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Applying Multiradio Access Technologies for Reliability Enhancement in Vehicle-to-Everything Communication

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ABSTRACT The design of the 5G cellular network should take account of the emerging services with divergent quality of service requirements. For instance, a vehicle-to-everything (V2X) communication is required to facilitate the local data exchange and therefore improve the automation level in automated driving applications. In this paper, we inspect the performance of two different air interfaces (i.e., LTE-Uu and PC5) which are proposed by the third generation partnership project to enable the V2X communication. With these two air interfaces, the V2X communication can be realized by transmitting data packets either over the network infrastructure or directly among traffic participants. In addition, the ultra-high reliability requirement in some V2X communication scenarios cannot be fulfilled with any single transmission technology (i.e., either LTE-Uu or PC5). Therefore, we discuss how to efficiently apply multi-radio access technologies (multi-RAT) to improve the communication reliability. In order to exploit the multi-RAT in an efficient manner, both the independent and the coordinated transmission schemes are designed and inspected. Subsequently, the conventional uplink is also extended to the case where a base station can receive data packets through both the LTE-Uu and PC5 interfaces. Moreover, different multicast-broadcast single-frequency network area mapping approaches are also proposed to improve the communication reliability in the LTE downlink. Last but not least, a system level simulator is implemented in this paper. The simulation results do not only provide us insights on the performances of different technologies but also validate the effectiveness of the proposed multi-RAT scheme.

INDEX TERMS 3GPP, 5-G cellular network, automated driving, radio access network, vehicle-to-everything communication.

I. INTRODUCTION

In Europe alone, around 40 000 people die and 1.7 million are injured annually in traffic accidents. Meanwhile, traffic is still growing on our roads, leading increases in traffic jams, travel time, fuel consumption and pollutions [1]. In order to cope with these problems, the cooperative intelligent traffic system (C-ITS) is able to warn drivers of dangerous situations and intervene through automatic braking or steering if the driver is unable to avoid an accident. Besides, cooperative driving applications, such as platooning (road-trains) and highly automated driving can reduce travel time, fuel consumption, and CO_2 emissions while improving road safety and traffic efficiency. The C-ITS relies on a timely and reliable exchange of information among different traffic participants, e.g., vehicles, pedestrians, road-side units (RSUs) and the network.

The local information exchange procedure is often referred to as the vehicle-to-everything (V2X) communication and considered as one of the emerging services for the fifth generation (5G) cellular network [1], [2]. Since the V2X communication requires a low end-to-end (E2E) latency (e.g., below 5 ms) and an ultra-high reliability (e.g., close to 99.999%) [1], the legacy cellular networks (e.g., LTE network) designed for human-driven traffic can not meet these service requirements. Therefore, in order to meet the corresponding demand of V2X communication, intensive research work has been performed to design the 5G network [3].

To support V2X communication with cellular networks, a lot of work in the literature focus on the exploitation of direct V2X communication [4]–[6] where the data packets are directly transmitted from the transmitter (Tx) to the receiver (Rx) without going through the network infrastructure. For instance, the 3rd Generation Partnership Project (3GPP) proposes to use the PC5 interface to facilitate the direct communication between the two ends of a V2X communication link [7] and this wireless link is usually referred to as sidelink (SL). With direct V2X communication, the transmission latency can be efficiently reduced, since network infrastructure is not involved in the user-plane (U-Plane) data transmission. However, it is worth noticing that, the evolution of the legacy 4G network (i.e., LTE network) is also considering to provide V2X communication by transmitting data packets through the cellular network infrastructure [8] where the radio transmission technology relies on the existing LTE-Uu radio interface [9].

In literature, the network performance of V2X communication is restricted by applying a single radio access technology (RAT) (e.g., by transmission over either the LTE-Uu interface or the PC5 interface). However, the ultra-high reliability requirement of V2X communication [10] poses a big technical challenge that cannot be sufficiently overcome by any single RAT in some scenarios [8]. For instance, in order to enhance the perception of the environment to avoid accidents, it is proposed in [10] that a reliability of 99.99% should be supported for message transfer among a group of V2X users (UEs) within a communication range of 500 meters. Therefore, in order to improve the communication reliability, a multi-RAT transmission scheme is proposed in this work to efficiently exploit the transmission diversity. To be more specific, both LTE-Uu and the PC5 interfaces are exploited to transmit the same data packet. Due to the introduced diversity, a higher reliability can be achieved and therefore traffic participants can obtain a better environment perception (e.g., road detection, traffic sign recognition, and vehicle movement). Moreover, we will inspect on the different approaches to facilitate the multi-RAT transmission, since they provide different performance w.r.t. latency, reliability, and signaling overhead.

At the beginning of this work, we inspect on how to apply the LTE-Uu interface and the PC5 interface separately to enable the V2X communication. In Sect. II, the V2X traffic is transmitted through the infrastructure of the 4G network by exploiting the LTE-Uu radio interface. And in Sect. III, the V2X communication takes place directly between two nearby UEs over the PC5 interface which is specifically designed for the proximity services in 3GPP. In order to improve the reliability of V2X communication, the proposed multi-RAT transmission scheme is described in Sect. IV and data packets travel through both the LTE-Uu and PC5 interfaces. In addition, the conventional uplink (UL) transmission over the LTE-Uu interface is extended to a new hybrid uplink scheme in Sect. V, in order to improve the transmission reliability in uplink. Following that, a dynamic multicast-broadcast single-frequency network (MBSFN) area mapping scheme, which takes the current channel state information into account, is proposed in Sect. VI. Following that, the system models which are used to evaluate the different technologies are described in Sect. VII and the simulation results demonstrate the performance comparison of the different transmission technologies. Finally, the conclusion of our work is drawn in Sect. VIII.

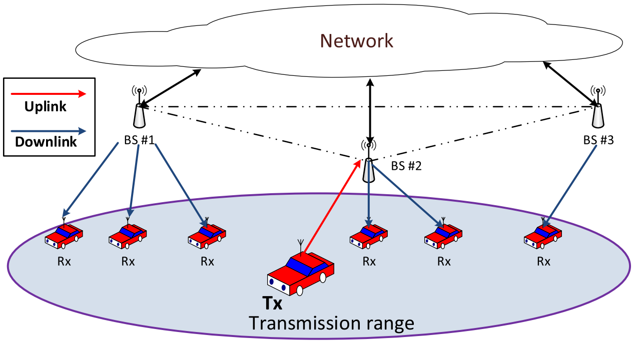


FIGURE 1. V2X communication through the cellular network infrastructure.

II. VEHICLE-TO-EVERYTHING COMMUNICATION THROUGH THE NETWORK INFRASTRUCTURE

Fig. 1 demonstrates the case where the V2X communication is performed over the LTE-Uu interface. LTE-Uu interface is the air interface between the base station (BS) and its serving UEs in the legacy LTE network. With this transmission technology, the vehicle Tx sends its data packets to the BS in uplink. And upon the successful reception, the network further forwards the packets to the relevant Rxs in downlink (DL). In order to assist cooperative driving, the packets are intended to be received by the traffic participants within a certain radius of the Tx. Therefore, if these users are served by different BSs, the transmission of a single packet in downlink can involve more than one BSs. As shown in Fig. 1, the network needs to route the received message from the BS #2 to the BSs #1 and #3, in order to distribute the received packet to all the relevant Rxs. Based on the above statement, the U-Plane E2E latency, which is the one way transmission time of a packet between the Tx and Rx, composes of three components, as listed below.

- Uplink latency - the time difference between the generation of a packet at the Tx and its successful reception by the serving BS.
- Propagation latency between BSs - the packet propagation time between the serving BS of the Tx and the serving BS of one Rx.
- Downlink latency - the time difference between the packet arrives at the serving BS of the Rx and its successful reception at the Rx.

In the rest of this section, we provide more insights into these components. Please note that the E2E latency in this work is inspected in the U-Plane and therefore the control-plane (C-Plane) functions (e.g., radio resource control (RRC) state transition, system information acquisition, and mobility control) are not considered here. Additionally, before a UE starts its communication with the network, a connection with the network in C-Plane needs to be established. This connection establishment procedure includes several steps to be executed by the UE [11] (e.g., being synchronized with the network, obtaining the network configuration by receiving the master information block (MIB) and system information blocks (SIBs), and performing the random access procedure). Please note that it is assumed in this article that the connection to the network is already established in case LTE-Uu interface is applied for V2X communication, as it is not the main focus of our work.

A. UPLINK TRANSMISSION LATENCY

The uplink transmission in LTE system refers to a point-to-point (P2P) communication process. Here, we highlight some critical aspects if the LTE-Uu interface is applied for the uplink transmission.

1) RESOURCE SCHEDULING

Before a Tx starts its transmission in uplink, it needs to obtain the scheduling information regarding the time-and-frequency resource for its transmission. In LTE network, two scheduling schemes (i.e., dynamic scheduling and semi-persistent scheduling (SPS)) can be applied to assign the transmission resource for V2X communication. In the dynamic scheduling procedure, the Tx needs to send a scheduling request (SR) message to the BS, once a data packet arrives at its buffer. After that, the network will schedule certain resource and send this configuration information in the downlink control information (DCI) back to the Tx. With this information, the Tx can find the time-and-frequency location for its transmission. However, this dynamic scheduling approach is not efficient for the V2X communication in some cases. For instance, in order to support for vehicle platooning where a group of vehicles is operated in a closely linked manner and the vehicles move like a train, the V2X packets need to be periodically transmitted with a frequency up to 40 Hz [10]. Thus, in this case, a Tx needs to send an SR message for every packet and a high signaling overload can be foreseen with the dynamic scheduling scheme. Alternatively, with the SPS scheme, the network is able to assign a set of time-periodic resources to a V2X Tx. Therefore, once the Tx obtains the SPS configuration information, it can periodically transmit its data without triggering another resource request procedure. Compared with the dynamic scheduling approach, the SPS approach has a better support for the periodical traffic of V2X communication due to its less signaling overhead.

2) HARQ TRANSMISSION

As pointed out before, a P2P communication is applied in uplink. Thus, depending on whether a packet is successfully received or not, either an acknowledgment (ACK) or a non-acknowledgment (NACK) message is sent back from the Rx to the Tx. In case a packet reception is failed, the NACK message triggers a hybrid automatic repeat request (HARQ) procedure where a retransmission will be executed by the Tx. With the retransmission, the Rx can utilize both the previously received packet and the retransmitted packet to correct the error. It is worth noticing that, according to the protocol of LTE, the minimal time interval between the end of a packet transmission and the start of its retransmission is set to be 7 ms. In order to meet the low latency requirement of V2X communication, it is currently under the consideration of 3GPP to reduce this minimal retransmission interval.

3) MODULATION AND CODING SCHEME

In order to guarantee a robust transmission, a modulation and coding scheme (MCS) with a low spectral efficiency is required. In LTE system, if the channel state information (CSI) is available at the Tx, the Tx selects the MCS which has the highest spectral efficiency and meanwhile offers a block error rate (BLER) lower than 10%. The consideration of LTE system is to find a good compromise between spectral efficiency and robustness, w.r.t. the human-driven traffic. However, due to the ultra-high reliability requirement in the emerging V2X communication services, the optimal selection of an MCS is related to the service requirements. For example, an MCS with good robustness should be selected for the services which require a low E2E latency, in order to avoid retransmissions.

B. PROPAGATION LATENCY BETWEEN THE RELEVANT BASE STATIONS

As shown in Fig. 1, an uplink received packet needs to be routed through the network to other relevant BSs before the transmission in downlink starts. This procedure refers to a point-to-multipoint (P2MP) transmission in the core network of an operator. An efficient way to realize this P2MP transmission is to apply the multimedia broadcast multicast services (MBMS) which is a P2MP interface specification [12]. And it is able to provide efficient delivery of broadcast and multicast services in the core network. Compared with the system architecture used for the P2P transmission, two additional components (i.e., Broadcast Multicast - Service Center (BM-SC) and MBMS-GW in [13]) are deployed in the core network. The BM-SC is responsible for the management of the MBMS service-related information, e.g., mapping the service information to the QoS parameters. And the MBMS-GW is the element to deliver MBMS traffic to multiple cell sites. Considering that the V2X communication requires a low latency and the Rxs are the traffic participants located in the geometrical proximity of the Tx, it has been proposed in 3GPP to localize certain functional entities of the MBMS architecture at the edge of the radio access network (RAN) [8].

C. DOWNLINK TRANSMISSION LATENCY

In downlink, two options exist to realize the V2X communication. One option is to apply a unicast transmission where one packet is transmitted to multiple Rxs in parallel. For instance, as shown in Fig. 1, the BS #1 applying the unicast transmission in downlink needs to send the same data packet for three times and each time targets at a specific Rx. However, this approach is not efficient for V2X communication in many cases. For instance, during the busy hours of a day, a high density of traffic participants can be expected and therefore the unicast transmission in downlink can easily overload the network. To solve this problem, applying a multicast transmission provides an efficient alternative to V2X communication in downlink.

As a specification of the LTE-Uu air interface, the MBMS can also be applied to multicast the same content to multiple Rxs. Therefore, this P2MP transmission scheme offers a good efficiency for the transmission of common contents. However, in order to successfully deliver one packet to multiple Rxs, the MBMS needs to apply an MCS by taking account of the Rx which experiences the worst radio channel condition. In this sense, a compromise between the spectral efficiency and the robustness needs to be achieved for the MBMS. Another character of the MBMS is the absence of the feedback channel and this means there is no ACK/NACK message sent back from a Rx to the Tx. Otherwise, the feedback messages from the group of the Rxs will introduce a large signaling overhead. Thus, in order to enhance the reliability of the multicast transmission in downlink, the BS can try to repeat the transmission of the same data packet, if there is enough resource available in the system. In this way, a maximal ratio combining (MRC) process can be carried out at the Rx. For instance, if the Rx #n is trying to receive the packet #m in its k-th trial, it will combine all the received copies of this packet. Thus, the signal-to-interference-plus-noise ratio (SINR) can be calculated as:

$$SINR^{MRC}(m,n,k) = \sum_{i=1}^{k} SINR(m,n,i). \tag{1}$$

The term $SINR^{MRC}(m,n,k)$ represents the post-MRC-processed SINR value of the transmitted packet #m at Rx #n after receiving the k-th packet copy. And $SINR(m,n,i)$ is the pre-MRC-processed SINR value of the packet #m at Rx #n for the i-th received copy. From this equation, we can see that the MRC process efficiently improves the SINR value by utilizing the multiple received copies of one packet.

Additionally, when a BS multicasts a data packet to multiple Rxs, the different Rxs will experience different radio propagation conditions. The SINR value, where the i-th Rx is served by the j-th BS, can be calculated as

$$SINR_i = \frac{|h_{i,j}|^2 P_j}{\sum_{k\neq j}(|h_{i,k}|^2 P_k) + \sigma^2}. \tag{2}$$

The $h_{i,j}$ is the channel coefficient between the i-th Rx and the j-th Tx (i.e., the serving BS of the Rx). Besides, the P_j is the transmission power of the j-th Tx and σ^2 denotes the noise power at the Rx. As can be seen here, the Rxs located on the cell border will experience bad channel conditions due to the weak received power of the desired signal and the strong superposed interference. Therefore, extra effort is required to improve the communication reliability for the cell-border Rxs. In LTE network, the multicast-broadcast single-frequency network (MBSFN) is a transmission technology enabling multiple BSs to synchronously multicast the same content. In this approach, the area covered by the synchronized BSs is referred as an MBSFN area. In order to avoid the inter-symbol interference (ISI) in an MBSFN area, the transmissions from the different BSs need to be well synchronized so that the maximal delay spread at a Rx should be within the cyclic prefix (CP) duration of one OFDM symbol. In this manner, the received signals can be constructively superposed at the Rx #i and its effective SINR can be calculated as:

$$SINR_i = \frac{\sum_{j\in MBSFN}(|h_{i,j}|^2 P_j)}{\sum_{k\notin MBSFN}(|h_{i,k}|^2 P_k) + \sigma^2}. \tag{3}$$

The term $j \in MBSFN$ represents the synchronized BSs belonging to an MBSFN area and '$k \notin MBSFN$' are the interfering BSs out of the MBSFN area. By comparing this SINR value with the one calculated in (2), it can be seen that the MBSFN enables a Rx to utilize the signals received from other synchronized BSs, instead of considering them as interference.

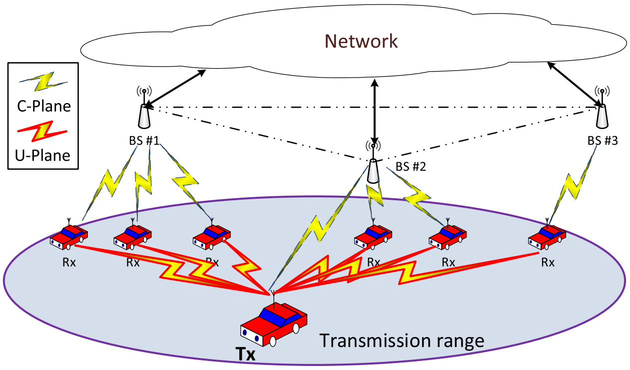


FIGURE 2. Direct V2X communication with network assistance.

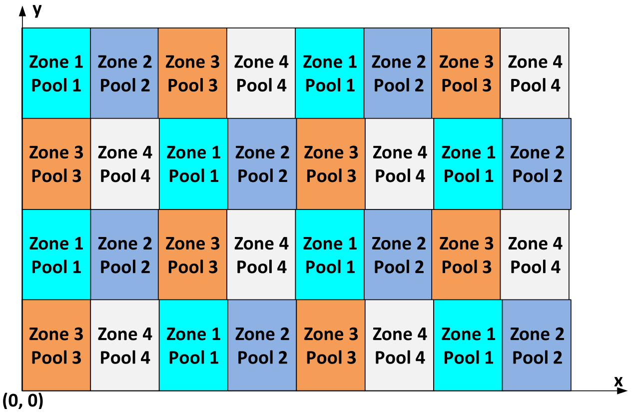
III. DIRECT VEHICLE-TO-EVERYTHING COMMUNICATION

As mentioned in Sect. I, V2X communication refers to a local information exchange procedure and the relevant Rxs are the ones located in the proximity of the Tx. Therefore, a packet transmission through the network infrastructure is not efficient from the latency perspective. With this motivation, a direct V2X communication scheme has been proposed in 3GPP [7]. In this mode, the Tx directly transmits its data packets to the surrounding Rxs in U-Plane, as shown in Fig. 2. Please also note that the UEs can establish a C-Plane connection with the network over the LTE-Uu interface and the direct V2X communication is w.r.t. the U-Plane transmission.

In 3GPP, the direct communication link between the two UEs is called as sidelink and the applied air interface is the PC5 interface [7]. Up to 3GPP release 14, the sidelink communication is connection-less which means there is no

RRC connection over the PC5 interface. In this way, a V2X Tx multicasts its data packets to the surrounding Rxs and a Rx will discard a received packet if it locally finds the packet is irrelevant.

Currently, there are two modes defined in 3GPP [14] to assign radio resource to V2X Txs. The sidelink transmission mode 3 corresponds to a sidelink transmission over the resource scheduled by the BS. In this mode, the V2X Tx needs to be in the RRC_connected state and it sends a Sidelink UE Information message to the BS for resource request. The RRC_connected state is a state where the UE has already established the connection with the network in the C-Plane. Correspondingly, the RRC_idle state is a state where the RRC connection to the network is not established (e.g., when a UE is just powered on). In sidelink transmission mode 3, the BS schedules certain resource upon receiving the resource request message and sends this information back to the Tx in the DCI. It is worth mentioning that the SPS introduced in Sect. II-A.1 can also be applied for the sidelink communication and therefore the Tx can exploit the time-periodic resource to transmit its periodical packets. To assist the resource allocation procedure at the BS, UE context information (e.g., traffic pattern, geometrical information) can be reported to the BS. In another case, the sidelink transmission mode 4 can be applied for V2X UEs in RRC_idle state or V2X UEs out of the cellular network coverage. In this mode, the information of the resource pools w.r.t. V2X communication is either broadcasted in the system information blocks (SIBs) [15] or pre-configured at the V2X UEs. And a V2X Tx can autonomously select a resource from the resource pool for its transmission over the PC5 interface. Meanwhile, in order to control interference, the BS can use SIB 21 to broadcast the information regarding how to map from a geometrical zone to the transmission resource pool [15], as shown in Fig. 3. Therefore, the V2X UE under cellular coverage can read this broadcasted system information without entering the RRC_connected state. It can be seen from the figure, in this scheme, the world is divided into different zones. At a V2X UE, it determines the index of the zone in which it locates, by means of modulo operation using its own geo-location and the information provided by the eNB (e.g., length and width of a zone, number of zones in length, number of zones in width, and a reference point with coordinates of (0, 0)). In addition, to reduce the inter-zone interference and avoid two desired V2X packets colliding at one Rx, different transmission resource pools are assigned by the network to two nearby zones. After obtaining the information of the transmission resource pool, a V2X Tx in sidelink transmission mode 4 autonomously selects a resource from the assigned resource pool and proceeds with its transmission. The resource selection can be carried out either randomly or by performing a channel sensing procedure beforehand [15]. In case a V2X Tx is out of the cellular network coverage, the mapping information from geometrical zone to transmission resource pool can be pre-configured in the UE.



Zone 1 Pool 1	Zone 2 Pool 2	Zone 3 Pool 3	Zone 4 Pool 4	Zone 1 Pool 1	Zone 2 Pool 2	Zone 3 Pool 3	Zone 4 Pool 4
Zone 3 Pool 3	Zone 4 Pool 4	Zone 1 Pool 1	Zone 2 Pool 2	Zone 3 Pool 3	Zone 4 Pool 4	Zone 1 Pool 1	Zone 2 Pool 2
Zone 1 Pool 1	Zone 2 Pool 2	Zone 3 Pool 3	Zone 4 Pool 4	Zone 1 Pool 1	Zone 2 Pool 2	Zone 3 Pool 3	Zone 4 Pool 4
Zone 3 Pool 3	Zone 4 Pool 4	Zone 1 Pool 1	Zone 2 Pool 2	Zone 3 Pool 3	Zone 4 Pool 4	Zone 1 Pool 1	Zone 2 Pool 2

FIGURE 3. An example of mapping from geo-location to geometrical zone and the corresponding transmission resource pool.

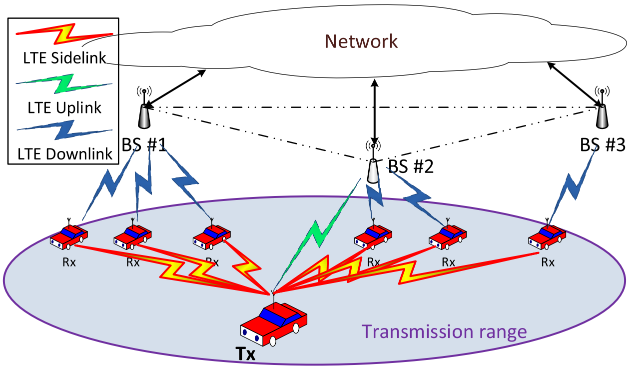


FIGURE 4. V2X communication over both LTE-Uu and PC5 in U-plane.

As mentioned before, the V2X transmission over PC5 is in a multicast manner and therefore there is no HARQ feedback from Rxs back to the Tx. In order to improve the reliability, a blind retransmission scheme can be applied where the identical copies of the original transmission will be multicasted. Corresponding to the blind retransmission scheme, Rxs perform the soft-combining of all received copies.

IV. RELIABILITY IMPROVEMENT BY APPLYING MULTI-RAT

The design of V2X communication should meet the requirements in the real world. In [10], the requirements of V2X communication in different use cases are proposed by 3GPP. For instance, in order to facilitate a fully automated driving, V2X communication with a reliability value of 99.99% within a range up to 500 meters is required. The reliability is defined here as the successful packet reception ratio (PRR) within a required latency range (e.g., 100 ms). Later in Sect. VII, where the system performance is evaluated, we will see it is challenging in some cases to fulfill the ultra-high reliability requirement by applying a single RAT. Therefore, a multi-RAT scheme is proposed in this section to enhance the reliability of V2X communication. Fig. 4 demonstrates the proposed reliability enhancement scheme where a V2X data packet is transmitted through both the LTE-Uu and PC5 interfaces. Compared with the schemes shown in Fig. 1 and Fig. 2, a Rx in the proposed multi-RAT scheme receives the same content of V2X data packets from two different air interfaces (i.e., the LTE-Uu and the PC5). Please note that the proposed multi-RAT transmission scheme requires additional resource compared with a single-RAT scheme. Actually, in real system design, it is considered as one of the effective approaches to improve reliability by consuming additional resource. For instance, the multi-connectivity concept which enables a bearer split with duplication for transmit diversity by using additional resource in 5G [16], can improve the robustness of mission-critical communication. In addition, the soft handover approach introduced in CDMA standard allows a user device to be simultaneously connected to multiple cells and to simultaneously receive signals from different cells. In this approach, some additional resource is also required to support the soft handover procedure to achieve a better reliability.

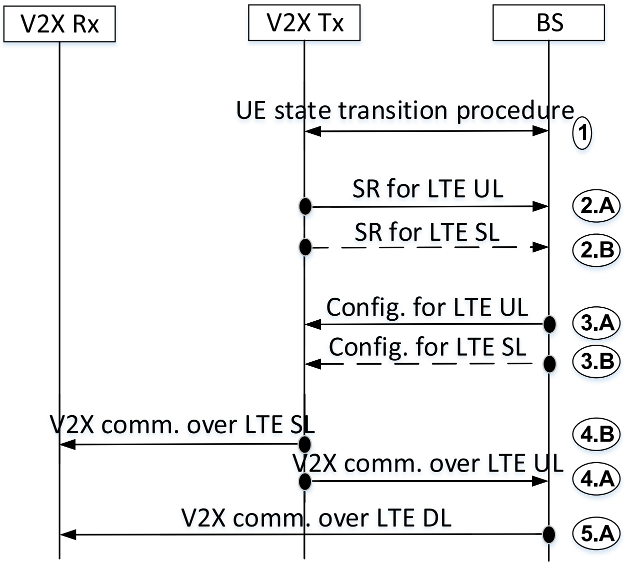


FIGURE 5. **Signaling diagram for independent multi-RAT transmission over LTE-Uu and PC5.**

A. INDEPENDENT TRANSMISSION OVER LTE-UU AND PC5

In order to send an SR message to the BS for uplink resource acquisition, the V2X Tx needs to be in the RRC_connected state. Therefore, the V2X Tx in the proposed multi-RAT scheme needs to enter the RRC_connected state before the start of its transmission over LTE-Uu, though the sidelink transmission over PC5 can support V2X Txs in both RRC_connected state (i.e., by sidelink transmission mode 3) and RRC_idle state (i.e., by sidelink transmission mode 4). The current standardized approach from 3GPP [11] enables an independent multi-RAT transmission over both LTE-Uu and PC5. In Fig. 5, the signaling diagram to support the independent V2X transmissions over both PC5 with transmission mode 3 and LTE-Uu is shown. As the first step, the V2X Tx can decide to apply the multi-RAT transmission scheme if the V2X communication service requires an ultra-high reliability. Following that, the V2X Tx in RRC_idle state needs to transit to the RRC_connected state and therefore the connection establishment procedure needs to be performed. Afterwards, the V2X communication can be independently performed over LTE-Uu and PC5, with details listed below.

- For communication over the LTE-Uu interface, the Tx sends an SR message to the BS and then the BS sends the resource configuration information back to the Tx. Afterwards, the Tx can send its packet in LTE uplink. After the BS successfully receives the packet, the packet will be further forwarded to other relevant BSs and then sent in downlink to the respective Rxs as stated in Sect. II.
- For communication over the PC5, as the sidelink transmission mode 3 is applied, the Tx sends a Sidelink UE information message to the BS to request sidelink transmission resource. Once the transmission resource information is available at the Tx, it multicasts the V2X message over the PC5 interface.

In order to differentiate the steps used for communication over LTE-Uu and PC5, different letters ‘A’ and ‘B’ are attached to the end of the sequential indexes in Fig. 5. The sequential indexes ended with a letter of ‘A’ and a letter of ‘B’ are used to refer to the communication steps over LTE-Uu and PC5 respectively. Please also note that these two letters are applied in the rest of this work with the same intention. As the communications over the two interfaces will take place independently, there is no sequential relationship between any two steps from two different RATs. For instance, the V2X Tx might transmit the SR message for LTE uplink (i.e., step 2.A) after the transmission over the PC5 (i.e., step 4.B) has ended. In addition, the above signaling scheme corresponds to a case where a V2X packet arrives at the buffer of the Tx and there is no granted resource at the Tx. This can refer to the cases where the V2X Tx initiates a new data transfer or the SPS configuration information has expired.

B. COORDINATED TRANSMISSION OVER LTE-UU AND PC5

The independent multi-RAT transmission scheme introduced in the previous subsection has a drawback that two scheduling request procedures need to be conducted, in order to obtain the resource configuration for the two different air interfaces. Therefore, it can introduce a large signaling overhead for V2X communication, especially for the cases where dynamic scheduling approach is applied or the resource configured by the SPS is not valid anymore. In addition, the event-driven type of traffic in V2X communication refers to the emergency messages sent out by a traffic participant if certain hazardous situations are detected. In this case, since a V2X Tx needs to dynamically request for transmission resource, a large signaling overhead can also be foreseen. In order to reduce the signaling effort, another multi-RAT transmission approach is

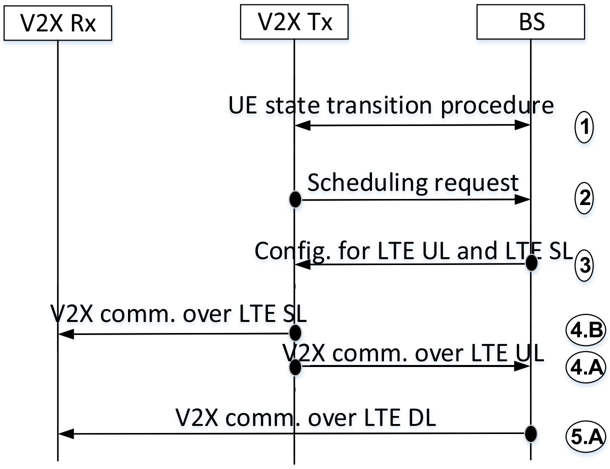


FIGURE 6. Signaling diagram to support the coordinated multi-RAT transmission.

proposed and shown in Fig. 6 to enable a coordinated packet transmission over LTE-Uu and PC5. As the first step, the V2X Tx needs to enter the RRC_connected state and establish a connection with the network. Afterwards, the V2X Tx sends an SR message to the network for resources configuration. Since this step relates to the decision of whether applying a single-RAT or multi-RAT transmission, there are two options to facilitate this step, as listed below.

1) The first option is that the V2X Tx sends a message to the BS for resource scheduling. In addition to that, the traffic profile information (e.g., traffic type, QoS requirement) is also embedded in this message. Therefore, based on the collected information, the BS analyses and checks whether a multi-RAT transmission should be applied to improve the communication reliability. If a multi-RAT transmission scheme is decided, the BS sends the configuration information back to the V2X Tx where the transmission resource information for both LTE-Uu and PC5 are carried.
2) The second option is to perform an analysis locally at the V2X Tx to derive the decision regarding the most appropriate transmission scheme. If a multi-RAT transmission scheme is selected by the V2X Tx, it sends an SR message to acquire for resources over both LTE-Uu and PC5. In this message, certain context information (e.g., the geometrical position of the Tx, the cellular pathloss value) can be carried. With the help of the information, the BS can perform an efficient resource scheduling for the different interfaces and send the configuration information back.

After obtaining the configuration information for both LTE-Uu and PC5, the V2X Tx can start its multi-RAT transmission.

Compared with the independent multi-RAT transmission approach, this coordinated approach has the advantages that only one SR message needs to be sent to the BS and the BS can jointly schedule the transmission resources for both the LTE-Uu and PC5 interfaces. Therefore, the signaling overhead can be efficiently reduced while providing a coordinated multi-RAT support to improve the communication reliability. Please note, the low signaling overhead is an advantage of the coordinated transmission scheme in the C-Plane. In the U-Plane, the performance of the different schemes (i.e., independent transmission and the coordinated transmission) will be the same since they both transmit a packet over the LTE-Uu and PC5 interfaces. In Sect. VII, the U-Plane performance of the two proposed multi-RAT schemes will be provided. To be specific, in the downlink of the LTE-Uu interface, both unicast and multicast transmission modes are inspected and they are respectively labeled as ‘direct V2X + unicast’ and ‘direct V2X + multicast’ in Fig. 15, Fig. 16, and Fig. 17.

V. HYBRID UPLINK

Comparing to the single RAT transmission, a larger spectrum resource is required in the multi-RAT scheme due to the fact that both the LTE-Uu interface and the PC5 interface carry the same data packet content. However, as the spectrum resource allocated to an operator is limited, an efficient spectral usage is essential for V2X communication.

A. HYBRID UPLINK PROCEDURE: EXPLOITING THE TRANSMISSION OVER PC5 INTERFACE

As mentioned before, the sidelink transmission over the PC5 interface enables a local data exchange. Compared with the Rxs far away from the Tx, the Rxs located near the Tx will experience statistically better reliability for sidelink communication due to the better radio condition. Moreover, the low E2E latency achieved by the sidelink communication helps the V2X Rxs to take their actions in a timely manner. Thus, the sidelink communication over PC5 is of high importance for the Rxs within a short range of the Tx, as they are quite vulnerable and demand a low latency and high reliability for the V2X communication. So far, the communication between a traffic participant and a BS takes place over the LTE-Uu interface, whereas the sidelink communication is used to facilitate the communication among different traffic participants (e.g., vehicles, pedestrians, and RSUs) [8]. However, there is always a possibility that the transmitted signal over sidelink can arrive at the BS with certain signal power strength. This provides the opportunity for the network to receive the data packet without using the uplink spectrum. A pre-request, in this case, is that a BS should be equipped with the capability to receive data packets over PC5. Please note that a V2X UE is proposed by 3GPP to have the feasibility to transmit over both the LTE-Uu and PC5 interfaces [8]. Therefore, to equip a BS with the transmission capability over PC5 will not be an implementation problem. In addition, it is proposed in 3GPP that a stationary infrastructure (e.g., road side unit) can receive V2X messages via different interfaces (e.g., PC5 or LTE-Uu) depending on implementation option [17].

In Fig. 7, the multi-RAT scheme is shown where a BS tries to receive the V2X packets over the PC5 interface. For

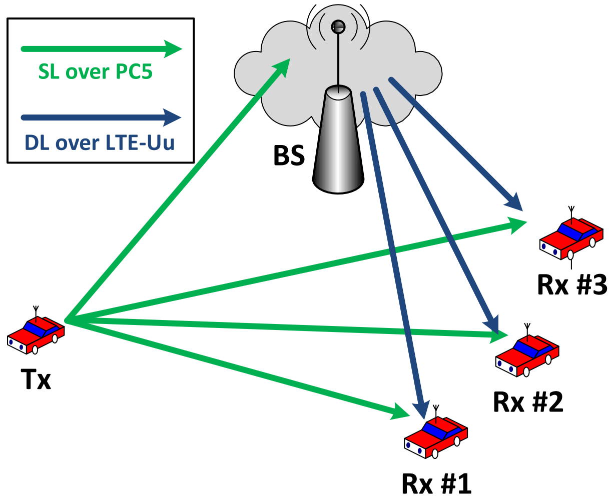


FIGURE 7. V2X communication where the network receives V2X packets via PC5 interface.

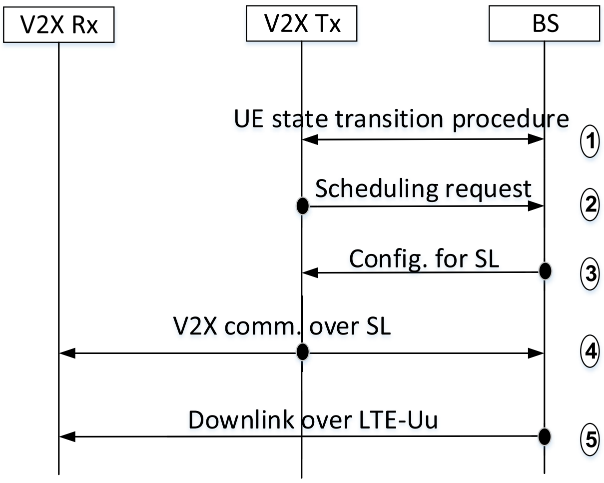


FIGURE 8. Signaling diagram to enable multi-RAT V2X communication where the BS receives data packets from PC5.

simplicity, only one BS is plotted in this figure. Once the vehicle Tx transmits its data packets over the PC5 interface, the packets do not only arrive at the vehicle Rxs, but they can also arrive at the BS. The BS equipped with sidelink communication capability can successfully receive the packets if the received signal quality is good enough. After that, the received packets will be transmitted through the network and be delivered to other relevant BSs for their downlink transmissions over LTE-Uu, as introduced in Sect. II-C. In addition, Fig. 8 shows the corresponding signaling diagram to support this scheme. Compared with the scheme shown in Fig. 6, the BS in this scheme will only provide the Tx with the resource configuration information for the sidelink communication. Correspondingly, the V2X data packets will be transmitted to the BS over the sidelink communication where the BS can be considered as one of the normal Rxs. Once a packet is successfully received by the BS, network can proceed with its downlink transmission by using the LTE-Uu interface, as stated in Sect. II-C.

Compared with the scheme shown in Fig. 6, the advantage of this proposed scheme is that no LTE uplink resource will be required and V2X packets are simply transmitted to the network over the sidelink resource. This procedure of using PC5 interface for transmission towards the BS is different from the conventional uplink procedure where LTE-Uu interface is applied. Thus, the conventional uplink procedure needs to be extended. In this article, a term of 'hybrid uplink' is used to represent the case where both the LTE-Uu and PC5 interfaces can be considered as options for the transmission from a UE to the BS. However, as the communication over PC5 interface corresponds to a P2MP transmission scheme and no ACK/NACK message will be fed back from a Rx to the Tx, the reliability of the sidelink transmission from a vehicle Tx to the BS can not be always guaranteed.

Please note that the above-proposed hybrid uplink transmission over PC5 is labeled as 'PC5 for uplink' in Fig. 18 and Fig. 19 where its performance will be provided.

B. HYBRID UPLINK: MULTI-RAT TO IMPROVE RELIABILITY

If a data packet is transmitted through the network infrastructure, the V2X communication is composed of two radio transmission hops, i.e., uplink and downlink. Since the downlink transmission will take place only if the uplink transmission is successful, a packet not successfully delivered in uplink will introduce a serious performance degradation. For instance, as shown in Fig. 7, if a packet is failed in its transmission from the vehicle Tx to the BS, it can not be further transmitted to the Rxs in downlink. Therefore, a PRR of 0% can be foreseen for this packet transmission, regardless of the performance in downlink. In another case where the packet can be successfully received at the BS and one downlink transmission fails, the PRR can still reach 66.67%. Therefore, a packet transmission failure in uplink causes a more serious performance degradation than a failure in downlink w.r.t. the PRR, and extra effort should be spent to enhance the reliability of uplink transmission.

As introduced in Sect. V-A, the hybrid uplink scheme is able to exploit both the LTE uplink and sidelink technologies for the transmission from a Tx to its serving BS. Thus, a multi-RAT transmission scheme shown in Fig. 9 can be applied for uplink transmission to enhance the communication reliability. As can be seen from the figure, a Tx will transmit its data packets to the BS over both the LTE-Uu and PC5 interfaces and this is the difference from the scheme shown in Fig. 7. In this scheme, the uplink transmission over PC5 is performed as a multicast transmission where the BS acts as one of the ordinary Rxs. Therefore, only the uplink transmission over LTE-Uu requires a dedicate resource.

C. COORDINATION BETWEEN DIFFERENT RATS IN HYBRID UPLINK

In order to efficiently support the hybrid uplink transmission over both the LTE-Uu and PC5 interfaces, as shown in Fig. 9, two different signaling schemes are proposed in this work.

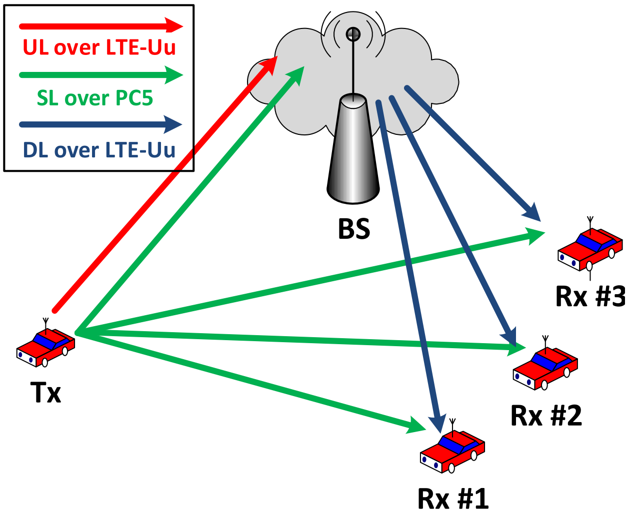


FIGURE 9. V2X communication where the network receives V2X packets via both the PC5 and LTE-Uu uplink interfaces.

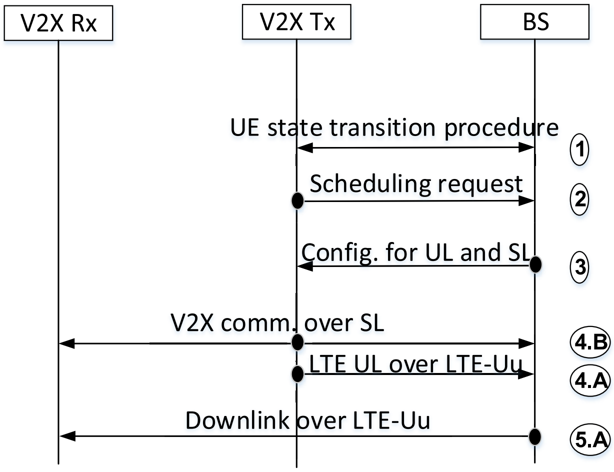


FIGURE 10. Signaling diagram to support the independent hybrid uplink transmission scheme.

1) INDEPENDENT HYBRID UPLINK TRANSMISSION SCHEME

In this approach, both the LTE uplink and sidelink in Fig. 9 will be independently configured for packets transmitted to the BS. Correspondingly, the signaling diagram is given in Fig. 10. Being independently configured, both transmissions over LTE uplink and sidelink can take place immediately after obtaining the configuration information from the BS. And the BS will try to receive data packets from both the uplink and sidelink interfaces. In this article, we name this scheme as the independent hybrid uplink transmission scheme.

2) SEQUENTIAL HYBRID UPLINK TRANSMISSION SCHEME

The independent hybrid uplink transmission scheme has the advantage of configuring the resource for LTE uplink and sidelink in a flexible way. However, as the LTE uplink is always applied to provide a diversity gain regardless of whether packages are successfully received by the BS from the LTE sidelink or not, a large resource for LTE uplink is required. In order to counter this, the BS can sequentially trigger the LTE uplink transmission if the BS does not successfully receive a data packet from the sidelink. The signaling diagram to support this sequential hybrid uplink transmission scheme can be seen in Fig. 11. After the network connection establishment procedure, the V2X Tx sends an SR message to the BS and the BS will reply with the resource configuration information for the sidelink communication. Based on the received configuration information, the V2X Tx transmits its data packets over sidelink. Together with other Rxs located in the proximity of the Tx, the BS will try to receive the transmitted packets from the sidelink. In case the BS fails in receiving a packet from the sidelink, it sends a message back to the Tx to trigger a transmission over the LTE-Uu uplink. And in this message, the configuration information for LTE-Uu is also embedded. Following that, the packet can be transmitted from the Tx to the BS in LTE-Uu uplink and then it will be delivered to the V2X Rxs in downlink. In case a packet is successfully received by the BS from sidelink communication, the LTE uplink transmission will not be triggered and the signaling diagram will be the same as the one shown in Fig. 8.

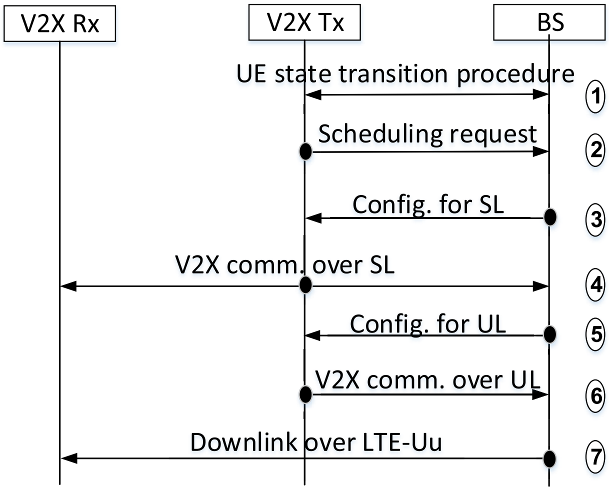


FIGURE 11. Signaling diagram to support the sequential hybrid uplink transmission scheme.

Since the LTE-Uu uplink corresponds to a P2P transmission, its MCS can be adjusted based on the estimated channel quality. However, as the MCSs in LTE are designed to operate within certain signal-to-interference-plus-noise-ratio(SINR) range, there is a chance that an LTE uplink channel experiences an SINR value which is even worse than the lower bound of the operation range and therefore none of the MCSs can provide a good robustness. To solve this problem, the Tx needs to select the most robust MCS and perform blind retransmissions of the same packet over LTE-Uu uplink. At the receiving end, the BS performs the MRC procedure to enhance the reliability of the LTE-Uu uplink. Please note that the effective SINR value by performing the MRC procedure has been calculated in Eq. (1).

As the blind retransmission scheme introduces a transmission redundancy, additional frequency resource is required. However, in the sequential hybrid uplink transmission scheme, since only the packets which are not successfully received from sidelink will be triggered for transmission over LTE-Uu uplink, there are fewer packets transmitted over LTE-Uu uplink compared with the independent hybrid uplink transmission scheme. In other words, more resource will be available for a single packet transmission over the LTE-Uu uplink in the sequential hybrid uplink transmission scheme and it enables the blink retransmission scheme. On the other hand, the packet E2E latency in the sequential transmission scheme can be large since the LTE-Uu uplink transmission is carried out sequentially after the sidelink transmission. Thus, compared with the independent hybrid uplink transmission scheme, an additional delay component for LTE uplink transmission is deduced and it corresponds to a round trip time of the sidelink communication. In details, this additional delay is composed of a packet transmission time, a time duration of two processing procedures, and a signaling message transmission time. The packet transmission duration is related to many parameters (e.g., the packet size, the efficiency of the applied MCS and the number of copies retransmitted blindly). Additionally, a duration of 3 ms is reserved for a processing procedure in LTE and the transmission duration of a signaling message can be 1 ms. Therefore, the proposed sequential transmission scheme introduces a minimal additional delay of *7 ms + the packet transmission duration*, compared with the independent hybrid uplink transmission scheme.

Please note that the independent hybrid uplink transmission scheme and the sequential hybrid uplink transmission scheme proposed in this subsection are respectively labeled as 'PC5 + LTE-Uu for uplink' and 'PC5 + enhanced LTE-Uu for uplink' in Fig. 18 and Fig. 19.

VI. FAST MBSFN AREA MAPPING

As introduced in Sect. II-C, an MBSFN area is a collection of cells where the same content will be multicasted in a synchronous manner. With this approach, the effective SINR values (i.e., calculated in Eq. (3)) experienced by the V2X Rxs in downlink can be improved. Since V2X communication has an ultra-high reliability requirement, the improvement of the radio condition is very critical, especially for the Rxs located on the cell border. However, an MBSFN area can not be arbitrarily large since that will bring certain drawback. For instance, as the transmissions from different BSs will introduce different propagation delays, a large MBSFN area causes a large delay spread at the Rx. In this case, in order to avoid the ISI, a longer cyclic prefix duration is required which will further decrease the transmission efficiency. Therefore, the size of an MBSFN area has clearly an impact on the system performance. In this work, the size of an MBSFN area is restricted to the coverage area of three cells and the Rxs out of the MBSFN area are served only by their serving cells.

In order to carry out the MBSFN procedure, a BS needs to forward its received data packets to the V2X server which will process the data and further distribute to all locally connected vehicle UEs [18]. Therefore, the V2X server will analyze the context information (e.g., user position, cell ID) carried in each data packet to derive the MBSFN area. Once the MBSFN area is decided, the network forwards the packet to all the relevant BS(s). To reduce the latency of a packet traveling through all relevant components in the core network, a fast MBSFN area mapping procedure which enables a local data exchange among different BSs is critical for V2X communication. In Fig. 12 and Fig. 13, two different schemes are proposed to implement the MBSFN area mapping. In these figures, we consider a cell layout of three sectors per BS and the cells with the same color form an MBSFN area. Further, it is assumed that the V2X Tx is located in the coverage area of cell #1 and served by the BS #1. The two proposals for MBSFN area mapping are detailed below.

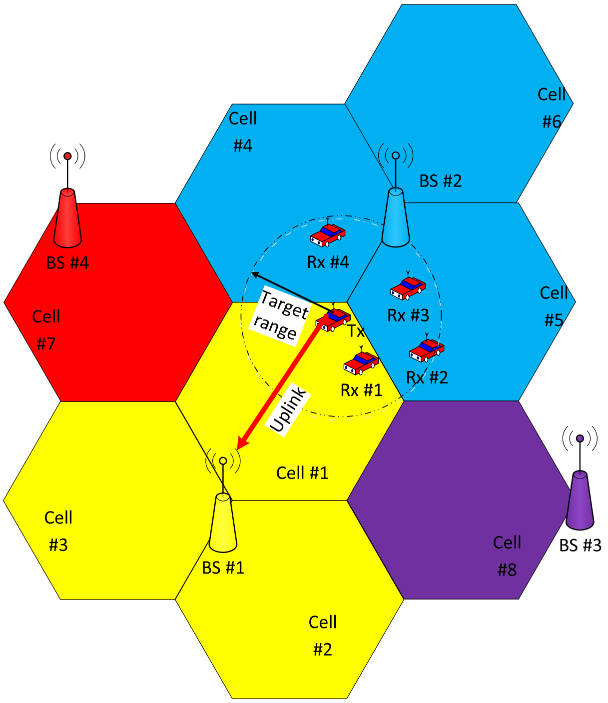


FIGURE 12. Fixed MBSFN area mapping based on the serving cell index.

- **Fixed MBSFN area mapping based on the serving cell index**: Upon the successful packet reception in uplink, the packet is synchronously transmitted by the BS #1 over its three cells (i.e., cells #1, #2 and #3 in Fig. 12). In this approach, an MBSFN area simply refers to the coverage area of the cells operated by the serving BS of the Tx.
- **Dynamic MBSFN area mapping based on channel estimation**: By performing channel estimation, the V2X Tx can be aware of the propagation conditions from the different cells. Thus, when a V2X Tx transmits its data packet to the BS, it also indicates the indexes of the three cells with the best channel conditions (i.e., the cells #1, #4 and #5 in Fig. 13) and these cells create the MBSFN area for packets generated by

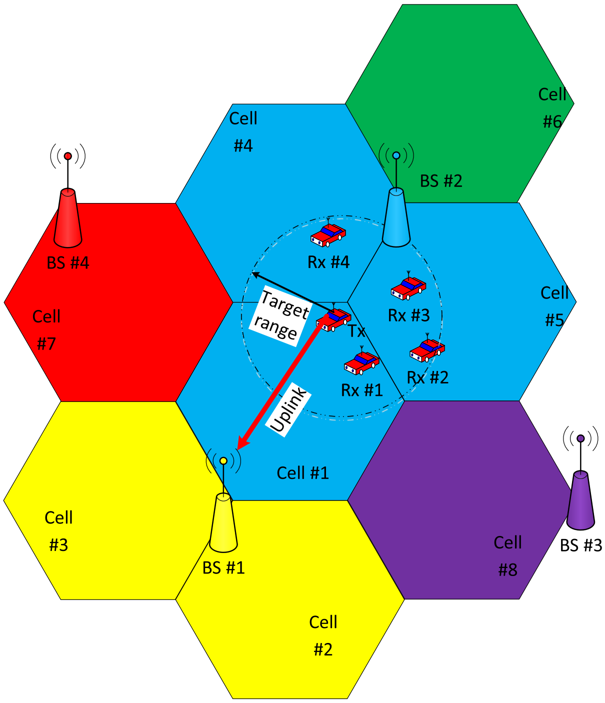


FIGURE 13. Dynamic MBSFN area mapping based on channel estimation.

the V2X Tx. Once a packet of the V2X Tx is successfully received by the BS #1, the packet will be directly routed from BS #1 to BS #2 and multicasted in cells #1, #4 and #5 in a synchronous manner. In this scheme, an MBSFN area refers to the coverage area of the cells which provide the best channel conditions to the V2X Tx.

In the first proposal, the function to coordinate resource usage among different BSs can be deployed at the edge of the RAN (e.g., at the BS). Thus, this proposal can simplify the network architecture to support MBSFN without requiring a tightly synchronized transmission over different BSs. In comparison, the second proposal poses higher complexity on the network. At first, context information (i.e., the channel situation experienced from different BSs) is required to derive an MBSFN area. In addition to that, a packet needs to be routed dynamically from one BS to another one and a synchronized transmission over the time-and-frequency domain has to be achieved among different BSs. However, as shown in Fig. 13, the synchronized transmission signals from cells #1, #4 and #5 can contribute to higher SINR values for the V2X Rxs located on the border of these cells. To be noticed, these V2X Rxs are located most closely to the V2X Tx and an ultra-high communication reliability is targeted. Thus, the higher SINR values can contribute to better transmission robustness for these Rxs.

Please also note, in Sect. VII, the two above proposed MBSFN area mapping approaches are applied along with the direct V2X communication over PC5 to inspect the performance of the corresponding multi-RAT technology. And they are labeled as 'direct V2X + fixed MBSFN' and 'direct V2X + dynamic MBSFN' in Fig. 15, Fig. 16, and Fig. 17 respectively.

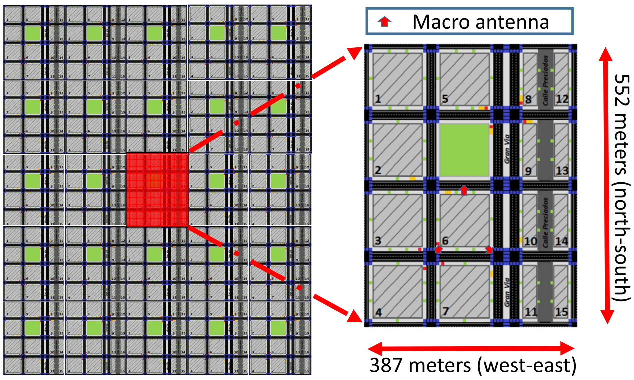


FIGURE 14. Environment model.

VII. SYSTEM MODELS AND NUMERICAL RESULTS

In order to evaluate the proposed technologies, a system-level simulator is implemented in this work and aligned tightly with the real world. The detailed information regarding the simulation models and assumptions have been captured in [19]. In this section, we highlight the most relevant models and parameters for our work.

A. SYSTEM MODELS AND THE SCHEDULING SCHEME

1) ENVIRONMENT MODEL

In order to characterize the real world environment, a Madrid-grid shown in Fig. 14 is implemented as the environment model. In this model, each Madrid-grid (i.e., colored as red) is composed of 15 buildings and one park.

2) DEPLOYMENT MODEL

A macro-base station with three sectors is deployed on the roof of the central building, as shown at the right hand of Fig. 14. The LTE-Uu interface operates on a carrier frequency of 2 GHz with a total bandwidth of 20 MHz (i.e., 10 MHz/10 MHz for LTE uplink/downlink) which is dedicated to V2X communication. Additionally, the transmission on PC5 is over 5.9 GHz with a bandwidth of 10 MHz. Besides, an isotropic antenna is installed on each traffic participants at 1.5-meter height. And each V2X Tx has a constant transmission power of 24 dBm in 10 MHz bandwidth.

3) TRAFFIC MODEL

A packet of 212 bytes is generated with 10 Hz periodicity [20] and the packet should be delivered to all traffic participants located within a target communication range.

4) CHANNEL MODEL

Both line-of-sight (LOS) propagation [19] and non-line-of-sight (NLOS) propagation [21] are modeled for the V2X communication over sidelink. Additionally, the single ray-tracing model proposed in [19] is also applied for the radio propagation over the LTE-Uu interface.

Algorithm 1 Evaluation of Uplink Latency

```
1: A V2X packet is generated at Tx. In a period of 100 ms, packets generation time among different Txs has a uniform distribution.
2: Perform transport block cyclic redundancy check (CRC) attachment and block segmentation if it has a size greater than 6114 bits.
3: Decide coding and modulation scheme w.r.t. SINR value of each transmitter.
4: BLER is derived from the SINR value of each transmitter w.r.t. the coding and modulation scheme selected from step 3.
5: Round robin scheduler is used to determine how many resource blocks are allocated to each uplink packet.
6: Uplink packet starts to be transmitted to the serving eNodeB.
7: If a packet is not successfully received, w.r.t. BLER of step 4, HARQ retransmission will be initialized and we inspect on whether HARQ retransmission is possible and successful.
8: Once a packet is successfully received by the serving eNodeB, the timing instance of when this packet is received is recorded. If the packet transmission can not be successful, the packet delay is considered as infinity.
```

Algorithm 2 Evaluation of Downlink Latency With Unicast Transmission

```
1: Only packets successful received by eNodeBs in the uplink will be transmitted in downlink.
2: A packet arrives at eNodeB, packet arrived time is decided by the uplink and the propagation latency between the eNodeBs.
3: Perform transport block CRC attachment and code block segmentation on each packet.
4: Decide coding and modulation scheme w.r.t. SINR value of each receiver.
5: BLER is derived from SINR value of each receiver w.r.t. the coding and modulation scheme selected from step 4.
6: eNodeB allocates the time and frequency resource to the most recently received packets. In case if multiple packets are ready to be transmitted simultaneously, round robin scheduler is used to decide how many frequency resource blocks are allocated to each downlink packet.
7: Downlink packet starts to be transmitted to the receiver.
8: If a packet is not received correctly, w.r.t. BLER of step 5, HARQ retransmission will be triggered and we inspect on whether the HARQ retransmission is possible and successful.
9: Once the packet is successfully received by the receiver, the timing instance is recorded. If the packet transmission can not be successful, the packet delay is considered as infinity.
```

5) MOBILITY MODEL

A maximal velocity of 50 km/h is assumed for each traffic participant, which corresponds to the maximal velocity allowance in most of the European cities.

6) SCHEDULING SCHEME

For direct V2X communication over PC5, the sidelink transmission mode 3 is used and therefore the resource for sidelink transmission will be centrally scheduled by the network. Specifically, an SPS algorithm is applied where the overall resource is evenly allocated to different V2X Txs. For instance, if there are ten Txs with a packet transmission periodicity of 10 Hz in the system, then each Tx periodically gets a resource of 10 ms to transmit one packet. In case a packet is not successfully received in the allocated resource, it is considered as being dropped.

B. SIMULATION RESULTS AND ANALYSIS

In this part, the simulation results obtained from the system-level simulator are provided. The evaluation methodologies of packet E2E latency over the LTE-Uu interface are presented in Alg. 1, Alg. 2, and Alg. 3, where the uplink latency and the downlink latency w.r.t. both the unicast transmission mode and the multicast transmission mode are inspected with details. Moreover, since our focus in this work is on the RAN, the message transition latency among different BSs is not inspected in detail. We assume that both the C-Plane and U-Plane functionalities of the BM-SC and MBMS-GW are localized at the edge of the RAN [8] and a latency value of 1 ms is assumed for the message transition among BSs. In addition, as mentioned in Sect. II and Sect. III, both the LTE MBMS and the sidelink communication correspond to a multicast transmission mode. Thus, the two MCSs with spectral efficiency of 0.6016 bit/Hz (i.e., corresponding to the CQI index 4 in LTE) and 0.887 bit/Hz (i.e., corresponding to the CQI index 5 in LTE) are used for sidelink and LTE MBMS respectively.

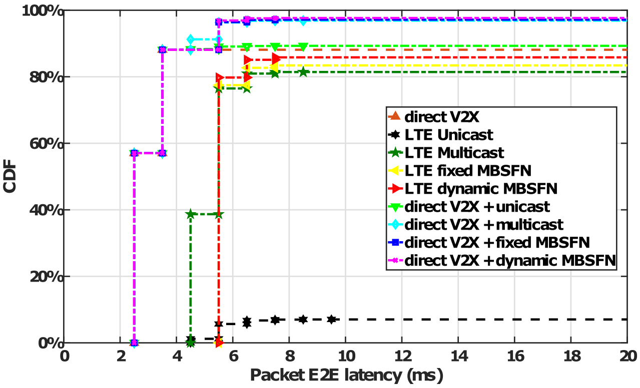


FIGURE 15. CDF of packet E2E latency (Target communication range = 200 meters, and 1000 UEs per square kilometer).

In Fig. 15, the cumulative distribution function (CDF) of the packet E2E latency is plotted where the target V2X communication range is set to be 200 meters and a vehicle density

Algorithm 3 Evaluation of Downlink Latency With Multicast Transmission

```
1: Only packets successfully received by eNodeBs in uplink will be transmitted in downlink.
2: A packet arrives at eNodeB, packet arrived time is decided by the uplink and the propagation latency between eNodeBs.
3: Perform transport block CRC attachment and code block segmentation on each packet.
4: Decide coding and modulation scheme based on the network condition, taking into account of the overall traffic volume and the overall available bandwidth.
5: The eNodeB allocates its time and frequency resource to the most recently received packets. In case if multiple packets are ready to be transmitted simultaneously, round robin scheduler is used to determine how many frequency resource blocks are allocated to each downlink packet.
6: Within the allocated resource, BS multicasts the packet. In case with extra available resource, the packet transmission will be repeated, in order to fully utilize the available resource.
7: BLER is derived from the SINR value of each receiver. Based on the BLER value, whether a packet transmission is successful or not can be derived.
8: In case a packet reception is failed and a repetition of this transmission is applied, an HARQ process referring to the chase combining is carried out at the receiver. The HARQ process will introduce a new effective SINR value and correspondingly a new BLER. With this new BLER value, the step 7 is repeated.
9: If a packet is successfully received, the reception timing instance will be recorded. If a packet is not successfully received in the allocated time resource, the packet will be discarded by the eNodeB and considered with an infinity delay.
```

of 1000 vehicles per square kilometer is assumed. In this figure, the performance of the direct V2X communication over PC5 and the performance of the LTE-Uu interface by using both the unicast and multicast transmission modes in downlink are provided. Please note that the CDF curves do not converge to 100% since there are packets failed in their transmission and therefore the PRR can also be reflected in this figure. As can be seen, the LTE unicast mode has the worst performance due to its large resource requirement in downlink. Comparing to that, the LTE multicast in downlink is more resource-efficient in the considered V2X scenario and therefore it has a better performance w.r.t. the packet E2E latency and the PRR. In addition, the two different MBSFN area mapping approaches stated in Sect. VI outperform the LTE multicast scheme due to the synchronized transmission among different BSs and therefore the V2X Rxs on the cell border experience better SINR values with the MBSFN technology. More precisely, the PRR can be improved from 82% in the LTE multicast scheme to 86% in the LTE dynamic MBSFN area mapping scheme. Moreover, taking account of the radio condition experienced by the V2X Tx, the dynamic MBSFN area mapping approach provides a better robustness and therefore contributes to a higher PRR than the fixed MBSFN area mapping approach. As mentioned before, the V2X communication refers to a local information exchange procedure and therefore the direct V2X communication over PC5 can provide a good performance within a moderate communication range. This point is also illustrated in Fig. 15, as the PRR for the direct V2X communication over PC5 is higher than the V2X communication schemes through the network infrastructure. Besides, since the data packets are not transmitted through the network infrastructure in the direct V2X communication scheme, its packet E2E latency is shorter than other schemes utilizing LTE-Uu and it can fulfill the latency requirement of 5 ms [1]. In order to improve reliability, the performances of four multi-RAT schemes are also given. In the first multi-RAT scheme (i.e., labeled as 'direct V2X + unicast'), the V2X packets are transmitted over both the PC5 and the LTE-Uu unicast interfaces. And the PRR is better than the case if the packets travel through a single-RAT. However, as the LTE-Uu unicast provides a comparably low PRR, the improvement from the multi-RAT is very slight compared with the performance of the direct V2X communication. In the other three multi-RAT schemes, both sidelink and LTE-Uu multicast schemes (i.e., downlink multicast without SFN, multicast with fixed MBSFN area mapping and multicast with dynamic MBSFN area mapping) are exploited. As can be seen from the curves, the PRR ratios can be improved from 88% in the single-RAT scheme to 97% in the multi-RAT scheme. We can also notice that the performance difference between the direct V2X + fixed MBSFN multi-RAT scheme and the direct V2X + dynamic MBSFN multi-RAT scheme is only 1% w.r.t. the PRR, and it is much smaller than the case if the direct V2X communication is not used (i.e., a performance difference of 4%). This is due to the fact that many vulnerable cell-border UEs can successfully receive the data packets from PC5.

In Fig. 16, the V2X communication range is increased to 300 meters and the vehicle density is decreased to 500 vehicles per square kilometer. As can be seen, the performance of the V2X communication through network infrastructure (i.e., the LTE unicast, LTE multicast, LTE fixed MBSFN and LTE dynamic MBSFN schemes) are better than the ones shown in Fig. 15, since a lower data volume contributes to more allocated resource for each packet transmission. However, the PRR of the direct V2X communication is worse than that in Fig. 15. This is due to the larger communication range and the V2X Rxs located far from the Tx experience bad radio conditions. Thus, the LTE multicast and LTE MBSFN schemes outperform the direct V2X communication w.r.t. the PRR in this specific case. Additionally, both the LTE multicast and direct V2X communication have a PRR worse than 86%. Again, by applying the multi-RAT scheme (i.e., direct V2X + LTE dynamic MBSFN area mapping), the PRR can be efficiently improved to be above 96%.

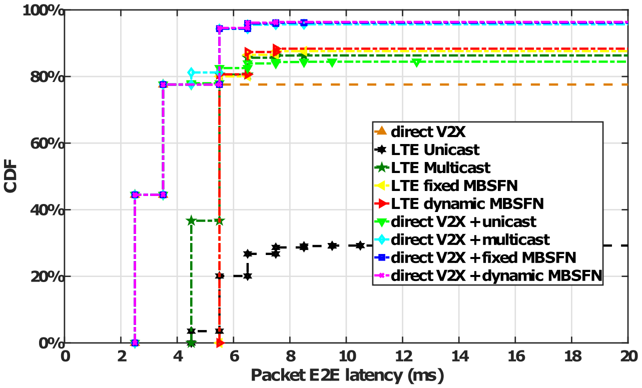


FIGURE 16. CDF of packet E2E latency (Target communication range = 300 meters, and 500 UEs per square kilometer).

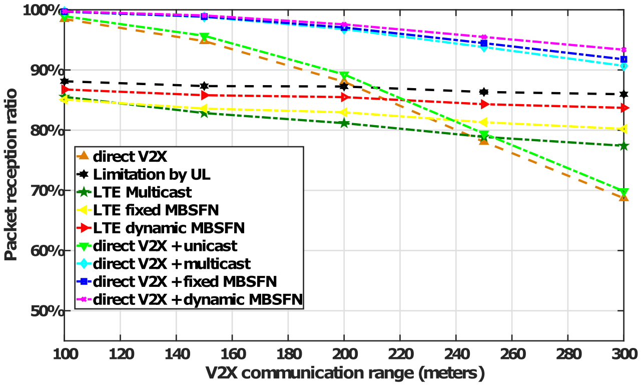


FIGURE 17. PRRs of different multi-RAT technologies w.r.t. the different communication ranges (1000 UEs per square kilometer).

In order to observe the performances of different schemes w.r.t. different communication ranges, the PRRs of the different schemes are plotted (i.e., from 100 meters to 300 meters with a step-width of 50 meters) in Fig. 17. The vehicle density is set to be 1000 vehicles per square kilometer. We notice that the performance of the direct V2X communication is significantly influenced by the communication range since the transmission range has an impact on the radio condition of the direct V2X communication. In comparison, the LTE-Uu multicast scheme is less sensitive to the communication range, as the signal propagation distance between a V2X UE and its serving BS is independent of the communication range. By comparing the different multi-RAT schemes, we can also see that the multi-RAT scheme of using unicast in downlink has clearly worse performance than the other schemes due to its low efficiency in downlink. In addition, the other schemes where V2X communication goes through the network infrastructure (i.e., LTE multicast, fixed MBSFN area mapping and dynamic MBSFN area mapping) have more outstanding performance difference with an increased communication range, and therefore the same tendency can be observed from the corresponding multi-RAT schemes. Last but not least, the performance limitation posed by the LTE uplink is also shown in this figure by assuming all the packets can be successfully received in downlink. We can see that the introduced dynamic MBSFN area mapping scheme approaches the uplink limitation quite well and therefore its performance is mainly limited by the transmission failures occurred in uplink.

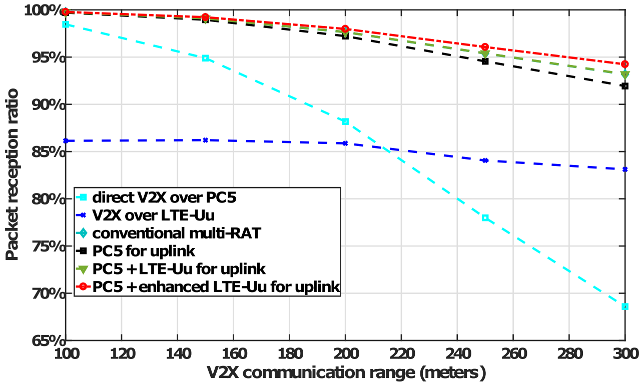


FIGURE 18. PRRs of different hybrid uplink technologies w.r.t. the different communication ranges (1000 UEs per square kilometer and MBSFN is applied in LTE-Uu downlink).

In Fig. 18, we provide the performance of different hybrid uplink transmission schemes where the downlink transmission is realized by the dynamic MBSFN area mapping approach. For instance, the curve labeled as 'PC5 for uplink' shows the performance of the multi-RAT scheme where the BS receives the packets of a V2X Tx from the sidelink carrier (i.e., as stated in Sect. V-A). And the curve labeled as 'PC5 + LTE-Uu for uplink' represents the multi-RAT transmission scheme where both the PC5 and LTE-Uu are applied in the hybrid uplink transmission (i.e., the scheme shown in Sect. V-B). In another case, the curve labeled as 'PC5 + enhanced LTE-Uu for uplink' shows the sequential hybrid uplink transmission scheme introduced in Sect. V-C.2 where the transmission over LTE-Uu uplink is only sequentially triggered if the BS does not successfully receive a V2X packet from the sidelink carrier. At the same time, we also provide the performances of the two single RATs (i.e., direct V2X communication over the PC5 interface and V2X communication over the LTE-Uu interface with MBSFN in downlink) as comparisons. Besides, the performance of the independent multi-RAT transmission scheme without using the hybrid uplink transmission is also plotted (i.e., labeled as 'conventional multi-RAT'). Comparing the curve where the BS only receives the V2X packets from the PC5 with the curves of the single RAT schemes, we can see that the PRR can be significantly improved. Therefore, by additionally exploiting the LTE-Uu downlink resource and equipping BSs with the capability to receive sidelink transmission, it contributes to a better reliability than the direct V2X communication. However, the performance of the two schemes where the packets are received at the BS either from LTE-Uu (i.e., the curve shown by 'conventional multi-RAT') or from both the LTE-Uu and PC5 (i.e., the curve shown by 'PC5 + LTE-Uu for uplink') are consistent and therefore these two curves overlap with each other. This is due to the fact that the additional transmission over PC5 can hardly provide any contribution if the uplink

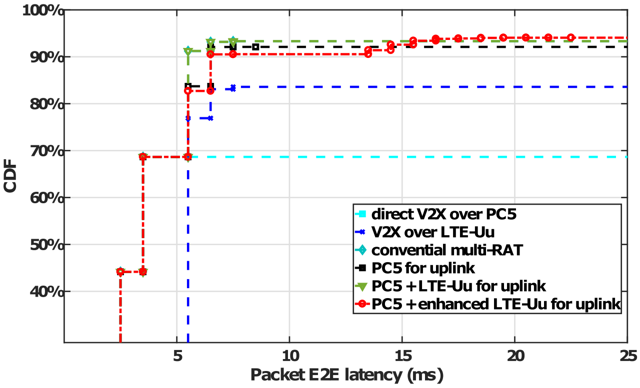


FIGURE 19. CDF of packet E2E latency w.r.t. different hybrid uplink technologies (Target communication range = 300 meters, 1000 UEs per square kilometer, and MBSFN is applied in LTE-Uu downlink).

transmission over LTE-Uu interface is unsuccessful. In our simulation, the PC5 interface operates on a carrier frequency (i.e., 5.9 GHz) higher than that of LTE-Uu (i.e., 2 GHz) and therefore the signal propagation loss is more severe on sidelink. Therefore, if a packet fails in its transmission over the LTE-Uu uplink, its transmission to the BS over PC5 will very likely experience a failure too. Comparing to that, since the sequential hybrid uplink transmission scheme (i.e., labeled as 'PC5 + enhanced LTE-Uu for uplink') conditionally triggers the uplink transmission over LTE-Uu, a better usage of the spectral resource can be achieved and therefore the PRR can be improved from 93% in the conventional multi-RAT scheme to 94%, if the communication range is up to 300 meters.

Besides the PRRs shown in Fig. 18, the packet E2E latency of the different hybrid uplink technologies is also of interest to us. In this sense, the CDF of their packet E2E latency is provided in Fig. 19 where the target communication range is set to be 300 meters and a vehicle density of 1000 vehicles per square kilometer is used. By looking at the low E2E latency scale (e.g., below 10 ms) in Fig. 19, we can see that the PRR of the sequential hybrid uplink transmission (i.e., the curve labeled as 'PC5 + enhanced LTE-Uu for uplink') within the low E2E latency scale is lower than the other hybrid schemes. This is due to the fact that the packets which are successfully received by the BS from LTE-Uu experience a large E2E latency value. As mentioned in Sect. V-C.2, in the sequential hybrid uplink transmission scheme, the packet transmission in uplink over LTE-Uu only takes place if the packet has not been successfully received by the BS over the PC5 interface. Thus, the packets which are successfully received by the BS from the LTE-Uu interface experience a minimal additional delay of 8 ms (i.e., 7 ms + the minimal packet transmission duration of 1 ms), compared with the other hybrid uplink technologies. In addition, please note that the PRR of the sequential hybrid uplink transmission scheme in the low E2E latency scale is even lower than that of the case where the BS receives the packets only from the sidelink carrier (i.e., the curve labeled as 'PC5 for uplink'). It is because there are more packets successfully received in uplink from the sequential hybrid uplink transmission scheme and thus more packets will be transmitted in downlink. With more packets to be transmitted in downlink, less resource will be allocated to per packet transmission and the packets successfully received by the BS from the sidelink carrier will experience a performance degradation in downlink. However, as mentioned before, the sequential hybrid uplink transmission scheme can contribute to a better PRR but with a large E2E latency. This point can be reflected by inspecting on the relatively high packet E2E latency scale in Fig. 19.

VIII. CONCLUSION

In this work, we have introduced the different cellular technologies (i.e., LTE-Uu and PC5) to enable the V2X communication. In particular, we have described both the unicast and multicast transmission modes of LTE-Uu interface with the focus on their application in V2X communication. Besides, as the PC5 interface is standardized in 3GPP to enable the proximity services between two nearby devices, we have also inspected its application in the direct V2X communication. In order to provide a better reliability for V2X communication within a large communication range, a multi-RAT scheme has been proposed where packets are transmitted through both the LTE-Uu and PC5 interfaces. Correspondingly, we have designed different signaling schemes to compromise between the flexibility and the signaling efficiency. In addition, in order to protect the packet transmission from a V2X Tx to its serving BS, the conventional uplink transmission over the LTE-Uu interface has been extended to a hybrid uplink transmission technology where the BS can flexibly receive data packets through either LTE-Uu or PC5 or both of them simultaneously. In order to show the performances of the different technologies, we have also implemented a system-level simulator and provided the simulation results. It can be seen that the performances of the different technologies are related to the concrete application scenarios. For instance, the direct V2X communication over PC5 provides a low E2E latency and a good reliability to the Rxs within a moderate communication range. However, its performance sensitively degrades with an increased communication range. In comparison, the V2X communication through the network infrastructure can utilize the LTE-Uu interface to multicast the data packets in downlink and it can contribute to a better reliability within a large communication range. In order to meet the ultra-high reliability requirement in some V2X scenarios, the multi-RAT transmission over both PC5 and LTE-Uu can be applied. If a BS is able to receive the packets from the PC5 interface, the proposed multi-RAT scheme has the ability to facilitate the transmission through the network infrastructure without using the uplink resource and it can still contribute to a large reliability improvement. Meanwhile, when uplink resources are available in the network, the hybrid uplink scheme can also be applied to further improve the communication reliability in an efficient manner. Last but not least, the communication reliability in downlink can be enhanced by the single-frequency network technology where the radio propagation information is taken into account to coordinate the transmissions from different BSs.

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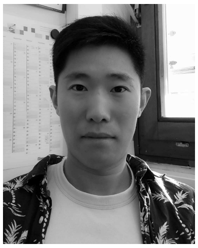

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