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Experimental Assessment of 5G-NR-V2X in a Real-life Highway

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ABSTRACT

This paper provides a comprehensive analysis of the practical assessment of 5G-NR-V2X technology in both an actual highway and a controlled testing facility. We propose a method designed to assess and verify the efficiency of self-driving services within a real-world road test environment, utilizing on-board and roadside units for 5G-NR-V2X communication. The evaluation required a minimum automation level of 4, a significantly high speed (150 Mbps or greater), minimal latency (3 ms or less), and a high degree of dependability (99.99%) to guarantee resilient communication even in hostile scenarios. This paper presents the 5G-NR-V2X communication system alongside its experimental evaluation, aiming to enhance V2X communication technologies known for their high speed, low latency, and reliable performance. Moreover, the proposed performance analysis technique is expected to enhance the technical competitiveness of road, transportation, logistics, and commerce industries by verifying services and testing hypothetical situations.

Key Words : V2X, 5G-NR-V2X, Self-driving, Communication, OBU, RSU, Autonomous Driving

Ⅰ. Introduction

The extensive use of automobiles as a mode of transportation in contemporary society has both positive and negative implications, including the potential to compromise road safety. The development of vehicle-to-everything (V2X) technology can be linked to progress in the Internet of Things (IoT). This technology aims to create links between automobiles, transportation infrastructure, pedestrians, and cloud platforms using various devices, including on-board units (OBUs) and roadside units (RSUs). The primary objective of V2X is to enhance road safety[1-5]. V2X facilitates the transmission of information and provides extensive driving solutions on a global scale through wireless connectivity and advanced processing technologies. Integrating intelligent decision-making and vehicle management systems can efficiently reduce traffic congestion, enhance driving efficiency, and improve road safety. Vehicles generate a significant amount of data to fulfill V2X requirements and address road safety concerns[6]. This data are essential for V2X communication and play a significant role in the development of future autonomous vehicles by providing vital driving information. Similarly, the consistent and precise transmission of V2X messages play a crucial role in ensuring safety. However, the spreading of false messages, whether intentional or unintentional, can cause confusion and even catastrophe among other drivers. Therefore, assessment of data precision in V2X communication is of substantial practical importance.

The existing global standards are outlined below. The 3rd Generation Partnership Project (3GPP) final-

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ized the specifications for long-term evolution (LTE) vehicle communication (Rel.14) in March 2017. This achievement established the basis for the extensive adoption of vehicle communication by significantly reducing communication delays using LTE technology and enabling direct connections between vehicles. The 5G-NR-V2X (Rel.16) standard was formally introduced in July 2020, marking another key development in this field.

Modern communication technology is characterized by its ability to achieve extremely low latency, large capacity, and excellent reliability[7]. The deployment of new services required to achieve the Fourth Industrial Revolution is supported by 3GPP Release 17, which builds upon the established 5G advanced standards. These standards encompass all the requirements imposed by the commercialization process[8,9].

The 5G Automotive Association (5GAA) recently developed detailed definitions and requirements for several V2X cases. In addition, the association defined several innovative and groundbreaking applications across various categories. The radio layer standards are governed by the 3GPP, which is currently working on developing Release 18. This project, expected to be completed by the end of 2023, will incorporate further enhancements for V2X.

Regional standard development groups, such as ETSI, SAE International, NTCAS, C-SAE, and ARIB, are responsible for standardizing the higher layers of communication. This effort is in response to the need for further investigation of profiles and protocols in emerging advanced application scenarios, such as group initiation. The ISO has launched standardization efforts for automated valve parking in Europe and other regions. Advancements in technology, such as improved location, reduced power consumption, and the implementation of multiaccess edge computing, provide connected assistance and cooperative driving services. These advancements have been made possible through ongoing global standardization efforts and the introduction of the 3GPP 5G-V2X. The revised edition of the Roadmap has been shaped by a heightened comprehension of the software (SW) complexity and the need for cooperation within the system. Network-based solutions have been explored as potential methods for increasing awareness among vulnerable road users. Furthermore, the incorporation of certain safety measures and sophisticated autonomous driving scenarios, such as collective initiation and collaborative movements, will require additional time[10,11].

- Safety: Safety procedures, including emergency braking, junction management, collision warning, and lane changes, are equally applicable to autonomous vehicles and driver assistance systems.
- Self-driving: The use of cases for autonomous vehicle levels 4 and 5 provided valuable insights into the specific circumstances in which autonomous driving was considered acceptable. These cases emphasize the significance of effective and secure control systems, remote driving capabilities, dynamic mapping, and collaborative interactions among vehicles.
- Platooning service: Platooning involves collaboration between transport corporations, road operators, and road traffic authorities to implement strategies such as cluster driving management and cluster driving stability. These strategies are designed to improve the efficiency of infrastructure usage and achieve environmental advantages such as reducing emissions.

The remainder of this paper is organized as follows: Section II provides a thorough overview of the current research and commercially available methods related to the architecture of 5G-NR- V2X. This section also covers the message format used to create a link between cars and the infrastructure. In Section III, we present an experimental test approach for evaluating 5G-NR-V2X. In addition, we provide specific and useful details and analyze examples of data structures that would benefit from resource sharing among various devices. Section IV outlines the methodology for evaluating the communication efficiency of 5G-NR-V2X. The paper concludes by discussing the challenges that arise during the implementation of the proposed approach.

Ⅱ. 5G-NR-V2X Architecture and Message Formats

2.1 5G-NR-V2X Architecture

This section explores various methodologies to optimize interactions and facilitate the exchange of data between V2X automobile devices and the infrastructure. Our study aims to ensure continuous connectivity while maintaining the full functionality of V2X stacks and SDKs provided by V2X device manufacturers or in compliance with international safety standards. The essential components of the V2X communication equipment are described below.

- OBUs are transceivers installed on vehicles that collect data and instantaneously transmit it to other interconnected vehicles or RSUs.
- RSUs are fixed communication nodes positioned along roads that can exchange data with other OBUs in passing vehicles and relay the data to a centralized station.
- Control units act as intermediaries between the control center and research support units (RSUs). Considering the fundamental characteristics of the RSUs, they are likely to be mounted on the top part of the telephone pole alongside the antenna, function as mechanisms that control and coordinate RSUs operations. The presence of this equipment depends on the prevailing circumstances.

Figure 1 presents a comprehensive depiction of the structure of the 5G-NR-V2X system, which comprises three separate systems: OBU/RSU system, and the 5G-NR-V2X modem IP system. Each system has specific roles and functions. The application system consists of five layers. The application layer comprises a service that employs a command line interface to perform real-time basic unit testing and debugging. In addition, it includes an application service that utilizes a graphical user interface (GUI) to display real-time graphical results. These scenarios are limited to the service-layer domain. Additional services, such as the service layer shown in Figure 1, can also be integrated. Examples of such services include platooning and analysis. The message layer is tasked with

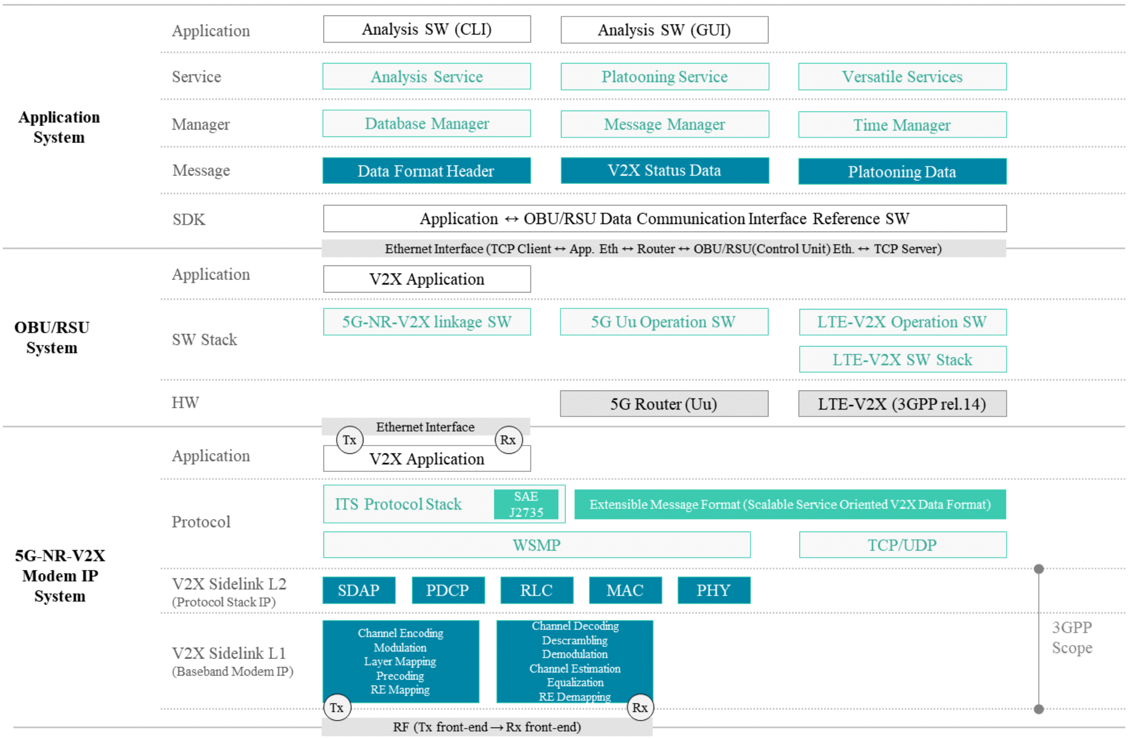

Fig. 1. Structure of 5G-NR-V2X communication performance verification system.

packetizing the V2X message data to meet the application service requirements. The SDK layer, as described in the previous section, plays a crucial role in the functionality of the system.

The OBU/RSU system consists of three separate layers: the application, SW stack, and hardware (HW). The application layer is responsible for managing the HW components of the device and facilitating communication with the application processor (AP) of the application service. The SW stack comprises 5G-NR-V2X SW for linking and 5G Uu operating SW. Moreover, the LTE-V2X operating SW and LTE-V2X SW stack guarantee backward compatibility as long as they are supported by the modem IP or configured as a separate LTE modem IP. The HW can function as either a 5G Uu or LTE-V2X modem within the OBU/RSU device, or it can create a link between the device and external environment. Figure 1 illustrates the setup consisting of an internal 5G Uu and LTE-V2X modem, as well as an external 5G-NR-V2X modem IP system. Currently, Qualcomm, AutoTalks, and Ettifos are collaborating on the development of the 5G-NR-V2X modem. The aim is to combine modern IP with Ethernet, allowing for the installation of various modems in the order they were initially released prior to their commercial availability[12].

2.2 Message Formats

The 5G-NR-V2X message format was established as a scalable service-oriented V2X) message structure to validate extremely fast and reliable communication performance in both safety and nonsafety applications. The details of this message format are listed in Table 1. Using the recommended framework, we can determine the credibility of specific situations, such as platooning, sensor-sharing, remote driving, and advanced driving services. Furthermore, Figure 2 illustrates the proposed extensible message structure that incorporates the single-sign-on vehicle (SSOV) data format to validate the V2X performance[13].

The following section presents the message format for verifying extremely fast and low communication performances in both safety and non-safety applications. By following the recommended framework, the authenticity of specific situations can be determined, such as platooning, sensor-sharing, remote driving, and advanced driving services.

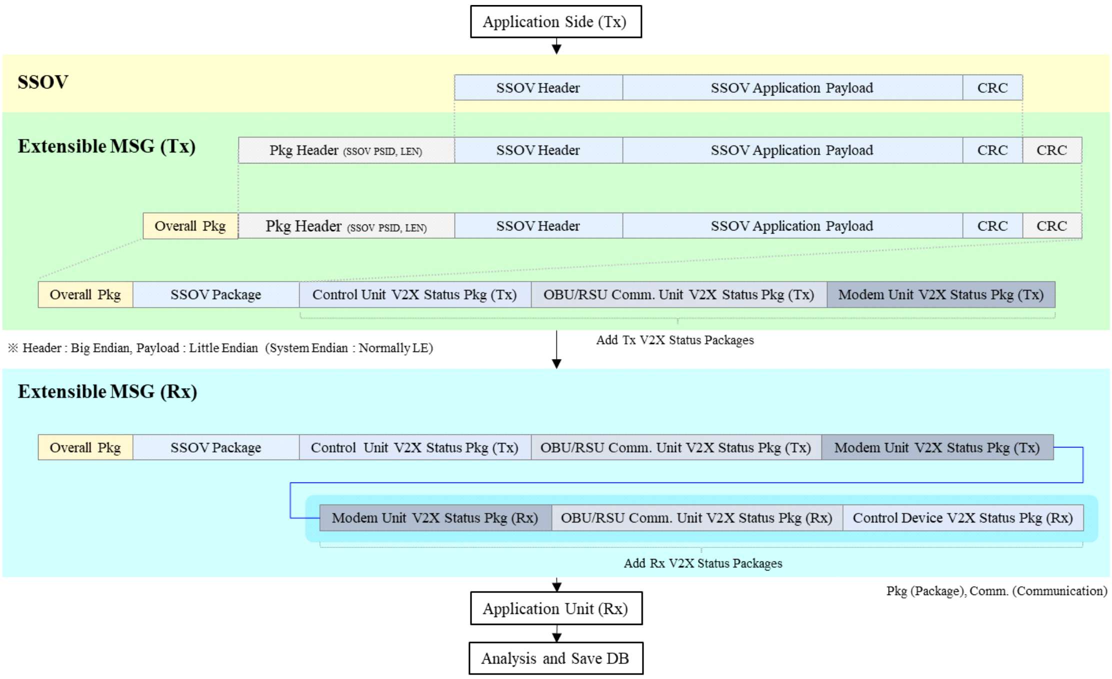

Fig. 2. Extensible message format of the 5G-NR-V2X protocol.

Table 1. Scalable service-oriented V2X data format.

Bit Offset	
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15	16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
DB_V2X_DEVICE_TYPE_E eDeviceType	DB_V2X_TELECOMMUNCATION_TYPE_E eTeleCommType
ulDeviceId (32 bits)	
ulTimeStamp (64 bits)	
DB_V2X_SERVICE_ID_E eServiceId	DB_V2X_ACTION_TYPE_E eActionType
DB_V2X_REGION_ID_E eRegionId	DB_V2X_PAYLOAD_TYPE_E ePayloadType
DB_V2X_COMMUNCATION_ID_E eCommId	usDbVer (16 bits)
usHwVer (16 bits)	usSwVer (16 bits)
ulPayloadLength (32 bits)	
Reserved (32 bits)	
Payload (Data)	
ulPacketCrc32	

Ⅲ. Testing Methodology

3.1 Overview of the Methodology

This section provides a concise explanation of the approach used to assess 5G-NR-V2X technologies on the Korea Expressway Corporation (EX) highway testbed. To ensure fair and unbiased test results for both equipment and automobiles, we used an identical HW version and application SW version and ensured that the communication model settings were identical as well. The communication modem was set up with the following configurations: the transmission power was configured at 20 dBm, the subcarrier spacing was set to 15 kHz, the central frequency was 5915 MHz, and the bandwidth was 20 MHz. The modulation and coding scheme (MCS) index achieved the maximum packet delivery ratio (PDR) with values ranging from 1 to 28 in the QAM64 table for MCS. Subsequently, the same experiment was conducted on both the autos.

3.2 ATHENA Framework

The autonomous telecommunication hyper-enhanced network architecture (ATHENA) functions as the core framework for overseeing the 5G-NR-V2X communication technologies of the South Korea V2X testbed, along with the services that utilize these technologies, as shown in Figure 4. This platform enables the incorporation of existing and future V2X technologies, such as C-V2X PC5 and C-V2X Uu (5G), over both short and long distances. Moreover, it enables the integration of sensors in vehicles or roadside infrastructure, vehicle actuators, human–machine interfaces, and third-party service providers. ATHENA offers assistance for SSOV services and is specifically built to accommodate a range of standardized cooperative intelligent transport system (C-ITS) services that may be activated dynamically. Moreover, the system can be easily upgraded in a modular manner to support future or customized C-ITS services. Messages can be conveyed in a flexible manner using one or several V2X technologies, which can enhance either transmission capacity or transmission reliability. In addition, the ATHENA framework is interoperable with several types of ITS devices, such as OBUs, RSUs, and servers. This SW has extensive logging capabilities that allow the collection of vital data for evaluating the efficiency of V2X technologies and their related services[14].

3.3 Logging of Data

To consolidate the data gathered from different tests, SQLite3 and CSV databases were set up on every communication device. The data collected from each device were organized systematically based on the dates when the tests were performed. To minimize the possibility of data loss owing to potential disruptions in connectivity, both OBUs and RSU locally store the data communicated and received during each test. After the test campaign is completed, local log files were transmitted to the central database server.

3.4 Test Cases

The evaluation of the 5G-NR-V2X wireless technology included organizing different test scenarios in which a series of tests were conducted, as shown in Figure 3. The test scenario was divided into four main sections. In the first and second test scenarios, as illustrated in Figures 3 (a) and (b), respectively, we determined the maximum effective communication area in a line-of-sight environment by varying the distance between the vehicle and the nearest and farthest points when the vehicle stopped. Furthermore, the PDR for

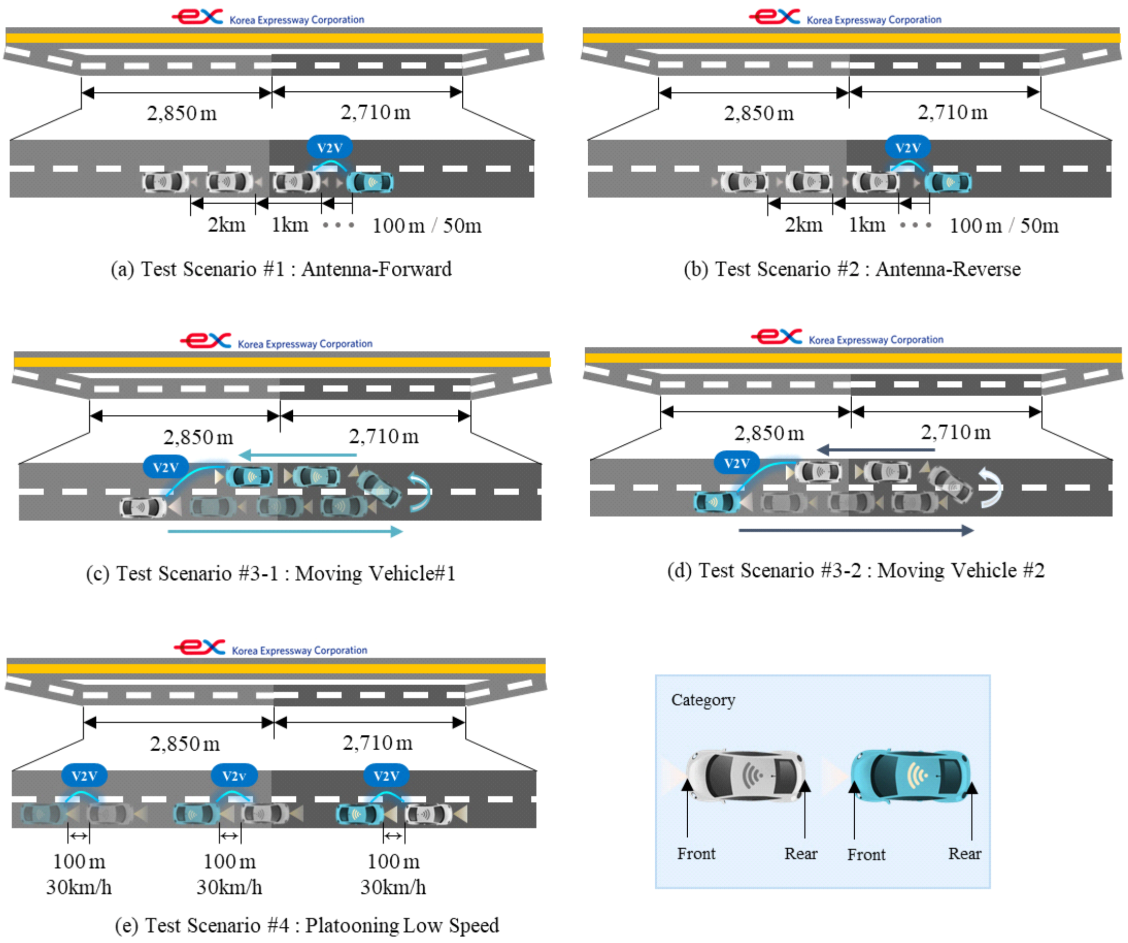

Fig. 3. Testing methdology of 5G-NR-V2X (scenarios of a test case).

each distance was confirmed to fall within the specified maximum effective communication range. The difference between the two scenarios is when the vehicle's antenna is facing in the opposite direction. You can see differences depending on the characteristics of the antenna.

Moreover, the experimental protocol entailed categorizing situations according to the orientation of the antennae of the vehicle, with one group having a line of sight towards the other and the other group looking in the same direction. The test evaluates the PDR at distances ranging from 50 m to 2 km. The distances analyzed were 50 m, 100 m, 250 m, 500 m, 750 m, 1 km, 1.25 km, 1.5 km, 1.75 km, and 2 km. Furthermore, one car underwent repair, and the resulting data were documented while the other vehicle was moving at a speed of 30 km/h within the specified maximum range for efficient communication. This experiment facilitated the assessment of communication efficiency in relation to mobility and the implementation of a mobile experiment based on antenna orientation (Figure 3 (c)). The experiment was conducted by replacing the vehicle to evaluate whether there were any variations depending on the vehicle used (Figure 3 (d)). The difference between the two scenarios can be used to determine whether there are differences in characteristics depending on the vehicle. Since the size and height are different for each vehicle, it is necessary to check whether there is a difference. Figure 4 (e) is a scenario to prove platooning performance when using 5G-NR-V2X technology. Vehicles can be used to conduct experi-

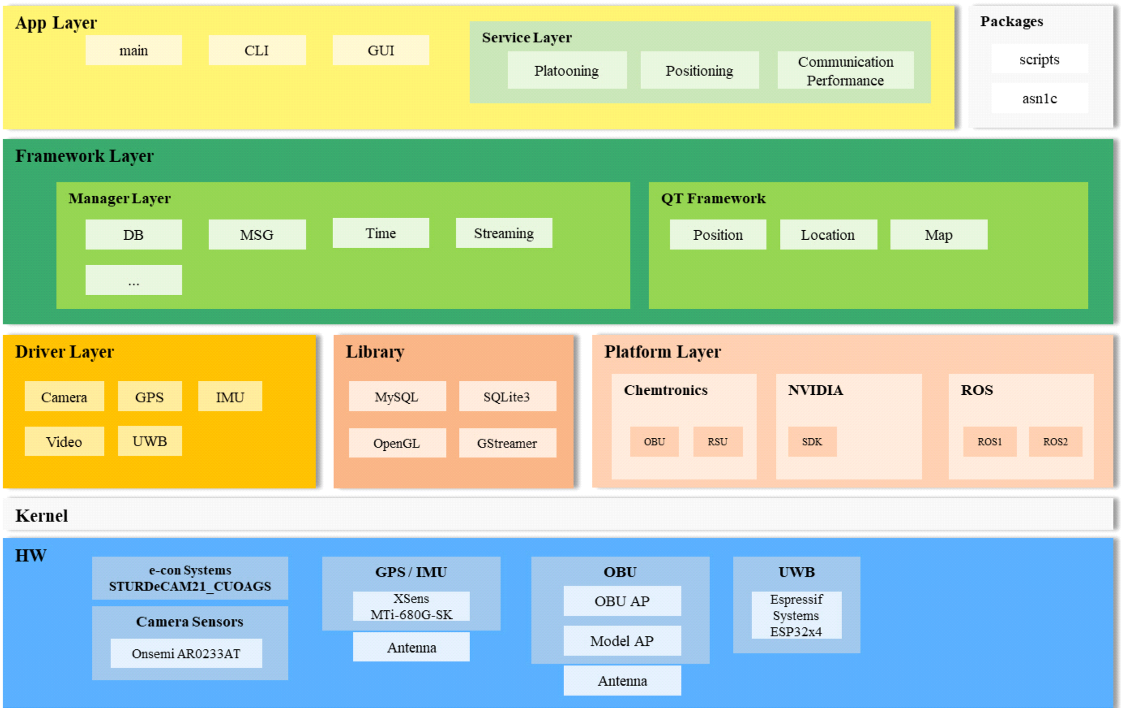

Fig. 4. SW Architecture of the ATHENA Framework.

ments to maximize verification.

Ⅳ. Experimental Results

This section analyzes and discusses the outcomes obtained from the assessment of several V2X technologies for the test scenarios outlined in Section III.

4.1 Test Environments

The Jetson Nano was employed as an AP linked to the OBU. Considering that the application service AP functions as a TCP/IP Packet, enabling the exchange of data between the OBU devices, no significant differences were observed in the performance of the high-performance Jetson ORIN and Nano devices in relation to the AP. The ATHENA SW, as outlined in Section III, was used to evaluate the communication efficacy of the AP.

4.2 PDR Measurement

The PDR was computed automatically using the ATHENA framework. The 5GAA set a service-level dependability of 99.9% at 800 m. The service-level reliability in the 5GAA was specified as 99.9% within a range of 800 m. A study was conducted to determine the relationship between 5G-NR-V2X and the 5GAA content. When the desired latency was specified as 100 ms, a transmission rate of once every 10 ms achieved a PDR of 99%. The probability of error for a single retransmission was determined to be 96.84% for this system. In this study, the minimum PDR per transmission was 96.84%. The objective was to achieve a PDR of 99.9%, assuming only one end[15].

The database was implemented in the database manager for automatic uploads, and the validated files are available as open databases[16].

4.3 Performance Evaluation

This section provided a description of the examination of V2V communication, as illustrated in Figure 5. Figure 5 (a) shows the outcome of the test case Scenario 1. The experimental findings demonstrated a PDR of 99.99% or higher in the range of 1.5 km. However, beyond this distance, the PDR decreased. The experiment confirmed that PDR values below 96.84% were obtained at 1.58 km, indicating that the

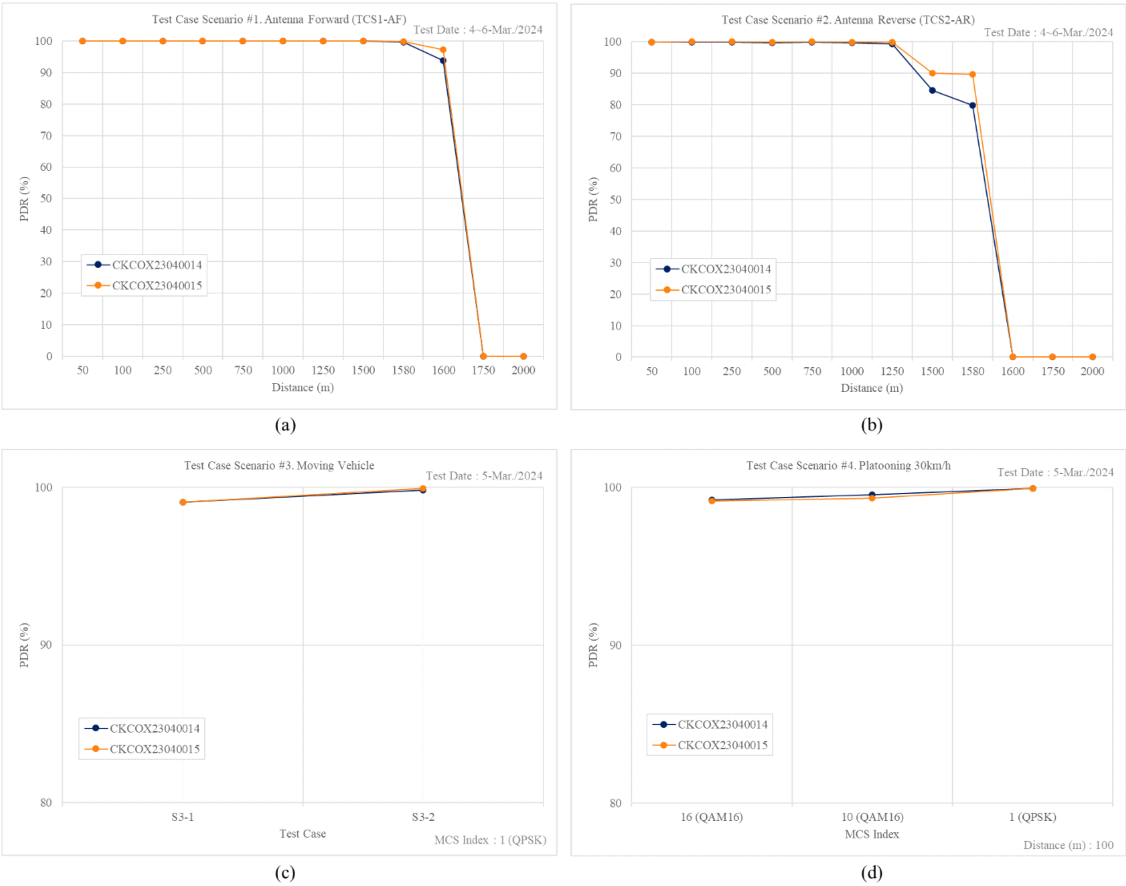

Fig. 5. Performance evaluation of 5G-NR-V2X

maximum effective communication area was within this range. According to the findings presented in Figure 5 (b), the maximum range of effective communication in test Scenario 2 was determined to be 1.25 km. The experiment confirmed that the antenna exhibits varying characteristics depending on its direction. As illustrated in Figure 5 (c), there are instances where the standard outlined in Section 4.2 is surpassed and others where it is not.

The establishment of a future plan was deemed necessary to enhance the trustworthiness of the results by conducting more repeated tests to confirm the minimum, maximum, and average outcomes. Figure 5 (d) shows the results of an experiment when two vehicles maintain a distance of 100m at a speed of 30km/h. The results showed that the PDR was over 99% and the delay time was within 10ms. The experimental results showed a minimum delay of 3ms, a maximum delay of 10ms, and an average delay of 5ms. Looking at the results, it was confirmed that 5G-NR-V2X was an excellent environment for cooperative driving compared to LTE and WAVE.

Table 2 shows the average results obtained through repeated experiments for scenarios 1 and 2. Because the experimental results are extensive, the minimum and maximum values are not included in this paper. The experiment measured PDR at various distances, Scenario 1 is when the antennas face each other, and Scenario 2 is the opposite. Each experiment was repeated for 5 minutes and was the average value, and a total of 10 experiments were repeated. In addition, in order to check the maximum distance, the MCS Index table was changed in various ways, and because the results for the values of QAM16 and QPSK showed excellent performance, only the corresponding results were presented in the paper. The results of the

Table 2. The test results of Scenario 1 and 2.

Test Case	Dist. (m)	Dev. ID	Antenna Directon	Table	MCS Index	Total Tx Packets	Total Rx Packets	PDR (%)	PER (%)	Rx File Name
S1	50	OBU#1	Forward	QAM64	10 (QAM16)	3173	3132	100	0	20240306-15-55-30_20240306-16-00-48_318secs.csv
		OBU#2	Forward	QAM64	10 (QAM16)	3132	3173	100	0	20240306-15-55-34_20240306-16-00-49_315secs.csv
	100	OBU#1	Forward	QAM64	10 (QAM16)	3047	3028	100	0	20240306-14-53-50_20240306-14-58-55_305secs.csv
		OBU#2	Forward	QAM64	10 (QAM16)	3028	3046	99.96	0.04	20240306-14-53-52_20240306-14-58-56_304secs.csv
	250	OBU#1	Forward	QAM64	16 (QAM16)	3044	3024	100	0	20240304-16-26-14_20240304-16-31-19_305secs.csv
		OBU#2	Forward	QAM64	16 (QAM16)	3024	3044	100	0	20240304-16-26-16_20240304-16-31-20_304secs.csv
	500	OBU#1	Forward	QAM64	10 (QAM16)	3084	3071	99.96	0.04	20240305-11-15-06_20240305-11-20-15_309secs.csv
		OBU#2	Forward	QAM64	10 (QAM16)	3072	3084	100	0	20240305-11-15-07_20240305-11-20-18_311secs.csv
	750	OBU#1	Forward	QAM64	10 (QAM16)	3247	3235	100	0	20240305-11-23-33_20240305-11-28-58_325secs.csv
		OBU#2	Forward	QAM64	10 (QAM16)	3235	3247	100	0	20240305-11-23-34_20240305-11-29-00_326secs.csv
	1000	OBU#1	Forward	QAM64	10 (QAM16)	3568	3565	99.97	0.03	20240305-11-48-32_20240305-11-54-30_358secs.csv
		OBU#2	Forward	QAM64	10 (QAM16)	3566	3567	99.97	0.03	20240305-11-48-32_20240305-11-54-31_359secs.csv
	1250	OBU#1	Forward	QAM64	8 (QPSK)	3070	3051	100	0	20240305-12-01-12_20240305-12-06-19_307secs.csv
		OBU#2	Forward	QAM64	8 (QPSK)	3051	3070	100	0	20240305-12-01-14_20240305-12-06-22_308secs.csv
S2	50	OBU#1	Reverse	QAM64	10 (QAM16)	3586	3580	99.88	0.12	20240306-15-47-26_20240306-15-53-25_359secs.csv
		OBU#2	Reverse	QAM64	10 (QAM16)	3584	3583	99.91	0.09	20240306-15-47-26_20240306-15-53-28_362secs.csv
	100	OBU#1	Reverse	QAM64	10 (QAM16)	3489	3470	99.94	0.06	20240306-14-45-36_20240306-14-51-25_349secs.csv
		OBU#2	Reverse	QAM64	10 (QAM16)	3472	3489	100	0	20240306-14-45-38_20240306-14-51-31_353secs.csv
	250	OBU#1	Reverse	QAM64	16 (QAM16)	3415	3402	99.94	0.06	20240304-16-06-27_20240304-16-11-31_304secs.csv
		OBU#2	Reverse	QAM64	16 (QAM16)	3404	3415	100	0	20240304-16-33-09_20240304-16-38-50_341secs.csv
	500	OBU#1	Reverse	QAM64	10 (QAM16)	3046	3024	99.63	0.37	20240305-11-07-43_20240305-11-12-48_305secs.csv
		OBU#2	Reverse	QAM64	10 (QAM16)	3035	3043	99.9	0.1	20240305-11-07-44_20240305-11-13-25_341secs.csv
	750	OBU#1	Reverse	QAM64	10 (QAM16)	3042	3030	99.96	0.04	20240305-11-31-44_20240305-11-36-49_305secs.cs
		OBU#2	Reverse	QAM64	10 (QAM16)	3031	3042	100	0	20240305-11-31-45_20240305-11-36-51_306secs.csv
	1000	OBU#1	Reverse	QAM64	10 (QAM16)	3257	3207	99.78	0.22	20240305-11-39-33_20240305-11-44-59_326secs.csv
		OBU#2	Reverse	QAM64	10 (QAM16)	3214	3256	99.96	0.04	20240305-11-39-36_20240305-11-45-00_324secs.csv
	1250	OBU#1	Reverse	QAM64	4 (QPSK)	3023	2991	99.33	0.67	20240305-12-13-52_20240305-12-18-54_302secs.csv
		OBU#2	Reverse	QAM64	4 (QPSK)	3011	3018	99.83	0.17	20240305-12-13-53_20240305-12-18-55_302secs.csv

experiment are published in an open DB, and you can check the experiment results through the corresponding file. Through the overall experiment, we were able to confirm the excellent performance of 5G-NR-V2X, although it is still under development. We plan to conduct more repetitive experiments, verify characteristics in various environments, and verify performance on real roads.

Ⅴ. Conclusions And Future Work

This paper presents an empirical assessment of 5G-NR-V2X on an actual highway and at a testing facility. The core structure, transmission protocol, and data format of 5G-NR-V2X are introduced. Moreover, the paper describes the testing methodology used and presents a detailed report of the experimental results in several test settings. Overall, this study achieved outstanding results; nevertheless, further testing is necessary to draw more reliable conclusions.

In the future, we will create a plan to evaluate the effectiveness of communication in 5G-NR-V2X, as shown in Figure 6. Our goal is to provide significant insights for autonomous driving businesses.

By implementing service validation and case scenario testing, the proposed performance analysis technique has the potential to enhance technical competitiveness in the road, transportation, logistics, and commercial sectors.

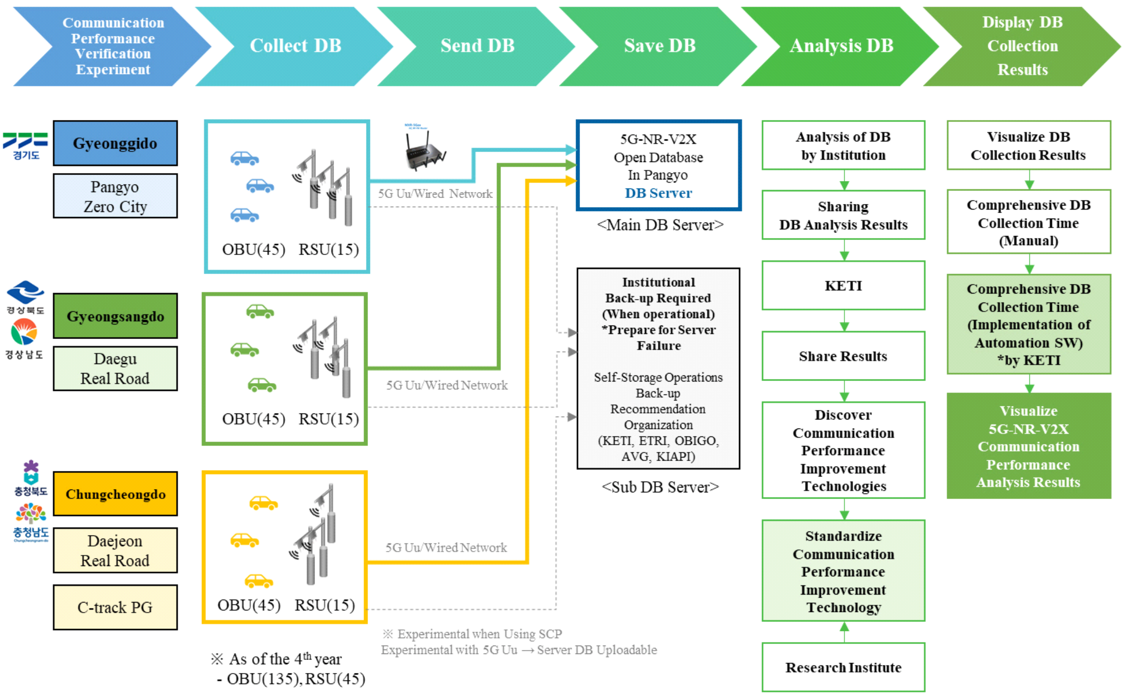

Fig. 6. Future work of 5G-NR-V2X communication verification.

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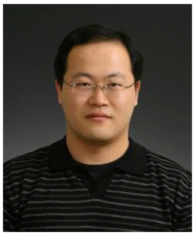

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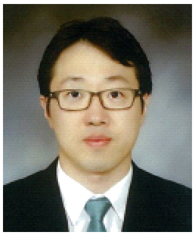

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