IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 1, 2020, accepted December 8, 2020, date of publication December 14, 2020, date of current version January 13, 2021.

Digital Object Identifier 10.1109/ACCESS.2020.3044358

Implementation and Performance Evaluation for DSRC-Based Vehicular Communication System

JEONG-KYU BAE[1], MYUNG-CHUL PARK[2], EUN-JU YANG[1], AND DAE-WHA SEO[3], (Member, IEEE)
[1]Research Department, CEST Company Ltd., Daegu 41566, South Korea
[2]Center for Embedded Software Technology, Daegu 41566, South Korea
[3]School of Electronics Engineering, Kyungpook National University, Daegu 41566, South Korea

Corresponding author: Dae-Wha Seo (dwseo@ee.knu.ac.kr)

This research was supported by the Ministry of Land, Infrastructure, and Transport (MOLIT, KOREA) [Project ID: 20TLRP-B146733-03, Project Name: Connected and Automated Public Transport Innovation (National R&D Project)].

ABSTRACT Traffic accidents and congestion are the most common on-road problems that might be anywhere and anytime. Recently, to deal with such problems, well-coordinated wireless communication system between vehicles, road side units (RSU), drones, etc., namely vehicle-to-everything (V2X) communication system, has been considered as a key technology enabling on-road human safety and convenience. One of the well-known building blocks of the V2X communication system is Wi-Fi based Dedicated Short Range Communication (DSRC) which performs stably, owing to a long year of study, simplicity and capability of distributed operation. In spite of promising opportunities brought by DSRC, its elaborate performance evaluation must be done under real-world scenarios, in advance to the actual use, since its performance is directly related to human and vehicle safety. In this context, this article presents field test results of DSRC-based V2X communication system we implemented. As a result of the line-of-sight (LoS) test, the distance represented by 90% or more of packet reception rate (PRR) was 720 meters at 5 dBm, and 1,035 meters at 11 dBm. In Non-LoS (NLOS) shadowing test, the distance represented by 90% or more of PRR was 175 meters at 5 dBm, and 520 meters at 11 dBm. And in NLoS intersection test, the distance represented by 90% or more of PRR was 320 meters at 5 dBm, and 515 meters at 11 dBm. Meanwhile, the distance for PRR 90% was up to 520 meters at urban environment, 1,219 meters on highway, and 1,700 meters inside a tunnel.

INDEX TERMS Vehicular communication, V2X, DSRC, C-V2X, performance evaluation.

I. INTRODUCTION

It has been a long time since social problems are caused by traffic accidents and congestion. In order to address the problems, various efforts have been made in both academic and industrial fields. Among them, wireless communication-based solutions are regarded as one of the most promising way to improve traffic safety and efficiency by transmitting small scale information, such as real-time status updates, to nearby vehicles or receiving the information from the others. Moreover, large scale information, such as overall traffic status and accident information, can be granted from the traffic center via road-side units (RSU) to the vehicles. In particular, it has recently been considered as a key method for enhancing autonomous driving stability and can extend the detection range of the ADAS sensor.

Such information exchanging done between vehicles and related communication end points over wireless is called vehicle-to-everything (V2X) communication, incorporating several communication types depending on the counterpart of the vehicles, such as vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P). There are two candidates in the enabler of V2X communication, i.e., Dedicated Short Range Communication (DSRC) and Cellular-V2X (C-V2X) on the basis of LTE and 5G cellular systems. Basically, DSRC employs IEEE 802.11p physical layer technology which is a modification of Wi-Fi to adapt to vehicular environments, and IEEE 1609.x defined upon

The associate editor coordinating the review of this manuscript and approving it for publication was Yang Tang.

upper layers. On the contrary, C-V2X has been developed as an expansion of cellular wireless systems, i.e., LTE, LTE-A, and 5G. Compared to C-V2X, DSRC shows stable performance over time, while C-V2X outperforms DSRC in terms of throughput and coverage. Until now, owing to the respective advantages of DSRC and C-V2X, academic debate still remains over which one is more suitable for wireless vehicular communication environments and attempts to integrate DSRC and cellular-based vehicle communication systems are continuing [1], [2].

Meanwhile, since V2X communication performances, including reliability and latency, are directly related to human safety, their evaluation must be done in advance to the actual usage in the real world. However, the problem is that the evaluations are mostly done by simulation-based experiments, while only a few experimental results are obtained from actual field tests. In [3], Lv *et al.* said that the research results of LTE-V2X have qualitative requirements for test scenarios through simple descriptions of road width, road length, obstruction size and material of obstructions, but there are no quantitative requirements. They proposed a quantitative evaluation method and test configurations for judging whether an external urban scenario meets 3GPP standard and carried out the actual test by analyzing performance characteristics: coverage, delay, PRR.

Shi *et al.* [4] said the theoretical performance evaluation of V2X could not fully demonstrate the real performance and real-world tests are important. They designed the performance evaluation method of intersection collision warning application by obtaining the results of V2V PDR and latency and compared the performance of 802.11p and LTE-V2X. Based on the result, they proposed V2V communication scheme that use RSU as a repeater and the experiment result is shown that PDR is improved a lot.

In [5], Klapez *et al.* said that industrial areas want to investigate the real-world effectiveness for general safety-related V2X applications and prove the actual guarantees but the many works on V2X is focused on the measurements of L1 and L2 metrics or performances in specific scenarios. They devised the performance metrics to evaluate the application level performances and conducted the tests against variables affect the performance results including network congestion. And they proposed L5 TDMA scheme using simple time-shifts to improve the PRR of safety-critical application that have the collision issues by hidden node problem.

Xu *et al.* [1] also pointed out that existing studies were mainly conducted to compare feasibility of software-based simulation-oriented DSRC and LTE V2X applications, and analyzed the performance of safety, non-safety, and multimedia applications using their vehicular communication platform. From the test results, it was said that DSRC is useful for safety critical and LTE is suitable for applications requiring high throughput, and that the combination of DSRC and LTE can be a good solution for connected vehicle. But this test is still conducted in a small scale and a limited environment, so it is difficult to analyze the effect on the actual road environment.

And there are some studies about comparing or integrating with simulation and real environments. Almeida *et al.* [6] compared the performance of the DSRC-based V2X communication system by evaluating it in a simulation using NS-3 and real environment. For the V2V and V2I scenarios, the effects on vehicle speed and transmission speed were evaluated by measuring PDR and PIR. From the test, the results in the simulation and the real environment showed weak correlation, and it was suggested that enhancement of the simulation model was necessary.

In [7], Hofer *et al.* said that vehicle-in-the-loop (ViL) test has an advantage in repeat test where it is difficult to do it repeatedly because it requires a lot of labor and cannot control variables. However, since most of the ViL tests use very simple channel models, delay models, and static statistics, its test results are different from the actual environment. They measured PER and RSSI by developing a ViL test system that reflects channel characteristics in real time according to vehicle location and speed. And they said that the results in the actual proving ground and the results using their ViL were different, and that further research on the channel model was needed.

In [8], Wang *et al.* investigated various test types and test methods including Conformance Testing, Function Testing. Performance Testing, Vehicle Gateway Testing, Pentration Testing, Accelerated Testing, Field Testing. They said that several methods for each test have been performed mainly by simulation, and situations for extreme cases in the field are extremely rare. They also said that each test method is limited to one or two test purposes and there are many shortcomings in the lab test to reflect the actual situation. And they said that it is necessary to test using many communication devices in the field test, but it is particularly important to effectively reduce the test cost. So, they proposed an end-to-end test system that combines a virtual and real environment that allows testing of the entire protocol stack. But there are lacks of specific system description and no contents on the performance of the system.

Our research is motivated by the paper published by 5GAA [9]. The paper describes the procedures and results of the performance evaluation on the two candidates of V2X communication system, i.e., DSRC and C-V2X, with experiments from laboratory and field tests. In this context, the key contribution of this article can be summarized as follows:

- We elaborate on performance evaluation methods of V2X communication system for general safety-related applications. Specifically, investigate evaluation metrics, test scenarios, and methodology of extracting test results, which are suitable for the real-world V2X communications.
- We examine the performance characteristics of DSRC based V2X communication system in various real road environments including urban, highway, and tunnel.

The rest of this paper is organized as follows. Section II describes DSRC based V2X communication system we implemented. Section III describes the performance evaluation methods and Section IV describes the vehicular environments in which the field testing is going to be conducted. In Section V, the results of the tests are analyzed, and the concluding remarks are provided in Section VI.

II. OVERVIEW OF DSRC COMMUNICATION SYSTEM

In this section, we describe the overview of DSRC based V2X communication system that we implemented and detailed technologies which are incorporated in the system. Originally, DSRC was for communication technology for basic ITS applications such as electronic toll collection in the 1990s, but the current DSRC is used in the same meaning as WAVE, which is a communication technology developed to provide higher level application services [10].

The WAVE, to support the next-generation ITS services, targets to achieve the maximum data rate of 27 Mbps in 5.9 GHz band, LoS communication area of 1000 m and maximum vehicle speed of 200 km/h. The WAVE protocol stack is currently a core part of DSRC technology and consists of IEEE 802.11p [11] and IEEE 1609.2/3/4 [12]–[14]. IEEE 802.11p, where the physical layer and the lower layer of the MAC sublayer are defined, is a standard modified to suit the vehicle environment from IEEE 802.11a, i.e. Wi-Fi. IEEE 802.11p uses 5.9 GHz band and supports high-speed transmission using OFDM communication technology with a bandwidth of 10 MHz in 7 channels. The IEEE 802.11p standard has been changed the frequency-related parameter to half and the time-related parameter to double in comparison with IEEE 802.11a's modulation parameters to fit in vehicular communication environment that network disconnection and Doppler spread occurs frequently. In addition, in order to change it to suit the vehicle environment, it supports OCB (Outside the Context of a BSS) mode so that messages can be transmitted directly between devices by removing the initializing process that is "probe-authentication-association" in IEEE 802.11a.

The IEEE 1609.x, which defines the upper layer of the WAVE protocol stack, is a newly added standard for vehicular communication. IEEE1609.3 defines the operation of the network layer, IEEE1609.4 defines the operation of the upper layer of the MAC sublayer, and IEEE 1609.2 defines the operation related to security. IEEE 1609.3 defines the format for WSM (WAVE Short Message), which is a message to be transmitted and received using the WSMP (WAVE Short Message Protocol). In particular, the format for WSA (WAVE Service Advertisement), which is different from general WSM, is also defined. The WSA message contains information on the services currently provided by the roadside side units and channel information used to transmit and receive these service messages. IEEE 1609.4 defines operations to provide multi-channel access to single-radio devices, and operations on channel switching, routing, and controls the division between channels [15]. In IEEE 1609.2, operations to transmit and receive PKI-based security messages, and technologies for digital signatures, encryption, vehicle certificates, etc. are defined. And messages that can be transmitted through 1609.2 standard are include unsecured, signed, and encrypted types [16].

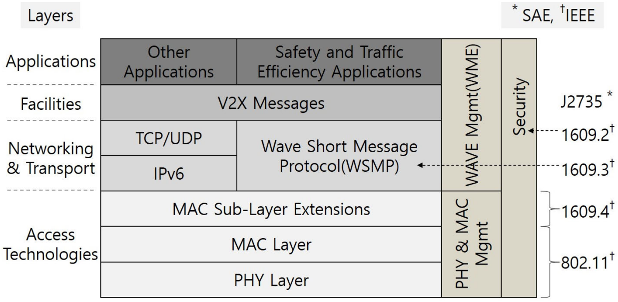


FIGURE 1. **WAVE protocol stack [18].**

Currently, vehicular communication application(such like C-ITS) uses a communication modules that satisfy the WAVE protocol stack to transmit and receive messages in accordance with SAE J2735 [17] that is about standardized message set between vehicles, and between vehicles and roadside units. In SAE J2735, the formats of the message are defined using ASN.1 and these messages are transmitted as UPER encoded data to reduce the physical communication bandwidth. Major messages transmitted by vehicle (referred to OBU: On-Board Unit) are included Basic Safety Message (BSM) and Prove Vehicle Data (PVD), and messages transmitted by base station (referred to RSU: Road Side Unit) are included Signal Phase And Timing (SPaT), Map Data (MAP), Road Side Alert (RSA), and Traveler Information Message (TIM). In the WAVE standard, unicast and multicast are also possible with MAC level address, but basically, messages are transmitted by broadcasting.

The DSRC-based V2X communication system we implemented satisfies the requirements of the physical layer, network layer, and application layer through a conformance test based on USDOT CVCOC specifications [19] for the aforementioned WAVE standards and SAE J2735 standards. In the CVCOC specifications, the test cases for the requirements to be met in each protocol layer, and the test procedures and configurations for each test are described. In order to automatically perform these tests, TCI (Test Control Interface) is used by defining an interface between test system and system under test. The DSRC based V2X communication system we implemented has an NXP i.MX6 Quad processor, and has ROM and RAM as storage. Its radio uses two WAVE modules from UBlox. Each module can be used as single or dual-channel, and antenna diversity can be utilized when using single. In addition, it can interface with traffic infrastructure devices and vehicle systems using USB, Serial, Ethernet, and CAN. For positioning, UBlox Neo-M8T was used. Table 1 shows the specifications of the V2X communication system.

TABLE 1. The specification of the CEST V2X communication system.

Component	Description
Processor	i.MX6
Memory	ROM 32GB/RAM 2GB
Radio	Dual DSRC
GPS	UBlox Neo-M8T
Operation Temperature	-33 to + 70 °C
Antenna / GPS Connectors	SMA type
Other Interfaces	USB, MicroSD, Serial, Ethernet, CAN
Standard Compliance	802.11p, IEEE 1609.x and SAE J2735 (2016), J2945

III. TEST PRELIMINARIES

This section provides preliminary information about Key Performance Indicators (KPIs) used to evaluate the performance of DSRC in the test, which are the packet error rate (PER), packet reception rate (PRR), received channel power indicator (RCPI), and inter-packet gap (IPG). In addition, we clearly describe the methods used for post-processing of the collected data.

A. KEY PERFORMANCE INDICATORS (KPIs)

1) PACKET ERROR RATE (PER)

The PER is the ratio between the number of missed packets at a receiver and the total number of transmitted packets at a transmitter [20]. The PER is calculated using the sequence number which is to identify the transmitted packets contained in each message, considering a connection between a receiving vehicle and a transmitting vehicle.

Supposing that the time is slotted, with each slot sized ω seconds as shown in Fig. 2, and initialized to 0 at the beginning, the PER is measured within the time window of n time slots, which results in the window size $\delta = n \times \omega$. Note the each time slot is normally set to $\omega = 100$ milliseconds, taking into account a single BSM length. Moreover, the number of time slots within the time window is set to $n = 50$, thereby having overall window size of 5 seconds. The PER is measured in every ω seconds by sliding the time window.

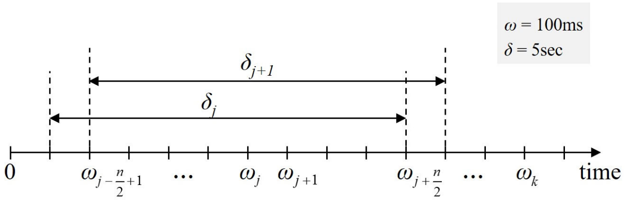


FIGURE 2. PER sliding windows.

Therefore, the j-th PER is calculated as

$$\mathrm{PER}(j) = \frac{m_j}{t_j}\left[\omega_{(j-\frac{n}{2}+1)}, \omega_{(j+\frac{n}{2})}\right], \tag{1}$$

where t_j is the number of total transmitted BSMs during the interval δ_j and m_j is the number of missed BSMs at receiving vehicle among t_j messages.

2) PACKET RECEPTION RATE (PRR)

The PRR is the ratio between the number of received packets and the total number of transmitted packets, which is defined as PRR $= 1 -$ PER. The PRR is used for determining the coverage, which is the range of ensuring reliable communication. The reliable range is determined by the PRR threshold which is normally set to 90%.

3) RECEIVED CHANNEL POWER INDICATOR (RCPI)

The RCPI is defined by following IEEE 802.11(2016). The RCPI is a measure of the radio frequency (RF) power received over the selected channel, which is expressed in an 8-bits value between 0 and 220, rounded to the rearrest 0.5 dBm as

$$\mathrm{RCPI} = \mathrm{Int}\{(\text{Power in dBm} + 110) \times 2\}, \tag{2}$$

where the RF power ranges can be expressed by RCPI from -110 dBm to 0 dBm.

4) INTER-PACKET GAP (IPG)

The IPG is the computed time interval, in milliseconds, between two consecutive messages received at the receiver, based on the Coordinated Universal Time (UTC time). Note the IPG is correlated to the PRR indicator and increases rapidly when the packet is lost.

B. DATA POST-PROCESSING

During the tests, data files that includes information on timestamp, position of both vehicles and content of the transmitted and received BSM, are stored as comma separated value (CSV) files. Next, the data from the data files of Rx vehicle and Tx vehicle is concatenated with Rx followed by Tx. And the data frames are prepared using the following columns in the log files:

- *Transmitted Time Stamp, Message Sequence Number, Latitude, Longitude, and Power*
- *Received Time Stamp, Message Sequence Number, Latitude, Longitude, and RCPI*

Then the Tx and Rx data match together only by the transmitted Time Stamp and Message Sequence Number columns. And data is then sorted by transmitted Time Stamp, which is used to determine IPG and RCPI values. The calculation for each KPI is performed according to the definitions mentioned in the previous clause. The IPG is calculated by the differences between iterated received packets.

IV. TEST ENVIRONMENTS

We implemented the DSRC-based V2X communication system and tested the performances by obtaining previous KPI's results as a function of distance in two different places: proving ground and real testbed. Based on the results, we determined communication range, which is the distance at which PRR or the reliability of the BSM message reception drops below an acceptable level. The PRR threshold for range determination is 90%. The proving ground is under the environment that has no obstacle between transmitting and receiving vehicles with open sky. While, the real testbed for connected vehicle service is under the environments that have various geographical conditions and the other vehicles affecting communication performance as obstacles. This section describes the testing environments of the two places.

A. PROVING GROUND TEST

First field tests were performed on the proving ground at KIAPI (Korea Intelligent Automotive parts Promotion Institute), Daegu, South Korea. The test track of the proving ground is 1.5 km long straightaway. Fig. 3 shows the conditions of the test track and considering scenarios. Note that the tests were conducted based on the test methods of 5GAA [9] in the sense of test procedures and parameters.

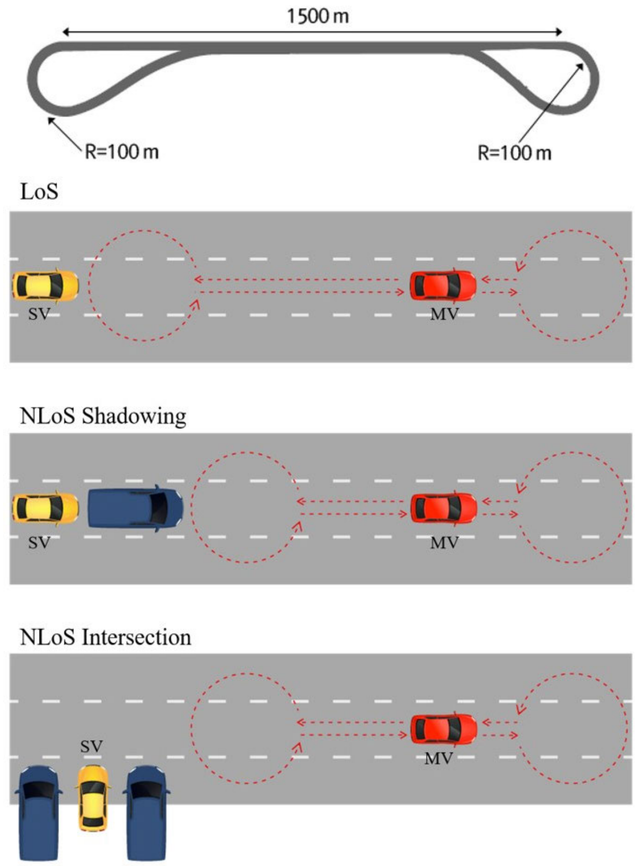


FIGURE 3. The conditions of the test track (above) and each test scenario: LoS, NLoS shadowing, NLoS intersection (bottom three).

1) LINE-OF-SIGHT (LoS) SCENARIO

This scenario considers an open sky and no obstacles between the vehicles, thereby enabling LoS communication. Here, Moving Vehicle (MV) first moves away from Stationary Vehicle (SV) at the speed of 32 km/h (20 miles/hour) until the MV is out of the communication range. Then, MV turns back and moves straight towards SV at the speed of 32 km/h.

2) NLoS SHADOWING SCENARIO

NLoS shadowing test, which assumes that the obstruction is in front of the SV and that the MV performs the moving in front of the blocker. The distance between the front of the SV and the back of the blocker truck is set at 5.3 m. MV starts close to SV and moves away in the same lane as the SV at speed 32 km/h until out-of-range. MV performs a U-turn and approaches SV in the same lane.

3) NLoS INTERSECTION SCENARIO

In NLoS intersection test, SV is placed between two large blocking objects. The blockers are placed 2.1 m from both sides of the SV. The MV starts close to the SV and moves away from the lane perpendicular to the SV at a constant speed of 32 km/h. At the out-of-range, MV performs a U-turn and moves back in the same lane. After closing the SV in the opposite direction, MV performs a U-turn and enters the starting position.

4) SYSTEM CONFIGURATION

A MV broadcasts unsecured BSM messages to a SV and the SV receives packets with the size fixed to 193 bytes. Three transmission power levels are tested: 5 dBm, 11 dBm, and 20 dBm and the same vehicle model is used for both SV and MV, so that the vehicle antenna characteristics are the same at both ends. The MV iteratively moves away from and returns towards the SV. For the sake of convenience, the two directions of movements are referred to as receding and approaching. The field test results show the averaged results for 10 loops while MV is approaching. The MV maintains a constant speed of 32 km/h per lap using cruise control. The CEST DSRC OBUs are used in the tests. Table 2 shows the system parameter settings for the field test.

TABLE 2. System parameters used in the field tests.

Parameter	Description
Modulation and coding	QPSK, 1/2
Channel	CH184 (5,920 MHz)
Bandwidth	10 MHz
Packet size	193 Byte
Message frequency	10 Hz
Antenna	ECOM6-5500 (5dBi)
Diversity	1Tx, 2Rx
Equivalent Tx Power	5 dBm, 11 dBm, 20 dBm

B. TEST IN CONNECTED VEHICLE TESTBED

1) TESTBED OVERVIEW

We implemented the Daegu Connected Vehicle Driving Testbed with several OBUs, 18 RSUs, 4 signal controllers with connected vehicles interface board (CVIB), 3 autonomous incident detection system (AIDS) from Daegu Forestry junction to Hyeonpung (15.25 km), Daegu, South Korea. And V2X server is connected with OBUs/ RSUs to monitor the information of each device: SPaT, MAP, PVD, RSA, and TIM defined as SAE J2735.

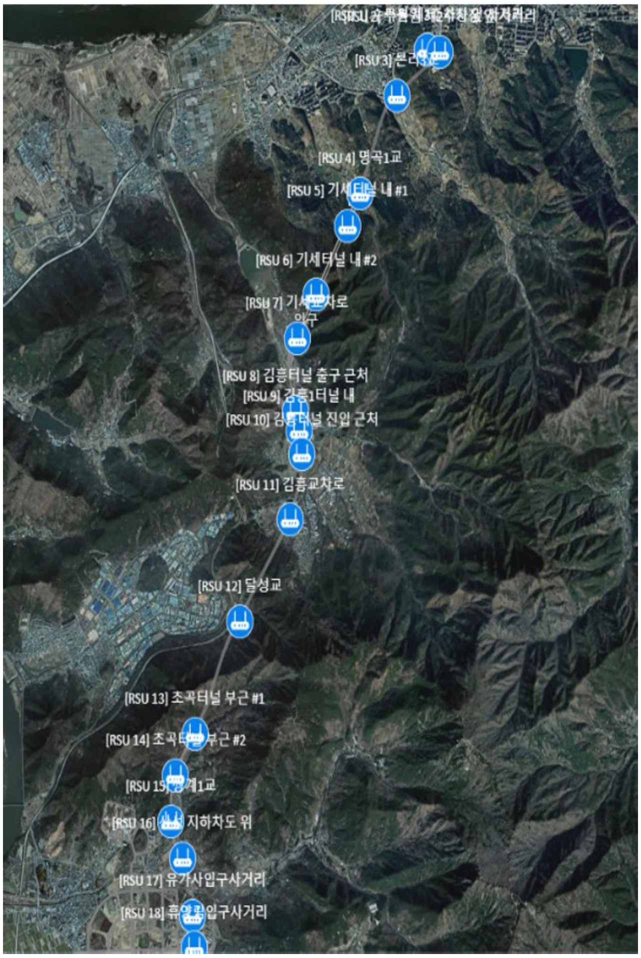


FIGURE 4. RSUs of connected vehicle testbed in Daegu, S. Korea(4 RSUs in urban, 11 RSUs in highway, 3 RSUs in tunnels).

CVIB in signal controller sends current signal phase and remain timing information to RSU. Then, RSU makes SPaT message and broadcasts to vehicles on DSRC, and RSU transfer the information to V2X server on Ethernet or LTE. AIDS detects objects on road with radar and closed-circuit television (CCTV), the detection information transfers to RSUs on Ethernet. RSUs broadcast self-defined RSA message from the detection information on DSRC and transfers to V2X server on Ethernet or LTE. V2X server monitors vehicle's position and status, sensing information, signal information, emergency information, and RSU's network status, etc. in the real-time. And V2X server checks and inquires vehicle status in the response of V2X messages and various statistics. And OBUs sense the emergency warning from the received RSA messages. Fig. 4 shows RSUs in whole region of testbed.

2) REAL ENVIRONMENTS: URBAN, HIGHWAY, AND TUNNEL

In the Daegu Connected Vehicle Driving Testbed, the performance of V2X communication system is evaluated in diverse environments: urban, open sky highway with limited speed 80 km/h (50 miles/hour), and tunnel. The testbed consists of 12.9 km highway with 6 tunnels (total 6.1 km) and 2.34 km urban environments. Positioning system is implemented using Woo system for estimating location inside tunnel where global positioning system (GPS) signal is disconnected [21]. Previous testbed [22]–[25] implemented V2X communication and evaluated the performance in urban, highway, and tunnel. Unlike previous testbed environments, highway of Daegu Connected Vehicle Driving Testbed consists of long tunnels and short open-sky highway.

3) SYSTEM CONFIGURATION

RSUs broadcast messages per 100 ms with data rate 6 Mbps and transmit power 20 dBm. And one vehicle receiving the messages moves over whole testbed. Moving vehicle maintains average speed of 80 km/h except urban region. The CEST DSRC OBU/RSUs are used in the tests. Table 3 and 4 show the specification of the OBU/RSUs and system parameters used in the field tests. Antenna gain is lower than that used in field test track.

TABLE 3. The specification of the CEST DSRC OBU/RSU.

Component	Description
Radio	Dual DSRC
GPS	UBlox NEO-M8T with [24]
Standard Compliance	802.11p, IEEE 1609.x and SAE J2735 (2016), J2945

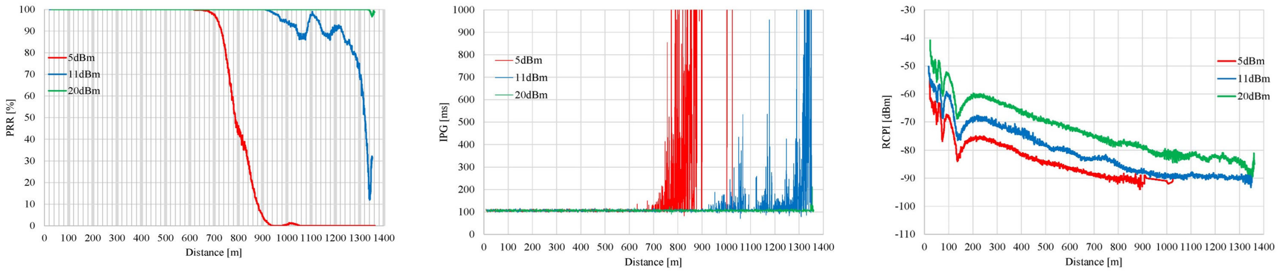
TABLE 4. System parameters used in the field tests.

Parameter	Description
Modulation and coding	QPSK, 1/2
Channel	CH182 (5,910 MHz)
Bandwidth	10 MHz
Message frequency	10 Hz
Antenna	PSKN3-24/55s (2.3 dBi)
Diversity	1Tx, 2Rx
Equivalent Tx Power	20 dBm

V. FIELD TEST RESULTS

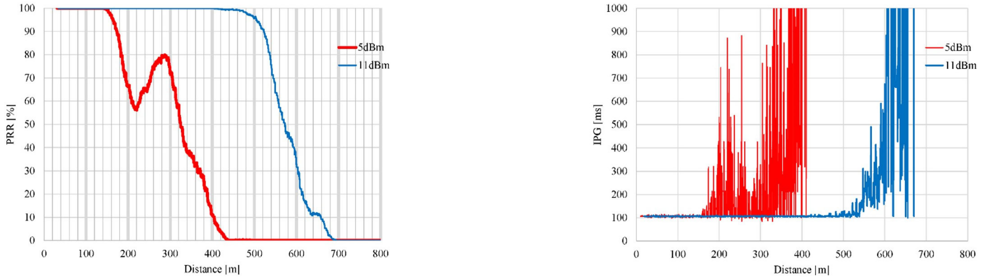
The performance of V2X communication is not only affected by various factors such as transmission power, antenna, geographical environment between transmitting and receiving terminals, but also the communication system itself depending on the implementation of HW and SW. In this test, it is assumed that there is no impact on the communication system itself as it satisfies the requirements of the protocol stack including physical standards and network layers by testing with a DSRC-based communication system that has passed the USDOT CVCOC specifications test.

There are some studies on the performance analysis with respect to the influence of various resources or parameters of communication system. Specifically in [2], Noor *et al.* investigated resource allocation (RA) schemes to enhance the performance in DSRC, C-V2X, heterogeneous based communication system respectively and analyzed the communication performance for that schemes. In DSRC based vehicular network, they surveyed various studies that



(a) Packet reception rate (PRR)   (b) Inter packet gat (IPG)   (c) Received channel power indicator (RCPI)

FIGURE 5. Test results against distance under LoS scenario in proving ground. Results are measured with 3 Tx-powers(5 dBm: Red, 11 dBm: Blue, 20 dBm: Green).



(a) Packet reception rate (PRR)   (b) Inter packet gat (IPG)

FIGURE 6. Test results against distance under NLoS Shadowing scenario in proving ground. Results are measured with 2 Tx-powers(5 dBm: Red, 11 dBm: Blue).

analyzed the effects of channels, MCS (modulation and coding schemes), and parameters for CSMA/CA in terms of performances metrics such like packet delivery ratio, delay, and throughput. In C-V2X based vehicular network, they said that resource allocation is an important issue because C-V2X-based systems share one common roadside base station and introduced various resource allocation methods to improve network sum rate and connectivity index packet latency. In particular, they said that cloud computing for vehicular communication, and resource allocation methods for platooning are emerging as a hot topic. And he also analyzed the performances of RA schemes in heterogeneous based vehicular, which has the LTE, DSRC, and Wi-Fi systems. Finally, they suggested future research directions on resource allocation using network slicing, machine learning, and context aware.

In [26], Wang *et al.* analyzed the influence of communication system and environmental parameters for spectrum efficiency and data rate using various spectrum sharing schemes in an environment that shares the spectrum of DSRC and Wi-Fi system. From the analysis result, they showed that SNR, CW size and especially DSRC node density are a key factor for that performances.

Moreover, in our previous research [27], Kang *et al.* proposed the architecture for performance evaluation under a high speed driving with previous DSRC based V2X communication system and evaluated the effect of V2I performance with varying application-level parameters. In the performance evaluation, PDR and RTT are used as performance indicators, and the influence on MCS, message size, and vehicle movement speed is evaluated. It has been confirmed that the size is affected, and the vehicle's moving speed does not affect the communication performance in accordance with the purpose of WAVE communication. In the rest of this section, the results are analyzed through the lens of PRR mainly using the performance analysis method described in the previous section.

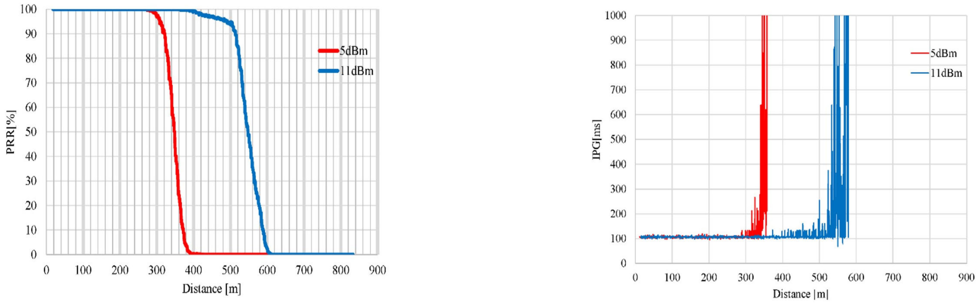
A. TEST RESULT IN PROVING GROUND

1) LoS

Fig. 5a shows the average PRR of the LoS scenario as a function of distance between SV and MV. Assuming 90% PRR as the threshold, PRR range for 5 dBm and 11 dBm is 720 m and 1035 m, respectively. Note that this is the same level with C-V2X of 5GAA and higher level with DSRC of 5GAA's results, though test environments and configuration is not completely same. And in [28], they also conducted similar tests and achieved better range performance of DSRC over long distances than C-V2X of 5GAA. Fig. 5b shows the average IPG as a function of distance between SV and MV. The average IPG is a fixed value 100 ms for distances below PRR range. Fig. 5c shows RCPI measured by the SV for the 5 dBm, 11 dBm and 20 dBm effective power levels. OBU reports RCPI approximately −92 dBm at PRR range.

2) NLoS SHADOWING

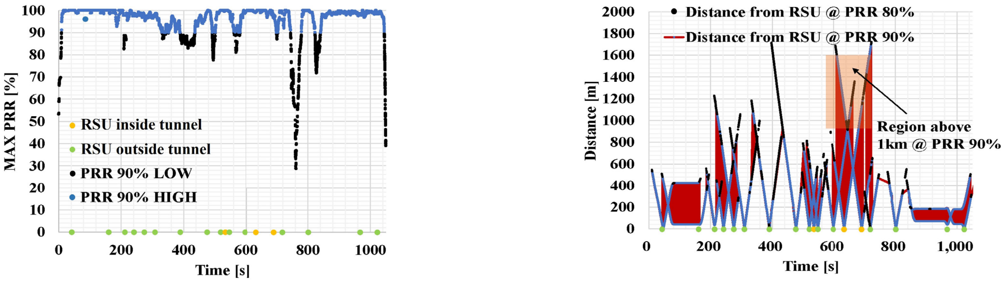
Fig. 6a shows average PRR at the SV as a function of distance between the vehicles while the MV is approaching.



(a) Packet reception rate (PRR)

(b) Inter packet gat (IPG)

FIGURE 7. Test results against distance under NLoS Intersection scenario in proving ground. Results are measured with 2 Tx-powers(5 dBm: Red, 11 dBm: Blue).



(a) PRR on real environments

(b) Distance above PRR 90%

FIGURE 8. Test results of PRR and RCPI on real environments through whole RSUs. The green and orange dots on X-axis indicate the time OBU has just passed the RSUs.

Using 90% PRR threshold, PRR range for 5 dBm and 11 dBm is 175 m and 520 m, respectively. Fig. 6b shows average IPG as a function of distance between SV and MV. A spike in IPG for 11 dBm at 520 m is closely correlated with a drop in PRR below 90% at the same distance. The average IPG is approximately 100 ms for distances below PRR range.

3) NLoS INTERSECTION

Fig. 7a shows average PRR at the SV. Using 90% PRR threshold, PRR range for 5 dBm and 11 dBm is 320 m and 515 m, respectively. Fig. 7b shows average IPG as a function of distance between SV and MV. At 5 dBm equivalent transmit power, the reliable range of the NLoS intersection test is significantly higher than that of the NLoS shadowing test.

B. PRR ON REAL TESTBED ENVIRONMENT

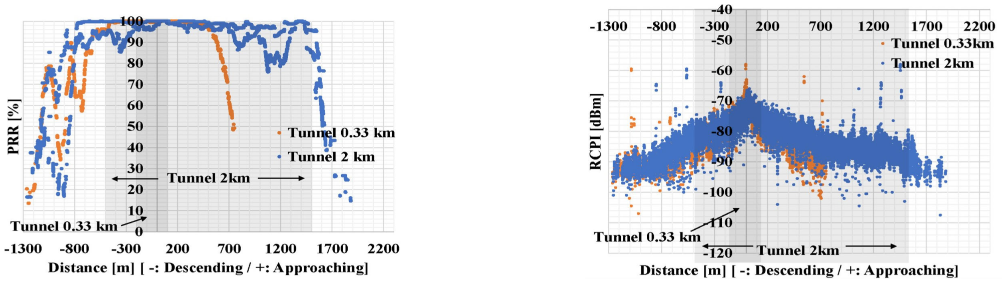
Fig. 8 shows the PRR and communication distance over whole region of the testbed. The highway and tunnel region is from 200 s to 800 s. And the other region is urban. In Fig. 8a, the blue dot represents the points when the maximum PRR is above 90% and the black dot represents when the maximum PRR is below 90%. The 85% region of the whole testbed satisfies the sensitivity requirement which is above PRR 90%. Fig. 8b shows the communication distance from each RSU when PRR is above 80%. Each V lines are the distance result when PRR is above 80% for each RSUs, while the horizontal lines denotes the waiting due to traffic lights, the black lines denotes the case PRR below 90% and the blue lines denote the case above 90%. Moreover, the red line implies the duplicated region with neighboring RSUs. In the box, the distance from RSU is above 1361 m which is result of the LoS scenario in proving grounding test track. RSUs in the box of Fig. 8b are implemented inside tunnel unlike RSUs of other region.

TABLE 5. Distance for PRR 90% on Daegu connected vehicle testbed.

Environment	Max Distance [m] @ PRR 90%
Urban	532
Highway outside tunnel	1219
Tunnel	1700

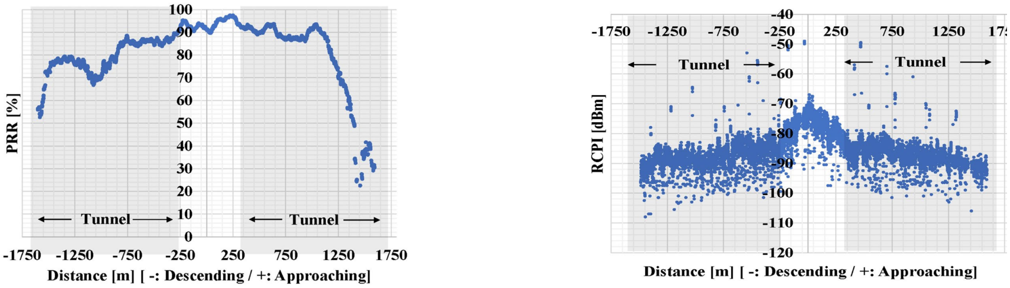
Fig. 9 shows the performance of two RSUs (of three), which are implemented inside tunnel. In Fig. 9a, blue dot represents the performance results of RSUs which are implemented in 2 km tunnel, and orange dot represents in 0.33 km tunnel. Distance at PRR 90% is 1700 m in 2 km tunnel and 683 m in 0.33 km tunnel. Tunnel effect improves PRR performance when RSU is inside tunnel [29]. Table 5 shows the maximum distance in each condition. Fig. 9b shows RCPI of RSUs which are implemented inside tunnel. In 2 km tunnel, average RCPI decreases rapidly after tunnel in descending 420 m. However, average RCPI decreases rapidly before tunnel in approaching 1410 m.

Tunnel effect improves PRR performance when RSU is outside tunnel as shown in Fig. 10. In Fig. 10a, RSU achieve PRR 90% for distances up to 1187 m, while the average RCPI maintains inside tunnel as distance increases as shown Fig. 10b.



(a) Packet reception rate (PRR)
(b) Received channel power indicator (RCPI)

FIGURE 9. Comparisons between RSUs inside short tunnel(orange) and long tunnel(blue) in terms of PRR and RCPI on real environments.



(a) Packet reception rate (PRR)
(b) Received channel power indicator (RCPI)

FIGURE 10. Test results of PRR and RCPI against distance on real environments. RSU is between outside tunnels.

TABLE 6. Distance for PRR 90% as tunnel length.

Distance of outside RSU from Tunnel Entrance [m]	Tunnel Length [m]	Distance for PRR 90% in tunnel from Tunnel Entrance[m]	Distance from RSU [m]
295	2000	924	1219
140	1200	720	860
184	1200	655	839
250	1200	467(@PRR 88%)	717
290	1200	896	1187
200	1000	353	553
106	334	433	558
147	334	408	555

In Table 6, it is shown that the distance for PRR 90% is up to 558 m which is same as urban case when tunnel length is shorter than 1km. However, distance for PRR 90% is up to 1219 m when tunnel length is longer than 1km.

VI. CONCLUSION

In this paper, we have implemented two testbeds to investigate the performance of the V2X technology according to our measurement campaign and the KPIs. We have evaluated PER, PRR, IPG, and RCPI as KPIs for V2X performance. The results of the proving ground test track have been presented for LoS and NLoS scenarios. In brief, the PRR range of the LoS shown to be significantly higher than that of the NLoS. Furthermore, the PRR range in the NLoS intersection at 5 dBm equivalent transmit power have shown higher than that in the NLoS shadowing. And the results of connected vehicle system on Daegu Connected Vehicle Driving testbed have been presented for urban, highway, and tunnel. The PRR range of tunnel is significantly higher than that of urban and highway.

As future work, we look forward to investigate the performance evaluation methods of next-generation V2X communication system, particularly, IEEE 802.11bd. IEEE 802.11bd is in the process of standardization, to be completed in 2021 with the aim of supporting more than twice the MAC throughput of 802.11p, relative speed up to 500 km/h, backward compatibility, and so on [30]. Thus, the performance comparing methods between 802.11p and 802.11bd and between 802.11bds are needed for short messages, which can be done by using the methods described in this paper. Moreover, since 802.11bd aims to provide services for autonomous driving such as sharing sensor information and downloading the high definition maps along with existing 802.11p application services [31], a new method for evaluating the performance of large messages is required.

REFERENCES

[1] Z. Xu, X. Li, X. Zhao, M. H. Zhang, and Z. Wang, "DSRC versus 4G-LTE for connected vehicle applications: A study on field experiments of vehicular communication performance," *J. Adv. Transp.*, vol. 2017, Aug. 2017, Art. no. 2750452, doi: 10.1155/2017/2750452.

[2] M. Noor-A-Rahim, Z. Liu, H. Lee, G. G. M. N. Ali, D. Pesch, and P. Xiao, "A survey on resource allocation in vehicular networks," *IEEE Trans. Intell. Transp. Syst.*, early access, Sep. 4, 2020, doi: 10.1109/TITS.2020.3019322.

[3] Y. Lv, Y. Wang, X. Liu, R. Xu, J. Fang, and X. Peng, "Research on performance testing for urban scenario based on terminal equipment of LTE-V2X vehicle network," in *Proc. 14th IEEE Int. Conf. Signal Process. (ICSP)*, Aug. 2018, pp. 993–996.

[4] M. Shi, C. Lu, Y. Zhang, and D. Yao, "DSRC and LTE-V communication performance evaluation and improvement based on typical V2X application at intersection," in *Proc. Chin. Autom. Congr. (CAC)*, Oct. 2017, pp. 556–561.

[5] M. Klapez, C. A. Grazia, and M. Casoni, "Application-level performance of IEEE 802.11p in safety-related V2X field trials," *IEEE Internet Things J.*, vol. 7, no. 5, pp. 3850–3860, May 2020.

[6] T. T. Almeida, L. de C. Gomes, F. M. Ortiz, J. G. R. Junior, and L. H. M. K. Costa, "IEEE 802.11p performance evaluation: Simulations vs. Real experiments," in *Proc. 21st Int. Conf. Intell. Transp. Syst. (ITSC)*, Nov. 2018, pp. 3840–3845.

[7] M. Hofer, T. Zemen, L. Bernado, B. Rainer, Z. Xu, G. Temme, S. Khan, D. Behnecke, F. Utesch, and M. Mahmod, "Evaluation of vehicle-in-the-loop tests for wireless V2X communication," in *Proc. IEEE 90th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2019, pp. 1–5.

[8] J. Wang, Y. Shao, Y. Ge, and R. Yu, "A survey of vehicle to everything (V2X) testing," *Sensors*, vol. 19, no. 2, p. 334, Jan. 2019, doi: 10.3390/s19020334.

[9] 5GAA. (2019). *V2X Functional and Performance Test Report: Test Procedures and Results*. 5G Automotive Association(5GAA) TR P-180106. [Online]. Available: https://5gaa.org/wp-content/uploads/2018/11/5GAA_P-190033_V2X-Functiona%l-and-Performance-Test-Report_final-1.pdf

[10] Y. L. Morgan, "Notes on DSRC & WAVE standards suite: Its architecture, design, and characteristics," *IEEE Commun. Surveys Tuts.*, vol. 12, no. 4, pp. 504–518, 4th Quart., 2010.

[11] *IEEE Standard for Information Technology-Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks-Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, Standard 802.11-2016 Std., 2016.

[12] *IEEE Standard for Wireless Access in Vehicular Environments-Security Services for Applications and Management Message*, Standard 1609.2-2016, 2016.

[13] *IEEE Standard for Wireless Access in Vehicular Environments (WAVE)-Networking Services*, Standard 1609.3, 2016.

[14] *IEEE Standard for Wireless Access in Vehicular Environments (WAVE)-Multi-Channel Operation*, Standard 1609.4-2016, 2016.

[15] M. van Eenennaam, A. van de Venis, and G. Karagiannis, "Impact of IEEE 1609.4 channel switching on the IEEE 802.11p beaconing performance," in *Proc. IFIP Wireless Days*, Nov. 2012, pp. 1–8.

[16] H. C. Kwon, S. J. Lee, J. Y. Choi, B. H. Chung, S. W. Lee, and J. C. Nah, "Security trends for autonomous driving vehicle," *TTA J.*, vol. 186, pp. 55–64, Nov. 2019.

[17] *V2X Communications Message Set Dictionary*, Standard J2735-2020, SAE Standard, Jul. 2020.

[18] A. Costandoiu and M. Leba, "Convergence of V2X communication systems and next generation networks," *IOP Conf. Ser., Mater. Sci. Eng.*, vol. 477, Feb. 2019, Art. no. 012052, doi: 10.1088%2F1757-899x%2F477%2F1%2F012052.

[19] CVCOC. (2018). *Conformance Test Specifications for Wireless Access in Vehicular Environments Test Suite Structure and Test Purposes*. Connected Vehicle Certification Operating Council. [Online]. Available: https://omniair.org/wp-content/uploads/2018/12/16094_TSS_TP_Test_Specif%ication_v1.3-20171008.pdf

[20] *On Board System Requirements for V2V Safety Communications*, Standard J2945/1, SAE Standard, 2016.

[21] R. Woo, E.-J. Yang, and D.-W. Seo, "A fuzzy-innovation-based adaptive Kalman filter for enhanced vehicle positioning in dense urban environments," *Sensors*, vol. 19, no. 5, p. 1142, Mar. 2019. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/30845757

[22] (2017). *New York City DOT Pilot*. [Online]. Available: https://www.its.dot.gov/pilots/pilots_nycdot.htm

[23] (2017). *California CV TestBed*. [Online]. Available: http://caconnectedvehicletestbed.org/index.php/index.php

[24] (2017). *Virginia Connected Vehicle Testbed*. [Online]. Available: http://cvi-utc.org/test-bed-development

[25] M. Chowdhury, M. Rahman, A. Rayamajhi, S. M. Khan, M. Islam, Z. Khan, and J. Martin, "Lessons learned from the real-world deployment of a connected vehicle testbed," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 2672, no. 22, pp. 10–23, Dec. 2018, doi: 10.1177/0361198118799034.

[26] J. Wang, T. Wu, Y. Liu, W. Deng, and H. Oh, "Modeling and performance analysis of dynamic spectrum sharing between DSRC and Wi-Fi systems," *Wireless Commun. Mobile Comput.*, vol. 16, no. 16, pp. 2743–2758, Nov. 2016. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/wcm.2723

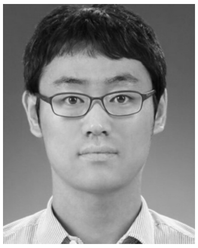
[27] B.-Y. Kang, J.-K. Bae, W.-C. Seo, J.-W. Park, E.-J. Yang, and D.-W. Seo, "Performance evaluation of V2X communication system under a high-speed driving," *J. KICS*, vol. 42, no. 5, pp. 1069–1076, May 2017.

[28] M. V. K. Moerman and A. Filippi, "On the 5GAA comparison between LTE-V2X and DSRC/IEEE 802.11p," NXP Semicond., Eindhoven, The Netherlands, Tech. Rep, 2011. [Online]. Available: https://www.nxp.com/docs/en/white-paper/LTEDSRC5GCOMWPA4.pdf

[29] J.-M. Molina-Garcia-Pardo, M. Lienard, and P. Degauque, "Propagation in tunnels: Experimental investigations and channel modeling in a wide frequency band for MIMO applications," *EURASIP J. Wireless Commun. Netw.*, vol. 2009, no. 1, Mar. 2009, Art. no. 560571, doi: 10.1155/2009/560571.

[30] G. Naik, B. Choudhury, and J.-M. Park, "IEEE 802.11bd & 5G NR V2X: Evolution of radio access technologies for V2X communications," *IEEE Access*, vol. 7, pp. 70169–70184, 2019.

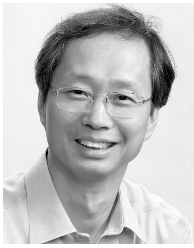
[31] Y.-S. S. H.-S. Oh, "Trends for V2X communication technologies standardization for ITS and autonomous driving service," *TTA J.*, vol. 188, pp. 60–65, Mar. 2020.



JEONG-KYU BAE was born in Changwon-si, Gyeongsangnam-do, South Korea, in 1981. He received the B.S. and M.S. degrees from the School of Electronics Engineering, Kyungpook National University, in 2007 and 2010, respectively. From 2007 to 2008, he was a Researcher with Refrigerator Research and Development Part, LG Electronics. From 2010 to 2016, he was a Junior Researcher with the Research and Development Part, Center for Embedded SW Technology, developed electronic shelf label (ESL) system and vehicular communication system. He is currently a Senior Researcher with CEST Company Ltd., Daegu. His current research interests include vehicular communication system based on DSRC, LTE-V2X, and next generation V2X communication.

MYUNG-CHUL PARK received the B.S. and M.S. degrees from Kyungpook National University, Daegu, South Korea, in 2013 and 2015, respectively. He is currently a Researcher with CEST. His main research interest includes wireless communication systems.

EUN-JU YANG received the B.S. degree from the School of Computer Science, Kyungsung University, in 2002, and the M.S. degree from the Department of Computer Engineering, Kyungpook National University, in 2004. She is currently a Research Director with CEST Company Ltd., South Korea. Her current research interests include V2X communication for autonomous vehicle/cooperative autonomous driving public transportation and real-time AV.



DAE-WHA SEO (Member, IEEE) received the B.S. degree from the School of Electronics Engineering, Kyung National University, in 1981, and the M.S. and Ph.D. degrees from the Department of Computer Science, Korea Advanced Institute of Science, in 1983 and 1992, respectively. He is currently a Professor with Kyungpook National University, South Korea. His current research interests include operating systems, flash storage solution, NVRAM, and V2X communication.

• • •