Field Trial of Dynamic Mode Switching for 5G New Radio Sidelink Communications towards Application to Truck Platooning

Manabu MIKAMI†,‡, Senior Member, Kohei MOTO†,‡, Koichi SERIZAWA†,‡, and Hitoshi YOSHINO†,‡, Members

SUMMARY — Fifth generation mobile communication system (5G) mobile operators need to explore new use cases and applications together with vertical industries, the industries that are potential users of 5G, in order to fully exploit the new 5G capabilities in terms of its application. Vehicle-to-Everything (V2X) communications for platooning are considered to be one of new 5G use cases requiring low-latency and ultra-reliability are required. This paper presents our field trial of dynamic mode switching for 5G New Radio (NR) based V2X sidelink communications towards application to truck platooning. The authors build a field trial environment, for V2X communications of truck platooning, with actual large-size trucks and a prototype system employing 5G NR technologies, and performed some field trials in rural areas. In this paper, we introduce the 5G NR-V2X prototype system. Its most distinctive characteristic is that the prototype system is equipped with vehicle-to-vehicle (V2V) Direct communication radio interface (i.e., sidelink), in addition to the traditional radio interfaces between base station (BS) and user equipment (UE), i.e., downlink and uplink. Moreover, it is also most distinctive that the sidelink (SL) interface supports a new function of dynamic mode switching between two modes of BS In-Coverage mode (SL Mode-1) and BS Out-of-Coverage mode (SL Mode-2) in order to achieve seamless V2V communications between BS in-coverage area and BS out-of-coverage area. Then, we present the evaluation results on over-the-air latency performance on the V2V Direct communication of the prototype using SL dynamic mode switching with two experimental base station antenna sites in a public express highway environment towards application to truck platooning. The results demonstrate that our developed SL dynamic mode switching achieves the seamless V2V Direct communications between in-coverage area and out-of-coverage area.

key words: 5G, V2V direct, in-coverage mode, out-of-coverage mode, dynamic mode switching

1. Introduction

Research and development efforts of Fifth Generation Mobile Communication System (5G) are continued for its evolution [1], [2], although the commercial services of 5G have been already started in several economically developed countries from 2020. 5G supports not only enhanced Mobile Broadband (eMBB) but also Ultra Reliable and Low Latency Communication (URLLC) and massive connectivity for Machine Type Communication (mMTC) [3], [4]. URLLC and mMTC in particular have potential for developing new markets, and establishing concrete 5G applications for these is an urgent matter. In Japan, the Ministry of Internal Affairs and Communications (MIC) has carried out 5G system trials in Japan from 2017 [5]. This trial project not only aims to demonstrate the technical evaluation of 5G, but also to invite vertical industries and a telecommunication industry to participate the field trials with a view to assessing potential 5G applications and use cases. Automated driving, including truck platooning [6]–[10] is one of the promising new 5G application areas because 5G offers the ultra-low latency and ultra-reliability required for the application areas of automated driving unlike the existing commercial Fourth Generation Mobile Communication System (4G) which does not. Therefore, we have been working on use cases of truck platooning utilizing 5G New Radio (NR) technologies to demonstrate the ultra-low-latency transmission capabilities with the over-the-air latency of below 1 ms, the network end-to-end (E2E) latency of below 10 ms in our trial project [5].

Meanwhile, the 3rd Generation Partnership Project (3GPP) has been recently discussing on requirements of 5G New Radio (NR) enhancements for Vehicle-to-Everything (V2X) communication service which includes, in particular, support of Vehicle-to-Vehicle (V2V) Direct communication over sidelink (SL) radio interface between user equipment nodes (UEs) [11], [12], as well as downlink (DL) and uplink (UL) radio interface between base station (BS) and UE. In our first 5G field trials [5], V2V Direct communication tests have not been carried out, although we have present field evaluation results on over-the-air transmission performance of V2N communication over the downlink and the uplink. In the trials [5], we have also clarified that V2N and V2N2V communications suffer from over-the-air transmission performance degradation at the points far from BS antenna site (i.e., cell boundary) and that it is difficult for V2N and V2N2V communications to provide stable communication for vehicle-message communications of truck platooning. Then, in order to provide more stable vehicle-to-vehicle communication for truck platooning, we have developed a new 5G NR-V2X prototype system equipped with UE-to-UE direct communication link interface (i.e., sidelink) for Vehicle-to-Vehicle (V2V) Direct communication before 3GPP defines the detail specifications, in addition to traditional communication radio links between BS and UE (i.e., downlink and uplink) for Vehicular-to-Network (V2N) communication or Vehicle-to-Network-to-Vehicle (V2N2V) communication [13]. In our second 5G field trials [13], the
The authors have also built a field trial environment with actual large-size trucks and the prototype system, and clarified the fundamental latency performance of the V2V Direct communication compared with that of V2NV communication in an automotive test course environment.

Meanwhile, 3GPP also discuss two SL modes of “BS In-Coverage mode” (i.e., SL Mode-1) and “BS Out-of-Coverage mode” (i.e., SL Mode-2) [12]. Since SL Mode-1 is suitable for V2V direct communications at in-coverage area served by a BS and SL Mode-2 is suitable for V2V direct communications at out-of-coverage area not served by BSs, the authors consider that dynamic mode switching between SL Mode-1 and SL Mode-2 is an important function for V2V Direct communications. On the other hand, another related work of the authors [14] reports the over-the-air latency performance results of V2V Direct communications on a public express highway environment in case that SL Mode-2 is only applied. However, for the best of the authors’ knowledge, the existing works have not experimentally demonstrated SL dynamic mode switching for 5G V2V Direct communications. In response, we have been developed SL dynamic mode switching as a new function of the prototype system. This paper introduces the overview of our developed 5G NR-V2X prototype with SL dynamic mode switching as a new function, and presents the experimental evaluation results on over-the-air latency performance of V2V Direct communications using SL dynamic mode switching with two experimental base station antenna sites at a public express highway environment in Japan. The results demonstrate that our developed SL dynamic mode switching achieves seamless V2V Direct communications between in-coverage area and out-of-coverage area.

The rest of this paper is organized as follows. Section 2 and Sect. 3 present the overview of our developed 5G NR-V2X prototype system, and the new function of SL dynamic mode switching, respectively. Section 3, Sect. 4 and Sect. 5 describe the field trial conditions and the field trial results, respectively. Finally, this paper is concluded in Sect. 6.

2. Overview of 5G NR-V2X Sidelink Prototype System

This section introduces our developed 5G NR-V2X prototype system with SL. Figure 1 illustrates the overall configuration of the prototype system with the view of applying 5G to truck platooning. As shown in Fig. 1, the 5G prototype system is roughly divided into two base station (BS) sides and a mobile station (MS) side. One of the BS sites (hereafter, Core BS site) is comprised of a core network equipment (CNE), two BS antennas, a central unit (CU) [15] which consists of base band unit (BBU) and a BBU controller, and a distributed unit (DU) [15] which consists of two radio frequency units (RFUs). The other (hereafter, Remote BS site) is comprised of two BS antennas and a DU which consists of two RFUs. Note that there is no CU at Remote BS site and that DU of Remote BS site is connected to CU at Core BS site via optical fibers, since the experimental inter-site BS network employs a Centralized Radio Access Network (C-RAN) structure. The MS side is comprised of three user equipment nodes (3UEs) i.e., UE#1, UE#2, and UE#3. Note that the three UEs (UE#1, UE#2, and UE#3) comprise a UE group.

Figure 2 illustrates the radio frame structure of the prototype with the radio frame length of 10 ms and the time slot length of 0.25 ms. As shown in Fig. 2, the radio frame is comprised of 40 time slots, the first and the second time slots are used for synchronization signals and physical broadcast channels (SS/PBCHs) of downlink and sidelink, respectively. The first time slot includes downlink SS/PBCH block, and the second time slot includes sidelink SS/PBCH block. As shown in Fig. 2, each time slot includes orthogonal frequency division multiplexing (OFDM) symbols of DL, UL, and SL, respectively. The DL OFDM symbols are used for physical downlink control channel (PDCCH) and physical downlink shared channel (PDSCH), respectively [1]. The UL OFDM symbols are used for physical uplink control channel (PUCCH) and physical uplink shared channel (PUSCH), respectively [1]. Note that demodulation reference signal (DMRS) is also multiplexed with each physical channel (i.e., PDCCH, PDSCH, PUCCH, PUSCH, PSCCH, PSSCH) for its demodulation and the received signal-to-interference-plus-noise-power-ratio (SINR) measurement.

Table 1 summarizes the major radio specifications of the prototype system. As shown in Fig. 2 and Table 1, the prototype system employs some 5G NR technologies, such as self-contained Time Division Duplex (TDD) frame structure, short transmission-time-interval (TTI), Polar coding, and so on. As shown in Fig. 1 and Table 1, the prototype...
Table 1 Major radio specifications of 5G NR-V2X prototype system.

<table>
<thead>
<tr>
<th>Radio interface</th>
<th>Between BS and UE</th>
<th>Among UEs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Downlink (DL)</strong></td>
<td><strong>Uplink (UL)</strong></td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>4.5 GHz band</td>
<td></td>
</tr>
<tr>
<td>Transmission bandwidth</td>
<td>20 MHz</td>
<td></td>
</tr>
<tr>
<td>Duplex</td>
<td>Time Division Duplex (TDD)</td>
<td></td>
</tr>
<tr>
<td>Radio access scheme</td>
<td>Orthogonal Frequency Division Multiple Access (OFDMA, 60 kHz subcarrier spacing)</td>
<td></td>
</tr>
<tr>
<td>Radio frame structure</td>
<td>Self-contained TDD frame structure</td>
<td></td>
</tr>
<tr>
<td>Radio subframe length</td>
<td>0.25 ms (= TTI length)</td>
<td></td>
</tr>
<tr>
<td>Radio frame length</td>
<td>10 ms (= 40 time slots)</td>
<td></td>
</tr>
<tr>
<td>Subframe ratio</td>
<td>DL : UL : SL = 1 : 1 : 1</td>
<td></td>
</tr>
<tr>
<td>Number of Tx antennas</td>
<td>8 Tx</td>
<td>2 Tx</td>
</tr>
<tr>
<td>Number of Rx antennas</td>
<td>8 Rx</td>
<td></td>
</tr>
<tr>
<td>Channel coding</td>
<td>Polar coding</td>
<td></td>
</tr>
<tr>
<td>Retransmission scheme</td>
<td>Hybrid Automatic Repeat reQuest (HARQ)</td>
<td></td>
</tr>
<tr>
<td>SL In-Coverage mode (Mode-1)</td>
<td>Support</td>
<td></td>
</tr>
<tr>
<td>SL Out-of-Coverage mode (Mode-2)</td>
<td>Support</td>
<td></td>
</tr>
<tr>
<td>SL dynamic mode switching</td>
<td>Support</td>
<td></td>
</tr>
</tbody>
</table>

The system is equipped with SL corresponding to UE-to-UE direct communication link for V2V Direct communication, as well as the traditional Uu [1] radio interface of DL and UL for V2N or V2N2V communications. Note that dynamic radio resource assignment function has not been implemented for the prototype system and the radio resource assignments to all the UEs in DL, UL, and SL are fixed so as to avoid co-channel interference including inter-user interference in this field trial. As shown in Table 1, the prototype system supports intra-site BBU inter-cell handover (HO) to achieve wider BS coverage with multi-cell configuration than single-cell configuration. The HO decision of the prototype is based on measurement results of physical random access channel (PRACH) [1] in uplink. Therefore, at in-coverage area, the BBU controller fundamentally controls serving cell of each UE so as to select the best cell with higher received signal power of PRACH in uplink.

As shown in Table 1 the SL radio interface is also equipped with two modes of In-Coverage mode (SL Mode-1) and Out-of-Coverage mode (SL Mode-2). For SL Mode-1, the UEs use the downlink SS/PBCH block as the target synchronization signals. For SL Mode-2 the UEs use the sidelink SS/PBCH block as the target synchronization signals. Furthermore, as a new function of the prototype system, dynamic mode switching between SL Mode-1 and SL Mode-2 (hereafter called SL dynamic mode switching) based on received signal quality of the Uu radio interface are also implemented. Note that there are some function limitations in the prototype system since the main objective of this field trial is to demonstrate the SL dynamic mode switching. For example, adaptive modulation and coding (AMC) scheme has not been implemented, although hybrid-automatic-repeat-request (HARQ) retransmission scheme is implemented. Moreover, since dynamic radio resource assignment function has not also been implemented, the radio resource assignments to all the UEs are fixed in DL, UL, and SL so as to avoid inter-user interference (IUI) in this field trial. The next section describes the fundamental concept of our developed SL dynamic mode switching.

3. Sidelink Dynamic Mode Switching

3.1 Fundamental Concept

Figures 3(a) and (b) illustrate the advantage and the disadvantage of SL Mode-1, respectively. As shown in Fig. 3(a), even if there are many user terminals of different UE groups, SL mode-1 possibly achieves less IUI than SL mode-2 since the radio resource assignment is controlled by BS side. However, SL Mode-1 is not available out-of-coverage area, as shown in Fig. 3(b). Therefore, SL Mode-1 is suitable for V2V direct communications in coverage area served by a BS.

Figures 4(a) and (b) illustrate the disadvantage and the advantage of SL Mode-2, respectively. As shown in Fig. 4(a), in case of SL Mode-2, IUI is possibly occurred by many user terminals due to the autonomous radio resource selection. On the other hand, as shown in Fig. 4(b), SL Mode-2 is available out-of-coverage area, such as inside of tunnels and mountain areas. Therefore, SL Mode-2 is suitable for V2V direct communications out of coverage area.
Table 2  Advantages and disadvantages of SL Mode-1 and SL Mode-2.

<table>
<thead>
<tr>
<th>SL modes</th>
<th>SL Mode-1 (Radio resource management)</th>
<th>SL Mode-2 (Management by base station)</th>
<th>SL Mode-2 (Autonomous resource selection)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter-user interference (IUI) from UEs which belong to different UE groups</td>
<td>Less interference even if there are many user terminals of different UE groups</td>
<td>Possible suffer from more interference when there are many user terminal of different UE groups</td>
<td></td>
</tr>
<tr>
<td>Availability out of base station coverage area</td>
<td>Not available</td>
<td>Available</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5  Fundamental concept of SL dynamic mode switching.

area not served by BSs.

Table 2 summarizes the advantages and disadvantages of SL Mode-1 and SL Mode-2 shown in Fig. 3 and Fig. 4. As shown in Table 2, since SL Mode-1 is suitable for V2V direct communications in BS coverage area and SL Mode-2 is suitable for V2V direct communications out of BS coverage area, we consider that the dynamic mode switching between SL Mode-1 and SL Mode-2 is an important function for NR-V2X communications. We consider that both SL Mode-1 and SL Mode-2 are required for practical use cases of truck platooning, the platoon trucks possibly travel at not only in-coverage area but also out-of-coverage area. Meanwhile, for the best of our knowledge, the existing works does not demonstrate SL dynamic mode switching for 5G NR-V2X communications. Therefore, we develop SL dynamic mode switching for the prototype system as a new function. Figure 5 illustrates the fundamental concept of SL dynamic mode switching. As shown in Fig. 5, when SL dynamic mode switching is applied, SL Mode-1 is selected in case that all UEs of the group is in-coverage status and SL Mode-2 is selected in case that a UE of the group detects out-of-coverage status or does not synchronized. Note that dynamic radio resource assignment function has not been implemented to the prototype system and that the radio resource assignments to all the UEs are fixed so as to avoid IUI in the prototype system, since we focus on demonstrating the concept of SL dynamic mode switching in this field trial. Therefore, the IUI is avoided in SL Mode-2 as well as SL Mode-1 in the prototype system.

Fig. 6  Sequence flow of SL mode selection in the prototype system.

3.2 Sequence Flows for SL Dynamic Mode Switching

The rest of this section describes the details of the SL mode selection in the SL dynamic mode switching function because the function is originally implemented to our developed prototype system, but not defined by 3GPP. Figure 6 shows the sequence flow of the SL mode selection in the SL dynamic mode switching function implemented on the prototype system, respectively. Figures 7(a) and (b) show subsequences in the SL mode selection. Figure 7(a) represents the Uu link state check procedure. Figure 7(b) represents the Uu synchronization and the Uu sync state check procedures. The Uu link state check shown in Fig. 7(a) is performed for decisions whether a UE is in the coverage area of the BS (i.e., “In-Coverage” status) or not (i.e., “Out-of-Coverage” status). The Uu synchronization procedure shown in Fig. 7(b) is performed for establishing and maintaining communication between BS and each UE. The Uu sync state check procedure shown in Fig. 7(b) is performed for the confirmation whether it is possible that a UE communicates with BS (“Uu In-Sync” status) or not (“Uu Out-of-Sync”).

As shown in Fig. 6, if BS confirms that all the UEs of the group are “In-Coverage” status from the results of Uu link state check, BS sends the information of “Mode-1 Allowed” to each UE of the group. Each UE runs the Uu synchronization and the Uu sync state check procedures after receiving “Mode-1 Allowed” information. On the other hand, in the case that a UE does not receive “Mode-1 Allowed” message from BS, the UE judges that Uu sync state of the UE itself is “Uu Out-of-Sync” and skips the Uu synchronization and the Uu sync state check procedures. Note that each member UE of the group, i.e., UE#2 or UE#3, establishes the SL synchronization by using the sidelink
SS/PBCH transmitted from the leader UE of the group (i.e., UE#1), if “Uu Out-of-Sync” status is detected. When BS sends “Uu In-Sync” status information to all the UEs of the group based on the results of the Uu sync state check, BS waits SL scheduling request message from each UE for “SL Mode-1”. When UE#1 (leader UE of the group) judges that the Uu sync state of UE#1 is “Uu In-Sync” from the result of the Uu sync state check, UE#1, information obtain “Uu In-Sync” status information from the other UEs of the group (i.e., UE#2 and UE#3). When UE#1 confirms that all the UEs of the same group are “Uu In-Sync” status, UE#1 sets SL mode flag with the value corresponding to “Mode-1”. Otherwise, it sets SL mode flag with the value corresponding to “Mode-2”. Then, UE#1 sends the SL mode flag information to the other UEs of the same group (i.e., UE#2 and UE#3). The SL mode is decided based on the SL mode flag value. Only when UE#1 sends the SL mode flag with the value corresponding to “Mode-1” and receives the acknowledgments fed back from the other UEs, SL Mode-1 is selected, otherwise SL Mode-2 is selected.

As described above, SL Mode-1 is selected in the prototype system, only when the leader UE (UE#1) sends SL mode flag with the value corresponding to “Mode-1” and receives the acknowledgments fed back from the other UEs after confirming that all the UEs of the group are “In-Coverage” status and “Uu In-Sync” status form the results of the Uu link state check and the Uu sync state check. Therefore, one of UE in the group is “Out-of-Coverage” status or “Uu Out-of-Sync” status, SL Mode-2 is selected. Meanwhile, the serving cells can be temporally different among the UEs especially at the points near cell boundaries, since all the UEs do not always have the same best cell with the highest received PRACH power described in Sect. 2. In the prototype system, although the serving cells are temporally different among the UEs at the points near cell boundaries, SL Mode-1 can be selected when a UE of the group with “Out-of-Coverage” status or “Uu Out-of-Sync” status is not detected. On the other hand, SL Mode-2 is selected when a UE with “Out-of-Coverage” status or “Uu Out-of-Sync” is unfortunately is detected at the points near cell boundaries.

4. Field Trial Conditions

We carried out field experimental evaluation tests on the SL transmission performance in order to demonstrate our developed SL dynamic mode switching function towards application to truck platooning using 5G NR-V2X with sidelink. This section describes the field trial conditions. Figure 8 shows the field trial area with two experimental BS antenna sites and the trial course with the length of about 7.5 km from point #a to point #d along Shin-Tomei Expressway at a rural high land area in Shizuoka Prefecture, Japan. One of the experimental BS antenna sites (hereafter called “Core BS Site”) where CU and CNE are installed is located near point #c, and the other (hereafter called “Remote BS Site”) where CU and CNE are not installed is located near point #b, respectively. In this trial, the total number of cells is four since each experimental BS antenna site site two cells. Figure 9 shows the appearances of Core BS site including BS antennas, RFUs, BBU, and CNE. Figure 10 shows that of Remote BS site including BS antennas and RFUs. We note that the points around #c on the evaluation course are unfortunately in Non-Line-Of-Sight (NLOS) radio propagation conditions from BS antenna due to the surrounding terrain, although we located at Core BS site along the evaluation course and the points of the middle part between #c and #d are fortunately in Line-Of-Sight (LOS) propagation conditions from the BS antenna of Core BS site, respectively. On the other hand, the points around #b on the course are in LOS propagation conditions from the BS antennas of Remote BS site, but the other points except around #b are in NLOS propagation conditions from the BS antennas of Remote BS site.

Figure 11 shows the appearances of the experimental MS side. As shown in Fig. 11, we prepared three actual large-size trucks for this trial. Each UE is installed in the cargo compartment of the backside of each truck vehicle, and UE antennas of each UE are mounted on the top of each truck cab, respectively. Table 3 summarizes the major parameters of the field trial and Fig. 12 illustrates the field trial conditions for performance evaluation on SL dynamic mode switching. As shown in Table 3, Cell IDs were set to different values among Cell#0-Cell#3, respectively. We selected QPSK modulation scheme and the coding rate $R$ of 0.3 as a modulation and coding rate set (MCS) for data transmission since a low-order MCS is indispensable, considering a use...
Fig. 8  Field trial area for SL dynamic mode switching tests (Shin-Tomei Expressway in Shizuoka Prefecture of Japan, Trial course length: 7.5 km).

Fig. 9  Appearance of Core BS antenna site.

Fig. 10  Appearance of Remote BS antenna site.

case of vehicle-control message transmission that requires high reliability. The target vehicle speed of all the trucks was set to 80 km/h. The UE antenna distance between UE#1 and UE#2 is about 47 m, and the UE antenna distance between UE#1 and UE#3 is about 94 m, since the target inter-vehicle distance of the trucks was set to 35 m and the vehicle length of the trucks was 12 m, respectively. As shown in Fig. 12, we evaluated SL transmission performance while all truck vehicles were moving on the trial course.

5. Field Trial Results

In this trial, we mainly evaluated the over-the-air latency performance in the V2V Direct communications over SL when the truck vehicles move on the trial course shown in Fig. 8 at the speed of 80 km/h. In order to evaluate the field trial results, uplink SINR (UL SINR) and sidelink SINR (SL SINR) are also measured, respectively. Figure 13 shows examples of field trial scenes at the experimental MS side. As shown in Fig. 13, general vehicles passed the trucks, as this trial was carried out in a practical test environment.

Figures 14 and 15 show the field trial results of the forward links (FLs; the links from the following vehicles to the leading vehicle) and the backward links (BLs; the links from the leading vehicle to the following vehicles) when SL dynamic mode switching is applied in Case I. These figures (a) and (b) plot the measured over-the-air latency of the link between UE#1 and UE#2, and that of the links between UE#1 and UE#3, respectively. In these figures (a), (b), the cell indexes, i.e., Cell#0, Cell#1, Cell#2, and Cell#3, denote the serving cell of UE#1. Figures 14(c) and 15(c) plot the measured UL SINR values of UE#1 for reference, respectively. Note that the UL SINR values are computed from the measurement results of the received signal power and the
interference-plus-noise power estimated by received DMRS for PUCCH transmitted from UE#1 in uplink. Figures 14(d) and 15(d) also plot the measured SL initial block error rate (BLER) for reference, respectively.

From Fig. 14(a) and Fig. 15(a), it is found that the prototype system dynamically switches SL Mode-1 and SL Mode-2 with the low latency of below 1 ms in SL1 between UE#1 and UE#2 while our developed 5G NR-V2X prototype system simultaneously realizes inter-cell HO and it always achieve over-the-air ultra-low latency performance of less than 1 ms in SL1 between UE#1 and UE#2 at all the points of the trial course. Compared with these figures (a) and (c), it is also found that the prototype judges “In-Coverage” status and “Uu In-Sync” status of all UEs at the points where the UL SINR value of UE#1 measured at the BS side is approximately over 0 dB in this field trial conditions, and that it selects SL Mode-1. The above results experimentally demonstrate SL dynamic mode switching in a real public express highway environment. From Fig. 14(b) and Fig. 15(b), it is confirmed that the prototype system dynamically switches SL Mode-1 and SL Mode-2 with the low latency of below 1 ms while the prototype system simultaneously realizes intra-site BBU inter-cell HO and it usually achieve over-the-air ultra-low latency performance of less than 1 ms in SL2 corresponding to the link between UE#1 and UE#3 at almost the points of the evaluation course.

Figures 14(b) and 15(b) also confirm that the measured latency values in SL2 unfortunately exceed 1 ms around several points near Point#c where SL mode switching occurs. The SL2 latency performance is degraded at the points, since block errors are observed as shown in Fig. 14(d) and Fig. 15(d) which cause HARQ retransmissions.

If all the points on the evaluation course are in LOS radio propagation conditions from BS antenna, once they are determined to connect in SL Mode-2, it is generally hard to be connected in SL Mode-1 again as the vehicles are moving apart from the BS. However, from the experimental results of Fig. 14(a), (b) and Fig. 15(a), (b), it is also found that the UEs are connected to Cell#3 in SL Mode-1 again after once the UEs are changed from SL Mode-1 to SL Mode-2 and disconnected from Cell#3 the point near #c. We consider the reasons why this trial obtains such results as follows. As described in Section 4, the points near #c are in NLOS radio propagation conditions from BS antenna of Cell#3, and the points of the middle points between #c and #d are in LOS radio propagation conditions from the BS antenna of Cell#3 in this field trial environment. In such radio propagation environment, UL SINR does not always monotonically decrease and lower UL SINR values are possibly observed at
the points near #c than the points apart from #c as shown in Fig. 14(c) and Fig. 15(c). This means that the UL received signal quality is not possibly enough to maintain the connection at the points near #c, although the UL signal quality is enough to establish the connection at the points apart from #c. Therefore, in this experiment, we consider that the UEs are connected to Cell#3 in SL Mode-1 again after once the UEs are changed from SL Mode-1 to SL Mode-2 and disconnected from Cell#3 the point near #c.

Meanwhile, in SL Mode-1 and SL Mode-2 of our prototype system, each UE tracks the radio frame timing based on the synchronization signals transmitted from BS at the first time slot of the radio frame, and the received sidelink synchronization signals transmitted from a UE at the second time slot of the radio frame, as shown in Fig. 2. This means that synchronization signals for SL Mode-1 and SL Mode-2 are different each other. Figures 16(a) and (b) plot the measured SL SINR values of FLs and BLs, respectively, for reference. In these figures, the SL SINR values from measurement results of the received signal power and the interference-plus-noise power of received DMRS for PSCCH transmitted from a UE to another UE in sidelink. Note that the power of IUI is possibly negligible from the interference-plus-noise-power in the measured SL SINR values for SL Mode-2 and SL Mode-1, since the radio resource assignments are fixed in the prototype system so as to avoid IUI described in Sect. 2.

Compared with Fig. 14(b), Fig. 14(c), and Fig. 16(a) or compared with Fig. 15(b), Fig. 15(c) and Fig. 16(b), we find that the measured SL SINR values of SL2 are degraded at the points where SL mode switching occurs near Point#c and block errors are observed. We consider that the latency performance possibly degrades since UEs cannot successfully receive the sidelink data channels and the low SL-SINR values are possibly observed until the UEs complete the radio frame and the timing re-synchronization procedure, around the points when the SL mode switches between SL Mode-1 and SL Mode-2. Therefore, our future works on SL dynamic mode switching include latency reduction due to the re-synchronization associated with changing target synchronization signals between DL and SL when the SL mode switches between SL Mode-1 and SL Mode-2.

From Fig. 14(b), Fig. 15(b), and Fig. 16, the latency performance and SL SINR of the link between UE#1 and UE#3 are temporally degraded after switching from SL Mode-1 to SL Mode-2 when the UEs moves away from #c (near Core BS site), but the degradations are not observed at the other points (e.g., around #b near Remote BS site). We describe the reasons why such results are obtained as follows. In this field trial, since the radio resource assignment are fixed so as to avoid the IUI for SL Mode-2 as well as SL Mode-1, it is unlikely to degrade the SL SINR degradation between the UEs due to the IUI. Consequently, we do not need to the influence of the ISI into account. On the other hand, since OFDM-based radio access scheme is employed in the prototype system, it is required that the UEs continue to search and to track a correct OFDM symbol timing while moving. If the OFDM symbol timing is not correctly detected through the synchronization establishment procedure (i.e., if the synchronization does not work well), it is probable that the demodulation of the received signal does not work well due to the inter-symbol-interference (ISI) and the channel estimation degradation caused by the incorrect OFDM timing detection, and to degrade the accuracy of SINR value estimated by DMRS. Meanwhile, as described
in Sect. 2, the UEs use the downlink SS/PBCH block as a target synchronization signal for SL Mode-1 and the UEs use the sidelink SS/PBCH block as a target synchronization signal for SL Mode-2. Consequently, in the prototype system, the target synchronization signals are different between SL Mode-1 and SL Mode-2. This means that the UEs change the target synchronization signal when the SL mode switching between SL Mode-1 and SL Mode-2 happens. If a UE of the prototype system changes the target synchronization signals when the SL mode switches, it is probable that the demodulation accuracy and the measured SL SINR are unfortunately and temporally degraded until the UE freshly searches and tracks a correct OFDM symbol timing with the target synchronization signal after being changed. Therefore, the latency performance and the SL SINR unfortunately and temporally degrades at the points near #c after switching from SL Mode-1 to SL Mode-2 when the UEs moves away from #c, but the degradations are not observed at the other points (e.g., around #b) because the synchronization fortunately continues to work well even when SL mode switching happens.

When dynamic radio resource assignment is applied to an autonomous resource selection of SL Mode-2 in the future practical application, IUI from other 5G user terminals around the UEs of the same group cannot be always avoided due to the autonomous resource selection. This means that there is a future study on mitigating the influence of IUI due to the autonomous resource selection in SL Mode-2 for the SL dynamic mode switching, especially when 5G is commercially deployed in a wide area and there are the other 5G user terminals. However, we consider that the influence of IUI is possibly mitigated for the following reasons. As shown in Table 3, in this field trial, a fixed MCS with QPSK modulation scheme and the coding rate $R$ of 0.3 for data transmission is used, because adaptive modulation and coding (AMC) scheme has not been unfortunately implemented to the prototype system due to its function limitation. Meanwhile, in the 3GPP specifications of 5G NR, several lower-order MCSs with QPSK modulation and adequately lower coding rate of less than 0.3 are also defined for the data transmission [16]. If an appropriate lower-order MCS with is applied, it is expected that the user data will be successfully transmitted over the sidelink under low SL SINR conditions caused by IUI, when SL Mode-2 is selected at the points of out-of-coverage area not served by BS for the SL dynamic mode switching. Therefore, if 5G is commercially deployed in a wide area and there are the other 5G user terminals, the over-the-air latency performance degradation due to IUI will be possibly avoided by selecting the lower-order MCS in SL Mode-2.

In the experimental results, the over-the-air latency performance is degraded at some points for the link between the leading vehicle (Truck#1) and the second following vehicle (Truck#3), although the over-the-air latency performance degradation are not observed for the link between the leading vehicle (Truck#1) and the first following truck (Truck#2). This is because the radio propagation distance of the Truck#3 from Truck#1 is longer than that of Truck#2 from Truck#1. However, we consider that the scalability of the V2V Direct communication is possibly enhanced while satisfying the system requirement for general case of truck platooning with vehicles in the row. The reasons are described as follows. Although the target of over-the-air latency performance is below 1 ms in general target URLLC requirements, 3GPP has discussed E2E communication performance requirements of V2X communications [11]. For example, 3GPP reports the target E2E communication latency of below 10 ms for message transfer among a group of UEs in a use case of vehicle platooning, through a study of 5G V2X services [11]. In the prototype system, the number of HARQ retransmissions are permitted by two times so as for the sidelink to satisfy the application IP-layer E2E latency of below 10 ms. although the over-the-air latency of exceeds 1 ms when a HARQ retransmission occurs. On the other hand, a fixed MCS with QPSK modulation scheme and the coding rate $R$ of 0.3 for data transmission is used in this field trial due to the function limitation. Since it is possible that a lower-order MCS generally achieves lower BLER performance, if the lower-order MCS is employed, the over-the-air latency performance is improved in case of longer radio propagation distance. Therefore, for general case of truck platooning with more and more vehicles in the row, the scalability of the V2V Direct communications with SL dynamic mode switching can be enhanced by employing a suitable lower-order MCS and/or a suitable the number of HARQ retransmission as long as the E2E latency requirement is satisfied.

In the last of this section, we describe the performance in another environment different from this field trial environment. Since this field trial was carried out on the highway with no steep up-down, the heights of UE antennas on the different trucks were almost the same. On the other hand, if there is a steep up-down and the heights of the UE antennas on the different trucks may be different, we discuss whether there is any impact from such misalignment. For example, when the platooning vehicles moves on the road with a reversed U-shaped slope where the height of the first following vehicle (i.e., Truck#2) is higher than the that of the leading vehicle (Truck#1) and the second following vehicle (Truck#2), the path loss of the links between UE antennas on Truck#1 and Truck#3 may increase with the shadowing effect caused by the body of Truck#2. In such case, we considered that the lower-order MCS may be selected in the links in order to avoid the latency performance degradation of the V2V Direct communication. Therefore, further performance evaluation of the V2V Direct communication is required in case that the trucks move on the road with steep up-down.

6. Conclusions

In this paper, we introduced an overview of our developed 5G-NR V2X prototype with sidelink (SL) dynamic mode switching as a new function, and presented the evaluation re-
sults on over-the-air latency performance on the V2V Direct communication using SL dynamic mode switching towards application to truck platooning, on a public express highway area in Japan. The results demonstrated that our developed the SL dynamic mode switching achieves the seamless V2V Direct communication between base station in-coverage area and out-of-coverage area with the target latency performance of below 1ms. However, the results also find that it is also possible to degrade the latency performance while SL mode switches between SL Mode-1 and SL Mode-2, because the synchronization signals for SL Mode-2, because the synchronization signals for SL Mode-1 and SL Mode-2 are different each other, and UEs cannot successfully receive the sidelink data channels and the low SL SINR values are possibly observed until the UEs complete the radio frame re-synchronization procedure. Therefore, our further works include how to mitigate the degradation. Furthermore, since dynamic radio resource assignment function has not been implemented to the prototype system and the radio resource assignments are fixed in this field trial so as to avoid IUI caused by the autonomous radio resource selection in SL Mode-2, our further works also include studies on the mitigating the IUI and the performance evaluation consider-ing the IUI in SL Mode-2 with dynamically autonomous radio resource selection. Then, since this field trial was carried out on the highway with no steep up-down and the heights of UE antennas on the different trucks were almost the same almost, further performance evaluation of the V2V Direct communication is required in consideration that the heights of the UE antennas on the different trucks may be different when the trucks move on the road with steep up-down.

Acknowledgments

This work was partially sponsored by the Ministry of Internal Affairs and Communications of Japan, under the grant to Wireless City Planning Inc., “Research and examination on technical requirements and others in 5G mobile communication system for realizing low-latency and ultra-reliability communications with the target over-the-air latency of below 1ms and end-to-end latency of below 10ms”. The field trials were carried out in cooperation with Mr. Yoshikazu Ishida and Mr. Hideya Nishiyori; the members of Advanced Technology Development Division, SoftBank Corp.

References


Manabu Mikami received the B.E. degree in information engineering, the M.S. degree in information science, and the Ph.D degree in electrical communication engineering from Tohoku University, in 1993, 1995 and 2008, respectively. From 2000 to 2006, he has been with Information and Communication Research Laboratories, Japan Telecom Company Limited (currently, SoftBank Corporation). From October 2006, he has been also a manager with Wireless R&D Division at SoftBank Mobile Corporation (currently, SoftBank Corporation), and engaged in R&D of mobile communication systems. He is currently a senior research engineer in Advanced Technology Development Division, SoftBank Corporation. From June 2019 to June 2021, he has been the Vice Chair of Editorial Committee of the Institute of Electronics, Information, and Communication Engineers (IEICE) Transactions on Communications for Japanese Edition. He received the Best Paper Award and the IEICE Paper of the Year both in 2020, respectively. He is a member of IEEE.

Kohei Moto received the B.E. degree in biological technology, and the master of intellectual property from Tokyo University of Science, Tokyo, Japan, in 2007 and 2009, respectively. He joined SoftBank Mobile Corporation (currently SoftBank Corporation) in 2009. From 2009 to 2016, he engaged in creating IPRs, and handling IP disputes in IPR department. Since 2017, he has been engaged in R&D of mobile communication systems in Advanced Technology Development Division.

Koichi Serizawa received the B.S. and M.S. degrees in mechanical engineering from the Science University of Tokyo, Tokyo, Japan, in 2015 and 2017, respectively. He joined SoftBank Corporation in 2017. He has currently engaged in R&D of wireless communication.

Hitoshi Yoshino received the B.S. and M.S. degrees in electrical engineering from the Science University of Tokyo, Tokyo, Japan, in 1986 and 1988, respectively, and the Dr. Eng. degree in communications and integrated systems from the Tokyo Institute of Technology, Tokyo, Japan, in 2003. From 1988 to 1992, he was with Radio Communication Systems Laboratories, Nippon Telegraph and Telephone Corporation (NTT), Japan. From 1992 to 2008, he has been with NTT DoCoMo Inc., Japan. Since 2009, he has been with SoftBank Mobile Corporation. He has been engaged in the areas of mobile radio communication systems and digital signal processing. He is currently a deputy manager in Advanced Technology Development Division, SoftBank Corporation. He received the Young Engineer Award and the Excellent Paper Award from the Institute of Electronics, Information, and Communication Engineers (IEICE) of Japan both in 1995. He also received the Best Paper Award and the IEICE Paper of the Year both in 2020. He is a member of IEEE.