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TOPICAL REVIEW

Vehicle-to-Everything (V2X) Evolution From 4G to 5G in 3GPP: Focusing on Resource Allocation Aspects

CHEOLKYU SHIN[1], EMAD FARAG[2], HYUNSEOK RYU[1], MIAO ZHOU[3], AND YOUNSUN KIM[1], (Senior Member, IEEE)
[1]Samsung Research, Seoul 06765, South Korea
[2]Samsung Research America, Plano, TX 75023, USA
[3]Samsung Research and Development Institute China-Beijing (SRC-B), Beijing 100028, China

Corresponding author: Cheolkyu Shin (ck13.shin@samsung.com)

ABSTRACT Cellular Vehicle-to-everything (V2X) is evolving from a communication technology for safety messages towards a platform for advanced V2X services such as platooning and autonomous driving. The development of technical specifications for V2X communications is done across several task specification groups (TSGs) and working groups (WGs) within 3rd Generation Partnership Project (3GPP). In this paper, we focus on radio access network (RAN) aspects for direct communication between user equipments (UEs), which is known as sidelink (SL) communication. Resource allocation for SL communication can be performed in one of two modes. In the first mode, resource allocation is centralized in the network. In the second mode, resource allocation is performed in a distributed manner among UEs, where resource selection is performed at a transmitting UE, i.e., the transmitting UE determines time and frequency resources for a SL transmission without the assistance of a base station. In this paper, we review V2X evolution from 4G to 5G in 3GPP focusing on resource allocation aspects defined in Long-Term Evolution (LTE) and New Radio (NR) specifications, with particular attention given to the difference in design and performance of each. We highlight the key 3GPP standard developments on V2X resource allocation which includes enhanced resource reselection mechanisms and partial sensing schemes. It is observed that NR V2X resource reselection mechanism can provide up to 20% of reliability improvement over LTE V2X and NR V2X partial sensing scheme can provide up to 95% of reduced power consumption over full sensing scheme.

INDEX TERMS Long-term evolution (LTE), new radio (NR), resource allocation, sidelink (SL), vehicle-to-everything (V2X), 3rd generation partnership project (3GPP).

I. INTRODUCTION

Over the last few decades, the number of road vehicles has been growing at a steady pace. Consequently, congestion and incidents in highways, metropolitan areas, and even rural areas are on the rise as well [1]. To address the safety concerns and provide additional services, Intelligent Transport System (ITS) will play a vital role. ITS supports V2X (vehicle-to-everything) communication which includes communication between vehicles, roadside infrastructure, pedestrians and wide area networks. V2X has attracted a great deal of attention as a means to guarantee pedestrian and driver safety while efficiently managing traffic congestion and providing advanced services [2], [3], [4], [5], [6], [7].

In this regard, a large number of research articles and tutorials have addressed V2X communications [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21]. In the following, we provide a brief literature survey of publications addressing this topic, highlighting aspects covered in this paper and not covered by earlier publications. The earlier works in [8], [9], [10], and [11] introduced V2X standardization based on Long-Term Evolution (LTE). Recently, tutorial works in [12] and [13] introduced New Radio (NR) based V2X standardization. Reference [14]

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provided the evolutionary path of V2X standardization from LTE to NR. Reference [15] presented the 5G technology evolution, standards, and infrastructure associated with V2X communcations by internet of vehicles (IoV). 3rd Generation Partnership Project (3GPP) presented a technical report [16] to give an overview across the Radio Access Network (RAN) specifications of the features introduced to LTE and NR in support of V2X services. However, performance evaluation was not included in their works [12], [13], [14], [15], [16]. Performance of NR V2X was analyzed in [17], [18], and [19] but enhanced features of resource allocation such as re-evaluation, pre-emption, and inter-UE co-ordination (IUC) supported in 3GPP specifications were not discussed. Also, power saving gain obtained from power-efficient resource allocation schemes was not analyzed. Research articles in [20] and [21] have focused on V2X resource allocation but performance evaluation was not provided as well.

This work reviews the key features on V2X resource allocation specified in LTE and NR and compares the peformance of these features. The contribution of this paper is to provide V2X performance based on thorough specified parts of resource allocation in 3GPP with possible configuration and implementation variation. This is aim to see the achievable performance of V2X resource allocation according to the standardized components in LTE and NR. Since network-based resource allocation is totally up to implementation, the specified parts for V2X resource allocation are for UE-based resource allocation which is based on sensing and resource (re-)selection procedure. The resource (re-)selection procedure has evolved for enhanced reliability by introducing re-evaluation, pre-emption, and IUC. In addition, the V2X resource allocation supports partial sensing schemes for reduced power consumption. In this paper, we discusses how V2X has been evolved in 3GPP from LTE to NR focusing on their specification supports on resource allocation from a physical layer perspective. Also, the performance of resource allocation schemes specified for LTE V2X and NR V2X is compared in terms of reliability (i.e., packet reception ratio) and power consumption.

To this aim, the rest of this paper is organized as follows: Section II explains V2X specification supports in 3GPP. Section III provides an exhaustive overview for SL operation. This review helps understand the background on the resource allocation framework. In Section IV, we present the details of UE-based resource allocation which consists of sensing and resource (re-)selection procedure. In that section, we highlight the differences between LTE and NR V2X. Also, we explain about enhanced reselection mechanisms and power saving resource allocation schemes with their technical motivation and differences. Section V provides evaluation results to compare the performance of LTE and NR V2X. Especially, the benefits of re-evaluation and pre-emption mechanisms and IUC scheme introduced in NR V2X when compared to UE-based resource allocation in LTE V2X. In addition, power consumption analysis of partial sensing schemes are provided. Section VI presents technical challenges on V2X resource allocation and future direction. Finally, conclusions are drawn in Section VII.

II. V2X SPECIFICATION SUPPORTS IN 3GPP

3GPP has introduced V2X capability first in LTE Rel-14. This is then being further enhanced in subsequent releases. LTE V2X was designed to support V2X messages such as basic safety messages (BSMs), cooperative awareness messages (CAMs) and decentralized environmental notification messages (DENMs) [22], [23], [24] that are exchanged via sidelink (i.e., PC5 interface) and uplink/downlink (i.e., Uu interface). Specifically, communication can be performed over the PC5 interface between the two user equipments (UEs), called as sidelink (SL) interface or through the network using the Uu interface. V2X includes communication between vehicles, i.e., vehicle-to-vehicle (V2V), communication between vehicle and pedestrian, i.e., vehicle-to-pedestrian (V2P), communication between vehicle and roadside infra-structure equipment, i.e., vehicle-to-infrastructure (V2I) and communication between vehicle and wide area network, i.e., vehicle-to-network (V2N) [22]. Rel-14 LTE V2X adopted the concept of sensing and resource identification, which is a procedure where a transmitting UE determines its resources before SL transmission to avoid collision with neighboring UEs accessing to the same resources. Also, in Rel-14 V2X, a power-efficient resource allocation scheme based on random selection or partial sensing was introduced for vulnerable road users (e.g., pedestrians) which are more sensitive to power consumption than vehicles. In Rel-15, V2X was enhanced to support advanced V2X services such as platooning, advanced driving, remote driving and extended sensor [25], [26]. Since these services have tighter requirements than ones supported by Rel-14 V2X in terms of latency, reliability and throughput, Rel-15 enhanced V2X (eV2X) adopted SL carrier aggregation and 64-QAM to meet the requirements.

On the other hand, 5G NR standardization was completed in Rel-15 and there was strong demand on the support of 5G NR-based V2X, which has more demanding requirements such as a maximum SL range of 1km, a maximum throughput of 1Gbps, a latency as short as 3ms, and a maximum reliability of 99.999% [27]. This motivated the development of NR-based SL in Rel-16 [28] with more functionalities compared to Rel-14 and Rel-15 LTE V2X as shown in Table 1. Solutions specified for NR SL in Rel-16 can be applied for V2X, and public safety use cases as long as the requirement can be met. Subsequently, additional SL enhancements were specified as a part of Rel-17 [29] which includes three aspects; 1) SL power saving for vulnerable road users in V2X and for UEs in commercial and public safety use cases where power consumption in the UEs needs to be minimized, 2) enhancement of SL resource allocation to support URLLC (ultra-reliable low latency communication)-type SL use cases and 3) UE-to-Network relay to increase Uu coverage reachability. Recently, 3GPP approved a new work item to further evolve SL in Rel-18 [30] focusing on four areas of evolution:

TABLE 1. Comparison of LTE V2X and NR V2X.

	LTE		NR		
	Rel-14 (2017[1])	Rel-15 (2018[1])	Rel-16 (2020[1])	Rel-17 (2022[1])	Rel-18 (∼2023[2])
Target use cases[3] based on work item description	Road safety services (BSMs, CAMs, DENMs) [22]– [24]	Advanced V2X services (platooning, advanced driving, remote driving, extended sensor) [25], [26]	Advanced V2X services (platooning, advanced driving, remote driving, extended sensor) [27], [28]	Public safety and commercial use cases with low power URLLC-type SL use cases [29]	Sensor information (video) sharing between vehicles with high degree of driving automation [30]
Physical channels/signals	Based on LTE frame structure		Based on NR frame structure		Under discussion about new physical channel design to support unlicensed operation
Subcarrier spacing	15 kHz only		$15 \cdot 2\mu$ kHz, $\mu \in \{0, 1, 2, 3\}$		
CP (cyclic prefix)	Normal CP only		Normal CP for all SCSs, Extended CP for 60 kHz only		
Waveform	DFT-s-OFDM		CP-OFDM		
Channel coding	TBCC[4]for SL control channel Turbo coding for SL data channel		Polar code for SL control channel LDPC code for SL data channel		
Modulation	Up to 16-QAM	Up to 64-QAM	Up to 256-QAM		
MIMO	N/A		Up to 2 layers		Under discussion about beam management operation in FR2[5]
SL CSI feedback	N/A		Supported by MAC-CE		
SL HARQ feedback	N/A		Supported by PSFCH[6]		
SL CA[7]	N/A	Up to 3 CCs[8]	N/A	N/A	Under discussion
Resource allocation	Mode 3 (resource allocation by base station) Mode 4 (resource allocation by UE using full/partial sensing-based resource selection, random resource selection)		Mode 1 (resource allocation by base station) Mode 2 (full sensing based resource selection, Resource reselection by re-evaluation and/or pre-emption)	Mode 2 (resource allocation by partial sensing based resource selection, random resource selection, Inter-UE coordination)	Under discussion about a new resource allocation mechanism with channel access in unlicensed spectrum

[1] The year of completion
[2] The expected year of completion
[3] Some of target use cases have very tight requirements [25], [27]. The requirements may not be reached for all scenarios and deployments.
[4] Tail Biting Convolutional Code
[5] Frequency Range 2, which includes frequency bands from 24.25 GHz to 71.0 GHz.
[6] Physical Sidelink Feedback Channel
[7] Carrier Aggregation
[8] Component Carriers

1) operation of SL in unlicensed spectrum, 2) more efficient co-existence between LTE SL and NR SL in the same band, 3) support of beam management for more efficient operation in FR2, and 4) SL carrier aggregation.

SL communication should be able to be performed in the cases not only when UEs are inside network coverage but also when they are in out-of-network coverage such as in a coverage hole (e.g., deep within a building or in a long tunnel). In the out-of-network coverage case, there is no centralized controller like a base station (BS) and it is not possible to apply a centralized resource allocation e.g., the controller collects all the channel state information of every UE in the system and allocates the available resources in order to maximize system performance according to a constraint such as fairness or power. Hence, resource allocation methods are one of most critical factors to design for the SL system, and is the focus of this paper. As shown in Table 1, the UE-based resource allocation method in LTE V2X and NR V2X is designated as Mode 4 and Mode 2, respectively. Mode 4 in LTE was designed especially for periodic traffic [22], [23], [24]. Thus, the sensing procedure was designed to fit into quasi-periodic broadcasted messages such as BSM and CAM. On the other hand, NR Mode 2 was designed targeting a mixture of periodic and aperiodic traffics with a tighter service requirements as described in [27] and [28]. As a result, NR V2X provides new and enhanced mechanisms for UE-based resource allocation. For example, new functionalities include resource re-evaluation and pre-emption mechanisms in order to improve resource selection reliability especially for aperiodic traffic. Moreover, considering the importance of low latency and efficient resource utilization, hybrid automatic repeat and request (HARQ) feedback based retransmissions was introduced in NR V2X. Additionally, SL UEs can exchange inter-UE co-ordination (IUC) information to aid resource allocation. With these new features, Autonomous resource selection in NR V2X would be able to support advanced 5G V2X services.

III. OVERVIEW ON SL OPERATION

This section gives an overview of SL physical layer design such as numerologies and frame structures. Also, a mechanism of SL transmission and reception including resource allocation modes is provided based on 3GPP V2X specifications.

A. NUMEROLOGIES

LTE V2X supports 15 kHz subcarrier spacing (SCS) and normal cyclic prefix (CP) only as summarized in Table 1. Hence, in LTE V2X, one sub-frame has a length of 1 ms which consisting of 14 OFDM symbols [31]. On the other hand, NR V2X supports multiple SCSs such as 15 kHz$\cdot 2^{\mu}$ where μ is the SCS configuration and is given by $\mu = 0, 1, 2, 3$ for 15 kHz, 30 kHz, 60 kHz and 120 kHz SCS, respectively. In FR1, $\mu = 0, 1, 2$, while in FR2, $\mu = 2, 3$ [32]. Since multiple SCSs are supported in NR V2X, the slot length is variable depending on which SCS configuration, μ is applied, i.e., the slot length is $2^{-\mu}$ ms. In NR V2X both, extended CP (ECP), for SCS configuration $\mu = 2$, as well as normal CP (NCP), for all SCS configurations are supported, with NCP one slot consists of 14 OFDM symbols while with ECP one slot consists of 12 OFDM symbols. Furthermore, in NR V2X, 7–14 CP-OFDM symbols in a slot can be used for SL transmissions with the start symbol and the number of symbols being configured in the SL bandwidth part (BWP) information [40]. The adjustable symbol length in NR V2X allows more flexible resource allocation and the concept of SL BWP was defined in a way similar to that of NR DL/UL interface.

B. RESOURCE POOL

A resource pool is defined as a set of resources used for SL communication in time domain and frequency domain [35], [36]. In time domain, the resource pool consists of a number of slots (NR V2X) [32] and a number of sub-frames (LTE V2X) [31]. To determine the slots/sub-frames in a resource pool, the slots/sub-frames in 1024 frames are considered, the following slots/sub-frames are excluded [35], [36]: 1) slots where at least one SL symbol is not semi-statically configured as an UL symbol, 2) slots used for the SL synchronization blocks (S-SSB), 3) Reserved slots which after exclusion, the remaining slots in 1024 frames are an integer multiple of the bitmap length. The remaining slots/sub-frames are denoted by $\{t_0^{SL}, t_1^{SL}, t_2^{SL}, \ldots\}$. A bitmap with a length $L : b_0, b_1, \ldots, b_{L-1}$ is applied to these slots. The slots remaining after applying the bitmap are the logical slots of a resource pool and are denoted by $\{t_0'^{SL}, t_1'^{SL}, t_2'^{SL}, \ldots\}$.

In frequency domain, the resource pool consists of a number of sub-channels where a sub-channel is the minimum resource allocation unit for both LTE V2X and NR V2X [35], [36]. One sub-channel has multiple resource blocks (RBs) and each RB consists of 12 resource elements (REs) (i.e., 12 subcarriers). The resource pool configuration also includes information about the number of RBs in one sub-channel (i.e., sub-channel size), the number of sub-channels and starting RB index of the resource pool [39], [40]. It is noted that the SL resource pool consists of a consecutive non-overlapping set of sub-channels in frequency domain. In Fig. 1, as an example, the resource pool is configured to have 5 sub-channels and a bitmap '110101011…' is applied where '1' represents the slot/sub-frame assigned for a UE as the SL resource pool.

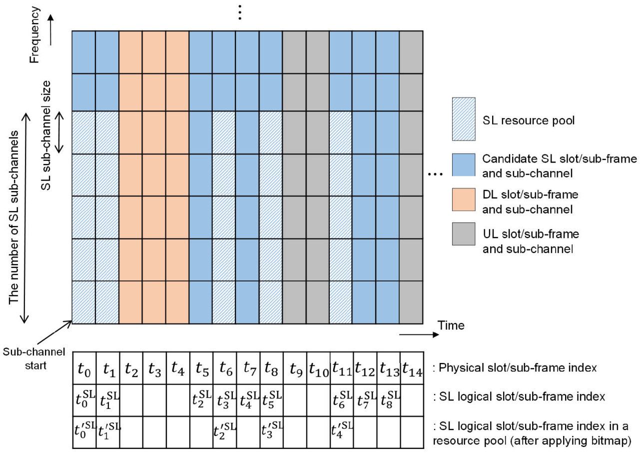
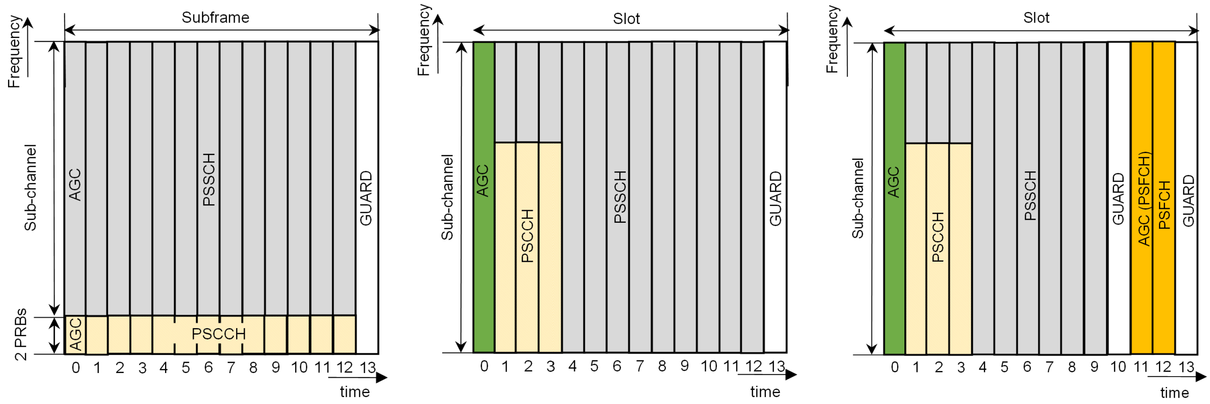


FIGURE 1. An illustration of SL resource pool.

There are two types of resource pools: one is a transmitting (TX) pool for SL transmission and the other is a receiving (RX) pool for SL reception [39], [40]. If a UE is in a network coverage, the UE can be configured with information about TX pool and RX pool from its serving base station (BS). Otherwise (i.e., if the UE is in out-of-network coverage), resource pool information is pre-configured. Multiple TX pools or multiple RX pools can be (pre-)configured for the purpose of load balancing or congestion control. In such a case, SL transmission should be performed only within a single TX pool and the BS indicates which TX pool has to be used by a TX-UE if the UE has a connection with the BS (i.e., RRC connected state) and a resource for SL transmission is scheduled by the BS. Otherwise the UE selects one TX pool by itself from the configured multiple TX pools. On the other hand, a receiving UE (RX-UE) has to monitor all the configured multiple RX pools.

C. SLOT STRUCTURE

Fig. 2 illustrates the slot structure in the LTE and NR V2X. In case of LTE V2X, as shown in Fig. 2(a), PSCCH (physical sidelink control channel) is assigned a fixed 2 RBs and whole PSCCH symbols are frequency division multiplexed (FDMed) with PSSCH (physical sidelink shared channel) [31]. On the contrary, for NR V2X as shown in Fig. 2 (b) and (c), PSCCH duration can be configured as 2 or 3 symbols and starting from the 2nd SL symbol in the slot. Additionally, PSCCH is transmitted from the lowest RB of the corresponding PSSCH in the corresponding symbols. Therefore, PSCCH is FDMed with PSSCH in symbols where



(a) LTE subframe (b) NR slot without PFSCH (c) NR slot with PFSCH

FIGURE 2. Comparison of SL slot structure between LTE and NR V2X.

PSCCH is transmitted [32]. For both LTE and NR V2X, a receiver can use the first symbol for automatic gain control (AGC) purpose. However, the starting symbol of PSCCH and PSSCH is the 1st symbol in a subframe in LTE V2X but it is the 2nd SL symbol in the slot in NR V2X, where the first SL symbol of a slot is duplicate (copy) of the second SL symbol of the slot. Hence, NR V2X provides one AGC training symbol independently by copying 2nd SL symbol of the slot to avoid distortion of PSCCH and PSSCH symbols due to the increased AGC relative settling time (relative to symbol duration) arising from support of higher SCSs and higher modulation order up to 256QAM. Lastly, in both LTE and NR V2X there is a guard symbol in the last symbol of SL slot/sub-frame. The guard symbols is to allow the UE to switch between reception and transmission. In NR, there are two types of slots. The first are slots that do not have PSFCH, these are shown in Fig. 2(b). The second are slots with PSFCH, there are shown in Fig. 2(c). For slots with PSFCH, PSFCH is transmitted the second to last symbol of the slot, with a duplicate symbol before that for AGC tuning. There is a guard symbol (i.e., gap with no transmission) between PSSCH/PSCCH and PSFCH.

D. RECEPTION OF SL CONTROL/DATA

In this subsection, we explain how a UE receives SL control and data information. In LTE V2X, the SL control information (SCI) is carried on PSCCH [33]. On the other hand, two-stage SCI was introduced in NR V2X [34]. Like LTE SCI, the 1st SCI is carried on PSCCH. The LTE SCI and NR 1st SCI are used to provide resource allocation information of PSSCH and due to the absence of scrambling of the CRC, any UE can decode this information and perform sensing for UE-based resource allocation. In the next section, we explain further details on sensing procedure with PSCCH decoding (i.e., LTE SCI or NR 1st SCI decoding). Unlike LTE SCI, the 2nd SCI is carried on PSSCH and it was introduced to provide application-specific information in NR V2X. For example, the 2nd SCI includes information to control SL HARQ feedback in unicast and groupcast scenarios.

As explained in the previous Section III-B, SL resource pools are configured to a UE separately for TX pools and RX pools. This allows the UE to monitor PSCCH and receive PSCCH and PSSCH in resource pools that can be different from those in which it transmits. In other words, the UE attempts to receive PSCCH and PSSCH transmitted by other UEs in RX pools. Also, the UE needs to search PSCCH candidate resources in the RX pools. Both in LTE (for adjacent PSCCH and PSSCH mapping [35]) and NR V2X, PSCCH and PSSCH are always transmitted together and the PSCCH resource is transmitted in the lowest RB of the corresponding PSSCH. Therefore, considering minimum one sub-channel PSSCH scheduling, every sub-channel can include the PSCCH. Fig. 3 illustrates an example of the PSCCH monitoring and PSCCH and PSSCH reception. Fig. 3 shows an example of 3 resource pools; pool A, B and C. UE-A receives in resource pool A, UE-B receives in resource pool B and UE-C receives in resource pool C. UE-A has two TX pools; pool B and pool C, when UE-A wants to transmit to UE-B, it uses TX pool B and when UE-A wants to transmit to UE-C it uses TX pool C. For UE-A, pool A is configured as an Rx pool, hence UE-A receives a PSCCH and PSSCH transmitted by UE-B or UE-C, in RX pool A; while pools B and C are configured as TX pools, hence UE-A can transmit PSCCH and PSSCH in different TX pools, i.e. pools B and C. As shown in Fig. 3, the UE-A can monitor the possible PSCCH candidate resources in RX pool A. If the UE-A receives and decodes PSCCH successively, the UE can receive corresponding PSSCH from the resource allocation information in PSSCH. In LTE V2X, UE-A can check the destination ID in MAC (medium access control) header [37] after PSSCH and the corresponding PSSCH decoding. On the other hand, in NR V2X a part of the destination ID is included in the 2nd SCI [34] and the UE-C can proceed PSSCH decoding if the destination ID both from the 2nd SCI and MAC header [38] is matched with the UE's ID.

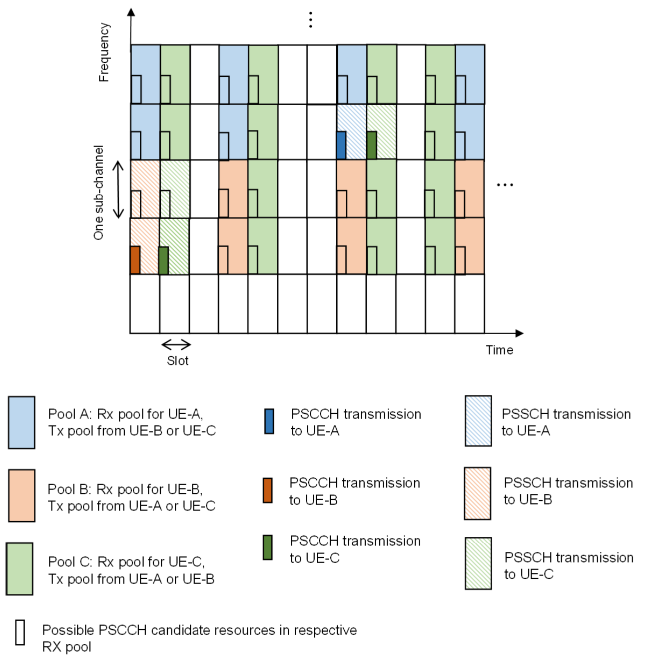


FIGURE 3. An illustration of receiving SL control/data.

TABLE 2. Resource allocation schemes in LTE V2X and NR V2X.

	Mode-A	Mode-B
NR V2X	Mode 1	Mode 2
LTE V2X	Mode 3	Mode 4

E. RESOURCE ALLOCATION MODES

Two resource allocation methods are supported for both LTE V2X and NR V2X [35], [36]. The first method is that the time and frequency resource(s) for SL transmission is scheduled by a BS (which is referred to as Mode-A resource allocation or just Mode-A, hereafter). The second method is that the resource(s) is selected by a TX-UE itself (which is referred to as Mode-B resource allocation or just Mode-B, hereafter). Please note that Mode-A and Mode-B are named differently in LTE V2X and NR V2X as shown in Table 2. A V2X UE can be capable of both Mode A and Mode B but from a TX-UE perspective, only one method is used within a given resource pool (i.e., either Mode-A or Mode-B). Which method should be utilized by the TX-UE is informed by resource pool configuration [39], [40].

In Mode-A, similar to a normal cellular system operation, the BS can dynamically schedule the resources for SL transmission via DCI (downlink control information) on PDCCH (Physical Downlink Control Channel). So, Mode-A is beneficial in terms of maximizing the spectrum utilization or minimizing interference to cellular networks but Mode-A is applicable only for the case where the UE is in network coverage. In Mode-B, on the other hand, a TX-UE has to select its time and frequency resources by itself, and/or using inter-UE co-ordination (IUC) information, if available, which was introduced in Rel-17, according to a resource selection mechanism which will be described in Section IV. Since there is no centralized scheduler like the BS in Mode-B, its performance optimization is more challenging than that of Mode-A given the distributed nature of the resource allocation. Mode-B can be applicable for outside network coverage scenario as well as inside network coverage.

In both LTE and NR SL, the general procedure of Mode-A includes: when the packet of SL data arrives at the MAC layer of a TX-UE, the TX-UE requests SL resources from a BS, e.g. via scheduling request (SR) and SL buffer status reporting (SL-BSR) procedure. The BS can allocate a set of periodical SL resources to TX-UE, or dynamically allocate a set of resources to the TX-UE by SL grants. More specifically, the BS can semi-statically allocate a set of periodical SL resources to TX-UE with up to 2 resources within a 16-slot interval for each period in LTE SL by a configured SL grant [35], [39], or with up to 3 resources within a 32-slot interval for each period in NR SL by a configured SL grant [36], [40]. The BS can dynamically allocate a set of up to 2 SL resources within a 16-slot interval in LTE SL, or a set of up to 3 SL resources within a 32-slot interval in NR SL to TX-UE by a dynamic SL grant. Dynamic grants are carried by DCI formats specifically designed for SL and transmitted on PDCCH. Configured grants are carried by RRC signaling [39], [40], and additionally can be triggered/released by DCI formats specifically designed for SL and transmitted on PDCCH [33], [34]. When the TX-UE receives SL grants from the BS, the resources scheduled by a dynamic grant or the resources in the same period scheduled by a configured grant can be used for initial transmission and/or retransmission(s) of a single transport block (TB). After the TB being transmitted successfully, the remaining scheduled resources, if any, cannot be used for the transmission of a new TB.

Unlike LTE V2X, HARQ-based retransmission is supported in NR V2X and in Mode-A, the UE can report SL HARQ-ACK to BS if the SL grant received by the TX-UE also allocates a PUCCH resource [34]. The key motivation of the HARQ-ACK reporting is to reduce the latency of acquiring new SL resources for retransmission of data, since the latency of SR/BSR-based resource allocation can hardly satisfy latency requirement of most typical SL traffic. Consequently, for Mode-A transmission with HARQ-ACK enabled, it is necessary to allow UE requesting retransmission resources to BS based on received HARQ-ACK feedback. Specifically, if NACK is reported to BS (by transmitting individual NACK or SL HARQ-ACK codebook), BS may schedule more SL resources for retransmissions of the TB via dynamic grant.

IV. RESOURCE SELECTION MECHANISM IN MODE-B

When a UE uses Mode-B, the resource selection mechanism is performed by the UE as shown in Fig. 4. In both LTE V2X and NR V2X, the resource selection mechanism in Mode-B is composed of a sensing procedure and a resource selection procedure, additionally, in NR V2X, re-evaluation & pre-emption operations are newly introduced for further optimization. Also, in NR V2X, a UE can perform resource

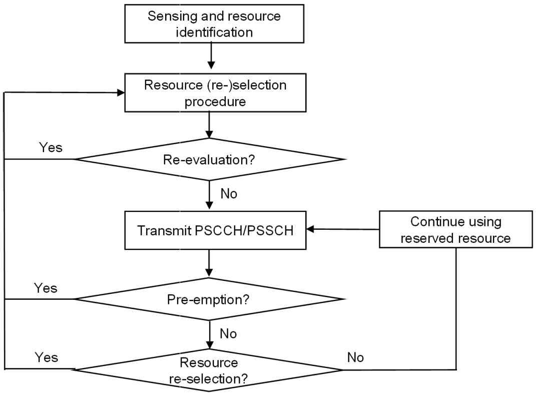


FIGURE 4. **Overall procedure for Mode-B resource allocation.**

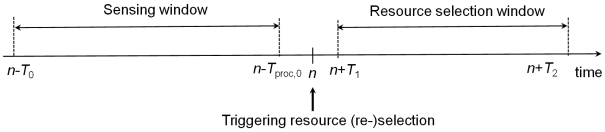


FIGURE 5. **Sensing window and resource selection window.**

re-selection by receiving inter-UE co-ordination (IUC) message(s) from other UE(s).

When a TX-UE starts its resource selection mechanism in time instant n, the sensing procedure and resource selection procedure should be performed for resources within a time interval which is called as a sensing window and a resource selection window respectively (please see Fig. 5. The sensing window is defined as $[n - T_0, n - T_{proc,0})$ and the resource selection window is defined as $[n + T_0, n + T_2]$ where T_0, $T_{proc,0}$, T_1 and T_2 are given in Table 3.

A. SENSING AND RESOURCE IDENTIFICATOIN

Sensing allows a TX-UE to predict potential collisions with other UEs accessing the same resources before selecting its resource(s) for SL transmission. The TX-UE (i.e., the sensing UE) monitors slots/sub-frames within the sensing window as shown in Fig. 5 by way of PSCCH decoding and SL reference signal received signal power (SL-RSRP) measurement. Specifically, the TX-UE obtains other UE's SCI (1st SCI in NR V2X as described in Section III-D) by PSCCH decoding. The SCI includes resource allocation information of PSSCH, i.e., location of the PSSCH in the time and frequency domains. Since the SCI can include the resource allocation information of the current transmission but also for the future transmission, as depicted in Fig. 5 the TX-UE can figure out in time instant n whether other UEs will occupy a resource(s) or not within the resource selection window. Therefore, if the TX-UE detects by PSCCH decoding that another UE occupies resource(s) within the TX-UE's resource selection window, the TX-UE performs the SL-RSRP measurement to estimate whether other UE's occupied resource leads to high interference or not.

For the SL measurement, the TX-UE calculates SL-RSRP from demodulation reference signal (DMRS) on PSSCH after PSCCH decoding. In NR V2X, in order to allow more flexibility, either the DMRS on PSCCH or the DMRS on PSSCH can be utilized for the SL measurement in sensing procedure. Then, the UE compares the result of SL measurement with a threshold to determine whether or not to exclude this resource for its SL transmission. The threshold depends on the priority of the SL transmission and SL reception (signaled in the PSCCH channel). Specifically, a priority value for the SL transmission and reception is defined with a range of 1 to 8 (smaller value has higher priority) which is determined based on QoS (Quality of Service) level [41], [42]. So, each SL UE knows the priority value associated with PSSCH and TX-UE includes the priority value into the SCI when it transmits PSCCH and PSSCH. In the sensing procedure, the sensing UE decodes SCI on PSCCH transmitted by other UEs and obtains the priority value. Assuming that p_i is a priority value of SL reception obtained from a SCI decoding and p_j is the priority value of SL transmission for TX-UE selecting resources, the threshold is configured by the sensing UE according to $[(n-1)\cdot 2-128]$ dBm where $n = p_i+(p_j-1)\cdot 8$.

From the SL-RSRP measurement and decoding of PSCCH, the TX UE can identity a set of candidate resources for its SL transmission within the resource selection window. This is referred to as resource identification procedure. The resource identification procedure is to determine the available SL resources within a resource selection window. If the SL measurement is smaller than a threshold, the UE can count this as a candidate resource for its transmission. Otherwise, the UE excludes this from the candidate resource for its transmission. If the available resource after resource exclusion are not sufficient, the SL threshold is incremented to reduce the number of excluded SL resources and increase the number of available SL resources within the resource selection window. More specifically, assuming that 'a' is the number of candidate resources identified from the resource identification procedure and 'b' is the total number of candidate resources within a resource selection window, if a/b is less than $X\%$, the threshold is increased by 3 dB and the resource identification procedure is repeated. If the ratio of a/b is equal to or larger than $X\%$, then the remaining resources are the identified candidate resource set provided by the physical layer to the higher layers for resource selection. LTE V2X supports a single X value set to 20. NR V2X supports multiple values, 20, 35 and 50, and one of those values is (pre-)configured depending on the priority level of the SL transmission. In general, the higher the priority the higher the X value and the more the candidate resources that are available for resource selection for SL transmissions. For example, SL transmissions with priority levels $\{1, 2\}$, $\{3, 4, 5, 6\}$, and $\{7, 8\}$ can be configured with X=50, 35, and 20, respectively.

B. RESOURCE SELECTION AND ALLOCATION

The resource (re-)selection procedure is an operation, performed by higher layers [37], [38], where single or multiple resources for a transport block (TB) are randomly selected in the identified candidate resource set from the sensing

TABLE 3. Parameters for sensing window and resource selection window in LTE V2X and NR V2X.

Parameters		LTE V2X [35]	NR V2X [36]
Sensing window[1]: $[n - T_0, n - T_{\text{proc},0})$	T_0	Fixed to 1000 ms	(pre-)configurable to either 1100 ms or 100 ms
	$T_{\text{proc},0}$	Fixed to 1 sub-frame (1 ms)	Variable depending on SCS values, e.g., $\{1, 1, 2, 4\}$ physical slots for 15, 30, 60, 120 kHz SCS, respectively
Resource selection window: $[n + T_1, n + T_2]$	T_1	≤ 4 sub-frames up to UE implementation	$\leq T_{\text{proc},1}$ where $T_{\text{proc},1}$ is $\{3, 5, 9, 17\}$ physical slots for $\{15, 30, 60, 120\}$ kHz SCS, respectively
	T_2	$T_{2\min} \leq T_2 \leq 100$ if $T_{2\min}$[2] is (pre-)configured from set of values $\{10, \ldots, 20\}$ sub-frames, otherwise $20 \leq T_2 \leq 100$	$T_{2\min} \leq T_2 \leq$ Remaining PDB[3] and $T_{2\min}$[2] is (pre-)configured from set of values $\{1, 5, 10, 20\} \cdot 2\mu$ slot(s), where $\mu = 0, 1, 2, 3$ for $\{15, 30, 60, 120\}$ kHz SCS, respectively.

[1] The sensing window for NR V2X is designed to provide more flexibility by considering the support of multiple SCSs, faster processing time and characteristics of NR V2X traffic.

[2] $T_{2\min}$ is decided based on TX-UE's priority which is the value indicated by the PSCCH. It was introduced to avoid that all UEs choose small T_2 value.

[3] PDB (packet delay budget) is the upper limit of the delay that can be incurred by a packet when it is transmitted from a UE It is determined by the Policy and Charging Enforcement Function (PCEF). LTE V2X has a fixed upper bound (=100 ms) for T_2 value but in NR V2X, a UE needs to decide T_2 by satisfying PDB requirement.

TABLE 4. Parameters for resource selection and reservation in LTE and NR V2X.

Parameters	LTE V2X [33], [35], [39]	NR V2X [34], [36], [40]
The maximum number of resources that can be selected for one TB (N_{MAX}) in a resource (re-)selection procedure	2	2 or 3
Resource signaling window (W)[1]	16 logical sub-frames	32 logical slots
The number of selected resource(s) within W (N_{selected})	1 or 2	1 or 2 if $N_{\text{MAX}} = 2$, 1, 2 or 3 if $N_{\text{MAX}} = 3$
Time resource assignment bits	4	5 if $N_{\text{MAX}} = 2$, 9 if $N_{\text{MAX}} = 3$
Frequency resource assignment bits	$\left\lceil \log_2 \left(\frac{N_{\text{subChannel}}(N_{\text{subChannel}}+1)}{2} \right) \right\rceil$	$\left\lceil \log_2 \left(\frac{N_{\text{subChannel}}(N_{\text{subChannel}}+1)}{2} \right) \right\rceil$ if $N_{\text{MAX}} = 2$, $\left\lceil \log_2 \left(\frac{N_{\text{subChannel}}(N_{\text{subChannel}}+1)(2N_{\text{subChannel}}+1)}{6} \right) \right\rceil$ if $N_{\text{MAX}} = 3$
Resource reservation period (T_{R})[2] [ms]	0, 20, 50, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000	0, 1:99, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000
The maximum number of (re-)transmissions[3]	2	32
SL HARQ operation	Blind retransmission	Both blind retransmission and HARQ-feedback-based (re-)transmissions

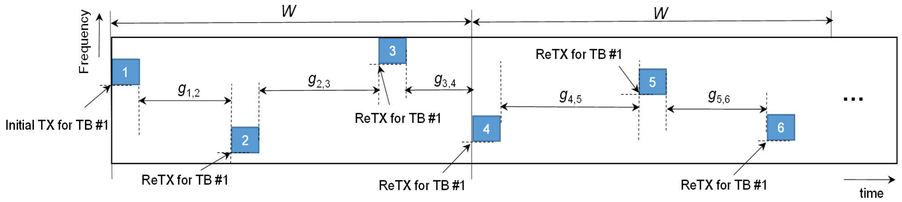
[1] NR V2X has larger W than LTE V2X to handle $N_{\text{MAX}} = 3$.

[2] For resource reservation period, $\leq$ 4 bits are used in SCI to indicate a period in NR V2X since an actual set of values is (pre-)configured. On the other hand, fixed 4 bits are used in SCI for LTE V2X.

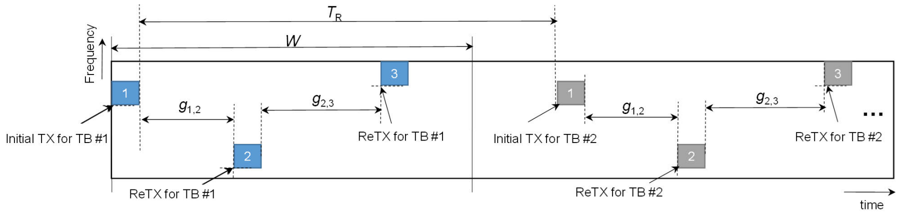
[3] In NR V2X, (pre-)configuration can limit the maximum number of HARQ (re-)transmissions of a TB.

procedure provided by the physical layer [35], [36]. A UE then allocates the selected resource(s) for SL transmission and this information is indicated by SCI not only for current transmission but also for future transmissions, hence resources are reserved for future transmissions. Here, the resource allocation information in the SCI for future transmission(s) is defined as reserved resource(s) by PSCCH. The reserved resource(s) by PSCCH can be initial and retransmission resource(s) for a different TB or retransmission resource(s) for the current TB corresponding to periodic and aperiodic resource allocation, respectively. There are multiple parameters impacting resource selection and reservation as shown in Table 4. These parameters are briefly explained in the following.

In a resource (re-)selection, the maximum number of resources that can be selected and indicated as reserved for a TB is defined as N_{MAX} where N_{MAX} is fixed to 2 in LTE V2X but it is (pre-)configurable from either 2 or 3 in NR V2X. For N_{MAX}, $N_{selected}(\leq N_{MAX})$ resource(s) can be selected and indicated in one SCI as reserved, including the current transmission. Notice that $N_{selected}$ resource(s) is selected randomly in the identified candidate resource set from the sensing procedure and if $N_{selected} > 1$, the resource selected earliest in time can be a resource used for initial transmission and the other becomes resource(s) for retransmission(s) in order. Additionally, for $N_{selected} > 1$, *a* time gap for $N_{selected}$ resources should be within a resource signaling window (W) as shown in Fig. 6 where $g_{a,b}$ represents the time gap between resource #*a* and resource #*b* selected adjacently. This time gap information is included in SCI and the time resource assignment bits in Table 4 are used for this indication. In frequency domain, each of $N_{selected}$ resources can have different position as shown in Fig. 6 but each resource has the same size (i.e., the same number of sub-channels, $N_{subChannel}$) in order to reduce SCI signaling overhead. Therefore, the frequency resource assignment bits in Table 4 are used for indicating frequency position.



(a) Periodic resource reservation



(b) Aperiodic resource reservation

FIGURE 6. Periodic and aperiodic resource reservation methods in LTE and NR V2X.

In addition, a UE can reserve resources periodically for $N_{selected}$ resource(s). This is enabled by the resource reservation period in Table 4 which is included in SCI. The resource reservation period is denoted as T_R in Fig. 6 and depending on T_R value, resource reservation can be further categorized; 1) periodic resource reservation ($T_R > 0$) and 2) aperiodic resource reservation ($T_R = 0$).

- For periodic resource reservation in Fig. 6(a), $N_{selected}$ resources for a TB can be reserved for different TB(s) in every T_R until a counter for resource reselection is reduced to 0 and the same time and frequency resource assignment is applied for $N_{selected}$ resources at the subsequent reservation period T_R. Periodic resource selection can avoid to perform the resource (re-)selection procedure frequently especially when the TX-UE generate periodic messages.
- For aperiodic resource reservation in Fig. 6(b), if a TX-UE transmits a TB K times and $K = N_{selected}$, retransmission resources for a TB can be reserved by one resource selection procedure. However, if a TX-UE transmits a TB K times but $K > N_{selected}$, the TX-UE needs to perform the resource selection procedure multiple times for SL transmission for the same TB as shown in Fig. 6(b). In NR V2X, to increase the performance of HARQ retransmission, the TX-UE shall select multiple resources so that HARQ retransmission resources can be reserved by a PSCCH in previous transmission of the same TB, except when no resource can be found for reservation or resource is dropped by prioritization, pre-emption, and congestion control.

Lastly, for the retransmission(s) of a TB, a TX-UE in LTE V2X can transmit a TB up to 2 times without receiving HARQ feedback from a RX-UE. This operation is called as a blind retransmission. NR V2X supports both blind retransmission and HARQ feedback-based retransmission with a maximum number of (re-)transmissions of up to 32 as shown in Table 4. In NR V2X, the TX-UE can release unused reserved resource(s) when the TX-UE receives HARQ feedback as 'ACK' from a RX-UE. For the blind retransmission, the time gap $g_{a,b}$ in Fig. 6 can be one slot/sub-frame and there is no restriction for the minimum value of $g_{a,b}$. On the other hand, for the HARQ feedback-based retransmission, a minimum value for $g_{a,b}$ should be guaranteed when the TX-UE selects resources to allow for sufficient time to receive the HARQ-ACK feedback and prepare the re-transmission if needed.

C. RE-EVALUATION AND PRE-EMPTION PROCEDURES IN NR V2X

In addition to sensing and resource selection procedures, Rel-16 NR V2X introduces two new procedures namely re-evaluation check and pre-emption check [36], [38]. Re-evaluation check is a procedure in which a UE keeps checking the availability of pre-selected SL resources before SL transmission actually happens on first selected resource, subject to processing time. The re-evaluation checking is performed according to sensing including SCI decoding and SL-RSRP measurement, in which the UE determines whether to drop pre-selected resource(s) that are also reserved by other UEs based on priority and SL-RSRP threshold following a similar principle as that used in the sensing procedure for resource (re-)selection. If the pre-selected resource(s) is dropped, the UE triggers new resource selection procedure to re-select new SL resources for a subsequent transmission. Re-evaluation is mandated to be performed and the sensing UE has to perform the re-evaluation check for the resource(s) selected in the resource selection procedure at least once. The pre-emption check is a procedure in which a UE checks the availability of SL resources which has already been reserved by an SCI. The timeline and principle of resource dropping in pre-emption check procedure is similar to that of re-evaluation check procedure, but this function can be

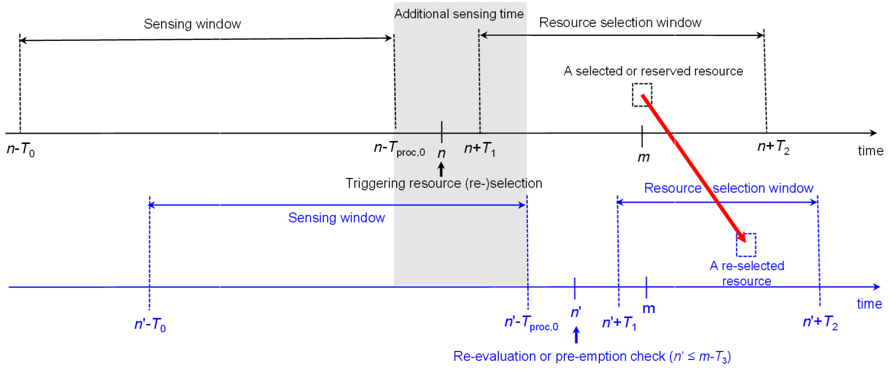


FIGURE 7. Re-evaluation and pre-emption by additional sensing time.

enabled or disabled by resource pool (pre-)configuration [40] and thus the pre-emption check is performed at least once only when it is enabled. While the re-evaluation check cannot be applied to the resources that have been indicated by TX-UE's SCI in current or previous resource reservation period, the pre-emption check can be applied to any reserved resource indicated by TX-UE's SCI.

As shown in Fig. 7, the same time line is applied for a TX UE to perform both re-evaluation and pre-emption checks. In Fig. 7, it is assumed that a TX-UE starts its resource (re-)selection mechanism in time instant n and the UE selects or reserves a resource in a moment m. Then the re-evaluation check or pre-emption check can be started at the time instance n' where $n < n' \leq m - T_3$ and $T_3 = T_{proc,1}$ is a processing time for resource re-selection (please see Table 3 for $T_{proc,1}$). However, the re-evaluation check or pre-emption check after $m - T_3$ but before m is not precluded if it is allowed by UE implementation. So, as shown in Fig. 7, the UE can have the additional sensing time and the UE can check whether its intended transmission at slot m is still available or not until $n' - T_{proc,0}$ (please see Table 3 for $T_{proc,0}$). The re-evaluation or pre-emption (if it is enabled) check should be performed at least once.

Though the same time line is used for re-evaluation and pre-emption checks, resource re-selection conditions for two procedures are different. Specifically, resource re-selection by re-evaluation or pre-emption can be performed when the following condition is met. At first, if the pre-selected or reserved resource(s) in slot m is not included in the identified resource set from the sensing over window $[n' - T_0, n' - T_{proc,0})$ (sensing procedure as described in Section IV-A), it means that the pre-selected or reserved resource(s) in m is not available for transmission now. For re-evaluation, only this first condition is applied and pre-selected or periodically reserved resource(s) in slot m is re-selected. On the other hand, for pre-emption, two more conditions are additionally applied. The second condition is that the SL-RSRP measured for the reserved resource(s) is higher than a SL-RSRP threshold which corresponds into the final threshold after reaching the identified resource set. The third condition is that the priority for the reserved resource at slot m has lower priority than that of the overlapped resource by a different UE. If all three conditions are met, the reserved resource(s) in slot m is pre-empted and re-selected both for full and partial frequency domain overlap in the same slot. The pre-emption can enhance transmission probability for the high priority of UE. On the other hand, the low priority of UE may need to perform resource reselection frequently for the pre-empted resource(s) and this results in delay for SL transmission. In order to handle this problem, application of the pre-emption can be limited only for the case where a priority level is configured and the priority of other UEs is higher than the configured priority level.

D. POWER SAVING RESOURCE ALLOCATION SCHEMES

Rel-17 NR V2X introduced low-power resource allocation. Low-power resource allocation schemes include partial sensing and random resource selection. The partial sensing can have two parts of periodic-based partial sensing (PBPS) and contiguous partial sensing (CPS) [36], [40]. The PBPS is similar to Rel-14 LTE V2X partial sensing [35], [39]. If a SL transmission from a UE is periodic (i.e., $T_R \neq 0$ in Fig. 6(a)), NR V2X partial sensing can be based on PBPS, and/or CPS. If a SL transmission from a UE is aperiodic (i.e., $T_R = 0$ in Fig. 6(b)), NR V2X partial sensing can be based on CPS and PBPS, if the resource pool supports periodic reservations.

When a UE performs PBPS, the UE selects a set of Y slots ($Y \geq Y_{min}$) within a resource selection window corresponding to PBPS, where Y_{min} is provided by higher layers [39] and [40]. The UE monitors slots $t'^{SL}_{y-k\times P_{reserve}}$, where t'^{SL}_{y} is a slot of the Y selected candidate slots. The periodicity value for sensing for PBPS, i.e. $P_{reserve}$ (e.g., P_1 in Fig. 8) is a subset of the resource reservation periods allowed in a resource pool. $P_{reserve}$ is provided by higher layers [39], [40]. If not configured, $P_{reserve}$ includes all periodicities allowed in the resource pool. The UE monitors k sensing occasions not earlier than $n - T_0$ (please see Table 3 for T_0). For a given periodicity $P_{reserve}$, the values of k correspond to the most recent sensing occasion earlier than $t'^{SL}_{y0} - (T_{proc,0} + T_{proc,1})$ and, if configured, to the last periodic sensing occasion prior

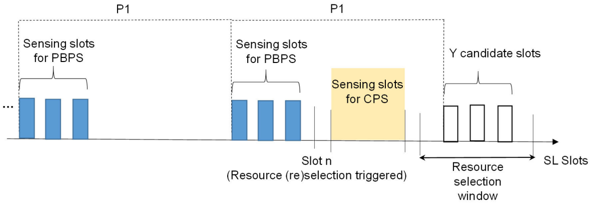


FIGURE 8. PBPS and CPS for low-power resource allocation.

to the most recent one. t'^{SL}_{y0} is the first slot of the selected Y candidate slots of PBPS (please see Table 3 for $T_{proc,0}$ and $T_{proc,1}$).

When a UE performs CPS, the UE selects a set of Y' slots ($Y' \geq Y'_{min}$) within a resource selection window corresponding to CPS, where Y'_{min} is provided by higher layers [40]. The sensing window for CPS starts at least M logical slots before t'^{SL}_{y0} (the first of the Y' candidate slots) and ends at $t'^{SL}_{y0} - (T_{proc,0} + T_{proc,1})$.

E. LATENCY AND RELIABILITY ENHANCEMENT

Rel-17 NR V2X introduced inter-UE co-ordination (IUC) to enhance the reliability and reduce the latency for resource allocation, where SL UEs exchange information with each other to aid Mode-B procedure [36], [38]. UE-A provides information to UE-B, and UE-B uses the provided information for its resource (re-)selection procedure. IUC addresses is designed to address issues with distributed resource allocation such as:

- Hidden node problem, where a UE-B is transmitting to a UE-A and UE-B can't sense or detect transmissions from a UE-C that interfere with its transmission to a UE-A.
- Exposed node problem, where a UE-B is transmitting to a UE-A, and UE-B senses or detects transmissions from a UE-C and avoids the resources used or reserved by UE-C, but UE-C doesn't cause interference at UE-A.
- Persistent collision problem.
- Half-duplex problem, where UE-B is transmitting to a UE-A in the same slot that UE-A is transmitting. UE-A will miss the transmission from UE-B as it can't receive and transmit in the same slot.

There are two schemes for IUC: Scheme 1 and Scheme 2. At first, in Scheme 1, a UE-A can provide to another UE-B indications of resources that are preferred to be included in UE-B's (re-)selected resources, or non-preferred resources to be excluded from UE-B's (re-)selected resources. When given preferred resources, UE-B may use only those resources for its resource (re-)selection, or it may combine them with resources identified by its own sensing procedure, by finding the intersection of the two sets of resources, for its resource (re-)selection. When given non-preferred resources, UE-B may exclude these resources from resources identified by its own sensing procedure for its resource (re-)selection. Transmissions of co-ordination information (e.g., IUC messages) sent by UE-A to UE-B, and co-ordination information requests (e.g., IUC requests) sent by UE-B to UE-A, are sent in a MAC-CE message [38] and may also, if supported by the UE, be sent in a 2nd SCI (SCI Format 2-C) [34]. The benefit of using the 2nd SCI is to reduce latency. IUC messages from UE-A to UE-B can be sent standalone, or can be combined with other SL data. IUC messages can be in response to a request from UE-B, or due to a condition at UE-A. An IUC request is unicast from UE-B to UE-A, in response UE-A sends an IUC message in unicast mode to UE-B. An IUC message transmitted as a result of an internal condition at UE-A can be unicast, groupcast or broadcast to UE-B. However, only non-preferred resource can be transmitted as IUC message in groupcast and broadcast. UE-A can determine preferred or non-preferred resources for UE-B based on its own sensing taking into account the SL-RSRP measurement of the sensed data and the priority of the sensed data, i.e., the priority field of the decoded PSCCH during sensing as well as the priority the traffic transmitted by UE-B in case of request-based IUC or a configured priority in case of condition-based IUC. Non-preferred resource to UE-B can also be determined to avoid the half-duplex problem, where, UE-A can't receive data from a UE-B in the same slot UE-A is transmitting.

On the other hand, in Scheme 2, a UE-A can provide to another UE-B an indication that resources reserved for UE-B's transmission, whether or not UE-A is the destination UE, are subject to conflict with a transmission from another UE. UE-A determines the conflicting resources based on the priority and SL-RSRP of the transmissions involved in the conflict. UE-A can also determine a presence of a conflict due to the half-duplex problem, where UE-A can't receive a reserved resource from UE-B at the same time UE-A is transmitting. When UE-B receives a conflict indication for a reserved resource, it can re-select new resources to replace them. The conflict information from UE-A to UE-B is sent in a PSFCH channel that is separately configured from the PSFCH of the HARQ-ACK information. The timing of the PSFCH channel carrying conflict information can be based on the SCI indicating reserved resource, or based on the reserved resource.

V. EVALUATION RESULTS

This section provides system level simulation results to compare the performance of Mode-B resource allocation in LTE V2X and NR V2X based on evaluation parameters and methodology in [43].

A. LATENCY AND RELIABILITY ENHANCEMENT

We evaluate the performance in Fig. 9 and Fig. 11 with simulation programing in C++. Average packet reception ratio (PRR) is used as the performance metric which is defined as $(\sum_{n=1}^{N} X_n)/(\sum_{n=1}^{N} Y_n)$ where N is total number of generated messages in simulation, Y_n is the number of UEs located between the range of a and b from the TX where $a = i \cdot 20$ meters and $b = (i + 1) \cdot 20$ meters for $i = 0, 1, \ldots, 25$, and X_n is the number of UEs receiving

TABLE 5. Traffic models [43].

Parameters	Periodic traffic model	Aperiodic traffic model
Inter-packet arrival time	100 ms	50 ms + an exponential distribution with the mean of 50 ms
Packet size	1200 bytes with probability of 0.2 and 800 bytes with probability of 0.8	Uniform distribution in the range between 200 bytes and 2000 bytes with the quantization step of 200 bytes

TABLE 6. Simulation parameters.

Parameters	Values
UE dropping	Highway Option A[1][43]
UE speed	140 km/h
Carrier frequency	6 GHz
Bandwidth	20 MHz
Subcarrier spacing	15 kHz
One TTI	1 ms (14 symbols)
The number of antennas	1-TX and 2-RX antennas
The number of data symbols	10 symbols[2]

[1] UEs are passenger vehicles with higher antenna position (length 5 m, width 2.0 m, height 1.6 m, antenna height 1.6 m) where vehicles are dropped in the same lane with an exponential distribution with the average of the 2·speed sec (max 2 m inter-vehicle distance).

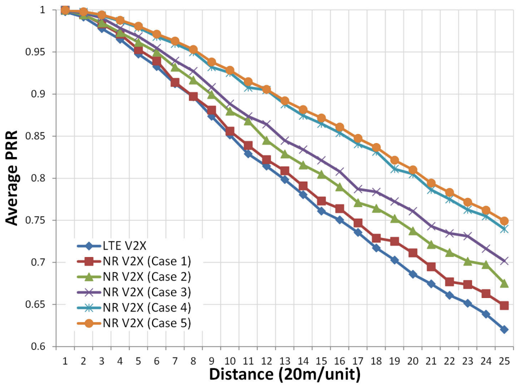
[2] Other 4 symbols in a slot are assumed for PSSCH DMRS and PSCCH transmission.

SL data successfully among Y_n. Both periodic and aperiodic traffic models are evaluated as shown in Table 5. The lowest modulation and coding scheme (MCS) is selected for UE to transmit the packet in one TTI (1 ms) without packet segmentation. Other simulation parameters and assumptions are provided in Table 6.

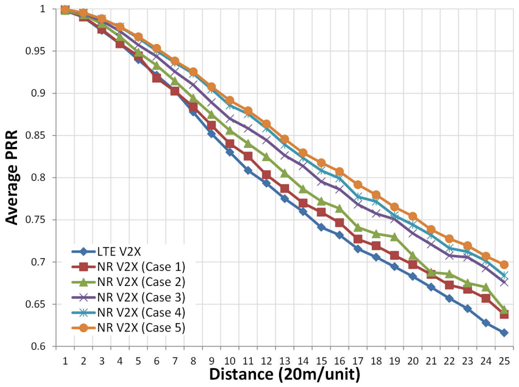
Since new procedures such as resource re-evaluation and pre-emption checks, and with inter-UE co-ordination (IUC) messages are newly introduced in NR V2X as mentioned in Section IV, the following five cases are considered for NR V2X:

- Case 1: Re-evaluation check is performed once i.e., only in slot $m - T_3$ without pre-emption
- Case 2: Both re-evaluation and pre-emption checks are performed once i.e., only in slot $m - T_3$
- Case 3: Re-evaluation check is performed in every slot until $m - T_3$ without pre-emption
- Case 4: Both re-evaluation and pre-emption checks are performed in every slot until $m - T_3$
- Case 5: IUC scheme 1 is applied with Case 4.

where T_3 is a resource reselection processing time as explained in Fig. 7. Notice that the re-evaluation or pre-emption (if it is enabled) check should be performed at least once but more frequent checking can be performed based on UE implementation. For Case 5, UE-A performs the Mode-B procedure for UE-B with Case 4. Then, the selected preferred resource(s) from UE-A is provided into UE-B as the IUC message without delay and UE-B uses this resource(s) for its transmission. Further details on IUC scheme 1 was explained in Section IV-E.



(a) Periodic traffic



(b) Aperiodic traffic

FIGURE 9. The PRR performance of Mode-B resource allocation in LTE and NR V2X.

Fig. 9 (a) compares PRR performance of LTE and NR Mode-B resource allocation mechanisms assuming that periodic traffic model and periodic resource reservation with 100 ms of resource reservation period. Fig. 9(b) provides PRR performance of LTE and NR Mode-B resource allocation mechanisms assuming aperiodic traffic model and aperiodic resource reservation. The following are observed from Fig. 9(a) and Fig. 9(b) in common: Firstly, NR provides better PRR performance than LTE which is contributed by re-evaluation or pre-emption or IUC. It is observed that NR can provide up to 20% of PRR performance gain over LTE. Secondly, Case 2 or Case 4 performing both re-evaluation and pre-emption checks provides better PRR performance than Case 1 or Case 3 performing re-evaluation only without pre-emption, respectively. Thirdly, in the cases of having re-evaluation check only without pre-emption (Case 1 and Case 3), performing re-evaluation check in every slot (Case 3) has better PRR performance as compared to performing re-evaluation check once (Case 1). Having multiple checks can appropriately reflect the case where the validity of previously selected or reserved resource(s) has been changed (i.e., previously selected or reserved resource(s) can be unsuitable anymore). Lastly, IUC (Case 5) can provide additional PRR performance gain over re-evaluation and pre-emption check in every slot (Case 4) by addressing hidden-node, exposed-node, and half duplex problems.

On the other hand, it is found that PRR performance of LTE V2X and NR V2X shown in Fig. 9(b) is decreased over Fig. 9(a) in general. This can be explained by the fact that total number of resources within the resource selection window applied for Fig. 9(b) is less than that applied for Fig. 9(a) and the opportunity to select a clean resource in Fig. 9(b) is reduced as compared to Fig. 9(a). This is because in Fig. 9(a), the value of T_2 for resource selection window is set to 100 ms (please see Table 3 in Section IV for T_2) to guarantee the latency requirements of the periodic traffic but in Fig. 9(b), T_2 is set to 50 ms to guarantee the latency requirement of the aperiodic traffic. Since aperiodic resource reservation is assumed in Fig. 9(b), pre-emption can be applied only for the case where retransmission resource(s) are reserved by an initial transmission. So, using pre-emption does not provide much gain, i.e., performance gain between Case 1 and Case 2 in Fig. 9(b) is smaller than that in Fig. 9(a), and also performance gap between Case 3 and Case 4 in Fig. 9(b) is smaller than that in Fig. 9(a).

B. REDUCED POWER CONSUMPTION

The benefit of partial sensing is to reduce power consumption, albeit at the expense of less accurate sensing results which in turn could lead to higher collisions. In this section, we consider the tradeoff between power saving and PRR performance of partial sensing. Partial sensing has several degrees of freedom, 1) the number of contiguous slots M sensed for CPS, 2) the number of periodicities sensed P (this is the same as $P_{reserved}$ value in Section IV-D for PBPS), and 3) the number of periodic occasions sensed for each periodicity (N). In this section, we consider the impact of these parameters on the power saving of partial sensing and the corresponding impact on PRR performance. We use the energy consumption model based on [23] and [44]. For power consumption analysis, we consider a probabilistic model to determine the number of slots used for each of the slot types shown in Table 7 where the energy consumption used for each slot type is shown. For resource selection in slot n, the UE performs full sensing or partial sensing, as illustrated in Fig.5 and Fig.8 respectively. Additionally, the UE performs sensing for re-evaluation check and pre-emption check as described in Fig.7. For each packet, sensing continues until, the UE receives a positive acknowledgment from the receiving UE, the maximum number of re-transmissions is reached or the packet delay budget is reached. The model used assumes a 30 kHz sub-carrier spacing. The packets arrive periodically once every 1 second, i.e., 2000 slots. We evaluate the performance with simulation programming in MATLAB. In the evaluation, we determine number of slots used for 1) sensing, these are considered as receive slots, and 2) the number of slots used for transmission, 3) the rest of the slots are idle slots. This is determined based on the number of transmission/re-transmissions for a packet, candidate slots selected and sensing type and parameters. For full sensing, the sensing window starts 1000 slots before slot n and continues until one of the aforementioned conditions is satisfied. Based on this modeling, the average power consumption is 0.52 units for full sensing. On the other hand, Fig.10 illustrates the average power consumption of partial sensing considering the impact of P, N and M. For $M = 0$, depending on P and N values, 84∼95% power saving can be achieved over full sensing (0.52 units).

TABLE 7. Power consumption model [23], [44].

Slot type	Power
Idle slots[1]	0.01 unit per slot
Transmission slots	4 unit per slot[2]
Reception slots[3]	1 unit per slot

[1] No transmission or reception. In this case, a user is in deep sleep.

[2] The power is linearly scaled with transmit power between 1 unit for 0 dBm and 20 unit for 31 dBm by assuming transmit power of 23 dBm.

[2] These are the slots used for sensing.

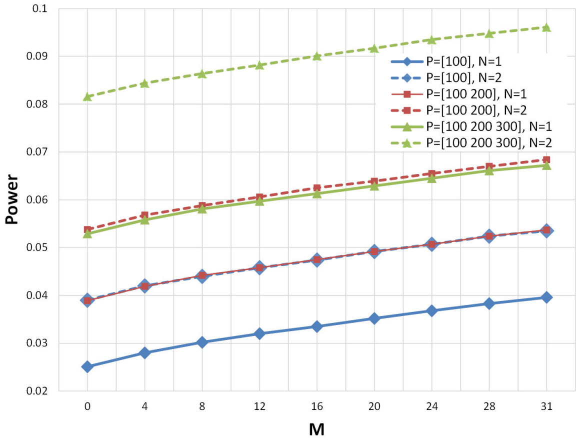


FIGURE 10. Power consumption of partial sensing. As a reference, full sensing has an average power consumption of 0.52 units. *M* is the number of contiguously sensed slots. *N* is the number of sensing occasions sensed per periodicity. *P* are the periodicities sensed.

Next, we consider the impact of partial sensing on PRR performance to observe the tradeoff between power saving and performance degradation as illustrated in Fig.10 and Fig.11. In Fig.11, a periodic traffic model is evaluated as shown in Table 5 with additional inter-packet arrival times being considered at 200 ms and 300 ms. Therefore, {100, 200, 300} ms traffics are generated with uniform distribution. Other simulation parameters and assumptions are provided in Table 6. In Fig.11, $M = 0$ is assumed and the impact for P and N values is observed. Fig.11 shows that reduced sensing occasions from partial sensing results in PRR performance degradation over full sensing. Specifically, at the distance of 300 m, 6∼33% performance degradation is shown over full sensing.

VI. LIMITATIONS AND FUTURE DIRECTION OF THE STUDY

This section presents the limitation of current resource allocation schemes and discusses open issues that should be investigated further as future works.

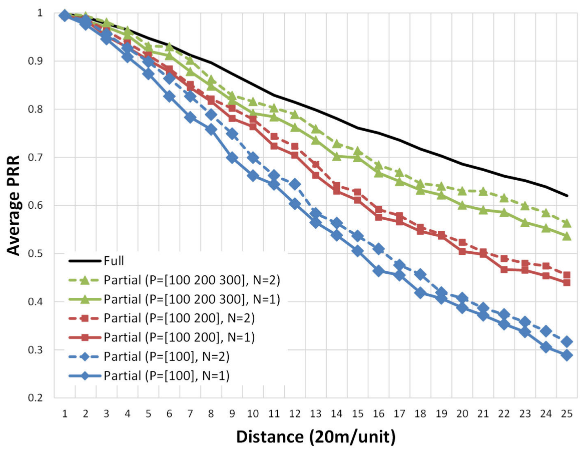


FIGURE 11. **The PRR performance of Mode-B partial sensing over full sensing.**

Firstly, one limitation of the current Mode-A is that BS cannot fully recognize SL conditions which means SL UE's status and SL channel between UEs communicates each other. As we explained in Section III-E, SL HARQ-ACK reporting from TX-UE to BS can be used by BS to understand SL channel indirectly. However, a more effective resource allocation would be possible as the BS knows more about SL conditions. For this reason, we note that more direct SL conditions such as channel and interference status should be reported to BS and this can be considered as one important enhancement. Also, UE's high mobility results in the rapid change of the topology and this is another challenge for Mode-A. In this regard, other information such as UE's position and mobility can be reported to BS to fully recognize SL conditions.

Secondly, even though Mode-B resource allocation has been evolved to overcome collision and half-duplex problems such as re-evaluation, pre-emption (See Section IV-C), and IUC schemes (See Section IV-E), the collision and half-duplex problems cannot be fully resolved. This is because there is no centralized controller in Mode-B to handle unpredictable data transmissions, e.g. due to resource re-selection, new aperiodic data transmission and variable UE topology under high mobility scenarios. In current Mode-B, a UE selects the resource in a distributed manner. Therefore, if a master UE is introduced and it can guarantee orthogonal resource allocation to member UEs belonging to the master UE, reliability of Mode-B can be improved assuming that the master UE can obtain SL conditions of the member UEs as much as possible. Then, it needs to be further investigated how the master UE is selected and how the master UE obtains other UEs' information with reasonable signalling overhead.

Lastly, wireless communication systems operating on shared spectrum (i.e., unlicensed spectrum) should comply-with regulation requirements. With this regards, Rel-18 V2X to support SL operation on unlicensed spectrum should take into account such requirements and SL resource allocation needs to reflect it. For example, listen before talk (LBT) has been used for sharing the unlicensed spectrum between different communication systems and it can be referred to as short-term sensing because it is performed within a short-term period. On the other hand, Mode-B is a long-term sensing performed by SCI decoding and SL-RSRP measurement (See Section IV-A). Therefore, it needs to study how to support LBT-based channel access on the top of existing Mode-B mechanisms for SL operation in unlicensed spectrum [45].

VII. CONCLUSION

In this paper, we present the V2X evolution from 4G to 5G in 3GPP by focusing on resource allocation aspect in LTE and NR. We provide fundamentals on resource allocation framework and present a detailed review on UE-based resource allocation which consists of sensing and resource (re-)selection procedure. It was specified in Rel-14 LTE V2X at first and was evolved in Rel-16 NR V2X by re-evaluation and pre-emption mechanism. In addition, inter-UE co-ordination (IUC) and partial sensing schemes were introduced in Rel-17 NR V2X. The evaluation results show that NR V2X resource reselection mechanism can provide up to 20% of reliability improvement over LTE V2X and NR V2X partial sensing scheme can provide up to 95% of reduced power consumption over full sensing scheme. The performance evaluations in this paper can provide insights to understand how V2X has been evolved in 3GPP. 3GPP is continuing their work to enhance V2X in future release. Rel-18 NR V2X focuses on SL operation in unlicensed spectrum.

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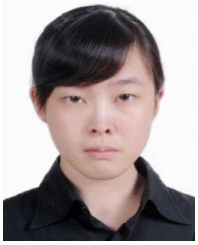
CHEOLKYU SHIN received the B.S. degree from Inha University, Incheon, South Korea, in 2007, and the M.S. and Ph.D. degrees from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, in 2009 and 2013, respectively. Since September 2013, he has been with Samsung Electronics and has been involved in 3GPP RAN1 LTE and NR technology developments standardizations. His research interests include MIMO, V2X, positioning, and the general area of communication theory and statistical signal processing.

EMAD FARAG received the B.S. and M.S. degrees in electrical engineering from Ain Shams University, Cairo, Egypt, in 1990 and 1994, respectively, and the Ph.D. degree in electrical engineering from the University of Waterloo, Waterloo, ON, Canada, in 1997. Since November 2019, he has been with Samsung Research America, working on 5G NR standardization. His current research interests include SL communication, positioning, and MIMO.

HYUNSEOK RYU received the B.S., M.S., and Ph.D. degrees from the Department of Information and Communication Electrical Engineering, Korea University, Seoul, South Korea, in 1999, 2006, and 2011, respectively. In 2011, he was a Research Fellow at BK21 Information Technology, Korea University. Since June 2012, he has been with Samsung Electronics, South Korea. His current research interests include physical layer design for V2X, UAV, NTN, and 5G-Advanced systems focused on 3GPP RAN1 standardization.



MIAO ZHOU received the B.S. degree in electronic engineering from Tsinghua University, in 2011, and the M.S. degree in communication engineering from the University of Bristol, in 2013. Since November 2017, she has been with Samsung Research and Development Institute China-Beijing, China, working for 4G LTE Advanced Pro and 5G NR standardization in 3GPP.

YOUNSUN KIM (Senior Member, IEEE) received the B.S. and M.S. degrees in electronic engineering from Yonsei University, in 1996 and 1999, respectively, and the Ph.D. degree in electrical engineering from the University of Washington, in 2009. He is currently a Master (VP of Technology) with Samsung Electronics and a member of the Standards Research Team, where he has been continues his contributions to the physical layer design of wireless communication systems, since joining the company, in 1999. He was a Vice Chairperson of 3GPP RAN1 (physical layer), from 2017 to 2021, where he has been serving as the Chairperson, since 2021.

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