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3GPP NR Sidelink Transmissions Toward 5G V2X

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ABSTRACT Featuring direct communications between two user equipments (UEs) without signal relay through a base station, 3GPP sidelink transmissions have manifested their crucial roles in the Long-Term Evolution (LTE) Advanced (LTE-A) for public safety and vehicle-to-everything (V2X) services. With this successful development in LTE-A, the evolution of sidelink transmissions continues in 3GPP New Radio (NR), which renders sidelink an inevitable component as well as downlink and uplink. Targeting at offering low latency, high reliability and high throughout V2X services for advanced driving use cases, a number of new sidelink functions not provided in the LTE-A are supported in NR, including the feedback channel, grant-free access, enhanced channel sensing procedure, and new control channel design. To fully comprehend these new functions, this paper therefore provides essential knowledge of 3GPP NR sidelink transmissions, including the physical layer structure, resource allocation mechanisms, resource sensing and selection procedures, synchronization, and quality-of-service (QoS) management. Furthermore, this paper also provides performance evaluation to assess the gains brought from the new control channel design. As NR sidelink transmissions have been regarded as a foundation to provide advanced services other than V2X in future releases (e.g., advanced relay), potential enhancements are also discussed to serve the urgent demand in corresponding normative works.

INDEX TERMS 3GPP NR, sidelink, V2X, fifth generation (5G) networks, device-to-device (D2D).

I. INTRODUCTION

The frameworks of downlink (i.e., signals are forwarded from a base station to a UE) and uplink transmissions (i.e., signals are forwarded from a UE to a base station) have been widely deployed in major mobile networks such as Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), LTE, and LTE-A to sustain commercial mobile voice/data services. Under these frameworks, base stations are inevitable, because all the physical signals transmitted from/to UEs should be relayed by base stations. However, in 2012, the Federal Communications Commission (FCC) of the United States endorsed 3GPP Release 12 as the next generation nationwide public safety network [1]–[3], which should support at least the push-to-talk (PTT) [4], [5] voice service and group communications when eNBs (base stations in LTE-A) are paralyzed by natural disasters or malicious attacks. This demand consequently drove the normative works of 3GPP sidelink transmissions in Release 12 to support direct transmissions between two UEs without signal relay through eNBs, which are also known as the device-to-device (D2D) proximity service (ProSe) [6].

Focusing on public safety, Release 12 sidelink transmissions include three particular designs [7]. Firstly, since the baseline service for public safety (i.e., PTT) relies on broadcasting transmissions, there is no feedback channel for a receiving UE to provide feedback information (e.g., the decoding status and channel state information) to a transmitting UE. In this case, the feedback-based packet retransmissions of link adaptation and the hybrid automatic repeat request (HARQ) are not allowed in Release 12 sidelink

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transmissions. Secondly, to achieve all UEs following the same timing reference (i.e., synchronization), a UE may transmit synchronization signals, even though this UE is not involved in sidelink transmissions. On the contrary, a UE may not transmit synchronization signals, even though this UE is involved in sidelink transmissions. In other words, timing synchronization and sidelink transmissions are decoupled procedures in such a decentralized manner. Thirdly, to perform downlink/uplink transmissions, a UE should identify the network, and/or the network should page a UE, which suggest that UE/network discovery is necessary in downlink/uplink transmissions. However, discovery and sidelink communications are two independent procedures in Release 12. In other words, a UE may launch sidelink transmissions regardless of the presence of a receiving UE(s). On the other hand, the purpose of performing UE discovery is not solely for sidelink transmissions. These three designs thus make the procedures of sidelink transmissions very different from that in downlink/uplink transmissions.

Although sidelink transmissions in Release 12 enable UEs that cannot be served by eNBs (known as out-of-coverage UEs) to directly exchange messages, it is still highly desired to access the network if eNBs are available. In this case, it is feasible to extend the service range of an eNB with the facilitation of UEs that can be served by an eNB (known as in-coverage UE). To this end, sidelink transmissions in Release 13 support *UE-to-Network relay*, in which an in-coverage UE is able to relay signals between an eNB and an out-of-coverage UE. To avoid significant impacts on the operations of Release 12 sidelink transmissions which have been deployed, a lot of countries that deploy Release 12 as their public safety networks also decide to keep the interface of sidelink transmissions unchanged. Under this constraint, Release 13 sidelink transmissions reuse all the Layer 1 and Layer 2 functions of Release 12. However, only Layer 1 and Layer 2 functions are insufficient to support the UE-to-network relay, and additional procedures on the top of Layer 1 and Layer 2 (i.e., Layer 3) are required. As a result, the UE-to-network relay in Release 13 is a Layer 3 based relay [8], [9].

In Release 14, the scenario of sidelink transmissions is extended from D2D ProSe solely for public safety to V2X [10]–[13], in which the major services include the cooperative awareness message (CAM) and the decentralized environmental notification message (DENM) exchanges among vehicles [14], [15], pedestrians, and infrastructures (i.e., eNBs or road-side units, RSUs). Observing the fact that these services also rely on broadcasting transmissions, most functions of sidelink transmissions in Release 12 can also be adopted in Release 14. Nevertheless, consider that the CAM and the DENM require low-latency transmissions, and the connection density in V2X is also higher than that in public safety. Hence, some functions in Release 12 sidelink transmissions should be redesigned, such as the multiplexing scheme for radio resources of the physical sidelink control channel (PSCCH) and physical sidelink shared channel (PSSCH). In addition, the capability of channel sensing (not supported in Releases 12 and 13) is introduced to Release 14 sidelink transmissions to avoid resource collisions among UEs [16], [17]. In Release 15, the 3GPP continues the evolution of Release 14 sidelink transmissions, and new functions such as carrier aggregation (CA), transmission diversity, and 64 quadrature amplitude modulation (QAM) are adopted to further enhance the throughput and reduce the latency [18].

In Releases 12 to 15, sidelink transmissions are designed based on the air interface of LTE-A, which however may not fulfill the service requirements imposed by the International Mobile Telecommunications-2020 (IMT-2020). To migrate to the fifth generation (5G) network, 3GPP subsequently launched the standardization progress of NR sidelink transmissions in Release 16 in Jun. 2018 [19]. Although the major scenario of Release 16 NR sidelink transmissions also targets at V2X, the services are no longer limited to the CAM and the DENM. Instead, sustaining the next generation driving use cases (including advanced driving, vehicle platooning, extended sensors, and remote driving) are the major goals [20]–[22]. These use cases demand low-latency, high-reliability and high-throughput transmissions, as well as a high connection density. To fulfill these new requirements, four new designs are particularly introduced to NR sidelink transmissions as follows: 1) Not only broadcast but also unicast and groupcast are supported in sidelink transmissions. For unicast and groupcast, the physical sidelink feedback channel (PSFCH) is newly introduced for a receiving UE to reply decoding status to a transmitting UE [23]. 2) To improve the latency performance, grant-free transmissions that are adopted in NR uplink transmissions are also provided in NR sidelink transmissions. 3) To alleviate resource collisions among different sidelink transmissions launched by different UEs, it enhances channel sensing and resource selection procedures, which also lead to a new design of PSCCH. 4) To achieve a high connection density, congestion control and thus the QoS management is supported in NR sidelink transmissions.

Despite above mentioned differences between the LTE-A sidelink and NR sidelink transmissions, NR sidelink transmissions also inherit a part of design spirits/concepts from the LTE-A sidelink, which renders NR sidelink a sophisticated interface. To fully understand this new feature in 3GPP NR, this paper therefore presents comprehensive knowledge on the operations of NR sidelink transmissions. The contributions of this paper include the followings:

- Since Release 16 sidelink transmissions are based on NR, an introduction to the physical layer structure of NR is provided. This paper then elaborates how such a physical layer structure is extended to sidelink transmissions, including numerology, waveform, frame structure, and all physical channels and reference signals.
- Detailed operations and procedures of NR sidelink transmissions are presented, including Mode 1 and Mode 2 resource allocations, feedback transmissions, synchronization, and QoS management.

- Since NR sidelink transmissions adopt an unprecedented PSCCH design (also known as two-stage sidelink control information, SCI) not provided in the LTE-A, the characteristics of such a new design are not clear. This paper therefore conducts simulation studies to evaluate the effectiveness of the two-stage SCI, and discusses practical constraints in the deployment of this new design.
- Although Release 16 sidelink transmissions solely focus on V2X, the 3GPP is planning the further enhancements to extend the sidelink scenarios to interactive games, enhanced public safety [24], enhanced V2X, advanced relay, etc. This paper therefore discusses potential issues in Release 16, and future enhancements of NR sidelink transmissions in subsequent releases.

The rest of this paper is organized as follows. In Sections II and III, the physical layer structure of NR sidelink transmissions and multiplexing of PSCCH, PSSCH and PSFCH are presented, respectively. In Sections IV and V, Mode 1 and Mode 2 resource allocations are provided, respectively, followed by power control and QoS management in Section VI. After elaborating the synchronization procedures in Section VII and performance evaluation of the two-stage SCI design in Section VIII, future enhancements of NR sidelink transmissions are discussed in Section IX, and this paper is concluded in Section X.

II. PHYSICAL LAYER STRUCTURE OF NR SIDELINK TRANSMISSIONS

A. NUMEROLOGY

To achieve the peak data rate of 20 Gbps as required by the IMT-2020, a large bandwidth may be needed. However, due to the existing bandwidth allocation policies in different countries, it has been a worldwide challenge to identify available bands with sufficient bandwidth on the spectra below 7 GHz (also known as the frequency range 1, FR1). With this concern, NR is designed to be able to be deployed on different carrier frequencies, including the FR1 and the spectra above 7 GHz (also known as the frequency range 2, FR2). As a result, signal propagation on different carrier frequencies may suffer from different levels of multi-path fading (and thus different levels of frequency selective fading). To facilitate equalization performed at the receiver side, it is desired to deploy orthogonal frequency division multiplexing (OFDM) subcarriers with a smaller subcarrier spacing (SCS) to the spectra of a lower carrier frequency, while deploying subcarriers with a larger SCS to the spectra of a higher carrier frequency. To this end, different SCS values are supported by NR [19].

On the other hand, different SCS values can be associated with different cyclic prefix (CP) lengths to combat with different levels of inter-symbol interference (ISI) caused by multipath fading. Based on different CP-length-to-symbol-duration ratios, NR has two types of CP: normal CP (NCP) and expended CP (ECP). To generally describe different pairs of SCS values and CP types, a terminology known as *numerology* is adopted in NR. NR sidelink transmissions support the following numerologies:

- For the FR1, the 15 kHz, 30 kHz, and 60 kHz SCSs with the NCP are supported, while the ECP can only be applied to the 60 kHz SCS.
- For the FR2, the 60 kHz and 120 kHz SCSs with the NCP are supported, while the ECP can only be applied to the 60 kHz SCS.

B. WAVEFORM

In LTE-A, the waveforms applied to downlink, uplink, and sidelink are CP-OFDM, discrete-time Fourier transfer spread OFDM (DFT-s-OFDM), and DFT-s-OFDM, respectively. In NR, CP-OFDM is applied to downlink, while both CP-OFDM and DFT-s-OFDM are available for uplink. For sidelink transmissions, only CP-OFDM is supported.

C. RESOURCE STRUCTURE IN THE TIME DOMAIN

In NR, resources in the time domain are formed by the following components:

- **Frame**: The length of a frame is fixed to 10 ms, which is composed of 10 subframes.
- **Subframe**: The length of a subframe is fixed to 1 ms.
- **Slot**: A slot is composed of 14 OFDM symbols in the case of NCP and is composed of 12 OFDM symbols in the case of ECP. Therefore, the length of a slot depends on the adopted SCS value. For the 15 kHz SCS, the length of a slot is 1 ms, which is exactly the length of a subframe. For 30 kHz, 60 kHz, and 120 kHz SCSs, the lengths of a slot are 0.5 ms, 0.25 ms, and 0.125 ms, respectively.
- **Mini-slot**: To further shorten the latency in uplink and downlink transmissions, mini-slots are further supported by NR. A mini-slot is composed of 2, 4, or 7 OFDM symbols, depending on practical configuration.

For NR sidelink transmissions, mini-slots are not supported, and therefore the minimum unit for the resource scheduling in the time domain is a slot. However, the partial slot transmission for sidelink is supported in case that only some of the symbols in a slot are available for sidelink transmissions and the remaining symbols are reserved or used for the Uu transmissions for the shared band operation.

D. RESOURCE STRUCTURE IN THE FREQUENCY DOMAIN

In NR, resources in the frequency domain are formed by the following components:

- **Resource element (RE)**: An RE is composed of a subcarrier over an OFDM symbol.
- **Resource block (RB)**: An RB is composed of 12 consecutive subcarriers with the same SCS, and thus the bandwidth of an RB depends on the SCS value of subcarriers.
- **Resource grid**: A resource grid is composed of a number of RBs with the same SCS.

- **Bandwidth part (BWP)**: In NR, the bandwidth of a carrier may be up to 400 MHz, which is composed of 275 RBs. However, in most mobile services, a UE may not fully utilize these 275 RBs, and only a part of RBs may be used to confine UE radio frequency (RF) operation bandwidth for power saving. To cope with this situation, a BWP is composed of a set of consecutive RBs within the carrier. For a UE, at most four BWPs can be configured over a carrier, and at most one BWP can be activated at any time instant.

The concept of the BWP also leads to two types of RBs: common RB (CRB) and physical RB (PRB). For a carrier composed of a number of RBs with the same numerology, these RBs are indexed increasingly from the lowest frequency of this carrier. In general, these RBs are called CRBs. However, RBs that are included in a BWP are called as PRBs, and the indices of these RBs are reset and re-indexed increasingly.

For NR sidelink transmissions, at most one sidelink BWP can be configured on a carrier, and the minimum unit for resource scheduling in the frequency domain is a **subchannel**, which is composed of 10, 15, 20, 25, 50, 75, or 100 consecutive RBs depending on practical configuration.

E. PHYSICAL CHANNELS AND REFERENCE SIGNALS

The NR sidelink provides the following physical channels and reference signals:

- **PSSCH**: The PSSCH is transmitted by a sidelink transmitting UE, which conveys sidelink transmission data, system information blocks (SIBs) for radio resource control (RRC) configuration, and a part of SCI. For the PSSCH, 16 QAM and 64 QAM with low density parity check (LDPC) code are supported, and 256 QAM can be possibly applied (depending on the UE capability).
- **PSFCH**: The PSFCH is transmitted by a sidelink receiving UE for unicast and groupcast, which conveys 1 bit information over 1 RB for the HARQ acknowledgement (ACK) and the negative ACK (NACK). In addition, channel state information (CSI) is carried in the medium access control (MAC) control element (CE) over the PSSCH instead of the PSFCH.
- **PSCCH**: When the traffic to be sent to a receiving UE arrives at a transmitting UE, a transmitting UE should first send the PSCCH, which conveys a part of SCI to be decoded by any UE for the channel sensing purpose, including the reserved time-frequency resources for transmissions, demodulation reference signal (DMRS) pattern and antenna port, etc. For the PSCCH, the SCI is transmitted using quadrature phase shift keying (QPSK) with polar code. As aforementioned, another part of SCI carries the remaining scheduling and control information to be decoded by the target receiving UE. It shares the associated PSSCH resources and the PSSCH DMRS with indications in the 1st-stage SCI for its resource allocation, and such a two-stage SCI design will be discussed later.

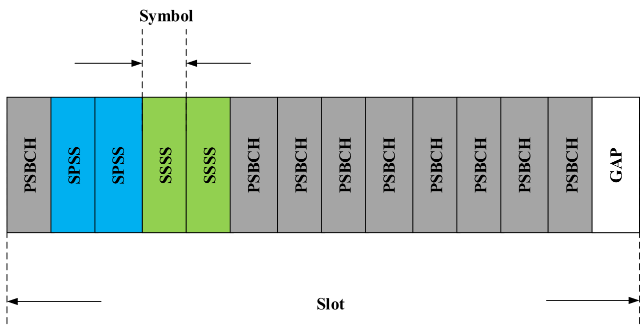

FIGURE 1. The SSB in NR sidelink transmissions.

- **Sidelink Primary/Secondary Synchronization Signal (SPSS/SSSS)**: Similar to downlink transmissions in NR, in sidelink transmissions, primary and secondary synchronization signals (called SPSS and SSSS, respectively) are supported, in which M-sequence and Gold sequence are used to generate the SPSS and SSSS, respectively. Through detecting the SPSS and SSSS, a UE is able to identify the sidelink synchronization identity (SSID) from the UE sending the SPSS/SSSS, where there are 2 SPSS sequences and 336 SSSS sequences forming 672 SSIDs. Through detecting the SPSS/SSSS, a UE is therefore able to know the characteristics of the UE transmitting the SPSS/SSSS, and this part will be detailed Section VII. A series of process of acquiring timing and frequency synchronization together with SSIDs of UEs is called initial cell search. Note that the UE sending the SPSS/SSSS may not be necessarily involved in sidelink transmissions, and a node (UE/eNB/gNB) sending the SPSS/SSSS is called a synchronization source. This part will be detailed in Section VII.
- **Physical Sidelink Broadcast Channel (PSBCH)**: The PSBCH is transmitted along with the SPSS/SSSS as a synchronization signal/PSBCH block (SSB), as shown in Fig. 1 which illustrates the structure of SSB for the NCP. The SSB has the same numerology as PSCCH/PSSCH on that carrier, and an SSB should be transmitted within the bandwidth of the configured BWP. The PSBCH conveys information related to synchronization, such as the direct frame number (DFN), indication of the slot and symbol level time resources for sidelink transmissions, in-coverage indicator, etc. The SSB is transmitted periodically at every 160 ms. In addition, there are N repetitions within the 160 ms period with configurable starting offset and the interval. N is (pre-)configured depending on the SCS.
- **DMRS, phase tracking reference signal (PT-RS), channel state information reference signal (CSI-RS)**: These physical reference signals supported by NR downlink/uplink transmissions are also adopted by sidelink transmissions. Similarly, the PT-RS is only applicable for FR2 transmission.

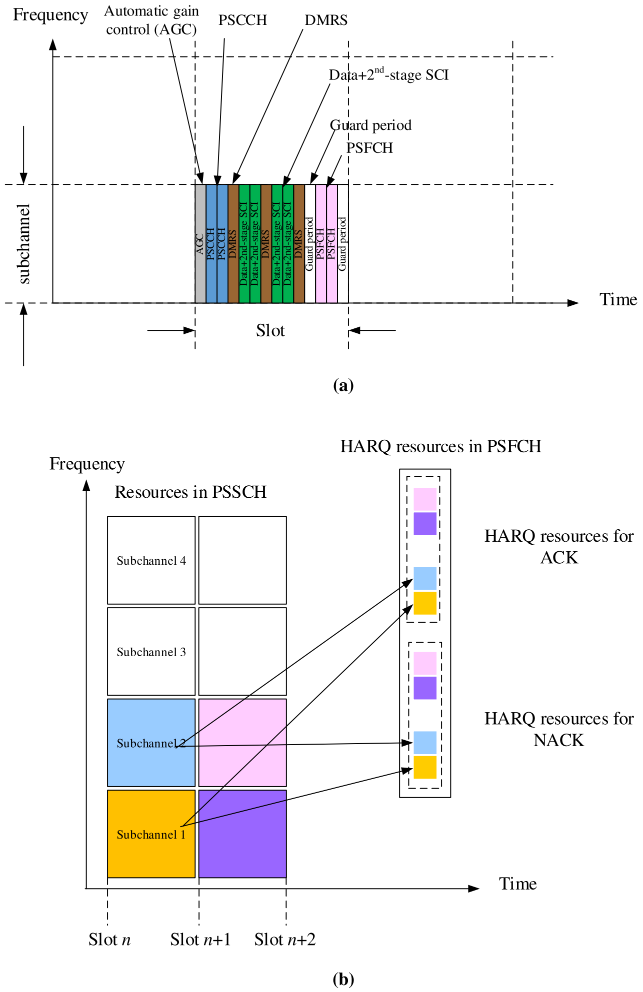

FIGURE 2. **Multiplexing of PSCCH, PSSCH and PSFCH. Please note that Fig. 2(a) is an example in which PSSCH (data and 2nd-stage SCI) only occupies a subchannel, while PSCCH can span over multiple subchannels in general.**

III. MULTIPLEXING OF PSCCH, PSSCH, AND PSFCH

For NR sidelink transmissions, multiplexing of PSCCH, PSSCH, and associated PSFCH is illustrated in Fig. 2(a), where the PSCCH and the PSSCH can be multiplexed both in the time and frequency domains. The PSCCH can occupy a number of consecutive RBs in the starting subchannel of the PSSCH transmission over 2 or 3 symbols at the beginning of a slot, while the PSSCH may span over multiple subchannels.

A. RESOURCES OF PSFCH

At every one, two, or four slots, the last two symbols excluding the guard period (GP) symbol are able to accommodate the PSFCH. Given a certain time-frequency location of the PSSCH, to identify the "actual" time-frequency location (resources) of the corresponding PSFCH, the candidate resources of the corresponding PSFCH should be identified first. For a PSSCH transmission, the candidate resources of the corresponding PSFCH is the set of RBs associated the starting subchannel and slot used for that PSSCH. Within the set of RBs configured for the actual PSFCH transmission, the first Z RBs are associated with the first subchannel in the first slot associated with the PSFCH slot, the second Z RBs are with the first subchannel in the second slot associated with the PSFCH slot, and so on, as illustrated in Fig. 2(b). The frequency resources for the actual PSFCH transmission are indicated by a bitmap for RBs in a resource pool. For each PSFCH, resources for ACK and NACK are separated.

B. CONTENTS OF SCI FACILITATING FEEDBACK TRANSMISSIONS

When a receiving UE has received a transport block (TB) on the PSSCH, to perform feedback transmissions, a receiving UE needs to know which UE launched this TB. For this purpose, when a transmitting UE launches a TB on the PSSCH, a 8-bits source identity (ID) and a 16-bits destination ID are conveyed by the corresponding 2nd-stage SCI. With the source ID, a receiving UE therefore knows who is the transmitter. For different PSSCH transmissions (transmitted by different transmitting UEs) with the same starting subchannel in the same slot, the candidate resources of PSFCH for these PSSCH transmissions may be overlapped. To avoid collisions among resources of actual PSFCH transmissions, PSFCH resources for actual transmissions can be determined by the source ID implicitly (conveyed by the corresponding 2nd-stage SCI).

In addition to the source ID and the destination ID, to facilitate feedback transmissions, the contents of SCI also include the 1-bit new data indicator (NDI), 2-bit redundancy version (RV), and 4-bit HARQ process ID. The NDI is used to indicate whether the current TB is a new transmission or a retransmission, while RV indexes the TBs involved in soft combination if the incremental redundancy based HARQ scheme is adopted. With the facilitation of the HARQ process ID, a transmitting UE and a receiving UE can associate a transmitted TB with the corresponding HARQ ACK/NACK. In addition, the source ID is also used to perform HARQ combination correctly when there are multiple sidelink HARQ transmissions from different UEs in parallel.

C. CONTENTS OF SFCI

The SFCI (i.e., HARQ ACK/NACK) conveyed by the PSFCH is a sequence-based signal. When a receiving UE sends an 1-bit ACK/NACK, ACK and NACK are differentiated using different cyclic shifts of the same base sequence. For unicast transmissions, a receiving UE may reply either ACK or NACK on the PSFCH. For groupcast transmissions with only the common NACK resource configured, there are two options for feedback: 1) Option 1 is to reserve only the common NACK resources for all group members; 2) Option 2 is to reserve group member specific ACK/NACK resources. As a result, it is possible that different receiving UEs may launch PSFCH transmissions on the same RB. To differentiate these PSFCH transmissions for unicast and groupcast Option 2, code division multiplexing (CDM) should be applied. For this purpose, in unicast, cyclic shift of the

ACK/NACK sequences can be selected based on the source ID, while in the case of groupcast Option 2, both source ID and group member ID of the receiving UE can be applied in the selection of its own ACK/NACK sequences.

IV. MODE 1 RESOURCE ALLOCATION

NR sidelink transmissions have the following two modes of resource allocations:

- **Mode 1**: Sidelink resources are scheduled by a gNB.
- **Mode 2**: The UE autonomously selects sidelink resources from a (pre-)configured sidelink resource pool(s) based on the channel sensing mechanism.

For the in-coverage UE, a gNB can be configured to adopt Mode 1 or Mode 2. For the out-of-coverage UE, only Mode 2 can be adopted.

A. RESOURCE ALLOCATION FOR PSCCH AND PSSCH IN MODE 1

Mode 1 supports the following two kinds of grants:

- **Dynamic grant**: When the traffic to be sent over sidelink arrives at a transmitting UE, this UE should launch the four-message exchange procedure to request sidelink resources from a gNB (similar to the case of uplink transmissions). During the resource request procedure, a gNB may allocate a sidelink radio network temporary identifier (SL-RNTI) to the transmitting UE. If this sidelink resource request is granted by a gNB, then a gNB indicates the resource allocation for the PSCCH and the PSSCH in the downlink control information (DCI) conveyed by PDCCH with CRC scrambled with the SL-RNTI. When a transmitting UE receives such a DCI, a transmitting UE can obtain the grant only if the scrambled CRC of DCI can be successfully solved by the assigned SL-RNTI. A transmitting UE then indicates the time-frequency resources and the transmission scheme of the allocated PSSCH in the PSCCH, and launches the PSCCH and the PSSCH on the allocated resources for sidelink transmissions. When a grant is obtained from a gNB, a transmitting UE can only transmit a single TB. As a result, this kind of grant is suitable for traffic with a loose latency requirement.
- **Configured grant**: For the traffic with a strict latency requirement, performing the four-message exchange procedure to request sidelink resources may induce unacceptable latency. In this case, priori to the traffic arrival, a transmitting UE may perform the four-message exchange procedure and request a set of resources. If a grant can be obtained from a gNB, then the requested resources are reserved in a periodic manner. Upon traffic arriving at a transmitting UE, this UE can launch the PSCCH and the PSSCH on the upcoming resource occasion. In fact, this kind of grant is also know as *grant-free* transmissions.

In both dynamic grant and configured grant, a sidelink receiving UE cannot receive the DCI, and therefore a receiving UE should perform *blind decoding* to identify the presence of PSCCH and find the resources for the PSSCH through the SCI. When a transmitting UE launches the PSCCH, CRC is also inserted in the SCI without any scrambling. With the facilitation of CRC in the PSCCH, a receiving UE should continue to solve CRC of received signals. If CRC can not be correctly solved, it implies errors in the PSCCH reception, or the absence of PSCCH. If the PSCCH can be successfully detected, then a receiving UE can obtain a part of SCI and thus the location of the corresponding PSSCH and the remaining part of SCI.

Note that, since the PSCCH and the PSSCH may be multiplexed both in the time and frequency domains, a receiving UE needs to sample signals over all the subchannels at every slot for detection of the PSCCH. These sampled signals may be stored in the memory, then a receiving UE solves CRC of all signals in the memory to detect the PSCCH. If the PSCCH can be detected, a receiving UE is able to decode the PSSCH, stored in the memory accordingly.

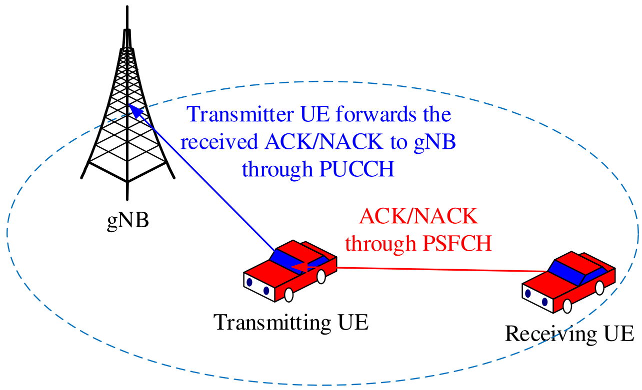

FIGURE 3. In Mode 1, a gNB does not receive ACK/NACK sent via the PSFCH from an in-coverage receiver. When a transmitting UE receives sidelink ACK/NACK, it needs to forward ACK/NACK to a gNB.

B. RESOURCE ALLOCATION FOR THE PSFCH AND RETRANSMISSIONS IN THE PSSCH IN MODE 1

In the time domain, the time gap between the PSSCH and the PSFCH is configured. However, when a receiving UE sends the HARQ ACK/NACK on the PSFCH, only the transmitting UE has the capability to receive such ACK/NACK messages, and a gNB cannot receive this feedback transmission. As a consequence, a gNB may not know whether to further allocate resources for a transmitting UE to retransmit a TB or not.

To obtain resources of the PSSCH for subsequent retransmissions, a transmitting UE needs to forward the sidelink HARQ ACK/NACK message to a gNB when a feedback message is received on the PSFCH, as illustrated in Fig. 3. To further obtain resources for a transmitting UE to send the sidelink HARQ ACK/NACK to a gNB, a gNB may allocate one physical uplink control channel (PUCCH) occasion after the last resource in the PSSCH set for initial sidelink transmissions. When a NACK is received by a gNB, a gNB further allocates PSCCH and PSSCH resources for sidelink retransmissions, and this resource allocation is indicated in the DCI in the case of dynamic grant. Alternatively, a transmitting UE can launch the TB retransmission through the reserved the PSCCH and the PSSCH in the case of configured grant.

V. MODE 2 RESOURCE ALLOCATION

In the Mode 2 resource allocation, when traffic arrives at a transmitting UE, this transmitting UE should autonomously select resources for the PSCCH and the PSSCH. To further minimize the latency of the feedback HARQ ACK/NACK transmissions and subsequently retransmissions, a transmitting UE may also reserve resources for PSCCH/PSSCH for retransmissions. To further enhance the probability of successful TB decoding at one shot and thus suppress the probability to perform retransmissions, a transmitting UE may repeat the TB transmission along with the initial TB transmission. This mechanism is also known as **blind retransmission**. As a result, when traffic arrives at a transmitting UE, then this transmitting UE should select resources for the following transmissions:

1) The PSSCH associated with the PSCCH for initial transmission and blind retransmissions.
2) The PSSCH associated with the PSCCH for retransmissions.

For 4), the maximum number of retransmissions is 32. Since each transmitting UE in sidelink transmissions should autonomously select resources for above transmissions, how to prevent different transmitting UEs from selecting the same resources turns out to be a critical issue in Mode 2. A particular resource selection procedure is therefore imposed to Mode 2.

A. RESOURCE SELECTION PROCEDURE IN MODE 2

When a transmitting UE attempts to reserve resources, it should launch the resource selection procedure, which is composed of two phases: **resource sensing** and **resource selection**. To avoid causing interference to existing sidelink transmissions launched by other UEs, in the resource sensing phase, a transmitting UE should find out candidate resources potentially available to be utilized for sidelink transmissions. The candidate resources include the resources unoccupied, and the resources occupied by ongoing sidelink transmissions but with an acceptable interference level to the transmitting UE.

1) RESOURCE SENSING

When traffic arrives at a UE, this transmitting UE sets a time instant as a trigger of the resource (re)selection, denoted as n. Prior to and after n, two windows called the sensing window and selection windows are set, respectively. During the sensing window (from the time instant T_0 to n), the transmitting UE measures the reference signals received power (RSRP) of all the considered subchannels. If either the RSRP on a subchannel does not exceed a threshold (i.e., the value of this threshold is determined by the priority of this TB transmission), or a subchannel is not occupied by other sidelink transmissions, this subchannel is regarded as a candidate resource in the following selection window; otherwise, a subchannel is not a candidate resource. However, the RSRP is the power level of DMRS on the PSSCH or the DMRS on the PSCCH depending on the configuration. To measure the RSRP, a transmitting UE should know the resources of the PSSCH or the PSSCH launched by other UEs. For this purpose, a transmitting UE should detect the PSCCH (and thus receive the SCI) launched by other UEs to know which subchannels have been occupied by other sidelink transmitters. If the ratio of the number of candidate resources to the total number of resources in the selection window is less than 20%, then the threshold can be increased by 3 dB, and the above-mentioned procedure can be repeated for resource identification.

From reading the contents of SCI launched by other sidelink transmitters, a candidate resource in the selection window can be either occupied by other sidelink transmitters but have an acceptable interference (RSRP) level, or not occupied by other sidelink transmitters.

2) RESOURCE (RE)SELECTION

After identifying candidate resources, a transmitting UE randomizes the selection of candidate resources to launch the PSCCH, PSSCH, and PSFCH during the selection window. When a transmitter begins launching the PSCCH, PSSCH and PSFCH, it may keep performing resource sensing. If this UE finds that there are other sidelink transmissions with a higher priority occupying the reserved resources, this UE triggers the resource re-selection.

B. TWO-STAGE SCI IN MODE 2

In the resource sensing phase, a transmitting UE should detect the SCI launched by other UEs. The contents of SCI may include a lot of fields, but a transmitting UE may only want to know which resources are occupied by other UEs. For the sake of resource sensing, it may not be necessary for a UE to transmit all the fields of SCI in a single stage. For this goal, the fields of SCI are transmitted in two stages. The first stage (1st-stage) SCI is conveyed by the PSCCH, while the second stage (2nd-stage) SCI is conveyed using the PSSCH resources but has the QPSK modulation and polar coding. The 1st-stage SCI mainly carries the information regarding the PSSCH resources and the information for decoding the 2nd-stage SCI (e.g., time-frequency resources of PSSCH/PSFCH, the priority of this TB transmission, etc.) which are mainly used for channel sensing purpose to be decodable by any UE. The 2nd-stage SCI mainly carries the remaining scheduling information for the PSSCH decoding by the target UE (e.g., MCS, UE-specific DMRS, NDI, RV, HARQ process ID, etc.). Both source ID and destination ID are carried in the 2nd-stage SCI to reduce the payload size of the 1st-stage SCI with the cost of the decoding attempts on two SCIs for all UEs.

Although the two-stage SCI design may decrease the complexity of resource sensing, there are two potential issues. The first issue is error propagation between the 1st-stage SCI detection and the 2nd-stage SCI decoding. A UE is able to decode the 2nd-stage SCI only if the blind detection for the 1st-stage SCI is successful. Hence, if the blind detection of the 1st-stage SCI fails, then the decoding of the 2nd-stage SCI must fail. To increase the probability of successful detection/decoding of both stages of SCIs, a possible scheme is to make the channels of the 1st-stage and 2nd-stage SCIs correlated (i.e., if the detection of the 1st-stage SCI is successful, then the decoding of the 2nd-stage is very likely to be successful). For this purpose, the resources of the 1st-stage SCI and 2nd-stage SCI should be placed as close as possible. We will evaluate the performance of this design in Section VIII. The second issue is what is a proper length of the 1st-stage SCI. In other words, the two-stage SCI design leads to a smaller number of bits to be transmitted on the PSCCH as compared with the single stage SCI design. We therefore should investigate how a shorter length of SCI on the PSCCH impacts the performance of the error rate of blind detection, as well as the coverage range. This part will also be discussed in Section VIII.

VI. POWER CONTROL AND QOS MANAGEMENT IN NR SIDELINK TRANSMISSIONS

A. POWER CONTROL

In sidelink transmissions, an open-loop power control scheme is adopted (i.e., a receiving UE cannot directly inform a transmitting UE to increase or decrease the transmission power level). Nevertheless, a receiving UE is able to measure the RSRP of the DMRS on the PSSCH, and report the measurement result through higher layer signaling to the transmitting UE, by which the transmitting UE can estimate pathloss of sidelink transmissions. To decide the transmission power, a transmitting UE can be configured to use only the downlink pathloss (between transmitting UE and gNB), only the sidelink pathloss (between transmitting UE and receiving UE), or both downlink and sidelink pathloss. If it is configured to use both downlink and sidelink pathloss to decide the transmission power, the transmission power is decided by $P_{TX} = \min\{P_{SL}, P_{DL}\}$, where P_{SL} is the sidelink transmission power derived from sidelink pathloss, and P_{DL} is the downlink transmission power derived from downlink pathloss. The maximum sidelink transmission power is configured to the transmitting UE. When the transmission power is decided, the total sidelink transmission power is the same in the symbols used for PSCCH and PSSCH transmissions in a slot.

For the transmission power of PSFCH, an open-loop power control is also adopted, in which a receiving UE estimates pathloss between itself and a gNB to decide the transmission power. In addition, a transmitting UE may provide its location information to a receiving UE (conveyed by the 2nd-stage SCI). If a receiving UE finds that the distance between a transmitting UE and a receiving UE is too large, a receiving UE may not transmit ACK/NACK on the PSFCH.

B. QOS MANAGEMENT

To enhance QoS of sidelink transmissions, congestion control is a crucial function (especially in Mode 2) to prevent a transmitting UE from occupying too many resources in sidelink transmissions. For the purpose of congestion control, two metrics are defined as follows:

- **Channel Busy Ratio (CBR)**: The CBR is defined as the portion of subchannels whose RSSI exceeds a preconfigured value over a certain time duration.
- **Channel Occupation Ratio (CR)**: Considering a particular slot n, the CR is defined as $(X+Y)M$, where X is the number of the subchannels that have been occupied by a transmitting UE within $[n-a, n-1]$, Y is the number of the subchannels that have been granted within $[n, n+b]$, and M is the total number of subchannels within $[n-a, n+b]$.

For congestion control, an upper bound of CR denoted by CR_{limit} is imposed to a transmitting UE, where CR_{limit} is a function of CBR and the priority of the sidelink transmissions. The amount of resources occupied by a transmitting UE may not exceed CR_{limit}.

VII. SYNCHRONIZATION IN NR SIDELINK

It is expected that all the UEs and eNBs/gNBs can follow the same timing reference if an eNB/gNB exists. If there is no eNB or gNB, then it is desired that the timing references of all the UEs are aligned with each other. Even with the deployment of eNBs/gNBs, there could be out-of-coverage UEs whose signals from eNBs/gNBs are blocked or shadowed. To achieve synchronization among all the UEs and eNBs/gNBs, there are two types of sidelink synchronization procedures: Global Navigation Satellite System (GNSS) based and gNB/eNB based synchronization. The procedures of these two types of sidelink synchronization are provided in the following:

GNSS based synchronization

1) When a UE is powered on, it searches for the GNSS signal.
2) If the GNSS signal can be received, it synchronizes with the GNSS and continues to receive potential SSBs.
   a) If the SSBs from another UE whose timing reference is derived from an eNB/gNB (directly or indirectly synchronized to an eNB/gNB) are received, this UE transmits its SSBs and becomes a synchronization source.
   b) If SSBs from another UE whose timing reference is derived from a GNSS (directly or indirectly synchronized to a GNSS), this UE does not transmit its SSBs.
   c) If SSBs from another UE whose timing reference is derived from neither a GNSS nor an eNB/gNB, this UE transmits its SSBs and becomes a synchronization source.

3) If the GNSS signal is not available, then it searches for and synchronizes to SSBs based on the following priority, where P1 is of the highest priority and P6 is of the lowest priority:
   - P1: UE directly synchronized to the GNSS
   - P2: UE indirectly synchronized to the GNSS
   - P3: eNB/gNB
   - P4: UE directly synchronized to eNB/gNB
   - P5: UE indirectly synchronized to gNB/eNB
   - P6: Remaining UEs
4) Upon synchronizing to SSBs sent from one of P1 to P6, a UE continues to receive potential SSBs. If SSBs from another UE whose timing reference is derived from a node with a lower priority, this UE transmits its SSBs and becomes a synchronization source.
5) If a UE cannot receive any SSBs or GNSS signal, this UE transmits SSBs with its local clock as a synchronization source.

eNB/gNB based synchronization

1) When a UE powers on, it searches for the eNB/gNB SSB signals.
2) If the eNB/gNB SSB signals can be received, it synchronizes with the eNB/gNB and continues to receive potential SSBs.
   a) If SSBs from another UE whose timing reference is derived from an eNB/gNB (directly or indirectly synchronized to an eNB/gNB) are received, this UE transmits its SSBs and becomes a synchronization source.
   b) If SSBs from another UE whose timing reference is derived from the eNB/gNB (directly or indirectly synchronized to the eNB/gNB), this UE does not transmit its SSBs.
   c) If SSBs from another UE whose timing reference is neither derived from the eNB/gNB nor from a GNSS, this UE transmits its SSBs and becomes a synchronization source.
3) If the eNB/gNB SSB signals are not available, then it searches for and synchronizes to SSBs based on the following priority:
   - P1: UE directly synchronized to eNB/gNB
   - P2: UE indirectly synchronized to eNB/gNB
   - P3: GNSS
   - P4: UE directly synchronized to the GNSS
   - P5: UE indirectly synchronized to the GNSS
   - P6: Remaining UEs
4) Upon synchronizing to SSBs sent from one of P1 to P6, a UE continues to receive potential SSBs. If SSBs from another UE whose timing reference is derived from a node with a lower priority, this UE transmits its SSBs and becomes a synchronization source.
5) If a UE cannot receive any SSBs or GNSS signal, this UE transmits SSBs with its local clock as a synchronization source.

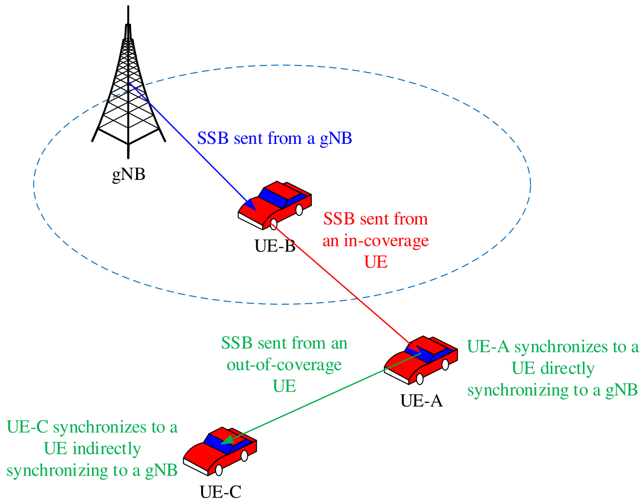

FIGURE 4. A UE may synchronize to a UE directly or indirectly synchronizing to a gNB.

From the above procedure, a UE is able to send sidelink SSBs (i.e., SPSS/SSSS and PSBCH) as a synchronize source. A UE is also possible to receive the SPSS/SSSS from other UEs and synchronize to other UEs. Therefore, if a UE (say, UE-A) synchronizes to another UE (say, UE-B), and UE-B synchronizes to the GNSS/eNB/gNBB, then we say that UE-A synchronizes to a UE directly synchronizing to the GNSS/eNB/gNB, as illustrated in Fig. 4. If UE-A is a synchronization source, and there is also a UE (say, UE-C) synchronizing to UE-A, then we say that UE-C synchronizes to a UE indirectly synchronizing to the GNSS/eNB/gNB.

We can also observe from the above procedures that a UE transmits SSBs if it receives SSBs from another UE whose timing reference is derived from a node with a lower priority. As a result, a UE sending sidelink SSBs is not necessarily a sielink transmitter or a receiver, and this synchronization source can even not be involved in sidelink data transmissions. Therefore, the sidelink synchronization procedures and communication procedures can be independent.

When the SSBs are received, the priority of the SSBs can be identified by the associated SSID. As aforementioned, there are 672 SSIDs in total, and these SSIDs are divided into two sets: the set {0, 1, ..., 335} for UEs with 1 or 2 hops of synchronization, and the set {336, 337, ..., 671} for out-of-coverage UEs with more than 2 hops of synchronization. In addition, a few SSIDs are used for the GNSS cases. The set of SSIDs is used for in-coverage and one hop out-of-coverage synchronization sources, which are differentiated by an in-coverage indicator.

VIII. PERFORMANCE EVALUATION OF THE TWO-STAGE SCI IN MODE 2

A. ERROR PROPAGATION OF THE TWO-STAGE SCI IN MODE 2

As aforementioned in Section V-B, we expect that the successful probability of both detecting/decoding the 1st-stage

TABLE 1. Simulation assumptions for error propagation evaluation.

Case ID	Case A1	Case A2	Case A3	Case A4
Parameter	Two stage SCI (1+1 symbol)	Two stage SCI (1+1 symbol)	Two stage SCI (2+2 symbol)	Two stage SCI (2+2 symbol)
Frequency	6 GHz	6 GHz	6 GHz	6 GHz
SCS (kHz)	30	30	30	30
CORESET RB	48	48	24	24
2nd CORESET RB	48	48	24	24
Payload (24-bit CRC included)	1st stage SCI: 61(37) bits 2nd-stage SCI: 46(22) bits	1st stage SCI: 61(37) bits 2nd-stage SCI: 61(37) bits	1st stage SCI: 61(37) bits 2nd-stage SCI: 46(22) bits	1st stage SCI: 61(37) bits 2nd-stage SCI: 61(37) bits
CORESET* time duration	1st-stage SCI: Symbol#0 2nd-stage SCI: Symbol#1	1st-stage SCI: Symbol#0 2nd-stage SCI: Symbol#1	1st-stage SCI: Symbol#0∼1 2nd-stage SCI: Symbol#2∼3	1st-stage SCI: Symbol#0∼1 2nd-stage SCI: Symbol#2∼3
Aggregation level (AL)	1st-stage SCI: AL8 2nd-stage SCI: AL8	1st-stage SCI: AL8 2nd-stage SCI: AL8	1st-stage SCI: AL8 2nd-stage SCI: AL8	1st-stage SCI: AL8 2nd-stage SCI: AL8
REG* bundle size	6	6	6	6
CCE-REG*** mapping	non-interleaved	non-interleaved	non-interleaved	non-interleaved
Antenna configuration	2×2	2×2	2×2	2×2
Delay spread	30 ns	30 ns	30 ns	30 ns
Channel model	TDL-C in TR 38.901	TDL-C in TR 38.901	TDL-C in TR 38.901	TDL-C in TR 38.901

* CORESET: Control Resource Set
** REG: Resource Element Group
*** CCE: Control Channel Element

and 2nd-stage SCIs can be improved if the resources for the 1st-stage and 2nd-stage SCIs are placed as close as possible. In this section, we therefore provide the simulation results for the two-stage SCI design to evaluate the impact of error propagation. The simulation assumptions for four different cases (Cases A1 to A4) are summarized in Table 1, and the block level error rate (BLER) is evaluated with the following four curves:

- **The 1st SCI**: BLER of only the 1st-stage SCI.
- **The 2nd SCI**: BLER of only the 2nd-stage SCI.
- **The 2 stage SCI**: BLER of jointly decoding the 1st-stage and 2nd-stage SCIs when the channels of these two SCIs are correlated with closed resource locations.
- **Independent**: BLER of jointly decoding the 1st-stage and 2nd-stage SCIs by assuming the fully independent channels.

In Figs. 5 to 12, the simulation results of BLER for Cases A1 to A4 under different moving speeds of 30 km/h (with a low Doppler frequency shift) and 260 km/h (with a high Doppler frequency shift) with different numbers of symbols per SCI and different payload sizes per SCI are provided. We can observe from these figures that the impact of error propagation is very limited in the practical operation when the channels between the 1st-stage and 2nd-stage SCIs are highly correlated by placing the 1st-stage SCI and the 2nd-stage SCI closely. As expected, the impact of error propagation becomes severe when the channels between the 1st-stage and 2nd-stage SCIs are independent, because the successful detection of the 1st-stage SCI does not implies that the 2nd-stage SCI can also be successfully decoded in the case of the independent channels.

It is up to around 0.5 dB performance loss in the worst case, which only happens in the high-speed case (260 km/h), and this case is not very likely to happen. In fact, such 0.5 dB loss can be compensated through improving the performance of channel estimation or slightly lowering the coding rate (only lowering 1% coding rate). In generally, the performance of the BLER for the two-stage SCI design is bounded by that of the **1st SCI**.

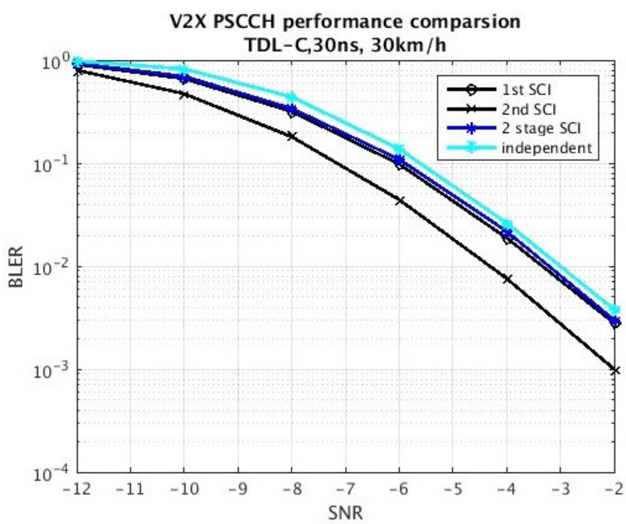

FIGURE 5. BLER of Case A1 with 61 bits in the 1st-stage SCI and 46 bits in the 2nd-stage SCI for 1 symbol per SCI (in which the moving speed is 30 km/h). The unit of the horizontal axis is dB.

Typically, the coverage ranges of the 1st-stage SCI (which has a larger coverage range for sensing and should be decoded by all UEs) and the 2nd-stage SCI (for data reception to be decoded only by the target UE) are different. From the perspective of sensing UEs, they only need to decode the 1st-stage SCI, and there is no error propagation issue. From the perspective of the target UE, the decoding performance of the 2nd-stage SCI is bounded by the **2nd SCI** because the 1st-stage SCI always has a better coverage range. As a result, there is no error propagation issue, and this issue only occurs when the coverage ranges of both SCIs are similar.

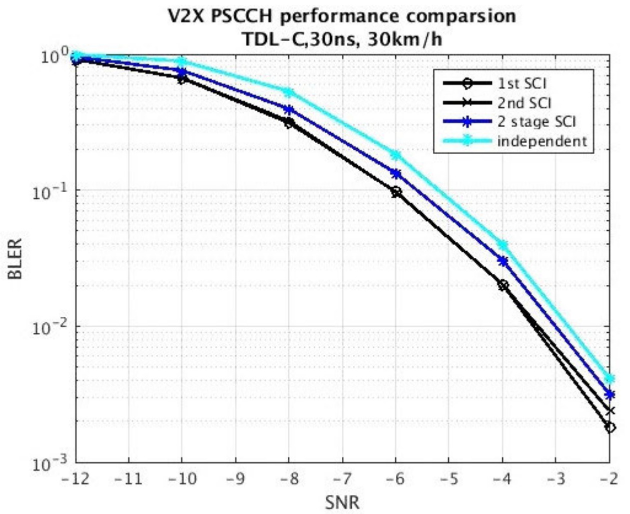

FIGURE 6. BLER of Case A2 with 61 bits in the 1st-stage SCI and 61 bits in the 2nd-stage SCI for 1 symbol per SCI (in which the moving speed is 30 km/h). The unit of the horizontal axis is dB.

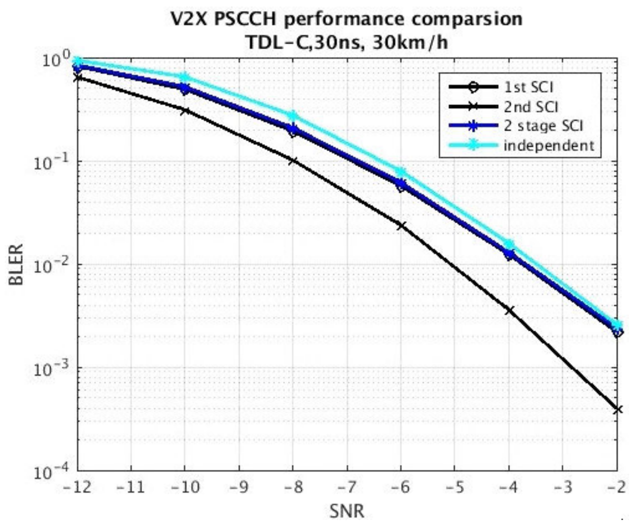

FIGURE 7. BLER of Case A3 with 61 bits in the 1st-stage SCI and 46 bits in the 2nd-stage SCI for 2 symbols per SCI (in which the moving speed is 30 km/h). The unit of the horizontal axis is dB.

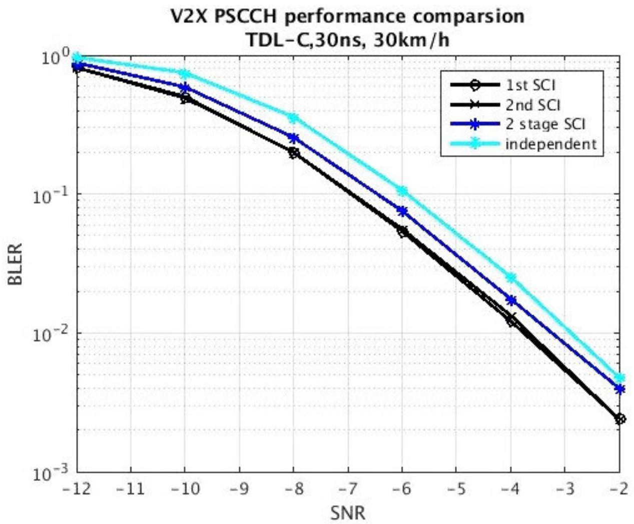

FIGURE 8. BLER of Case A4 with 61 bits in the 1st-stage SCI and 61 bits in the 2nd-stage SCI for 2 symbols per SCI (in which the moving speed is 30 km/h). The unit of the horizontal axis is dB.

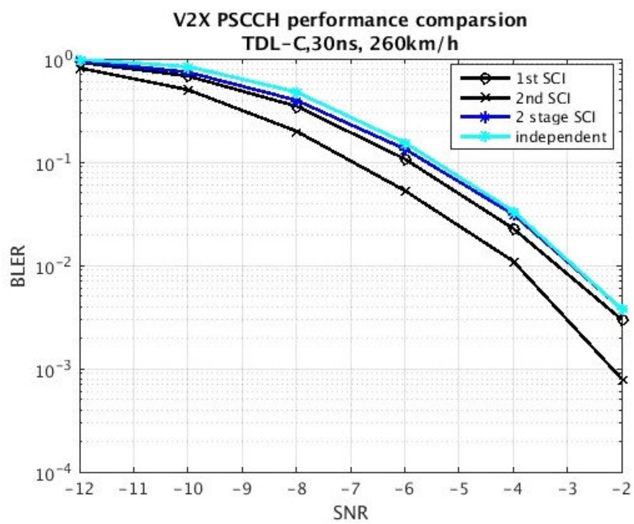

FIGURE 9. BLER of Case A1 with 61 bits in the 1st-stage SCI and 46 bits in the 2nd-stage SCI for 1 symbols per SCI (in which the moving speed is 260 km/h). The unit of the horizontal axis is dB.

Note that the 2nd SCI targeting the receiving UE can be subject to the link adaptation together with the data channel, which can improve the overall resource utilization and avoid the resource waste caused by the fixed low coding rate as the single-stage SCI.

B. SIZE OF THE 1ST-STAGE SCI

This subsection evaluates the BLER performance of different lengths of the 1st-stage SCI (60 bits, 90 bits, 120 bits including 24-bit CRC) under the cases **Case B1** to **Case B4**, and the simulation assumptions of these considered cases are summarized in Table 2. In this simulation, aggregation level (AL) denotes the number of consecutive CCEs carried in one PSCCH, and a lower AL accommodates less bits in the PSCCH. The simulation results of the BLERs for Cases B1 to B4 are shown in Figs. 13 to 16, respectively.

We can observe from these figures that, under a given number of bits to be transmitted by the PSCCH, a larger AL leads to a better performance in terms of the BLER. Since a larger AL accommodates a larger number of bits, more bits imposed on a channel code can be inserted, which results in a lower channel coding rate to improve the BLER performance. On the other hand, given a certain AL (i.e., given a fixed capacity of the PSCCH), a smaller number of bits of SCI leads to a better performance. When the SCI has less bits, more space in the PSCCH can be used to accommodate redundant bits inserted by a channel code so as to lower the channel coding rate. Therefore, the performance

TABLE 2. Simulation assumptions for different lengths of the 1st-stage SCI.

Case ID	Case B1	Case B2	Case B3	Case B4
Parameter	Single CSI	Single CSI	Single CSI	Single CSI
Frequency	6 GHz	6 GHz	6 GHz	6 GHz
SCS (kHz)	30	30	30	30
CORESET RB	48	48	48	48
Bandwidth	40 MHz	40 MHz	40 MHz	40 MHz
Payload	60 (36+24) bits 90 (66+24) bits 120 (96+24) bits	60 (36+24) bits 90 (66+24) bits 120 (96+24) bits	60 (36+24) bits 90 (66+24) bits 120 (96+24) bits	60 (36+24) bits 90 (66+24) bits 120 (96+24) bits
CORESET time duration	Symbol#0 Symbol#1	Symbol#0 Symbol#1	Symbol#0 Symbol#1	Symbol#0 Symbol#1
AL	AL 4/8/16	AL 4/8/16	AL 4/8/16	AL 4/8/16
REG bundle size	6	6	6	6
CCE-REG mapping	non-interleaved	non-interleaved	non-interleaved	non-interleaved
Antenna configuration	2×2	2×2	2×2	2×2
Delay spread	30 ns	30 ns	30 ns	30 ns
Channel model	TDL-C	TDL-C in TR 38.901	TDL-C in TR 38.901	TDL-C in TR 38.901
Delay spread	30 ns	30 ns	300 ns	300 ns
Moving speed	30 km/h (Doppler shift=167 Hz)	260 km/h (Doppler shift=144 Hz)	30 km/h (Doppler shift=167 Hz)	260 km/h (Doppler shift=144 Hz)

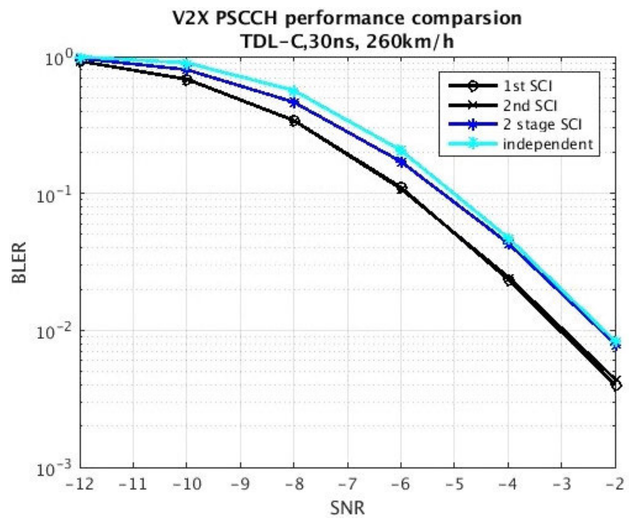

FIGURE 10. BLER of Case A2 with 61 bits in the 1st-stage SCI and 61 bits in the 2nd-stage SCI for 1 symbol per SCI (in which the moving speed is 260 km/h). The unit of the horizontal axis is dB.

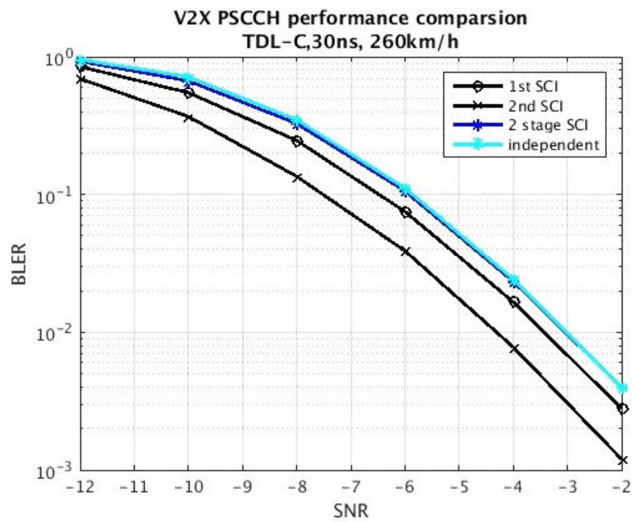

FIGURE 11. BLER of Case A3 with 61 bits in the 1st-stage SCI and 46 bits in the 2nd-stage SCI for 2 symbols per SCI (in which the moving speed is 260 km/h). The unit of the horizontal axis is dB.

can be enhanced. In general, a performance gap up to 2 dB can be observed between the cases of the 60-bit and 90-bit SCI sizes, and a performance gap up to 1.5 dB can be observed between the cases of the 90-bit and 120-bit SCI sizes.

It may not be feasible to support more than one size of SCI, because it should largely increase the times of blind decoding and may not be affordable for a UE with limited processing capability. For example, if there are 25 subchannels and two possible SCI sizes for each subchannel, then the blind decoding should be performed 50 times, and this number is even larger than the existing capability of the Uu interface. As a result, a new hardware may be required rather than reusing the existing enhanced mobile broadband (eMBB) chipset to support NR sidelink transmissions.

IX. FUTURE ENHANCEMENTS OF NR SIDELINK TRANSMISSIONS

Release 16 is the first release of NR sidelink transmissions, which paves an operable foundation and the following functions can be further enhanced in future releases.

- **Beamforming schemes**: Since the scenario of Release 16 sidelink transmissions focuses on V2X to be deployed to the 5.9 GHz Intelligent Transportation System (ITS) spectrum, the signal propagation range can be sufficient. As a result, directional transmissions/receptions with the beamforming technology to extend the signal coverage range may not be mandatory. Limited to V2X using the ITS spectrum, beamforming and thus beam sweeping/management is not supported in Release 16 NR sidelink transmissions. Nevertheless,

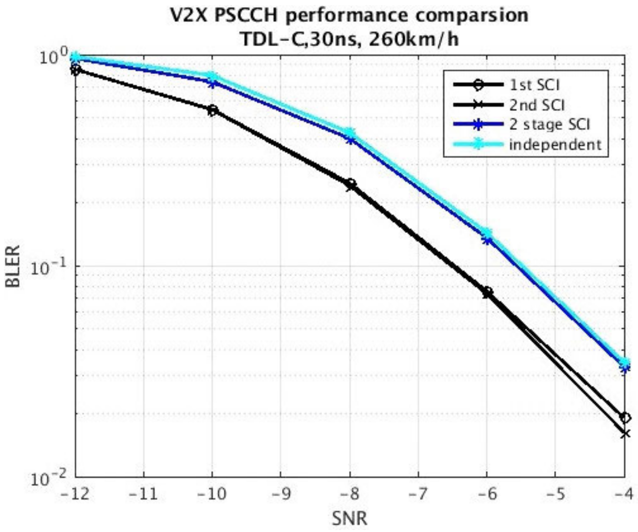

FIGURE 12. BLER of Case A4 with 61 bits in the 1st-stage SCI and 61 bits in the 2nd-stage SCI for 2 symbols per SCI (in which the moving speed is 260 km/h). The unit of the horizontal axis is dB.

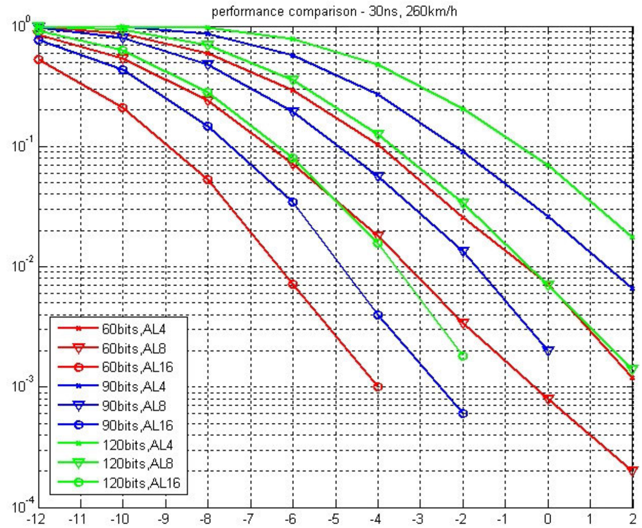

FIGURE 14. BLER of Case B2, where the metric of the horizontal axis is SNR in the unit of dB.

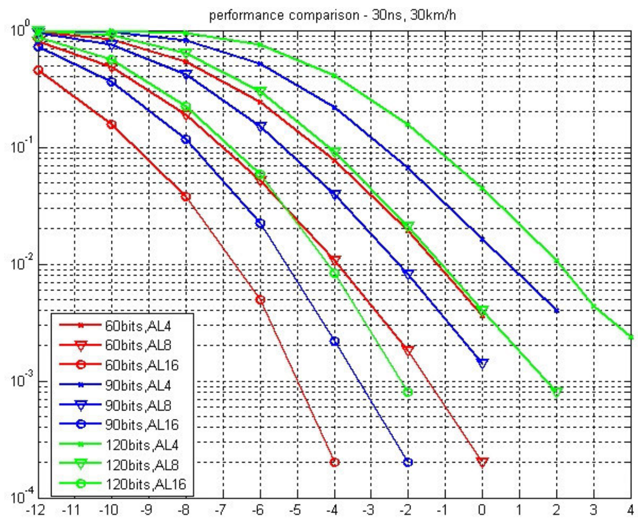

FIGURE 13. BLER of Case B1, where the metric of the horizontal axis is signal to noise power ratio (SNR) in the unit of dB.

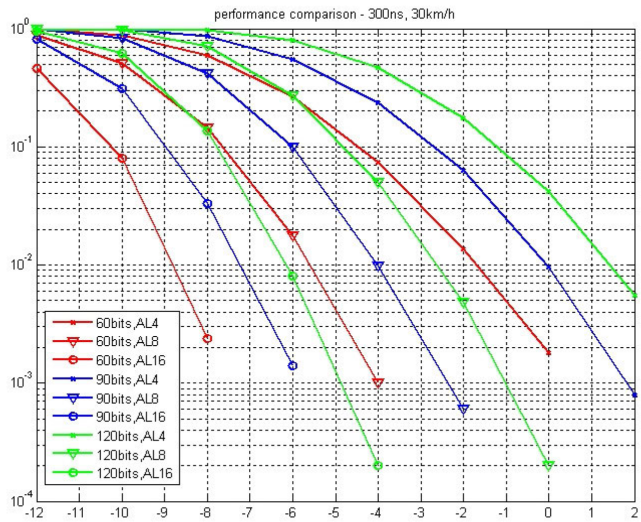

FIGURE 15. BLER of Case B3, where the metric of the horizontal axis is SNR in the unit of dB.

it has been agreed that beam sweeping/management will be supported to deploy sidelink transmissions on the FR2 in future releases. However, performing beam sweeping/management among mobile vehicles may be a critical challenge, especially in achieving low-latency beam alignment.

- **Scheduling UE**: During the standardization progress of Release 16 NR sidelink transmissions, a particular sub-mode of Mode 2 known as Mode 2(d) had been discussed. In Mode 2(d), a UE called a scheduling UE is able to schedule resources for sidelink transmissions between other two UEs. Due to limited time in the normative works, this sub-mode is not included in Release 16 eventually. For further V2X enhancements, this sub-mode is projected to be supported to sustain vehicle/drone cooperative platooning.
- **Power saving**: For vehicular UEs, energy consumption is not a concern in the designs of sidelink transmissions, which is however a crucial issue for pedestrian UEs in V2X, drone UEs in aerial V2X, wearable UEs in interactive games, or mobile UEs in public safety. In Release 16, performing blind decoding of the PSCCH is one of major causes of energy consumption both in Mode 1 and Mode 2. In Mode 2, the existing channel sensing procedure requiring a receiving UE to sample all the receive signals in decoding the PSCCH and the PSSCH also squanders considerable energy. To save power at a receiving UE, the transmission and reception procedures

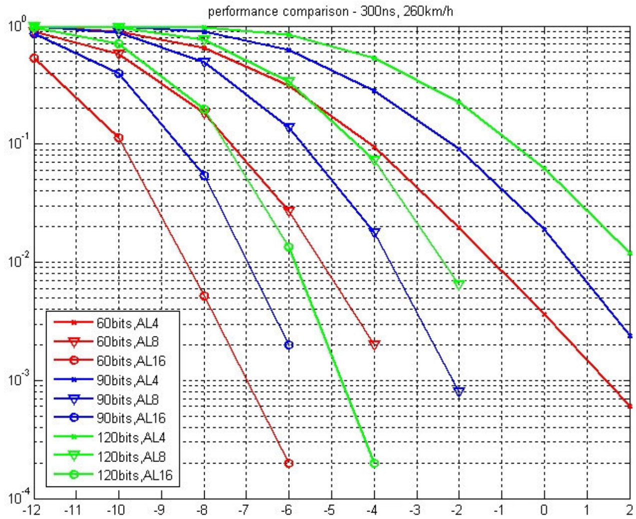

FIGURE 16. BLER of Case B4, where the metric of the horizontal axis is SNR in the unit of dB.

of PSCCH and PSSCH in Release 16 may be further improved.

- **Multiple-input-multiple-output (MIMO)**: In Release 16 sidelink transmissions, the MIMO scheme is only limited to 2×2 up to 2 layers. Since a vehicle is feasible to install more antennas, the MIMO schemes with more layers are projected to be future releases to improve the data rates.

X. CONCLUSION

In this paper, detailed operations of 3GPP NR sidelink transmissions have been thoroughly presented, including numerology, waveform, resource structure in both time and frequency domains, physical channels and reference signals, resources of PSFCH, contents of SCI for PSFCG, contents of SFCI, resource allocation for PSCCH/PSSCH/PSFCH in Mode 1, resource sensing/selection and two-stage SCI in Mode 2, power control, QoS management, and synchronization procedures. Through our simulation studies, it demonstrates that although error propagation may be a concern in the two-stage SCI design of Mode 2, this issue can be alleviated through arranging the resources of two SCIs as close as possible. Our simulation results also show that a shorter length of the 1st-stage SCI may lead to a better BLER performance, and therefore the two-stage SCI design shortening the length of SCI in the PSCCH may practically boost the decoding performance. Release 16 is the first release of NR sidelink transmissions, and thus future enhancements including directional transmission/reception, Mode 2(d) with a scheduling UE, power saving, and MIMO with more layers are projected to be provided in subsequent releases.

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