeter waves for a point-to-point line of sight connections up to a few hundred meters. In addition, due to the high operating frequency of 60 GHz, Doppler spread will be more pronounced in millimeter wave communications than in the 2-6 GHz band. Thus, there is a need for special frame design and numerology for millimeter wave communications [30].

Moreover, delay and reliability, security, and broadcasting issues may arise in millimeter wave connections [84]. In the millimeter wave, there might be a delay while generating a physical layer key as well as during the beam search at the initial access. In addition, the millimeter wave increases randomness and may generate the key with a shorter delay. This quick key generation complicates the information reconciliation process due to the generation of different keys in two communicating vehicles. Broadcasting is another issue in the millimeter wave due to beamforming communications. In millimeter wave, messages are transmitted by beamforming towards a particular group of users which cause problem while broadcasting the messages towards vehicles located in an angular direction.

2) Solutions: Location based improvement techniques like iterative search can be used to reduce the delay associated with beam search at the initial access in millimeter wave communications. The problem associated with broadcasting messages towards vehicles located in an angular direction can be solved with the use of in-vehicle transceiver with the combination of wider beams broadcasting the same information in a different direction.

In [85], the authors stated that beamforming and directional transmission can be used in millimeter wave to prevent high path loss. In addition, ultra-dense deployment of base stations or RSUs can be used to tackle the short communication range of millimeter wave. In [86], the authors proposed a contextual online learning algorithm. The authors have applied the online learning algorithm to identify data blockages for each vehicle based on aggregated received data and user location information. In addition, the proposed algorithm automatically provides larger coverage in areas with heavy traffic to maximize the system capacity.

C. Massive MIMO

1) Challenges: Massive MIMO which employs hundreds or even thousands of antennas at the base stations provides the high magnitude of spectral efficiency gains and can satisfy the escalating traffic demands of next-generation wireless communication networks [87]. In [88], the authors have proposed a reproducible test method for the evaluation of MIMO antennas in V2X communications and have shown that high data rates up to 40 Mbps can be achieved at the real test drive using MIMO antennas. However, in massive MIMO systems, the availability of accurate channel state information is one of the major requirements to avoid multi-user interference and to achieve high spectral efficiency gain. SINR and achievable rate in such systems is limited by pilot contamination which is more pronounced in high mobility situations. In high mobility situations, the length of the pilot signals is restricted due to short channel coherence time. Due to this restriction on the length of the pilot signals, pilot reuse distance between interfering base stations is reduced [77]. In addition, the network performance is significantly impacted by channel estimation and beamforming which are the key issues in a massive MIMO system [89].

2) Solutions: Several solutions have been suggested to tackle some issues of massive MIMO in vehicular communications. In [90], the authors proposed a model for three-dimension MIMO techniques based on vehicular communications. The proposed model increases the overall network efficiency and is applicable for various communications environments such as pico, micro and macro cell. In [91], the authors optimized the design of the superimposed pilot in massive MIMO systems. In the proposed scheme, the specific sequences for different cells are first designed based on the Grassmannian link packing (GLP) approach and then extended to form the superimposed pilot matrices for the users in different cells. In [92], the authors proposed a scheme in which pilots are reused among device user equipment to shorten the pilot overhead in a single cell. In the proposed scheme, pilot contamination due to pilot reuse is reduced with the help of the revised graph coloring algorithm. In addition, the authors employed iterative power control algorithms for the minimization of the data transmit power of D2D links.

In [88], the authors recommend the use of different modulation in different areas according to the channel properties for enhancing the throughput in the MIMO system. The authors suggested using transmit-diversity with quadrature phase-shift keying (QPSK) modulation in the area with a very bad channel condition. Whereas, the authors suggested the use of spatial-multiplexing with 64-quadrature amplitude modulation (QAM) in the area with a very good channel condition. In the areas with moderate channel conditions, the authors recommended using a mixture of both together with 16-QAM modulation to increase the throughput in the MIMO system.

Table VIII, IX and X compare benefits, challenges, solutions, limitations, and feasibility of various technologies in 5G based vehicular communications. Feasibility indicates the suitability for deployment which is decided based on the complexity of the proposed solution and changes in the existing architecture. The term very high in the feasibility column means very high suitability for deployment followed by the term high, whereas the term low means the low suitability for deployment.

D. Vehicular Cloud and Fog Computing

Vehicular cloud computing (VCC) can provide realistic cloud services for vehicular communications. By collecting and mining the data from various sensors within a vehicle and roadside infrastructures, different applications can be provided for customers. However, due to the huge volume of

TABLE VIII
BENEFITS, CHALLENGES, SOLUTIONS, LIMITATIONS, AND FEASIBILITY IN 5G BASED VEHICULAR COMMUNICATIONS

Technology	Benefits	Challenges	Solutions	Limitations	Feasi-bility
Hetero-geneous and small cell networks	Spectrum utlization and high data rates.	Frequent handover and increased signal load.	Macro assisted small cells and dual connectivity to macro and small cells [78].	High backhaul signaling overhead.	Very High
		Handover decisions depend on single threshold value [76].	Cooperative transmissions [79].	Increases handoff rate.	High
			Mobility aware catching and Self-sustaining caching stations [81].	Hard to define candidate cells for caching.	Low
			Joint optimization of cell association and power control [83].	Hard to define cell association parameters	Low
			Smart collaborative networking [76].	Limited prediction using on-board multi-access manager.	Low
Millimeter wave commu-nication	High data rate.	Short communication range. High pathloss. Delay and reliability.	Directional transmission, beamforming and higher deployment of base stations [85].	Hard to accurately identify V2X application area for beamforming.	High
		Broadcast communications and security [84].	Contextual online learning for beam selection [86].	Need periodic data and location information.	Very High
Massive MIMO	High magnitude of spectral efficiency gain. Meet increasing traffic demands [87].	Pilot contamination [77].	3-D and full-dimensional (FD) MIMO [90].	Need whole new architecture for the deployment.	Low
		CSI estimation and beamforming [89].	Block-diagonal Grassmannian link packing [91].	Hard to achieve specific sequences for different cells.	Very High
			Revise graph coloring based algorithm [92].	Iterative power control algorithm introduces delay.	High
			Diverse modulation [88].	Hard to accurately identify channel properties in different area.	High

data coming from various sources, providing realistic vehicular applications has been a challenging issue in vehicular cloud computing [93], [94]. To some extent, these challenges can be solved with the use of vehicular fog computing (VFC). VFC utilizes vehicles as infrastructures for communications and computation. VFC can accommodate the growth of mobile traffic in vehicular communications. In addition, it can reduce the latency of traditional vehicular cloud computing. In fog computing, services are hosted on the fog close to the end users to eliminate the network hops [95]. Moreover, fog computing reduces the risk of data exposure due to the short distances between end devices and fog nodes. Vehicular crowdsensing based on vehicular fog computing is another emerging area in which vehicles collect and share location and environment-specific data for the common interest [96]. Most of the challenges and solutions in vehicular fog computing are also applicable to vehicular crowdsensing.

Several challenges of VCC and VFC are highlighted below.

1) Challenges:

a) Mobility model: An appropriate and accurate mobility model is required to predict and evaluate the movement of surrounding vehicles so that vehicles can connect with each other and share data [97].

b) Resource utilization and management: Resource utilization and management should be addressed to take full advantage of VFC. There exist various challenges for resource management in vehicular cloud computing. There is a requirement of an efficient protocol to discover and management of the resources. In addition, suitable architectures and schemes are required to access V2X resources from the vehicular cloud in heterogeneous wireless networks [101].

c) Virtualized network functions: In cloud and fog computing, virtualized network functions (VNF) runs on the vehicle hardware and configures security and operation of network

TABLE IX
BENEFITS, CHALLENGES, SOLUTIONS, LIMITATIONS, AND FEASIBILITY IN 5G BASED VEHICULAR COMMUNICATIONS

Technology	Benefits	Challenges	Solutions	Limitations	Feasibility
Vehicular cloud and fog computing	Vehicular fog accommodate the surge of mobile traffic and reduce latency [95]. Mitigate risk of data exposure to adversaries due to short distances.	Fog experiences excessive number of demands that are far beyond its capacity [95].	Vehicular mobility model [98].	Need to tune a lot of parameters in lognormal model.	Low
		Appropriate and accurate mobility model [97].	Fog resource reservation and allocation [99].	Multiple hops for non real-time vehicular services.	High
		Resource utilization and management. Virtualized Network Function.	Traffic identity and VNF selection [100].	Longer delay for inaccurate traffic identification.	Very High
		Security and incentives [96].	Privacy preserving incentive [102].	Issue with the delay due to use of signcryption.	Very High
			Real-time privacy preserving [104].	Problem with forward and backward secrecty due to use of group signature.	High
SDNs	Reduced signalling overhead and improved communication quality [106]. Exploit heterogeneous resources in an agile and flexible manner [107]. Lower frequency of handover between RSUs and vehicles [108].	Inter-operation, network management and dynamic programming [107].	Open source SDN using API for radio access [109].	Problem with RAN slicing and load balancing for V2X services.	Very High
		Control plane design in hybrid cellular and DSRC vehicular communications [110].	Control plane optimization [110].	Introduce difficulty on communication between controllers and vehicles.	Low

functions such as load balancing, packet inspection and firewalls. However, there are issues associated with virtualization management, selection and deployment of VNFs.

d) Security and incentives: Due to the sharing of content and data between vehicles in the fog computing environment, there can be several security attacks such as information stealing attacks, hostile attacks and virus spreading attacks. In addition, when vehicles are acquiring navigation results and reporting traffic information in vehicular crowdsensing applications, privacy is exposed [96]. Thus, there is a need to carefully designed security mechanisms for vehicular fog computing. Moreover, in vehicular fog computing, as vehicles rent out their resources, there should be a provision of some kind of incentives to vehicle owners. There exist several challenges for designing incentive models in vehicle cloud computing. Appealing compensation or incentive models should be proposed to stimulate vehicle to share their resources as vehicle owners may incur extra operational costs while sharing their resources or data. Moreover, the assurance of the privacy and security of the involved vehicles is one of the difficult challenges to be addressed in vehicular cloud computing.

2) Solutions:

a) Mobility model: Vehicular mobility models such as in [98] can be utilized to predict the movement of surrounding vehicles. In [98], the authors compared the unit disc and lognormal shadowing models with obstacle-based channel model and have shown that the obstacle channel model provides realistic vehicle mobility and topology characteristics. Moreover, the authors have used a matching mechanism to tune various parameters of the lognormal model to provide a good match with the obstacle-based channel model. This kind of mechanism can be employed as a mobility model in 5G based vehicular networks.

b) Resource utilization and management: In [99], the authors discussed resource management strategies in a fog computing environment to enhance the real-time service quality of vehicular services. In this article, the authors mainly discussed resource reservation and allocation strategies for fog. In these strategies, real-time vehicular services are given

TABLE X
BENEFITS, CHALLENGES, SOLUTIONS, LIMITATIONS, AND FEASIBILITY IN 5G BASED VEHICULAR COMMUNICATIONS

Technology	Benefits	Challenges	Solutions	Limitations	Feasi-bility
Mobile edge computing	Low latency [111]. Dynamically manage vehicular neighbor group [112].	Increase the cost of RSU or edge system [111]. Content prefetching in edge computing assisted 5G-VANET [113].	Content pre-fetching based on machine learning [113].	Problem with accurately identifying suitable vehicles for content pre-fetching.	Very High
		Content distribution in edge computing assisted 5G-VANET [113].	Content distribution based on graph theory [113].	Problem with proper scheduling of all vehicles at once.	Very High
Network slicing	Manage different access technology of 5G [111]. Slice for autonomous driving and other safety critical services, slice supporting tele-operated driving etc. [111].	Configure multiple slices per device simultaneously and to adapt slice configuration at runtime [114]. Security threats and trust relationships [114].	Integrated vehicular network slicing [115].	Trust issue between slice manager and vehicles.	High
Dynamic spectrum sharing	High quality of user experience [116].	High vehicular mobility limits availability of 5G spectrum resource [116]. Spectrum efficiency reduced due to spectrum heterogeneity [116].	Cellular V2X communications in Unlicensed Spectrum [117].	Interference issue in unlicensed spectrum.	Very HIgh

higher priority over other services so that real-time vehicular users can access the services within a single hop.

c) Virtualized network functions: In [100], the authors proposed the VNFs selection strategy by identifying traffic packets. In vehicular cloud networks, VNFs are sequentially deployed according to the order in a specific service function chain (SFC). The authors have combined the traffic packet identification at the source vehicles with the VNFs selection strategy. For traffic identification, the authors have considered different machine learning models including deep neural network and gcForest. For VNFs selection, the network is divided into layers according to the order of VNFs in SFC. Transmission priority and network congestion are jointly considered for the scheduling of different layers. Moreover, the authors have done simulations and have shown that the proposed traffic identification and VNFs selection strategy reduces the number of packets failing to reach the destination by 30% to 50%.

d) Security and incentives: In [102], the authors proposed a privacy-preserving incentive mechanism to stimulate vehicles to share their sensing resources. The authors have considered resource sensing evaluation mechanisms to guarantee fairness evaluation. Moreover, the authors have considered a role based bargain game model to guarantee the price of sensing resources to be more accurate and mutual benefit for both parties. In addition, to prevent the privacy exposure of the vehicle and to achieve the mutual authentication between vehicles and vehicle cloud servers, the authors have employed signcryption technique. The authors have done simulations and have shown that both vehicles and vehicle cloud servers receive desired utility while preserving privacy. In [103] the authors have employed partial prepayment strategy in which the vehicles co-operating to download a file will receive partial payment before the requesting vehicles receive the full packet. This kind of virtual payments or virtual checks will stimulate more vehicles to participate in vehicular cloud computing.

In [104], the authors proposed a privacy-preserving scheme for real-time navigation systems by utilizing vehicular crowdsensing. In the proposed scheme, a vehicle requests navigation information from nearby vehicular fog nodes. Group signature is sent along with the navigation request to preserve the privacy of a requesting vehicle. Moreover, crowdsensing vehicles use a randomized signature while sending traffic and safety-related information to fog nodes to prevent exposure of their identity. Thus, the proposed scheme provides privacy to vehicular user equipment while sending and obtaining information from vehicular fog nodes.

E. SDN

SDNs have been conceived as a novel technology to provide network resilience and flow programmability in 5G networks [105]. SDN enabled 5G vehicular networks consist of macro and small cells including base stations and access points [106]. In SDN vehicular networks, a centralized controller with OpenFlow protocol controls macro cell base stations and access points. In addition, SDN relocates the control logic from the infrastructure to the control layer to host various applications and provide new functions. Moreover, the SDN controller is responsible for access networks including authentication, traffic management, and other issues while base stations constitute the data plane of the SDN and implement the controller defined policies. Thus, SDNs can help in reducing the signaling overhead of the vehicular network with improved communication quality.

In addition, SDNs can be used for inter-networking and exploiting resources in heterogeneous networks in an agile and flexible manner. Through inter-networking, advantages from different segments and technologies can be utilized to support various vehicular services in an efficient and flexible manner [107]. Moreover, SDN enabled vehicular networks can be composed of cloud computing centers, SDN controllers and fog computing clusters [108]. In such networks, SDN controllers transfer the state information from fog clusters to cloud centers. These fog computing clusters or fog cells include RSU centers, RSUs, base stations, users and vehicles and are positioned at the edge of 5G-SDN based vehicular networks. Fog cells based on 5G-SDN can use multi-hop relays to lower the frequency of handover between RSUs and vehicles [108]. In addition, they provide higher throughput than traditional transportation management systems.

However, there are several challenges for software-defined vehicular networks [107].

1) Challenges:

- *Inter-Operation:* SDN enabled 5G vehicular networks can be used for inter-operation between various technologies. However, due to different communications standards and communications links in various networking paradigms, inter-operability may be limited.
- *Network Management:* In SDN networks, there are different hardware and software specifications with various services. Such networks will be more complex to manage. Thus, dynamic and flexible reconfiguration cannot be performed in such networks.
- *QoS Provisioning:* Due to the dynamic topology in a vehicular network, resource availability may vary over time. In addition, this problem is worsened due to the high heterogeneity in SDN based vehicular networks.

2) Solutions: In [109], the authors have proposed an open-source SDN for inter-operation and network management in heterogeneous networks. The proposed SDN consists of an application program interface (API) for radio access that clearly separates the user plane and control plane. Proposed SDN supports active RAN slicing as well as load balancing and mobility management. The proposed platform simultaneously manage heterogeneous networks such as cellular and Wi-Fi networks. Authors have done extensive simulations and have shown that the low overhead is introduced by the proposed platform with heterogeneous services.

Control plane can be designed effectively to tackle the issues related to SDN in heterogeneous and integrated vehicular networks. In hybrid DSRC and cellular network based V2X, SDN can utilize both ad-hoc and cellular networks to control the network. However, the hybrid control plane can bring some difficulty in communications between controllers and vehicles [110]. Thus, there is a need for an efficient control plane scheduler to schedule different SDN events with a different priority to different heterogeneous links.

F. Mobile Edge Computing

Mobile edge computing has been envisioned for future 5G vehicular communications to provide low latencies. In such system, some core network functionalities are moved to the edge of the network, that is, nearer to the consumer. Network function virtualization (NFV) can be used for mobile edge computing to provide different services. In NFV, core network functionalities are placed in the eNB and RSUs with storage and processing capacities [111]. In addition, mobile edge computing can be utilized to bolster the control of 5G-SDN based vehicular networks [112]. Moreover, mobile edge computing servers can administrate the vehicular group in 5G-SDN based vehicular networks. SDN's control plane and mobile edge computing servers can be positioned in the same place so that mobile edge computing servers can act as local controllers to localize the control plane of 5G-SDN based vehicular networks. In addition, improved network and resource management, and sustainable development are some other advantages of mobile edge computing with SDN.

There are several challenges for edge computing assisted 5G vehicular networks due to huge data volume, dynamic topology changes and uneven traffic distributions. Moreover, moving the core network functionalities to RSU and eNB will increase the cost for large scale deployment. In addition, there will be a challenge for providing high computing capability and storage capacity as well as security in those edge systems. In [113], the authors discussed challenges and solutions related to content sharing in edge computing assisted 5G vehicular networks which are described below.

1) Challenges:

- *Content Pre-Fetching:* Content pre-fetching can be used to lower the network access delay and the consumption of resources. But there is a challenge in content pre-fetching due to the vehicle's mobility and traffic distributions. Thus, for unbalanced and different dwell time, flexible and network-wide content pre-fetching strategy is required.
- *Content Distribution:* After the pre-fetching of the content at the desired nodes, content distribution should be scheduled by macro base stations or roadside units according to the requests of the vehicle. The macro base station should try to meet the requests of all vehicles by proper scheduling and by considering link capacity.

2) Solutions:

- *Content Pre-Fetching Based on Machine Learning:* Machine learning can be used for predicting driving trace, traffic situation and the congestion of the base station. Using machine learning, data from the congested base station can be offloaded to un-congested ones. Part of data can also be pre-fetched into the vehicles when it enters the congested area using machine learning and then vehicles can serve the content request to other vehicles through DSRC.
- *Content Distribution Based on Graph Theory:* Graph-based approach can be used to efficiently schedule data dissemination. The neighbor graph can be obtained at the macro base station by aggregating received information and then the neighbor graph can be converted into a directed matched graph. A maximum weighted independent set problem is then formulated in the constructed conflict graph for content sharing.

G. Network Slicing

Network slicing is a partition of network functions into various virtual network slices and parameter configurations with each slice supporting particular functions and market requirements [114]. Different network slices can be operated in parallel to provide real-time services. Thus, network slicing aims to isolate network functions and resources of a single network infrastructure. Slicing logically divides the network by splitting a single control plane into multiple control planes and it affects several control function functionalities such as authentication, mobility and session management. In addition, it affects user plane functionalities such as being programmable and auto-reconfigurable.

1) Challenges: Different network slices can be used such as safety application network slice for applications that required low latency and infotainment application network slice for applications that required high bandwidth [111]. However, network slicing required several capabilities [114] such as:

- *Slice Description:* Service level agreement (SLA) requirements are captured by a slice description. This slice description should be adapted by network elements.
- *Slice Instantaneous:* Common virtual network functions, control plane and user plane architecture and interface should be identified for slice instantaneous.
- *Slice Life Cycle Management:* Proper configuration, adaption and monitoring of network elements are required for slice life cycle management.

There are several challenges for network slicing assisted 5G vehicular networks.

- Slice manager should configure multiple slices per device simultaneously.
- Network slicing can emerge security threats as different security services may be required for different slices.
- Trust relationships are required between the slice manager and provider owning to the infrastructure.

Thus, for network slicing to be effective, vehicular applications need to be translated to technical specifications and slice manager should be able to configure multiple slices per vehicular application. In addition, there should be a proper guideline to determine whether the network functions need to be centralized or sliced.

2) Solutions: Some literatures have tried to address issues of network slicing in vehicular communications. In [115], the authors introduced network slicing for vehicular networks based on air-ground integrated architecture to support specific vehicular applications while guaranteeing the quality of service. In the proposed architecture, three slices are introduced. The first slice is a high definition map slice used for navigating vehicles. The second slice is a file of common interest slice for distributing popular content. The third slice is on-demand transmission slice for real-time interactive sessions and voice calls. Each of these slices supports specific applications and guarantees the quality of service in integrated vehicular network architecture.

H. Dynamic Spectrum Sharing

1) Challenges: Licensed and unlicensed spectrum such as cellular, DSRC and millimeter wave spectrum can be dynamically shared to provide a high quality of user experience in 5G vehicular communications [116]. Multi-radio technology can be used to dynamically share and to enhance the utilization of these spectrum resources. However, high vehicular mobility limits the availability of 5G spectrum resources. Moreover, spectrum efficiency is greatly reduced due to spectrum heterogeneity. Thus, vehicular users need to collaborate with each other to dynamically share different spectrum resources and to enhance spectrum utilization.

2) Solutions: In [117], the authors studied the vehicular network where cellular V2X and DSRC users coexist in the unlicensed spectrum. This unlicensed spectrum can be utilized for supporting V2X services. In addition, the authors designed a scheme in which cellular users and DSRC users share the spectrum based on energy-sensing. The proposed method allows cellular and DSRC users to coexist in the same unlicensed spectrum without data transmission collision between them.

VI. Discussion and Future Research Directions

Vehicular communications are evolving rapidly with the emergence of novel technologies in cellular communications. There are various benefits and challenges due to the latest technological concepts. There are still many areas to be explored in the domain of the novel concepts to ensure efficient vehicular communication networks. Few insights on some of the important evolving issues, based on lessons learned from existing concepts, are highlighted below.

A. Physical Layer Structure

Various works have already been done to modify the frame structure or physical layer structure of cellular V2X communications. As discussed before, 3GPP has considered agile frame structure on NR Release 16 [12]. Shorter TTI and larger SCS are desired in cellular based V2X communications to reduce the Doppler effect. Scalable SCS as discussed in [31] can be used for growing V2X use cases. Although wider SCS can better handle frequency offset and Doppler shift, inter-symbol interference will be high. For reducing the inter-symbol interference extended CP can be used which in turn reduces the OFDM efficiency. Thus, further research is required to address the issue of inter-symbol interference in scalable SCS in NR Release 16. Moreover, a unified frame structure with a suitable number of DMRS symbols is required to address the issue of highly dynamic vehicular communications.

B. Synchronization

Synchronization issues will be more exacerbated in out of network and in partial coverage areas in V2X networks. GNSS can be used as a synchronization source as explained in [29], however, there still exist problems with the absolute time offset error in partial coverage and out of coverage. Absolute time offset error is more pronounced for out of coverage vehicular users due to the radio wave propagation time from GNSS. Further research should try to minimize the absolute time offset error for out of coverage users and should design a protocol that will allow vehicle UE to easily switch the synchronization source.

C. MBMS

The use of MBMS has a great advantage in cellular based V2X communications. However, determining the V2X broadcast area and latency are still major challenges. Arranging small non-overlapped MBMS service areas is a challenging task. In addition, it is difficult to transmit V2X messages in different overlapped areas. To transmit messages in overlapped areas, TMGI, as discussed in [35], can be used. However, TMGI management in overlapped areas is complicated and should be addressed in future research. For the latency issues in MBMS, localized MBMS can be used. However, the current architecture of cellular V2X does not support the joint local and centralized MBMS service and should be addressed in future research.

D. Resource Allocations

Resource allocation is one of the most researched areas in cellular based vehicular communications. However, there still exists a lot of challenges in resource allocations. NOMA based techniques are envisioned in 5G based vehicular communications which can provide various V2X services and supports massive connectivity [126]. However, resource allocation using the NOMA based technique is challenging due to a lot of interference produced at the receiver side. Information can be exchanged between receiver and sender to cancel successive interference as discussed in [51]. However, a lot of communication overhead is introduced due to information exchanged. Thus, future research should try to address the interference cancellation issue without causing a lot of communication overhead. Another promising area is the reinforcement learning based resource allocations in which reinforcement or Q-learning is used for the distributed power selection. For large state state-action pairs, graph and Deep Q-learning based resource allocations as proposed in [118] can be used for distributed power allocation. Further research is needed to analyze delays and other issues associated with Deep Q-learning for resource allocations in vehicular communications.

E. Security

Most of the existing cryptographic schemes as discussed in this survey can provide protection from external attacks but are found to be less effective against the attacks generated within the network. A misbehavior detection system (MDS) can be deployed to prevent such attacks. Misbehavior or anomaly detection systems are complicated computing systems for monitoring and detecting malicious behaviors [119]–[123]. In vehicular communications, machine learning based MDS can be used to detect several attacks such as false alert attack and position falsification attack [124], [125]. Thus, it is essential to address both cryptographic and MDS based schemes for strengthening the security of LTE V2X communications. Future research direction in V2X security should address both cryptographic and misbehavior detection issues.

5G V2X will incorporate SDN, mobile edge computing and network function virtualization which will bring additional security challenges. In SDN based V2X networks, the attackers may attack the northbound and southbound application program interface (API) and can have control over the SDN network through the controller. Attackers will then be able to create their own policies and disrupt the V2X services. SDN based privacy-preserving and mutual authentication framework can be used for simplifying the network management and enhancing privacy [127], [128]. However, these schemes lack real test-beds implementation. Future work should address the authentication and privacy issues of V2X communications using real test-beds implementation. Moreover, network function virtualization will allow the movement of security functions throughout the network. However, there might be issues while moving security functions throughout the network [129]. In addition, edge computing will bring security services closer to the user which will introduce additional challenges related to security.

F. Heterogenous Networks

Macro, micro, and pico cell will be the components of heterogeneous networks in 5G V2X. Especially in micro and pico cells, there arise issues of handover. As discussed earlier various works have been proposed to address the issue of handover in highly dynamic vehicular communications. The promising solutions are cell co-operation and dual connectivity [78], [79]. However, there might be high backhaul signaling overhead. Future work should address the issue related to signaling overhead in co-operative handover schemes. Another promising solution is the identification of candidate cells to pre-fetch the content during handover. However, there is a need for reliable prediction schemes such as machine learning based prediction to identify the candidate cell for the handover process.

G. Millimeter Wave Communications

Millimeter wave communications will provide a high data rate in 5G based V2X communications. Broadcast communication and directional transmission for V2X use cases remain the challenging problems in millimeter wave communications. Contextual online learning [86] is a promising solution to identify the V2X application area and beamforming. However, contextual online learning requires a huge amount of periodic data and location information. Future research should address the challenges associated with the data gathering for contextual online learning in millimeter wave communications.

H. Massive MIMO

Pilot contamination and CSI estimation are the major challenges for the massive MIMO system in V2X communications. Promising solutions such as Block-diagonal [90] and graph based scheme [91] have been proposed to address the issues related to Massive MIMO. However, these schemes have issues related to obtaining specific sequences and iterative power control algorithms. Future research should clearly address the issues related to obtaining sequences in different cells and reducing pilot contamination. Graph based or machine learning based scheme can be used to reduce pilot contamination.

I. Vehicular Cloud or Fog Computing

Resource management, security and incentives are major challenges in vehicular cloud computing. As discussed various solutions have been proposed to address these challenges. However, delay and inaccurate predictions are the main issues in most of the proposed solutions [100], [102]. For privacy-preserving and incentive schemes, delay plays an important factor. There is a tradeoff between privacy and delay and it should be balanced according to V2X applications. Future works in vehicular fog computing should try to address the issues related to delay for resource management, privacy and incentives solutions.

J. SDN

SDNs based vehicular communications will reduce the signaling overhead and allows to access heterogeneous resources in real-time. However, inter-operation network management using SDN in heterogeneous networks is still an open challenge. Dynamic and flexible configuration systems in heterogeneous environments as proposed in [109] can be used. However, such schemes introduce load balancing issues due to the attachment of different types of loads in heterogeneous V2X networks. Future works should clearly address the issues related to load balancing and slicing various V2X applications.

K. Mobile Edge Computing

Mobile edge computing will provide low latency and bring various V2X use cases close to the user. Content pre-fetching and content distribution are the major challenges in edge computing. The machine learning algorithm can be used for content pre-fetching. However, there is an issue with accurately identifying suitable vehicles for content pre-fetching. The mobility model along with a trust model combined with the machine learning model can be used to select a suitable vehicle for content pre-fetching. Similarly, graph and mobility based vehicle selection should be performed for content distribution.

L. Network Slicing

Network slices can be tailored to specific V2X use cases to provide real time V2X applications. However, there exists a slice configuration and security or trust issues. A trust model can be developed between the slice manager and provider owning to the infrastructure. The dynamic trust model based on reinforcement learning can be used to establish trust between network slice manager and vehicles. Moreover, SDNs should be integrated into V2X networks which can be virtualized and sliced network functions according to V2X use cases.

M. Dynamic Spectrum Sharing

Dynamic spectrum sharing in multi-radio technology can be used to enhance the spectrum utilization in V2X networks. V2X users should dynamically share the spectrum with other users to enhance V2X capabilities. The co-existing of V2X and DSRC users in the unlicensed spectrum as discussed in [117] can be considered. However, interference will be the main issue in such schemes. A complex channel estimation method can be used for avoiding the interference during dynamic spectrum sharing. Future works should consider the graph and machine learning based channel estimation method in dynamic spectrum sharing applications.

VII. Conclusion

In this article, we provide a comprehensive survey of the recent development in LTE and 5G to support V2X communications. We show how strong aspects of LTE such as wide coverage, high capacity and high penetration paved the path for LTE based V2X communications. We also show that several challenges lie ahead before LTE can be massively utilized for vehicular communications. Physical layer structure and synchronization are some of the main challenges for LTE V2X communications due to high relative velocity, high frequency and frequent handover in V2X communications. Resource allocation will be another challenge where the resources being used by the vehicular system should not conflict with the resources being used by cellular users. Moreover, the security and MBMS system of LTE needs to be redesigned and analyzed for V2X communications. We also discuss various 3GPP and non-3GPP based solutions to address these challenges. In addition, the incorporation of various emerging technologies such as massive MIMO, device-to-device communications, multi-radio access technology, full-duplex radios, millimeter waves, cloud technologies and SDN in 5G will bring various challenges to V2X communications. There are active researches going on to address these challenges. Furthermore, a cross-industry organization such as 5GAA is working to develop end-to-end solutions for 5G based V2X communications.

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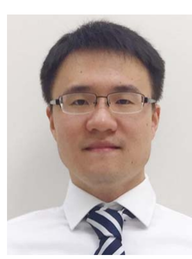

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