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Field Trial on 5G Low Latency Radio Communication System Towards Application to Truck Platooning

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SUMMARY The fifth generation mobile communication system (5G) is designed to have new radio capabilities to support not only conventional enhanced Mobile Broadband (eMBB) communications but also new machine type communications such as Ultra-Reliable Low-Latency communications (URLLC) and massive Machine Type communications (m-MTC). In such new areas of URLLC and m-MTC, mobile operators need to explore new use cases and/or applications together with vertical industries, the industries which are potential users of 5G, in order to fully exploit the new 5G capabilities. Intelligent Transport System (ITS), including automated driving, is one of the most promising application areas of 5G since it requires both ultra-reliable and low-latency communications. We are actively working on the research and development of truck platooning as a new 5G application. We have developed a field trial system for vehicular-to-network (V2N) communications using 5G prototype equipment and actual large-size trucks in order to assess 5G capabilities, including ultra-low-latency, in automotive test courses in the field. This paper discusses the fundamental performance evaluation required for vehicular communications between platooning trucks, such as low-latency message communication for vehicle control and low-latency video monitoring of following platooning truck vehicles. The paper also addresses the field evaluation results of 5G V2N communications in a rural area. It clarifies the fundamental radio propagation issues at the leading and the following vehicles in truck platooning for V2N communications, and discusses the impact of the radio propagation over a road to the over-the-air transmission performance of 5G V2N communications.

key words: *5G, low latency, truck platooning, field trial*

1. Introduction

Research and development efforts are underway towards the commercial roll-out of the Fifth Generation Mobile Communication System (5G) in 2020. 5G supports not only enhanced Mobile Broadband (eMBB) but also Ultra Reliable and Low Latency Communication (URLLC) and massive connections for Machine Type Communication (MTC), massive-MTC (m-MTC) [1], [2]. URLLC and m-MTC are particularly attractive as potential enablers to expand the mobile communication market to the new areas, such as mission critical and networked industrial applications. It is therefore urgent to identify new and concrete use cases as applications utilizing 5G [3]. In Japan, the Ministry of Internal Affairs and Communications (MIC) began its 5G Integrated Verification Trials in 2017 [4]. This trial project not only attempts to demonstrate the technical evaluation of 5G for their future commercial roll-out, 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 both passenger-car and truck platooning [5] 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 to demonstrate the ultra-low-latency capabilities of 1 ms over-the-air transmission in our trial project [6].

In our trials, we first noticed that the propagation condition between a base station (BS) and a leading truck or the propagation condition between the BS and a following truck, i.e. the second truck, would greatly be different in Vehicular-to-Network (V2N) communication via a Base station, since an inter-vehicle distance of a leading truck and its follower truck is short and relatively constant in a moving platooning structure, while the radio propagation conditions between a BS and each truck are typical mobile propagation conditions. Then, we conclude that it is important to evaluate transmission performances of V2N communications, considering these different propagation conditions for both cases of between a BS and a leading truck and between a BS and a second truck, since, in general, the over-the-air transmission performance of radio systems heavily depends on the radio propagation conditions. A lot of previous work on field trials for 5G systems has been carried out [7]–[13]. For examples, the literature [10] experimentally evaluate latency and throughput performance for 5G URLLC with network slicing, but it is not enough to consider over-the-air transmission characteristics in practical radio propagations for 5G frequency band candidates since it focuses on wired 5G communication. The literature [11] presents the field evaluation results on over-the-air latency and reliability performance using a new radio frame structure for 5G URLLC with the target mobility speed of 25 km/h. The literature [12] demonstrates and evaluates throughput and high-speed beam tracking performance of Massive MIMO for 5G using 28 GHz band in high mobility environments up to car speed of 170 km/h. The literature [13] experimentally evaluates throughput and performance of Distributed MIMO for 5G using 15 GHz band with mobility environments up to a speed of 40 km/h. However, to the best of the authors' knowledge, these previous works including [10]–[13] have not yet addressed the radio propagation conditions focusing on a structure of truck pla-

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tooning and their impacts on transmission performance in 5G based V2N communications using higher 5G frequency bands of 4.5 GHz and 28 GHz [14]–[17].

Second we noticed that there is a trade-off between retransmission scheme in a cellular system and over-the-air latency. Cellular systems, such as 4G and 5G as well, employ Hybrid-Automatic-Repeat-reQuest retransmission (HARQ) and Adaptive-Modulation-and-Coding-rate-control (AMC) based on ACK/NACK feedback. The ACK/NACK based HARQ and AMC techniques degrade the over-the-air transmission latency performance, while they contribute to improve the over-the-air transmission reliability and the spectral efficiency with permitting retransmission when an over-the-air transmission error occurs. In our 5G trials, we also consider that it is important to evaluate the impact of HARQ and AMC on the latency characteristics when applying 5G to truck platooning. This trade-off was also examined in our field trials of truck platooning and is discussed in this paper. Moreover, we also found that the appropriate choice of optimum target initial BLock Error Rate (BLER) for AMC is also important in 5G ultra-low-latency communications. We evaluate and discuss the impact on the target initial BLER in this paper.

We built a field trial environment for 5G V2N communication with actual large-size truck vehicles and a 5G prototype system consisting of a BS and user terminals [18], considering a typical radio environment in a rural area, e.g. a highway in a rural area, for vehicular communications of truck platooning. From the field experimental results, this paper contributes to identify the fundamental radio propagation issues of the leading and the following vehicles in a moving truck platooning structure in 4.5 GHz and 28 GHz bands, respectively. Moreover, it also contributes to evaluate the over-the-air transmission performance of the prototype with a view of applying 5G to truck platooning experimentally, and discusses on the radio propagation over a road and the relation between the difference and the over-the-air transmission performance of 5G. Moreover, it also discusses the impact of HARQ and AMC on the over-the-air latency characteristics in actual field trials.

The rest of this paper is organized as follows. Section 2 overviews 5G utilization for truck platooning. Section 3 presents overall configuration our field trial system using the 5G prototype and its field evaluation environment. Section 4 describes and discusses the field evaluation results. Finally, this paper is concluded in Sect. 5.

2. Applications of 5G for Truck Platooning

2.1 Truck Platooning

Truck platooning is the electrical linking of two or more trucks in convoy. They move on the highway together as one group to reduce fuel consumption and CO_2 emission as well as to achieve more efficient use of roads, i.e. to improve road traffic capacity. The research and development of truck platooning are currently being conducted all over the world to this end [19], [20].

Truck platooning can solve several social problems, such as CO_2 emission, traffic congestion, shortage of truck drivers, their severe work environment, cost of logistics. If platoons drive with a shorter inter-vehicle distance, air resistance affecting vehicles could be reduced, resulting in lower fuel consumption and less emission of CO_2 into the atmosphere. For example, it has been demonstrated that three trucks running in a platoon, driving at 80 km/h while separated by the distance of 4 m, decreases those vehicles' fuel consumption by 15% [20]. If the distance between the trucks further reduces to be only 2 m, there could be fuel savings of 25% [20]. At the same time, this would also lead to an increase in the capacity of roads while mitigating traffic congestion. This would result in further CO_2 reductions. In Japan, the aging of drivers and their overworking are becoming crucial social issues, since these increase traffic accidents and severe working environment. It is expected that stress of the truck driver be reduced and safety be improved by the introduction of the truck platooning.

Adaptive Cruise Control (ACC) measures a distance between a lead vehicle and a following one by using radar and keeps an inter-vehicle distance safe, corresponding to its vehicle speed [21]. ACC is widely introduced in trucks to help to improve safety on the roads. There is, however, a large time delay from the instant that the deceleration of the vehicle ahead begins and that the distance between the lead and following vehicles becomes shorter. It further takes a larger delay until the deceleration of the following vehicle begins. So, in general, the longer inter-vehicle distance is needed to prevent a collision by using ACC alone. On the other hand, a Cooperative ACC (CACC) can significantly improve the controllability when the vehicle ahead suddenly brakes, because the CAAC controls vehicle speed by transmitting the speed and acceleration data of the vehicle ahead to the following vehicles [21]. In addition, CACC provides stable running without hunting (fluctuation of inter-vehicle distance) due to its shorter latency. To realize further improvement in fuel economy and to increase road traffic capacity, less inter-vehicle distance and larger numbers of vehicles in the truck platooning is necessary without compromising safety. The application of 5G URLLC to the area of truck platooning is highly expected since 5G provides ultra-low latency and high reliability [22].

2.2 5G Use Cases for Truck Platooning

The authors are working on two use cases to demonstrate 5G's low-latency capabilities as follows;

(i) Communications between vehicles for platooning,
(ii) Communication for remote monitoring and remote operation of platoon from a remote site.

These use cases are shown in Fig. 1 and Fig. 2.

Communication requirements for these use cases can be classified into two categories; (i) low capacity and low latency communication and (ii) high capacity and low latency.

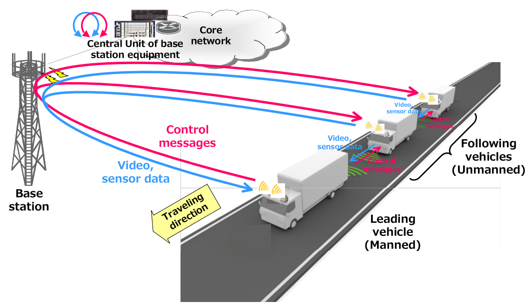


Fig. 1 Communications between vehicles in truck platooning.

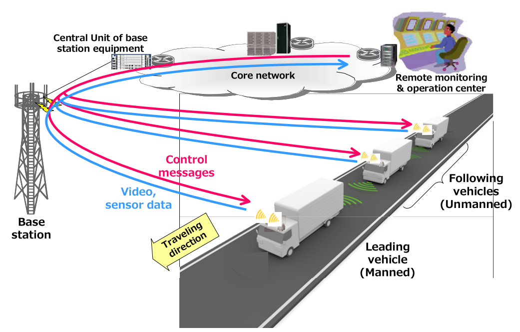


Fig. 2 Communications in remote monitoring and operations for truck platooning.

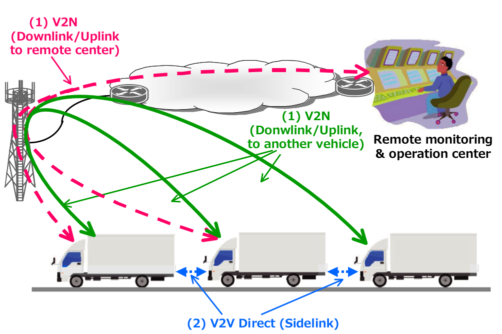


Fig. 3 Types of vehicular communication in truck platooning.

The first category is required for vehicle control system, which transmits and receives information of vehicle speed, acceleration and vehicle positioning. This category also requires high reliability. The second category is required for video monitoring system for platooning, which transmits and receives video streams to monitor areas around the following vehicles.

As shown in Fig. 3, The communication types for truck platooning are roughly divided into (1) Vehicle-to-Network (V2N) using the downlink and the uplink between a base station and user terminals and (2) Vehicle-to-Vehicle (V2V) Direct using the sidelink between user terminals, in terms of the over-the-air transmission. V2N is a communication link which connects the vehicles to a mobile network via a base station or a vehicular-to-vehicular communication link via a base station to connect vehicles. The V2N links are required for communication between vehicles or for a remote monitoring of vehicles and a remote operation of vehicles. Note that this paper defines that Vehicle-to-Network-to-Vehicle (V2N2V), which is a vehicular-to-vehicular communication link via a base station to connect the vehicles, is included in the category of V2N, since the downlink and the uplink are used in V2N2V. V2V Direct is a communication link, which directly connects the vehicles. The V2V Direct links provide lower latency communication, being compared with the V2N based vehicle-to-vehicle links, but has a possibility of less reliable communication due to the interrupt of radio waves by other blocking vehicle i.e., other vehicle going in between the two trucks. On the other hand, the V2N links provide relatively low latency and stable communication with the support of a base station. Therefore, this paper focuses on and evaluates radio propagation and over-the-air transmission performance in V2N communication.

3. Field Trial System and Environments

3.1 Overview of 5G Prototype System

Figure 4 illustrates the overall trial configuration of the 5G prototype system for V2N communication test with the view of applying 5G to truck platooning. As shown in this figure, the 5G prototype system is roughly divided into a base station (BS) side and a mobile station (MS) side. The BS side is comprised of a core network equipment (CNE), and a base station equipment (BSE) which consists of a base band unit (BBU) and a radio frequency - antenna unit (RAU). The MS side is comprised of a test user equipment (TUE) equipped with a personal computer (PC) for control and measurement data logging. Note that Fig. 4 also show data flow of packet for measurement of over-the-air round trip time (RTT) delay.

Figure 5(a) and Fig. 5(b) illustrate the radio frame structure of the prototype. As shown in Fig. 5, it specifies the downlink and the uplink slot ratio of 1 : 1 and the transmission-time-interval (TTI) of 0.125 ms for both the 4.5 GHz and 28 GHz bands shorter than that of 1ms for 4G, in order that the 5G prototype system achieves the low-latency performance compared to 4G. In this paper, we define that the over-the-air latency includes TTI and delay processing delays of both physical layer (Layer-1: L1) and higher layers (Layer-2/Layer-3 : L2/L3), just like the definition of user-plane (U-plane) latency discussed in 3GPP [2]. Therefore, the shorter TTI contributes reducing over-the-air latency. Note that the target value of 1ms for L1 processing delay of 5G URLLC is defined in ITU-R [1], and that the target minimum L1 processing delay of 3 ms is specified in 3GPP for 4G [2].

Table 1 summarizes the major radio specifications of 5G prototype system for 4.5 GHz and 28 GHz bands, respectively. From Table 1, since the prototype employs Hybrid-Automatic-Repeat-reQuest (HARQ) retransmission technique for improvement of the over-the-air transmission reliability based on ACKnowledgement (ACK) and Negative ACK (NACK) feedback, it employs outer-loop link adaptation technique with Adaptive Modulation and Coding rate

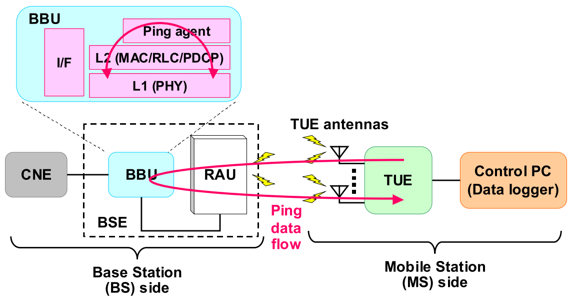
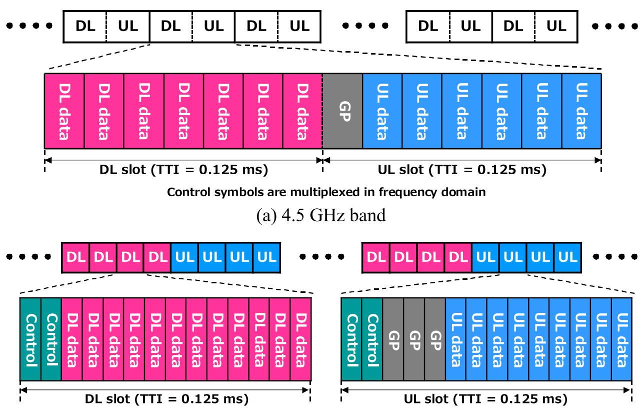


Fig. 4 Fundamental system configuration of 5G prototype for field trial.



(a) 4.5 GHz band

(b) 28 GHz band

Fig. 5 Radio frame structure of prototype system.

Table 1 Major radio specifications of prototype system.

		4.5 GHz band equipment		28 GHz band equipment
Data radio bearer type		URLLC	eMBB	eMBB
Carrier frequency		4.74 GHz		27.9 GHz
System bandwidth		100 MHz		700 MHz
Radio access (Duplex)		OFDMA (TDD)		
Sub-carrier spacing		60 kHz		120 kHz
TTI length		0.125 ms		
Maximum RB allocation size		10 RBs	136 RBs	476 RBs
Data modulation scheme	DL	QPSK, 16QAM	QPSK, 16QAM, 64QAM, 256QAM	
	UL		QPSK, 16QAM, 64QAM	
Data channel coding scheme		Turbo coding		
Data channel coding rate		QPSK:0.08-0.59, 16QAM:0.37-0.50	QPSK: 0.08 - 0.59, 16QAM : 0.37-0.60, 64QAM: 0.46 - 0.85, 256QAM : 0.69-0.93	
Adaptive Modulation and Coding rate control (AMC)		Outer-loop link adaptation with HARQ ACK/NACK based AMC		
Target initial BLER for AMC		1%	10%	
Antenna polarization		±45° cross polarization		
Tx/Rx antenna port configuration	BSE	64Tx/64Rx		4Tx/4Rx
	TUE	2Tx/4Rx		
Maximum number of spatial layers	DL	1 layer	4 layers	
	UL		2 layers	
Rank adaptation		Not applied	Applied	
Target initial BLER		1%	10%	
Retransmission scheme		ACK/NACK based HARQ retransmission		
Layer-1 (L1) processing delay		0.375 ms	1.125 ms	

control (AMC) based on the HARQ ACK/NACK feedback and target initial Block Error Rate (BLER) for the spectral efficiency improvement. In the prototype, it is most distinctive to configure two dedicated data radio bearer types of URLLC bearer and eMBB bearer for 4.5 GHz band. Note that it is possible for 28 GHz band to configure eMBB bearer only, and that the target initial BLER values in the outer-loop link adaptation are 1% and 10% for the URLLC and the eMBB bearers, respectively. For the URLLC and the eMBB bearers, the shorter TTI contributes to the L1 processing delay reduction to 0.375 ms and 1.125 ms compared to the target value of 3 ms for L1 processing delay of 4G whose TTI of 1 ms, respectively. These radio bearers are described below.

The URLLC bearer is to demonstrate 5G use cases in which ultra-low-latency and high-reliability are more important than capacity. In the multi-antenna transmission for the URLLC bearer, MIMO spatial multiplexing is not employed but MIMO antenna diversity technique is employed in order to obtain higher-order diversity gain that contributes the reliability improvement of over-the-air transmission. The transmission and received signal processing for the URLLC bearer is prioritized compared to that for the eMBB bearer, although the maximum number of resource block (RB) assignment is limited to a part of RBs, i.e., 10 RBs. On the other hand, the eMBB bearers are to demonstrate 5G use cases in which capacity (or throughput) is more important than reliability. In order to obtain higher throughput performance, it is possible to allocate all the RBs except for common and control channels for the eMBB bearers, and MIMO spatial multiplexing is employed in the multi-antenna over-the-air transmission for the eMBB bearers.

3.2 Field Evaluation Environment and Conditions

The system performance of the prototype was evaluated for V2N communications with large-size truck vehicles in an automotive test course, Tsukuba-city, Ibaraki-prefecture, Japan, considering rural radio environment for platooning, e.g. a highway in a rural area. Figure 6 shows the field trial environment and its evaluation course. Figure 7(a) and Fig. 7(b) illustrate the overall system setup for the field evaluation. Table 2 summarizes major evaluation conditions. Figure 8(a) and Fig. 8(b) shows examples of the field evaluation scenes at BS and MS sides, respectively.

As shown in Fig. 6, the evaluation course was set to the straight zone with the length of about 1.88 km and 1.15 km in the test course for 4.5 GHz and 28 GHz bands, respectively. As shown in Fig. 7(a) and Fig. 7(b), four vehicles were used for the field evaluation. One was a specialized vehicle for high-place works, another was a stationary truck vehicle for installing BSE and CNE, and the others were two truck vehicles for measurements. RAU of BSE was mounted on the maintenance box of the high-place work vehicle by the end of the evaluation course, as shown in Figs. 7–8. The height of RAU for the BS was set to 5 m for both 4.5 GHz and 28 GHz bands, as shown in Table 2. BBU of BSE and CNE were installed in the container of the stationary truck vehicle. As shown in Fig. 7(a) and Fig. 7(b), the two measurement truck vehicles correspond to a leading vehicle and a following vehicle in truck platooning, respectively. TUE was installed in the container of either the leading or the following vehicle. As shown in Table 2, the antenna height of TUE was set to about 2.8 m and 1.8 m, for 4.5 GHz

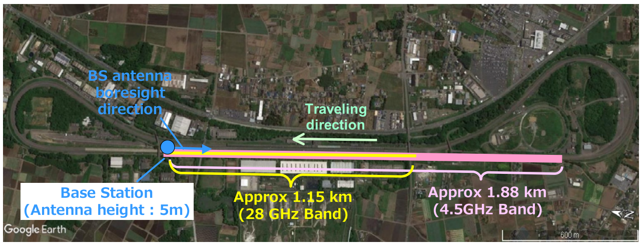
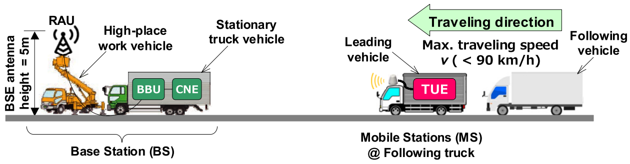
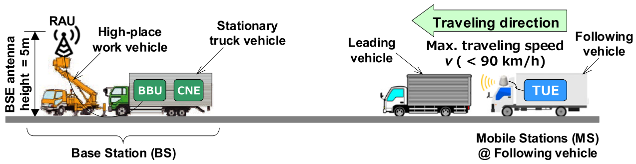


Fig. 6 Field trial environment and evaluation course.



(a) For evaluation at leading vehicle



(b) For evaluation at following vehicle

Fig. 7 Overall system setup for field evaluation.

Table 2 Major evaluation conditions in field trial.

		4.5 GHz band	28 GHz band
DL/UL slot ratio		1 : 1	4 : 4
Antenna height	BSE	5 m	
	TUE	2.8 m	1.8 m
Communication traffic load	Latency test	1 packet/sec periodic traffic (60 bytes/packet)	
	Throughput test	Full buffer traffic (1500 bytes/packet)	
Total size of measurement vehicle truck		Length : 12 m, Width : 2.4 m, Height : 3.8 m	
Inter-vehicle distance between leading and following truck		10 m	
Measurement vehicle speed		v = 10 km/h, 30 km/h, 60 km/h, 90 km/h	

and 28 GHz bands, respectively. As shown in Fig. 8(b), the leading and the following vehicles traveled on the evaluation course with platoon formation.

The location of RAU and TUE antennas are additionally described below. As shown in Fig. 8(a), RAU is located on the right road shoulder and TUE antennas are located on the right lane in the course with three lanes in our experiment campaign. As a result, RAU and TUE antennas are located on almost the same straight line when vehicles move on straight lanes, since the direct distance between RAU and the center of the lane of the course is short compared to normal deployments of RAU in our experiment campaign. However, we consider that the radio propagation in the case that RAU is deployed to roadside is approximately simulated at the location where the distance between RAU and TUE antennas, d, is sufficiently longer than the direct distance between the center of the right lane and RAU on the road shoulder, r (i.e., $d/r \gg 1$), because we can assume that RAU and TUE antennas are located on almost the same straight line in the case of $d/r \gg 1$ when platooning trucks move on straight lanes.

(a) BS side

(b) MS side

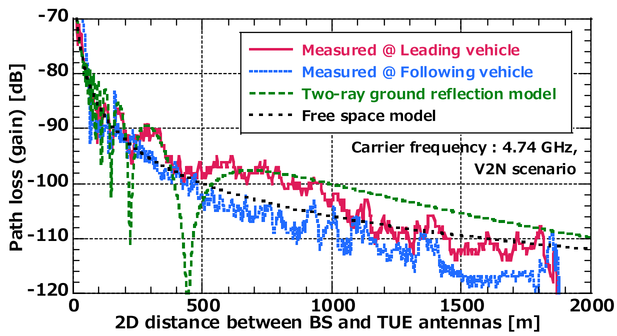
Fig. 8 Examples of field evaluation scenes.

4. Field Trial Results

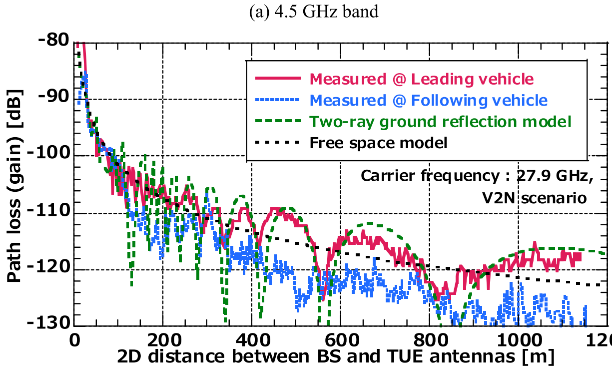
4.1 Radio Propagation Environment Evaluation

Radio propagation environments were first evaluated at the evaluation course. The evaluation was carried out to measure reception power strength by using Reference Signal (CSI-RS: Channel State Information – Reference Signal) which is periodically transmitted from BS in order to calculate path loss considering antenna gain, its pattern and feeder cable loss. Figure 9 plots measured path losses band at the leading and the following vehicles, respectively. Note that Fig. 9(a) and Fig. 9(b) show the results in 4.5 GHz and 28 GHz bands, respectively. In both Fig. 9(a) and Fig. 9(b), the path loss curves predicted by two-ray ground reflection and free space models [16] were also plotted as references. From Fig. 9(a) and Fig. 9(b), it is found that the measured path loss characteristics at the leading and following vehicles are different each other. The difference is descried bellow.

Figure 9(a) and Fig. 9(b) confirm that the path loss fluctuation measured at the leading vehicle approximately meets that of the two-ray ground reflection model in both 4.5 GHz and 28 GHz bands, except at the points with the distance lager than about 1000 m. This is because the direct wave suffers from interference caused by the dominant path reflected at the road surface in the measurement course although the



(a) 4.5 GHz band



(b) 28 GHz band

Fig. 9 Path loss evaluation results.

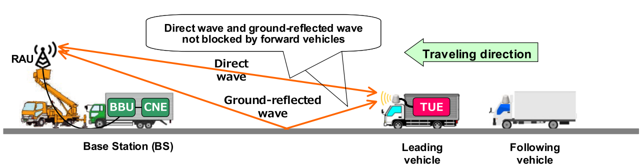
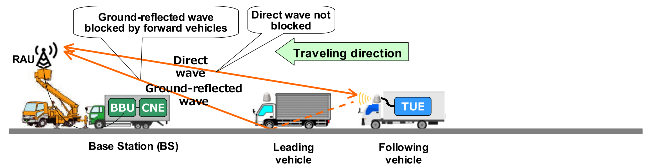
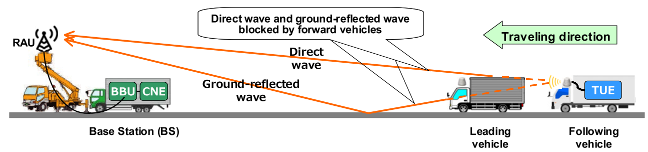


Fig. 10 Typical propagation for V2N communications at leading vehicle.



(a) Near BS antenna site (LOS propagation scenario at following vehicles)



(b) Far from BS antenna site (NLOS propagation scenario at following vehicles)

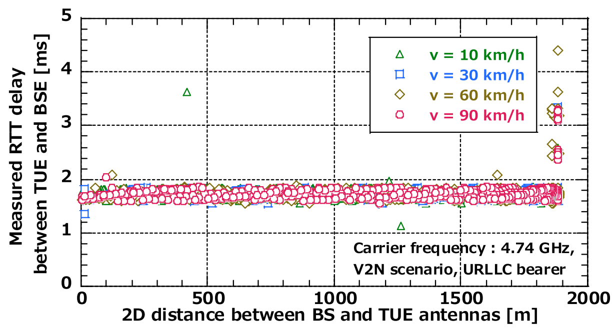
Fig. 11 Typical propagation for V2N communications at following vehicles.

TUE antennas of the both frequency bands the Line-Of-Sight (LOS) radio propagation from the BS antennas, as shown in Fig. 10. From the result, it is possible that the LOS radio propagation of V2N communications of the leading vehicle for platooning trucks is further well modelled by modifying the two-ray ground reflection model.

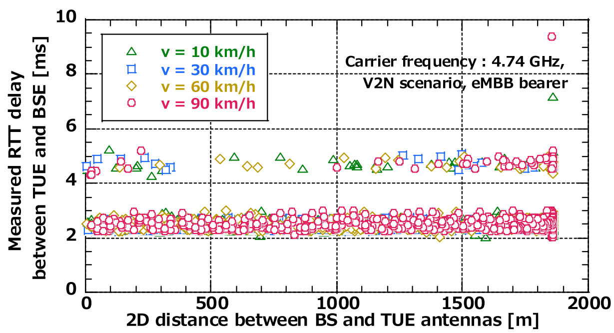
On the other hand, Fig. 9(a) and Fig. 9(b) confirm that the path loss fluctuation measured at the following vehicle well meets that of the free space model at the points near the surrounding with the distance of less than just about 400 m and 100 m from the BS side, respectively, for the both 4.5 GHz and 28 GHz bands. Their figures also confirm that the path loss fluctuation measured at the following vehicle is larger than that of the free space model at the points farther than the surrounding with the distance of just about 400 m and 100 m distance from the BS side for 4.5 GHz and 28 GHz bands, respectively. Furthermore, Fig. 9(a) and Fig. 9(b) confirm that the noticeable fluctuation caused by the path reflected at the road surface are not observed at the following vehicle unlike the case of the leading vehicle, since it is possible that the reflected wave at the road surface is blocked by the body of the leading vehicle, although the direct wave is not blocked. From the above results shown in Fig. 9(a) and Fig. 9(b), we consider that boundary points of the Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) propagation condition at the following vehicle are the points with the distance of 400 m and 100 m for 4.5 GHz and 28 GHz bands, respectively. Figure 11(a) and Fig. 11(b) illustrate two typical radio propagation scenarios with the LOS and NLOS conditions at the following vehicle, respectively. Note that the NLOS condition at the following vehicle is when the direct wave is blocked by the body of the leading vehicle as shown in Fig. 11(b). The reasons why the boundary points of the LOS/NLOS condition are different between 4.5 GHz and 28 GHz bands and why the influence the noticeable fluctuation caused by the path reflected at the road surface are not observed at the following vehicle, are described below.

As shown in Table 2, the TUE antenna heights of 2.8 m and 1.8 m for both 4.5 GHz and 28 GHz bands are lower than the vehicle height of about 3.8 m. The TUE antenna height difference between 4.5 GHz and 28 GHz bands causes the difference of the boundary points of LOS/NLOS condition at the following vehicle. Since the TUE antenna height of 28 GHz is lower than that of 4.5 GHz, the boundary point is close to RAU at BS side for 28 GHz compared to 4.5 GHz. Moreover, as shown in Fig. 11(a) and Fig. 11(b), it is possible that the reflected wave at the road surface is blocked by the body of the leading vehicle although the direct wave is not blocked in the LOS condition. As a result, it is considered that the noticeable fluctuation caused by the path reflected at the road surface are not observed at the following vehicle, unlike the case of the leading vehicle. Therefore, at the points farther than about 400 m and 100 m distance from the BS side for 4.5 GHz and 28 GHz bands, the path loss measured at the following vehicle is larger than that of the free space model, respectively, as shown in Fig. 9(a) and Fig. 9. From their results, it is considered that the radio propagation of V2N communications for the following vehicle of platooning trucks near BS antenna sites is near LOS propagation as shown in Fig. 11(a), and that of the points far from BS antenna sites is near Non-Line-Of-Sight (NLOS) propagation as shown in Fig. 11(b).

From the results described in this subsection, it is clar-



(a) URLLC bearer



(b) eMBB bearer

Fig. 12 Examples of latency measurement results (4.5 GHz band).

ified that the fundamental radio propagation issues of "interference wave reflected from road surface" at the leading vehicle and "direct wave blocked by the leading vehicle" at the following vehicle, respectively, for the 5G spectrum candidates. Meanwhile, the blockage of direct wave due to the leading vehicle causes that RAU and TUE antennas are located on almost the same straight line, since the direct distance between RAU and the evaluation course is short. Therefore, we note that longer direct distance between RAU and the course possibly decreases the probability of direct wave blocked by the leading vehicle at the following vehicle.

4.2 Latency Characteristics

4.2.1 Examples of Measurement Results

Considering a 5G application to the vehicle control system in truck platooning and the remote operation of vehicles, the latency characteristics of the 5G system were evaluated. The expected message size of around 50–1200 bytes have discussed in 3GPP for use cases of high density platooning [23]. Therefore, in the latency evaluation, the packet size is set to 60 bytes, for an example of evaluation. Fig. 12 and Fig. 13 plot examples of over-the-air round trip time (RTT) delay between TUE and BSE of our 5G prototype using 4.5 GHz and 28 GHz bands, respectively. Note that Fig. 12(a) and Fig. 12(b) plot the performance for the URLLC and the eMBB bearers of our 5G prototype using 4.5 GHz band, respectively.

Figure 12(a) confirms that the over-the-air RTT is usually less than 2 ms, regardless of the vehicle speed v. It can

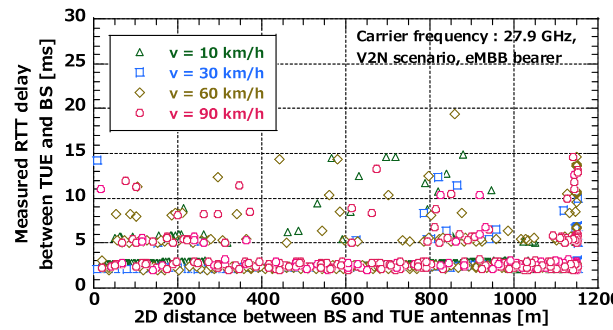


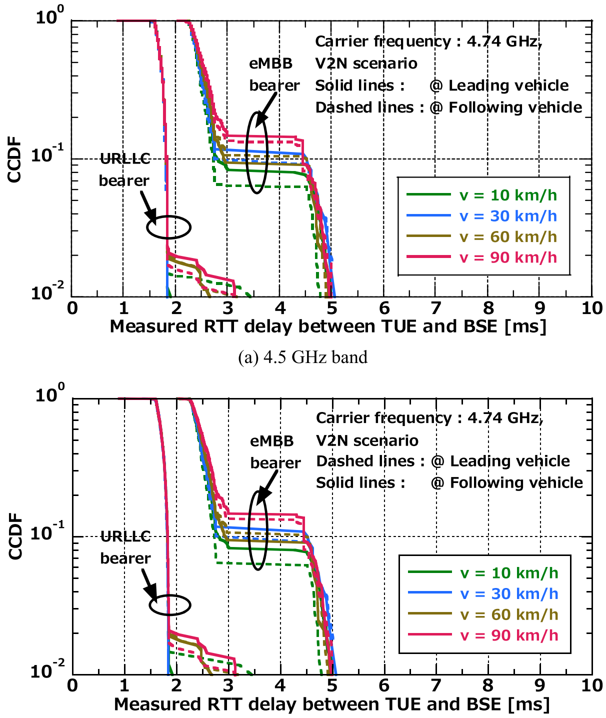
Fig. 13 Examples of latency measurement results (28 GHz band).

be concluded that our 5G prototype system can achieve one-way over-the-air latency of the target value of 1 ms for 5G URLLC use cases in ITU-R [1]. Note that the 1 ms target value for 5G URLLC corresponds to a quarter of the minimum over-the-air latency of 4 ms for 4G [24]. Figure 12(a) also confirms that the over-the-air RTT occasionally exceeds 2 ms corresponding to the one-way over-the-air latency of 1 ms especially, at the start point of the evaluation course corresponding to cell edge because of HARQ retransmissions. This over-the-air latency performance degradation is discussed in the following Sect. 4.2.2.

Figure 12(b) and Fig. 13 confirm that the measured over-the-air RTT values of the eMBB bearers for both 4.5 GHz and 28 GHz bands are almost increased compared to that of the URLLC bearer for 4.5 GHz band regardless of vehicle speed v, although the measured over-the-air RTT often less than the minimum RTT delay for 4G of 8 ms [25]. This is because the receiver L1 processing delay of 1.125 ms for the eMBB bearer is more than 0.375 ms for the URLLC bearer, and less than 3 ms for 4G [26]. The probabilities of the measured over-the-air RTT exceeding 8 ms are less than 1% and 10% for 4.5 GHz and 28 GHz band, respectively. From the above results, it can be concluded that the prototype of the both frequency bands achieve one-way over-the-air delay for the eMBB bearer of less than the target minimum User-plane latency value of 4 ms for eMBB use cases discussed in ITU-R [24].

4.2.2 Discussions on Latency Characteristics

Figure 14(a) and Fig. 14(b) plot complementary cumulative distribution functions (CCDFs) of the measured over-the-air of our 5G prototype for 4.5 GHz and 28 GHz bands, respectively, as a parameter of the truck vehicle speed v. In these figures, the CCDFs measured at both the leading and the following vehicles evaluated on the measurement course are plotted by the dashed and solid lines, respectively. In Fig. 14(a), the CCDFs for both URLLC and eMBB bearers of 4.5 GHz band equipment are plotted simultaneously. In Fig. 14(b), the CCDFs are plotted for eMBB bearer since it is possible for the 28 GHz band equipment to configure eMBB bearer only. Note that the measured RTT delay values are not constant because Layer-2 (L2) processing delay values are fluctuated due to the software-based processing although



(a) 4.5 GHz band

(b) 28 GHz band

Fig. 14 Distribution of measured over-the-air latency.

L1 processing delay is constant.

We now discuss the impact of the different values of the target initial BLER on the over-the-air latency performance. It is easily thought that guess that over-the-air latency of radio access systems strongly depend on the L1 processing delay. Moreover, since the prototype employs HARQ retransmission and outer-loop link-adaptation with AMC based on the HARQ ACK/NACK feedback and the target initial BLER, the latency performances also strongly depends on the target initial BLER value associated with the distribution of HARQ retransmission delay.

As shown in Table 1, the prototype has the different L1 processing latency of 0.375 ms and 1.125 ms, and also have the different target initial BLERs of 1% and 10%, for the URLLC and the eMBB bearers, respectively. As a result, it is considered that their RTT delay characteristics of the prototype are different between those of the URLLC and the eMBB bearers, as shown in Fig. 14(a). Figures Fig. 14(a) also finds that the over-the-air for the URLLC bearer is decreased compared to those for the eMBB bearer, since lower L1 processing latency is realized and lower target initial BLER values is applied for the URLLC bearer.

From Fig. 14(a) and Fig. 14 (b), it is found that significant influence of the vehicle speed for both the leading and the following vehicles are not observed on the delay characteristics, although the radio propagation characteristics at the vehicles are different each other described in Sect. 4.1. This is because the prototype selects appropriate data modulation level and channel coding rate so as that the measured initial BLERs correspond the target values of 1% and 10% for the URLLC and the eMBB bearers, respectively. From these figures, it is also found that 10-percentile values of measured RTT delay approximately increase with the vehicle speed, especially for eMBB bearers of both 4.5 GHz and 28 GHz bands. This is because the following reasons. When the vehicle speed is faster, it is more difficult for the eMBB bearers employing MIMO spatial multiplexing to select adequate modulation and coding rate set (MCS) in the link adaptation based on ACK/NACK feedback, since the time-varying radio propagation possibly becomes a cause of the inadequate MCS selection. This means that the BLERs caused by the inadequate MCS selection possibly increase with the vehicle speed in the time-varying radio propagation. As a result, the 10-per-centile values of the measured RTT delay since the probability of HARQ retransmissions increases with the vehicle speed.

On the other hand, Fig. 14(a) and Fig. 14(b) confirm that all the CCDFs of the delay performance have step-like shapes, since the delays increase with the number of HARQ retransmissions based on the ACK/NACK feedback. This means that the ACK/NACK-based HARQ retransmission scheme degrade the delay characteristics although it contrib-utes improvement of over-the-air transmission reliability. In this manner, there is a trade-off problem in order to realize low latency and reliability simultaneously. Moreover, these figures also confirm that the values of the first floors of CCDFs curves are different due to the different initial target BLER values between the URLLC and the eMBB bearers.

Meanwhile, evaluation results on packet loss rate of another important performance indicator for URLLC communication is described as follows. The upper limit on the number of HARQ retransmissions is five times for both 4.5 GHz and 28 GHz bands in the prototype. In this test environment, packet losses after HARQ retransmissions are not observed (i.e., packet loss rate = 0%) in both downlink and uplink regardless of the frequency bands, the bearer types, and the measurement vehicle speeds. Therefore, we do not show figures of the evaluation results on the packet loss rate in this paper. However, if the upper limit on the number of HARQ retransmissions is decreased in order to reduce the variance of the over-the-air latency (or RTT delay), we should note that packet losses cannot be avoided especially when TUE is located at near cell edge or cell boundary. Therefore, our future works include more evaluations on the packet loss rate at the conditions where packet losses are not avoided.

The rest of this subsection describes the other our future works on latency evaluations. The packet size of 60 bytes is fixed in the latency evaluation of this field trial, although the over-the-air latency possibly increases as the packet is packet size becomes large [11]. Therefore, our future works include further latency evaluations on the various packet sizes. On the other hand, in practical use cases for truck platooning, we should also consider the delay caused by handovers such as inter-cell handover and inter-frequency handover, since the delay caused by handovers may be more critical than the latency performance degradation due to HARQ retransmissions. However, this field trial does not consider the latency increase in case that handovers happen, because the field trial equipment does not unfortunately support handover functions. Therefore, our future studies also include the over-the-air latency evaluation considering various handovers.

4.3 Throughput Characteristics

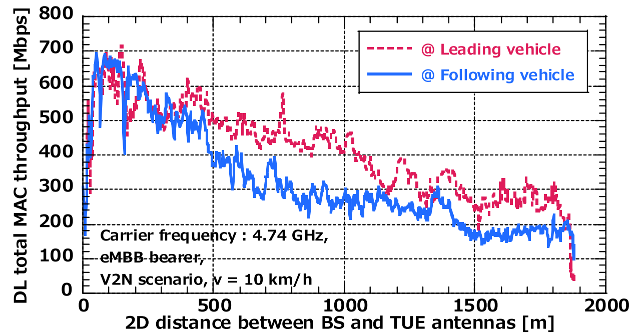
4.3.1 Examples of Measurement Results

In truck platooning, it is required to monitor the surrounding of following vehicles at the leading vehicle and that of all the vehicles at the remote monitoring and operation center. Field trial tests were carried out to assess the feasibility of low-latency and high capacity (or high throughput) communication systems by 5G. In the tests, throughput perfor mance is evaluated for the eMBB bearer only, since we consider that the eMBB bearer is more suitable than the URLLC bearer in order to require high user data rate. Figure 15(a) and Fig. 15(b) show examples of measured downlink over-the-air throughput performance versus the distance between BS and TUE antennas for 4.5 GHz and 28 GHz band V2N communications, respectively, as a parameter of the vehicle speed. In these figures, the dashed and the solid lines shows the performance for the leading and the following vehicle, respectively.

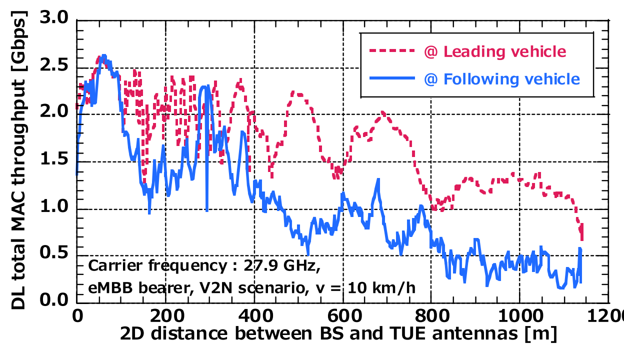
Figure 15(b) also confirms that large rolling of the throughput curve, associated with the interference wave reflected from the road surface, is observed at the leading vehicle in case of 28 GHz band, since the measured path loss fluctuation of 28 GHz band has deep null points as shown in Fig. 9(b). On the other hand, Fig. 15(a) confirms that such large rolling of throughput curve is not observed in case of 4.5 GHz band, since deep null points are not observed on the measured path loss fluctuation of 4.5 GHz band as shown in Fig. 9(a).

Figure 15(a) and Fig. 15(b) find that the measured throughputs at the following vehicle is lower than that at the leading vehicle on almost points far from BS antenna with the distance of over about 400 m and 100 m, for 4.5 GHz and 28 GHz band, respectively. This is because higher signal power is received at the leading vehicle compared to the following vehicle the points far from BS with the distance of over about 400 m and 100 m, as shown in Fig. 9(a) and Fig. 9(b). Figure 15(a) and Fig. 15(b) also finds that almost the same performance at the leading and the following vehicles is measured on the points near BS antenna with the distance of less than about 400 m and 100 m for both 4.5 GHz and 28 GHz bands. This is because the radio propagation conditions are LOS propagation at both the leading and the following vehicles, and the influence of the reflected wave from the road surface is small at the both vehicles.

From the above over-the-air throughput performance evaluation results, we conclude that V2N communication possibly suffers from throughput performance degradation due to the interference reflected from the road surface at the leading vehicle, and that it also possibly suffers from the



(a) 4.5 GHz band



(b) 28 GHz band

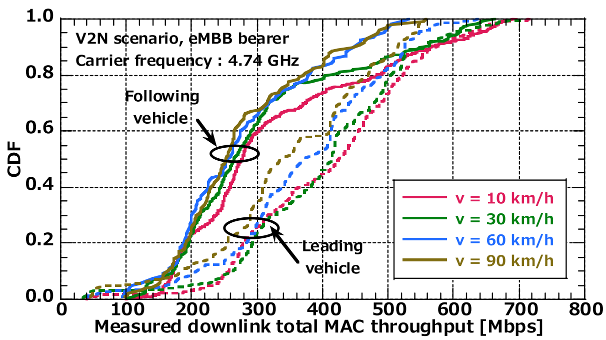
Fig. 15 Examples of over-the-air throughput measurement results.

degradation due to the increase of the path loss at the following vehicle in the NLOS condition described in Sect. 4.1 because the direct wave is possibly blocked by the leading vehicle especially at the points far from BS.

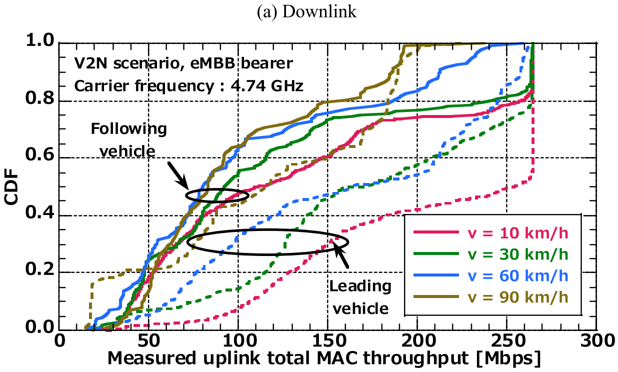
Since lower latency and higher reliability are given priority over data rate or spectral efficiency for a lot of URLLC applications as described in [11], throughput performance evaluations of URLLC bearer have not been yet carried out in this field trial. However, it is important to confirm the throughput performance of the URLLC bearer whether it could provide adequate capacity enough to realize truck platooning. Therefore, our future works include the throughput performance evaluation of the URLLC bearer.

4.3.2 Distribution of Measured Throughputs

Figure 16(a) and Fig. 16(b) show the cumulative distribution functions (CDFs) of the measured over-the-air throughputs for 4.5 GHz band V2N communications in the downlink and the uplink, respectively. Figure 17(a) and Fig. 17(b) also show those of the measured throughputs for 28 GHz band V2N communications in the downlink and the uplink, respectively. In Fig. 16 and Fig. 17, the truck vehicle speed v is a parameter, and the CDFs of the throughput measured at both the leading and the following vehicles are plotted. Figure 16(a) and Fig. 16(b) find high peak throughputs of about 700 Mbps and 260 Mbps are obtained in the downlink and the uplink for 4.5 GHz band, respectively. Figure 17(a) and Fig. 17(b) also finds that the very high peak throughputs of 2.6 Gbps and 1.8 Gbps in the downlink and the uplink

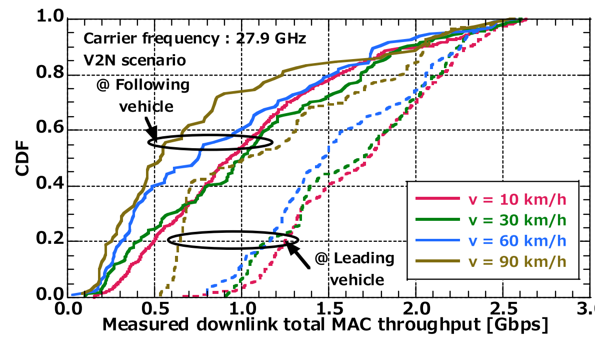


(a) Downlink

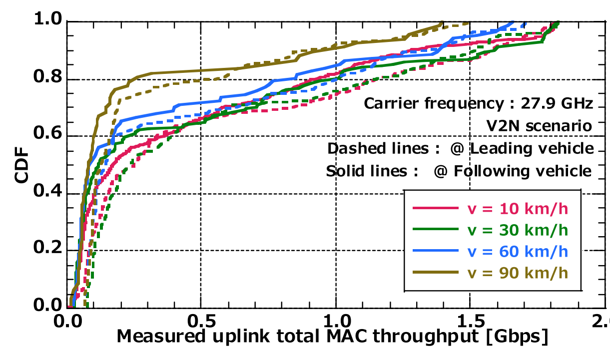


(b) Uplink

Fig. 16 Distribution of measured throughput (4.5 GHz band).



(a) Downlink



(b) Uplink

Fig. 17 Distribution of measured throughput (28 GHz band).

for 28 GHz band, respectively. Their results demonstrate that 5G systems offer high peak data rate because of the wider frequency bandwidth e.g., 100 MHz and 700 MHz for 4.5 GHz and 28 GHz bands, respectively.

On the other hand, from Fig. 16 and Fig. 17, it is also confirmed that 5 percentile throughputs are significantly lower than the peak throughputs for both 4.5 GHz and 28 GHz bands regardless of the downlink and the uplink, since the desired signal power decreases with the distance between BS and TUE antennas. This means that sufficient throughputs required for the video monitoring in truck platooning are not obtained by 5G, especially at the points far from BS antenna site e.g. cell edge. Therefore, our future works also include study and evaluation on throughput performance improvement at cell edge area for V2N communications in truck platooning.

5. Conclusion

We built a field trial environment for 5G communication system with a prototype consisting of base station equipment and test user terminal equipment using candidate 5G spectrum bands of 4.5 GHz and 28 GHz in Japan. The radio propagation environment evaluation and the over-the-air transmission performance evaluation of 5G low latency communication were carried out in real automotive test course with a view to applying 5G system to truck platooning, considering two use cases of (1) low capacity and ultra-low latency V2N communications for vehicular control, and (2) high capacity and low-latency communication for video monitoring. The major field evaluation results are as follows;

(i) The radio propagation environment evaluation results identified the two fundamental radio propagation issues; (1) "interference wave reflected from road surface" at the leading vehicle and (2) "direct wave blocked by the leading vehicle" at the following vehicle for the 5G spectrum considered.

(ii) The over-the-air transmission performance results clarified the impact of radio propagation to the over-the-air throughput performance. The results showed that the over-the-air latency characteristics are affected by the target initial BLER value when employing link adaptation and HARQ retransmission based on ACK/ NACK feedback. The results also showed that the throughput performance is also degraded at cell edge area.

Further field tests on the reliability of 5G communication is planned towards complete truck platooning test, including further studies on mitigating the latency performance degradation due to HARQ retransmissions, especially when link adaptation and HARQ retransmission techniques are employed based on ACK/NACK feedback and on throughput performance improvement at cell edge.

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