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RESEARCH ARTICLE

Enhancing Reliability in 5G NR V2V Communications Through Priority-Based Groupcasting and IR-HARQ

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ABSTRACT Vehicle-to-vehicle (V2V) communication is a technology that can wirelessly exchange information on the speed and position of nearby vehicles, helping to avoid collisions, to alleviate traffic congestion, and to improve the environment. The 3rd Generation Partnership Project (3GPP) has specified methods to improve the reliability of V2V sidelink (SL) technology by implementing hybrid automatic repeat request (HARQ) in a casting strategy composed of broadcast, unicast, and groupcast. However, the retransmission process in HARQ results in increased delay and reduced throughput. In this paper, we propose the priority-based groupcasting method to achieve high reliability and throughput when applying HARQ in various casting strategies. Additionally, the amount of retransmitted data is adjusted through constraints on delay and outage probability to maximize throughput. Simulation results evaluate HARQ performance in various casting strategies and confirm that the proposed method significantly improves reliability and resource efficiency compared to the conventional broadcasting. The system performance is enhanced with throughput increasing from 1.05 [Mbps] to 2.08 [Mbps], indicating an improvement of over 98%. These results emphasize that the proposed method significantly enhances communication reliability and efficiency in the 5G new radio (NR) V2V environment.

INDEX TERMS 5G-NR-V2X, V2V communications, HARQ, broadcast, unicast, groupcast, resource allocation.

I. INTRODUCTION

Vehicle-to-everything (V2X) technology improves traffic safety and road efficiency by enabling communication between vehicles, roadside units, and pedestrians. It provides short latency and high reliability, overcoming the sensor range limitations of autonomous vehicles and enabling fully autonomous driving at Level 4 or higher. In addition, it offers various advantages such as improved road safety, enhanced traffic efficiency, and various car application functions [1]. To achieve these goals, 3GPP introduced V2X communication based on the 5G NR wireless interface by releasing Rel. 16 in 2018 [2]. The design goal of 5G NR V2X SL is to improve V2X technology based on the previous long-term evolution (LTE) interface, while supporting various advanced use cases and a high level of automation, and meeting more stringent requirements [3]. The system architecture of 5G NR V2X supports NR and LTE SL V2V communication using a direct interface called PC5. In Rel. 16, two new modes (mode 1 and mode 2) are defined for NR V2X SL communication using the PC5 interface to select subchannels. Vehicles using mode 1 must operate within the network range, and the allocation and management of SL wireless resources for V2V communication is performed

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using the Uu interface that supports communication between the vehicle and the gNB. On the other hand, vehicles using mode 2 can operate autonomously by pre-configuring SL resources using a semi-persistent scheduling scheme outside the network range [4].

Supporting advanced V2X services using the NR PC5 and Uu interfaces is beneficial for various applications. In particular, the PC5 interface supports three transmission types, including unicast, groupcast, and broadcast, beyond the existing LTE broadcast strategy, to respond to more diverse situations. Broadcast communication provides services such as sharing traffic information by allowing vehicle user equipment (VUE) to communicate with other VUEs within the transmission range. Unicast transmission is a casting strategy that sends packets only to a specific target VUE and is suitable for delivering specific information or commands. Groupcast transmission is a method used when communicating with a specific group of VUEs and is useful for delivering information to vehicles in a specific area. SL broadcast, unicast, and groupcast transmissions can coexist on the same carrier, allowing a single VUE to use multiple casting strategies simultaneously. This means that operations are possible within the network range, outside the range, and in partial range using mode 1 and 2 methods, greatly improving the flexibility and efficiency of V2X communication [5]. Additionally, 5G NR V2X improves communication reliability by providing feedback related to the success or failure of SL transmissions through the physical sidelink feedback channel (PSFCH), unlike LTE V2X, which only supports blind HARQ. In particular, the use of feedback composed of HARQ for unicast and groupcast communication enhances the reliability of SL transmission. The HARQ method sends an acknowledgment (ACK) signal to the sending VUE when the packet transmission is successful, allowing for the transmission of new packet information, and a negative ACK (NACK) signal when the transmission fails, prompting the sending of failed packets again. However, using HARQ for retransmission increases the delay time, and there is a fundamental trade-off between delay time, reliability, and throughput [6].

This paper proposes an efficient transmission allocation system and analyzes the trade-off between delay time, reliability, and throughput when applying HARQ to broadcast, unicast, and groupcast in 5G NR V2X mode 2 environments. Furthermore, we propose a method to maximize reliability using HARQ while placing constraints on delay time and outage probability, and we calculate and analyze throughput based on this proposal. The main contributions of this paper are as follows:

- We provide an explanation of 3GPP specifications and mode 2 scheduling method for performance analysis of 5G NR V2X communication. The paper also models and abstracts the HARQ method at the physical (PHY) layer, providing principles for PHY layer abstraction and describing details of implementation, performance, and verification.
- We design a cellular system model for V2X performance comparison using the system-level simulation (SLS) methodology proposed by 3GPP in a highway environment. Through simulations, the paper measures the packet reception ratio (PRR) of vehicle communication for each casting strategy and provides insights into the impact of HARQ on overall system performance.
- The paper proposes an algorithm for appropriately allocating casting strategies depending on the situation, in the context of HARQ application. The paper utilizes priority-based groupcast scheduling method to allocate casting strategies to each VUE, maximizing the advantages and minimizing the disadvantages of each casting strategy, and optimizing reliability and resource efficiency.
- The paper provides constraints on delay and outage probability to resolve the trade-off of delay, reliability, and throughput in the situation where HARQ is applied. The paper maximizes throughput by considering the number of retransmissions and packet reception probability that occur due to the application of HARQ to each casting strategy.
- Finally, the paper evaluates the proposed method through simulation results. The paper compares the performance of each casting strategy with HARQ applied and analyzes the impact of a groupcast priority-based resource allocation strategy with HARQ on reliability and throughput. Furthermore, the paper verifies performance improvement through comparison and evaluation of throughput optimization methods using delay and outage probability constraints while maintaining reliability in the proposed method and simulated existing methods.

The paper is organized as follows: Section II discusses previous research related to the proposed method and similar previous studies. Section III provides the key numerical and physical parameters used in 5G NR V2X mode 2 and explains the physical layer abstraction and resource allocation methods. Section IV describes the procedures for designing and evaluating the system model according to the 3GPP methodology using the open-source simulator WiLabV2Xsim. In Section V, we propose a priority-based groupcasting method to enhance reliability in a V2V communication environment and introduce a resource allocation method using IR-HARQ. Furthermore, we suggest a method for maximizing throughput considering delay and outage probability constraints. Section VI provides simulation results along with insights for performance evaluation and improvement. Finally, Section VII presents our conclusion.

II. RELATED WORKS

V2V communication based on 5G NR now supports not only broadcast transmission but also unicast and groupcast transmission. Additionally, the application of feedback-based HARQ technology has become possible. Given these changes, as V2V communication aims to achieve high communication reliability and throughput, HARQ technology has become an essential component. Therefore, previous HARQ-related studies have presented research results for various scenarios and explored methodologies for efficiently utilizing HARQ technology at the link layer. In this section, we introduce other research that uses similar scenarios and evaluation methods as the research discussed in this paper, emphasizing the similarities and differences between these studies and our research.

For HARQ technology to be applied to V2V communication, the encoding/decoding process for each transmission must occur at the link layer, which incurs a considerable cost in terms of time and resources. Therefore, numerous previous studies have pursued research methods that combine models executed at the link layer with system-level evaluations for V2X communication simulations. Notably, studies [7], [8], [9] introduced the physical layer abstraction (PLA) technology to support and evaluate 5G NR V2V communication. This technology reduces computational complexity during the simulation process, while offering a modeling method that can evaluate the performance of the proposed technology under various channel conditions and reliability requirements. The study conducted in [7] evaluated and compared the performance of V2V technology at the PHY layer. In this study, various standard communication methods (5G NR V2X, LTE V2X, IEEE 802.11bd, and IEEE 802.11p) were analytically calculated at the same data transmission speed and delay time, and compared with theoretical calculation results. In addition, through simulation, it was confirmed that the V2V performance based on 5G NR was superior to other technologies in terms of transmission delay and data speed, providing realistic performance measurements close to actual scenarios. This method demonstrated its suitability for evaluating V2V performance. The study conducted in [8] utilized PLA technology for V2X communication, deriving the results of packet error rate (PER) against signal to interference plus noise ratio (SINR). This enabled the modeling of the PHY layer in SLS. The researchers developed and utilized parametric models varying depending on the applied scenarios, thereby proposing a methodology to evaluate performance without additional link-level simulations (LLS). This proposed methodology, when compared to traditional approaches that required complex calculations for each situation, demonstrated remarkably similar results and improved processing speed in terms of time utilization, as confirmed through simulation. Ultimately, the proposed methodology demonstrated its applicability in accurately evaluating V2X communication technology at the system level. In the study conducted by [9], a PLA technique that calculates SINR values considering inter carrier interference (ICI) effects was proposed and applied to V2X communication for evaluation. The PLA technique proposed in this study confirmed its ability to accurately model ICI and multipath fading effects, and through simulation, evaluated and compared various performance metrics such as PER, PRR, and packet arrival interval time in communication methods. In the performance evaluation, the study verified that the performance metrics were correctly modeled considering encoding methods, modulation and coding schemes (MCS), and overhead ratios that matched the specifications of each communication method. Ultimately, it demonstrated that the proposed method in this study can be appropriately applied and utilized for the evaluation of V2X communication.

From another perspective, not only were there studies measuring V2X performance at the link level, but also research utilizing HARQ technology in various scenarios in V2V communication was conducted at the system level. Particularly, in the studies [10], [11], [12], [13], research was conducted applying HARQ technology in various casting methods in V2V communication. The study conducted in [10] focuses on groupcast for 5G NR V2V communication. This research addresses the communication issue of signal blocking due to other VUEs in the conventional groupcast method by proposing two approaches: a heuristic approach that optimizes the control of receiving VUEs and time resource allocation to achieve a high groupcast success rate, and a groupcast method that minimizes total time consumption through the Markov decision process (MDP). The proposed methods demonstrated superior performance compared to the blind HARQ method and feedback-based HARQ method in conventional groupcast. These results indicate the possibility of reliable and efficient groupcast depending on the groupcast scenario method, and the improvement of the efficiency in wireless resource utilization. In [11], a study was conducted to improve reliability in the 5G NR V2X environment by applying blind retransmission in groupcast. The research proposed a method where, after the initial transmission, the Tx retransmits to Rx VUEs in the same group to maximize the group packet reception ratio (GPRR) values during the retransmission process. The proposed method not only demonstrated improved performance compared to the existing broadcast method in terms of GPRR, packet inter-reception (PIR) time, and possible group size but also proved through simulations that the application of the proposed blind HARQ method significantly enhances the reliability of NR V2X. In [12], [13], a study proposes a method to enhance reliability in the 5G NR V2V environment through cooperative retransmission of data packets using numerous independent communication links between the target VUE surrounding VUEs. The proposed method analyzes the impact on V2X communication reliability, both theoretically and experimentally, considering additional retransmissions through cooperative VUEs using HARQ techniques and within the allowed delay budget in the V2X environment. The experimental results demonstrate a significant improvement in reliability when performing retransmissions using HARQ techniques as suggested by the proposed method.

In the previously introduced research, there was an investigation into enhancing the reliability and data efficiency by applying HARQ technology in various scenarios of 5G

NR V2V on both LLS and SLS. However, these studies did not consider performance issues occurring at the link level when applying HARQ technology, and simply considered whether retransmissions were successful. Moreover, despite the scenario allowing various casting methods, only some were researched and evaluated. Therefore, in this study, we incorporated a large number of coded bits, whose redundancy increases with each retransmission at the link level, into the modeling using the incremental redundancy (IR)-HARQ method, a standard in 5G NR. This was applied to the new scenario proposed in this paper, and its performance was evaluated. Based on these research findings, this paper presents a new resource allocation method that can compensate for and enhance the advantages and disadvantages of different casting methods. Through this, we derived research results that are differentiated from the studies previously mentioned.

III. HARQ UTILIZATION AND SCHEDULING IN MODE 2

In this section, we provide an explanation of the characteristics of the 3GPP specifications for 5G NR SL and the scheduling method of mode 2 used in the paper. We also introduce a modeling approach for HARQ utilization in 5G NR V2X environment and present an evaluation method based on link-to-system mapping (L2S) and SLS to compare and evaluate the performance of the proposed techniques. This is necessary to establish a foundation for properly understanding the literature reviewed in the following section.

A. 5G-NR V2X SIDELINK SPECIFICATIONS

5G NR V2X has introduced two new resource allocation modes, mode 1 and mode 2, each ideally suited for V2X SL communication. The scheduling method of mode 2, employed in this paper, allows vehicles to independently select, manage, and configure the sub-channels within the frequency domain, thereby eliminating the need for base station infrastructure. Moreover, vehicles utilizing mode 2 have been meticulously designed to operate even beyond the network coverage area.

Delving into the details of mode 2, as applied in this paper, according to 3GPP Rel. 16, 5G NR V2X SL has been designed to operate in frequency range 1 (FR1) from 410kHz to 7.125GHz and in frequency range 2 (FR2) from 24.25GHz to 52.6GHz. However, the design of NR V2X SL is primarily based on FR1 due to the lack of specific optimizations for FR2 [14]. In the FR1, the PHY layer of 5G NR V2X is transmitted using orthogonal frequency division multiplexing (OFDM) waveforms and a cyclic prefix (CP). The flexible numerical values of the transmitted CP-OFDM waveforms are provided by scalable SCS configuration coefficients, which can extend the SCS subcarrier spacing from 15kHz to 120kHz at intervals of $2\mu \cdot 15$kHz (where $\mu = 0$, 1, 2, 3). According to the numerical interpretation structure of the 3GPP 5G V2X document, all vehicles are assumed to have the same SCS value of 30kHz, and the typical length of the CP is consistently maintained at 2.39 μs [5]. In such a frequency domain, NR V2X is pre-configured to only accommodate SL transmission in specific slots and defines a resource pool (RP), which is a subset of available SL resources, for this purpose [4]. The RP consists of subchannels, which are the minimum units for SL data transmission or reception, and subchannels within the RP are made up of continuous groups of common resource blocks called physical resource blocks (PRBs) [15]. In these subchannels, data packets are transmitted in the form of a transport block (TB) via physical sidelink shared channel (PSSCH), with physical sidelink control channel (PSCCH) being sent alongside PSSCH. At this time, PSSCH and PSCCH contain information of two stages of sidelink control information (SCI) [4]. The first stage SCI contains information about the current TB and the PSCCH resources reserved for its retransmission, and it delivers information necessary for decoding the second stage SCI via PSCCH. The second stage SCI, carrying additional control and scheduling information, is transported with the TB on the PSSCH [16]. Moreover, the demodulation reference signals (DMRS) for demodulating PSCCH and PSSCH is also transmitted within the slot [17]. The configuration of the supported numerology in the NR V2X SL is as shown in Table 1, and these parameters are represented by being applied in a subsequent simulation.

TABLE 1. Numerologies in NR V2X Mode 2.

Parameters	Value
Carrier frequency	6 GHz
Bandwidth	20 MHz
Waveform	CP-OFDM
Subcarrier spacing,	30 kHz
Symbols per slot,	14
Subchannel size per PRB	20
Nr. Subcarriers per PRB	12
Nr. PSCCH per symbol	2
Nr. DMRS per slot	12

NR V2X mode 2 conducts scheduling for resource selection for TBs transmitted via sensing based semi-persistent scheduling (SB-SPS). V2X messages have regular and predictable characteristics. Utilizing these characteristics, SB-SPS performs detection procedures [18]. Each VUE proceeds with a process of reserving a subchannel in the frequency domain using the random value of periodic transmissions in the time domain. Such reserved subchannels are used to select resources for multiple consecutive reselection counter TBs. Also, the resource reservation interval (RRI) included in the first-stage SCI is utilized to select the subchannel reservation and time intervals between resources for continuous TB transmission. Through this process, other VUEs can estimate which resources will be reserved in the future. The

3GPP standard provides possible values for such RRI and reselection counters [19]. After each vehicle transmits a TB, the reselection counter decreases by one. When a vehicle's reselection counter reaches zero, a new subchannel should be selected with a probability of (1-P) according to the preset reselection probability P. In this paper, the value of P is set to 0.6. The standard also defines the maximum number of times the same resource can be used. Mode 2 resources have full flexibility in frequency and time within a window of 32 slots. Therefore, within the same selection window, it can be reserved up to 32 times for blind or HARQ feedback-based retransmission [16].

B. LDPC BASED IR-HARQ DESIGN

In 5G NR, the channel coding method for data employs a flexible low-density parity-check (LDPC) method, which is standardized for all block sizes. For 5G NR V2X, feedback using HARQ is introduced to enhance transmission efficiency. The LDPC channel coding technique designed for NR data channels supports both IR-HARQ and chase combining (CC) HARQ methods [20]. This section presents and designs the encoding process for IR-HARQ using LDPC techniques in the proposed research.

The 5G LDPC encoding process, as defined in 3GPP documents, consists of four stages: cyclic redundancy check (CRC) attachment, LDPC encoding, rate matching, and bit-interleaving. In the rate matching stage, various redundancy versions (RVs) required for the HARQ protocol are utilized, and the starting bit position of the circular buffer, comprising systematic bits and parity bits, is assigned for each RV. For IR-HARQ, differently coded bit sets are used for each retransmission, resulting in coding gains for each RV in addition to the accumulated reception gain [20]. The RVs used in the 5G standard are divided into four RVs, and the starting points for each RV follow the LDPC base graph in the 3GPP standard document [22]. The document sets the position of the circular buffer for each RV, allowing the receiver to know the starting position of the received packet in the circular buffer using the RV value, enabling soft combining. By selecting different RVs, different coded bit sets representing the same information can be generated. For the LDPC code used in NR, system bits are more important than parity bits. Consequently, the initial transmission must include all systematic bits and some parity bits at the very least. For retransmissions, parity bits not included in the initial transmission can be included, and both RV0 and RV3 are defined to be self-decodable. In other words, system bits are included in typical scenarios [23].

LDPC can support flexible block sizes by adjusting submatrix sizes and increase flexibility using zero-padding. LDPC codes can also reduce CRC overhead and may not strictly require channel interleaving due to their submatrix-based structure. NR supports HARQ, and the redundancy version information is transmitted with the resource allocation information within the SCI on the PSCCH. In cases where the RV order is not explicitly signaled, it can be predefined or configured by higher layers. RV0 is suitable for the first transmission and can be self-decoded. Therefore, RV0 can be used to transmit data such as paging or system information (SI) and an implicit RV order may be applied for SI transmission requiring soft combining.

C. PHYSICAL LAYER ABSTRACTION METHODOLOGY

To evaluate and compare the performance of proposed technologies in a 5G NR V2X environment through SLS, system-level research is needed that satisfies various channel conditions between transmitters and receivers, and meets the required reliability criteria. However, SLS suffers from slow simulation times and high computational complexity due to high-density vehicle environments, real-time changing vehicle locations, and link complexity, making it difficult to accurately measure signal levels at the PHY level. Therefore, to accelerate such simulations, a modeling technique called PLA is used to abstract the PHY. Through PLA, by modeling various fading and interference effects as functions of SINR, it is possible to investigate complex wireless transmission systems and effectively evaluate the performance of new technologies [9]. In order to obtain PLA for use in SLS, it is necessary to perform LLS process that approximates the PER vs. SINR curve available in specific settings. In the LLS, we use the Vienna 5G LL Simulator, an open-source MATLAB-based simulator, to model link-level performance according to the 5G LDPC Codes IR-HARQ design method [24]. This simulator utilizes the contents mentioned in Section III-A and Section III-B, as well as methodologies from 3GPP for V2X evaluation [5]. The LLS used focuses on the PHY layer of the communication system, conducting simulations with a high level of accuracy as it implements signal transmission through the wireless channel between transceivers. The settings of the PHY layer are based on an OFDM-based wireless system, and adjustments are made through MCS settings and flexible numerical system adjustments. In the used CP-OFDM waveform, carrier frequency, subcarrier spacing, and channel conditions can be adjusted according to standards, and these are set according to the numerologies value presented in Table 1. After initial settings, the simulation considers all PHY feature objects, including channel coding, modulation, channel generation and estimation, and channel state information (CSI) feedback calculations. The LDPC method is used for channel coding, which undergoes the four encoding processes mentioned earlier. Particularly during the Rate matching stage, simulations are conducted according to different RV settings for HARQ application. For the decoding algorithm, an approximation of the double piecewise linear PWL-Min-Sum [25] is used. Then, simulations are conducted for the desired packet size under AWGN channel conditions with the set MCS values. At the receiving end, an Ideal channel estimation method and a maximal-ratio combining (MRC) receiver algorithm are used to generate the PER vs. SINR curve. Table 2 summarizes

TABLE 2. **Parameters for the IR-HARQ LLS settings.**

Parameters	Value
Channel coding scheme	LDPC
Construction/encoding	5G NR
Decoding algorithm	PWL-Min-Sum
Beacon Size Bytes	800 bytes
CP length	Normal CP
Modulation	16QAM
Coding rate	436/1024
Fading model	AWGN
Channel estimation	Ideal
VUE receiver algorithm	MRC

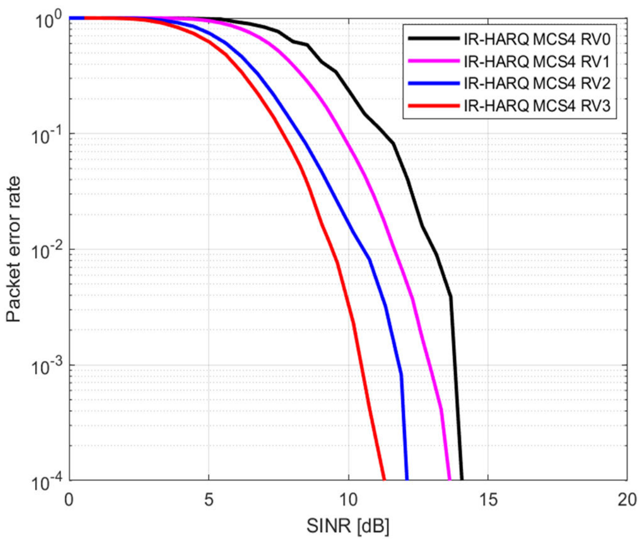

FIGURE 1. **Comparison of PER performance curves according to RV value differences.**

these channel coding schemes and decoding algorithms, including the settings for LLS parameters.

The results of the methodology and figures used in the LLS are presented in Figure 1. The results in Figure 1 apply the simulation assumptions used to evaluate resource allocation mode 2 of TR 38.885, and it shows the LLS PER vs. SINR curve, considering the RV values and retransmission gains according to the retransmission, based on the design approach in the PHY layer where LDPC-based IR-HARQ technology is applied. To obtain these results, all VUEs are assumed to transmit packets of the same size (800 bytes) at regular intervals (100 ms), and the vehicle transceivers are assumed to use a fixed MCS for packet transmission. The experimental results illustrate the relationship between PER and SINR for a single transmission with different RV values. This confirms that the calculated results for different RV values, based on the circular buffer, are presented heterogeneously. In the LLS results of Figure 1, the PER 10^{-1} point serves as a benchmark for SNR-CQI mapping, playing a significant role in the performance evaluation of this study. Also, this point greatly influences the assessment of packet reception in the SLS process. The SINR threshold values satisfying the Target PER $= 10^{-1}$ are approximately 12dB, 9.8dB, 8dB, 7.5dB for RV0, RV1, RV2, RV3, respectively. This shows a trend of decreasing required SINR values as the redundancy values increase. These results are applied to the SLS. The SLS quantifies network performance through packet-level performance indicators such as instantaneous PER [7]. However, the full PHY layer LLS is typically performed in the link simulator, and the SLS in the PHY layer, which is costly in terms of execution time, is used to obtain packet performance at a single receiver. Running a full PHY layer simulation including channel implementation and transceiver signal processing within the SLS is not realistic. As a result, a modeling technique called PLA is used to abstract the PHY layer. This is also known as a link quality model (LQM) [9].

The received SINR of each data symbol can vary. To calculate a single link quality metric for the PLA, it is necessary to map the instantaneous SINR of all data symbols to an effective SINR. The PER vs. SINR curve obtained through the LLS can be used for system-level evaluation, and the effective SINR can be used to estimate PHY layer performance or select the optimal MCS for link adaptation. Therefore, we perform L2S using the mutual information effective SNR mapping (MIESM) algorithm. The effective SNR mapping (ESM) algorithm provides important link layer abstraction for SLS. When MIESM is applied in this study, it provides higher accuracy than other ESM methods by calculating the effective SINR based on the non-linear mapping relationship from SINR to mutual information using equations (1) and (2).

$$SINR_{eff} = \beta \cdot I^{-1}\left(\frac{1}{N}\sum\nolimits_{n=1}^{N} I\left(\frac{SINR_n}{\beta}\right)\right) \tag{1}$$

$$\begin{aligned} I_{mp}(x) = m_p - E_y \\ \times \left\{\frac{1}{2^{mp}}\sum\nolimits_{i=1}^{mp}\sum\nolimits_{b=0}^{1}\sum\nolimits_{z\in X_b^i} log\frac{\sum_{\tilde{x}\in X}\exp(A)}{\sum_{\tilde{x}\in X_b^i}\exp(A)}\right\} \end{aligned} \tag{2}$$

where

$$A = -\left|Y - \sqrt{x/\beta}\,(\tilde{x} - z)\right|^2$$

Here, β is a correction coefficient selected to minimize the mean square error between the effective SNR and the fixed SNR derived from the Rayleigh channel [26]. Such measurements are based on the mutual information function I(SINRn). Additionally, equation (2) represents the number of bits per symbol for the selected modulation scheme, where X is the symbol set and Y is a zero-mean complex Gaussian variable with unit variance [27].

D. HARQ STR ATEGI ES IN CASTING STRATEGIES

5G NR offers more flexible messaging transmission options compared to LTE. This is made possible by the use of RP, where multiple VUEs can share SL transmissions. This structure allows the utilization of various casting methods including broadcast, unicast, and groupcast. Specifically, the introduction of two-stage SCI messages that are transmitted along with TB via PSSCH enables a custom SCI architecture that supports each casting method [4]. These diverse casting methods enable communication targeted at specific devices or groups of devices within a communication radius. In enhanced V2X scenarios, groupcast is a transmission method, similar to flooding, in which data packets are sent to multiple destinations in a specific group simultaneously. This method is used in V2V environments to deliver data to group members simultaneously. On the other hand, unicast is a method in which packets are individually transmitted and exchanged to a specific target receiver, such as a nearby group leader. Each of these casting methods offers different advantages depending on the specific network environment and requirements, enabling support for more services. Particularly, 5G NR V2V introduces SL HARQ at the PHY layer that supports both unicast and groupcast. Through this, resources can be selected and retransmitted for various purposes. At this point, it supports three methods: the blind HARQ that performs multiple retransmissions for TB, the HARQ method based on ACK/NACK transmission, and the NACK-only HARQ method. The blind HARQ is a method that has been continuously used from the existing LTE, in which the transmitting VUE transmits the same resource twice within the RRI, and retransmission combination is implemented in the transmitting VUE. In the HARQ method based on ACK/NACK transmission, if the VUE successfully decodes the TB containing the received resource from the associated PSCCH, it generates an ACK, and if it fails to decode the TB, it generates a NACK and transmits the ACK/NACK signal generated through the PSFCH. In addition, the NACK-only HARQ method generates a NACK only when it fails to successfully decode the TB from the associated PSCCH and transmits the NACK signal generated through the PSFCH. In these HARQ methods, the blind HARQ method minimizes the delay of retransmission because the transmitting VUE does not need to wait for HARQ feedback before sending a retransmission, but it is inefficient in resource utilization when the initial transmission of TB is successful. On the other hand, feedback-based HARQ is a method that can reduce the SL resource demand when there are many receiving VUEs that need to send feedback to the same transmitting VUE, and greatly improves the efficiency of retransmission. Despite the advantages and disadvantages of each HARQ method, many places use the feedback-based HARQ, the HARQ method based on ACK/NACK transmission, and conduct experiments, and this paper also uses the HARQ based on ACK/NACK transmission for evaluation and analysis. To simplify the analysis, a minimum set of resources in the frequency domain is allocated to deliver ACK/NACK information so as not to overlap with the resources assigned for packet transmission, and it is assumed that all ACK/NACKs are received without errors. This paper focuses on scenarios where various casting methods that receive control data including resource allocation information from groups are mixed, and the remaining OFDM symbols in slot t can be used for other groups using the same V2V channel or different casting methods.

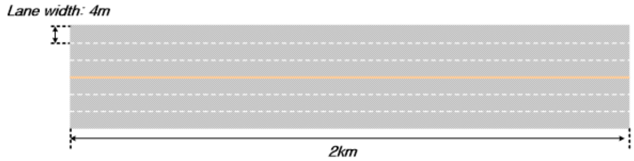

FIGURE 2. Road configuration for highway scenario.

IV. SYSTEM MODEL AND ASSUMPTIONS

As mentioned in the previous section, the results of LLS are used to determine the PHY abstraction model employed at the system level. To evaluate the reliability of vehicle communication using HARQ applications at the system level, we use the MATLAB-based open-source simulator WiLabV2Xsim [16]. WiLabV2Xsim enables the analysis of the SL resource allocation method for V2V communication, taking into account the PHY and MAC layer settings and procedures based on the 3GPP standard. The evaluation at the PHY stage applied in SLS uses the PER vs. SINR curve as an essential measurement criterion, as shown in Figure 1. In this section, we will discuss the system settings, including network layout, channel model, and resource allocation method, based on the methodology for V2X evaluation presented by 3GPP, to meet the requirements of the 5G NR environment.

A. NETWORK LAYOUT

We implement a V2V simulation model in a V2X highway scenario as presented in the methodology for V2X by 3GPP [5], [28], [29]. The network layout configuration for implementing the highway scenario is shown in Figure 2. We also assume a wrap-around model where vehicles exit from one side and re-enter from the opposite side for all VUEs within the scenario. The distribution of vehicles on the road that satisfies the above conditions is based on a spatial Poisson process, with each vehicle distributed along the road, and the vehicle density on each road varies according to the assumed vehicle speed. The spatial Poisson process used distributes points along the road based on the occurrence of point events within a specific area of interest [30]. The applied 1-D Poisson point process (PPP) method models the vehicle locations within the simulation according to equations (3) and (4).

$$P\left(N\left(D\right)=K\right)=\frac{e^{-\lambda D}\left(\lambda D\right)^{k}}{k!} \tag{3}$$

where

$$k = 0, 1, 2, 3, \ldots, N$$
$$\prod_{j=1}^{N+1} U_j < e^{-\lambda} \tag{4}$$

At this point, the number of vehicles N(D) located on each lane can be represented by the point density λ and the length D of each lane. In the scenario, the absolute speed of all vehicles in the same lane is set to 140km/h, and the average distance between vehicles is defined as the vehicle density times (2.5 seconds x absolute vehicle speed). Once the vehicle density parameter λ for each lane is determined based on this, points obtained from the PPP are evenly distributed onto each lane in the simulation using equation (4). The Uj value represents an independent random variable uniformly distributed between 0 and 1, and the number of vehicles is determined by equation (3) based on the N value and λ. The vehicles are then placed in the simulation accordingly.

B. CHANNEL MODEL

In this study, the V2V SL channel model used is based on two states in the highway environment. The path loss model follows the two-state V2V SL channel model presented in the 3GPP document [5]. The link between two vehicles on the same road is represented as either line-of-sight (LOS) or non-line-of-sight (NLOSv). The V2V link, in which the LOS path is not blocked by other vehicles during the wireless signal transmission and reception between two vehicles, is represented as the LOS state. Conversely, the V2V link, in which the LOS path is blocked by other vehicles, is represented as the NLOSv state. The probabilities of LOS and NLOSv in the simulation follow equations (5) and (6), and the state transition between LOS and NLOSv occurs when the VUE location is updated every 100 ms.

$$LOS : If \ d \leq 475m, P\left(LOS\right) = min\left\{1, a * d^2 + b * d + c\right\} \tag{5}$$

$$If \ d > 475m, P\left(LOS\right) = max\left\{0, 0.54 - 0.001 * \left(d - 475\right)\right\}$$
$$NLOSv : P\left(NLOSv\right) = 1 - P\left(LOS\right) \tag{6}$$

Here, the value a = 2.1013*10-6, b = −0.002, and c = 1.0193 and d represents the distance between the transmitting and receiving UEs. The path loss model in each state, based on the previously mentioned equation, is represented by equation (7). For the V2V link corresponding to NLOSv, additional vehicle blockage loss is added, as shown in equation (8).

$$Pathloss = 32 + 20\,log(d_{3D}) + 20\,log(f_c) \tag{7}$$
$$\mu : 5\,dB + max(0, 15 * log10(d) - 41), \sigma : 4\,dB \tag{8}$$

In equation (7), the value f_c represents the center frequency in GHz, and the value d_{3D} represents the Euclidean distance between the TX and RX in 3D space, measured in meters. In equation (8), the value of μ represents the average value of additional blockage loss, taking the form of a log-normal random variable, and the value of σ signifies the standard deviation. V2V shadowing follows a log-normal distribution with a standard deviation of 3 dB and a decorrelation distance of 25 m. In the case of fast fading, the clustered delay line (CDL) model derived from the V2X SCM model in 3GPP TR is used to calculate the NLOS case [31]. For the antenna gain being applied, we use antennas that meet the 2TX/4RX configuration, and the noise figure at the receiving end is set to 9dB. Also, the gain of the transmitting and receiving antennas is set to 3dBi for calculations. The propagation loss for the transmission link from each VUE considers path loss, shadowing, and fast fading. The proposed primary propagation loss model is implemented and used according to (9) [32].

$$G = AntennaGain - PathLoss - Shadowing - Fading \tag{9}$$

In the simulator, the situation is updated through packet generation and slot occurrence events mentioned in Section II-D, as well as the vehicle update method in Section III-A. Accordingly, path loss, shadowing, and fast fading values are applied to each vehicle's situation, and resource allocation is processed considering the previously occurred events. In the resource allocation method, a new resource allocation is reserved before the start of the slot, and transmission begins according to the reserved resource allocation for packets in the queue. Packet transmission success or failure is evaluated through the update of the output metric at the end of the slot and the update of the SINR value measured according to the SB-SPS procedure. The most important measurement criterion is SINR, which accumulates the attenuated signal from all interference located at the desired transmitter and receiver position. When considering resource allocation for slot t with transmitting vehicle i and receiving vehicle j, the received SINR of the vehicle is obtained as follows:

$$SINR_{ij,t} = \frac{h_{ij,t} P_{i,t} / L\left(d_{ij}\right)}{P_n + I_{i,j,t}} \tag{10}$$

Here, the numerator of equation (10) represents the received power. $P_{i,t}$ is the transmission power generated by i, $h_{ij,t}$ is a function of the shadowing and fast fading occurring between i and j for slot t, and $L(d_{ij})$ represents the path loss value from i to j as a function of the distance between i and j. In addition, in the denominator representing the noise power and interference, P_n is the noise power, $I_{ij,t}$ represents the average interference, and the sum of the two is assumed to have a Gaussian distribution with a mean of 0.

$$I_{ij,t} = \sum\nolimits_{k \in Vt, k \neq i} \mu_{ki} \frac{h_{kj,t} P_{tk}}{L\left(d_{kj}\right)} \tag{11}$$

Equation (11) defines the applied interference, where V_t represents the set of nodes transmitting in slot t. Additionally, μ_{ki} is a multiplication coefficient between 0 and 1 that

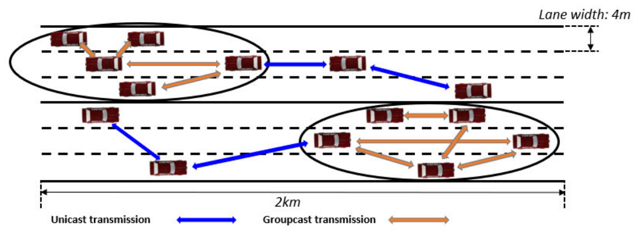

FIGURE 3. Uni/Groupcast scenario in simulation.

quantifies the power of node k transmitted in the subchannel used by node i, compared to node k's transmission power. μ_{ki} is equal to 1 if node k uses the exact same subchannel as node i, and lower than 1 if the signals overlap or interfere partially. The calculation of μ_{ki} considers in-band emission (IBE) according to the specification in [21].

C. SINR DERIVATION FOR BROAD/UNI/GROUPCAST

In Rel-17 and 18, unicast and groupcast can be supported in 5G NR environments with minimal impact on VUE hardware and network aspects due to their similarity to the commonly used broadcast. As depicted in Figure 3, we discuss SL transmission in a cellular network that supports broadcast, unicast, and groupcast. The SINR calculation presented earlier is for a broadcast environment where data is transmitted to all users, while in this section, we calculate the received SINR of VUE in unicast and groupcast based on the SINR formula presented earlier. For unicast, the SINR of the vehicle is obtained according to equations (12) and (13).

$$SINR_{is,t}^{U} = \frac{h_{is,t}P_{is,t}^{U} \Big/ L\left(d_{is}\right)}{P_n + I_{is,t}^{U}} \tag{12}$$

Here, $SINR_{is,t}^{U}$ represents the SINR value for vehicle s receiving a signal from Tx VUE i in unicast. For unicast, the useful signal power $P_{is,t}^{U}$ is provided only for the VUE s that is being serviced, and the path loss value $L(d_{is})$ is calculated assuming LOS without additional vehicle blockage loss from i to s.

$$I_{is,t}^{U} = \sum\nolimits_{k \neq i} \mu_{ki} \frac{h_{ks,t}P_{tk}}{L\left(d_{ks}\right)} \tag{13}$$

In equation (12), the interference $I_{is,t}^{U}$ is calculated as the interference caused by signals from other nodes located in the same slot as the information transmitted from vehicle i. For groupcast, the simulation represents the group set as $\hat{G} := \{1,2,\ldots,g\}$, and the received SINR in groupcast is calculated according to equations (14) and (15).

$$SINR_{ig,t}^{G} = \frac{h_{ig,t}P_{i,t}/L_G\left(d_{ig}\right)}{P_n + I_{ig,t}^{G}} \tag{14}$$

For a Tx VUE, it is assumed to belong to the same group as the Rx VUE, and the group is determined based on distance and group size at the application layer. The value of $SINR_{ig,t}^{G}$ in groupcast is the SINR measurement for the Tx VUE i belonging to the group and the RX VUE, and unlike unicast, the path loss value $L_G\left(d_{ig}\right)$ considers both LOS and NLOSv cases.

$$I_{ig,t}^{G} = \sum\nolimits_{k,g \in \hat{G}, k \neq i} \mu_{ki} \frac{h_{kg,t}P_{tk}}{L\left(d_{kg}\right)} \tag{15}$$

In equation (14), interference $I_{ig,t}^{G}$ the signals transmitted by other VUEs in the same group as Vt, including the node set Vt transmitting in the same slot, are considered as interference. Equations (10), (12), and (14) demonstrate the calculation of SINR values for each casting method. In the case of unicast, all path losses are assumed to be in LOS without any additional blocking losses during calculation. When using unicast, it's presumed that communication will primarily occur with the nearest vehicle, hence, it is expected to exhibit relatively high received SINR values. Furthermore, when unicast is used alone, there's hardly any overlapping resources in the same PRB during resource block allocation, leading to a reduction in delay and, as a result, higher throughput is expected. On the other hand, in the calculation of groupcast SINR, NLOSv cases, which include all path losses with additional blocking losses, are probabilistically involved, leading to relatively high interference. When using groupcast method alone for resource block allocation, the number of overlapping resources in the same PRB increases, causing delay and affecting the throughput. These SINR calculation methods reflect the advantages of unicast such as high reliability and the disadvantage of data overload, as well as the advantages of groupcast like data reliability and low data usage. These advantages and disadvantages complement each other and are used in the resource allocation method presented in Section V.

V. V2V COMMUNICATIONS RELIABILITY ENHANCEMENT WITH THE PROPOSED PRIORITY BASED GROUPCASTING AND IR-HARQ

In the previous section, we discuss the resource allocation method for mode 2 and the details of applying IR-HARQ based on the 3GPP technical document concerning the 5G NR V2X methodology. In this section, we propose methods to enhance transmission reliability and maximize the amount of data transferred when IR-HARQ is applied in various casting strategies, in a highway environment, as introduced earlier.

A. PRIORITY-BASED GROUPCASTING WITH IR-HARQ

IR-HARQ can enhance reliability and resource efficiency in various casting strategies such as broadcast, unicast, and groupcast. Unicast is highly reliable as messages are transmitted only to intended receivers, while groupcast reduces server load since groups share the same data. However, when unicast is used alone, resource efficiency decreases when many VUEs are interested in the same data, leading to an overload in resource allocation. On the other hand, compared to unicast, groupcast has the disadvantage of lower reliability due to difficulties in correcting packet loss and erroneous packets. Therefore, utilizing broad/uni/groupcast appropriately according to the situation is desirable for next-generation wireless communication. To maximize the advantages and minimize the disadvantages of the casting strategies, we propose a method of assigning casting strategies to each VUE by using a combination of broad/uni/groupcast based on groupcast priority scheduling. The groupcast-based resource allocation system prioritizes groupcast transmission and applies the selection method for grouping and each vehicle's casting strategy according to Algorithm 1.

Algorithm 1 Allocate Casting Strategies Based on Groupcast Priority

For each VUE $j \in$ V
Initialization
    Initialize parameters (i, SINR, Group leader, Group size, Groupcast VUE, Unicast VUE, time slot)
Step 1. Group leader selection and grouping for each VUE
    Randomly select a group leader in the scenario. $l \in$ V
    Users are grouped in consideration of distance and group size to belong to a group.
    Group of VUE with l as the group leader $j \in l_G$
    Maximum group size is predefined G ∈ [4], [6], [8]
        for each VUE $j \in$ V
            Measure the distance between Tx and Rx VUE. Maximum distance between for VUE $landl_G : d_G$
            Check $d_{l,j} < d_G$
            $j \in l_G, l_{\text{Groupsize}} = l_{\text{Groupsize}} + 1$
            False according to group size G
        end for
    VUE(Groupcast VUE) are classified based on Priority
Step 2. Apply IR-HARQ method to each communication method
    for t = 1 to 100 d**o** (**t** is time slot)
        If $SINR_{i,j} < SINR\_threshold_{i,j}$
            Send ACK
        else
            Send NACK
        end if
    end
    while NACK**do**
        Case 1: no. retransmission < 4 go back step 2
        Case 2: no. retransmission < 4 VUE ∈ Unicast VUE
    end while

The method proposed according to Algorithm 1 initially assigns resources to all vehicles in the simulation environment using the groupcast method. Afterwards, it applies broadcast and unicast methods considering the vehicle's location, the size of the group it belongs to, and the received SINR. In the proposed scenario, all VUEs are placed according to the vehicle distribution scenario introduced in Section III-A, and grouping is performed first for the vehicles on the high-density highway to form platoons. Grouping starts with setting a random group leader l for all VUEs, and it proceeds based on the group leader's location, the distance to surrounding vehicles, and the group size. Once the group leader is set, the maximum distance $d_{i,j}$ between the group leader VUE l and each VUE j is measured. If a vehicle has a shorter distance than the maximum distance d_G within the existing group, it is considered to be part of the same group. Each group is formed based on a predetermined group size of 4-8. Three assumptions are applied when forming a group. First, each group is composed of vehicles moving in the same direction at the same speed on the road. Second, a group is formed according to the proposed method and is maintained until packet transmission fails. Third, no new VUEs are added between groups while maintaining the group. Afterwards, for the vehicles that have not yet joined a group according to the proposed method, communication between vehicles is conducted using the traditional broadcast method.

Broadcast and groupcast communication for each VUE is conducted based on the SINR calculation formula previously introduced. Using this value, VUEs determine whether the packet reception was successful or not. The SINR value, $\text{SINR}_{i,j}$, between the transmitting and receiving VUEs is evaluated for packet transmission success or failure through the update of the SINR value measured according to the SB-SPS procedure. The SINR threshold used for the evaluation should not exceed a certain threshold that satisfies the PER 10^{-1} value of the previously measured LLS results. Packet retransmission is allowed up to three times according to the SLS methodology. If the packet is not successfully transmitted even after three retransmissions, the VUE is excluded from the group and packet transmission is conducted using unicast.

B. THROUGHPUT OPTIMIZATION

To maximize throughput, our primary objective is to optimize the packet transmission methods and the number of retransmissions resulting from the application of HARQ for each casting strategy. For each casting strategy, we calculate the received power and interferences from the Tx transmitting the packets, as described in Section IV-C, and the calculated SINR affects the link-layer throughput, delay, and packet outage probability. In this section, we consider the number of retransmissions caused by the application of HARQ and the corresponding packet reception probability to formalize and analyze the delay-limited throughput. The delay-limited throughput is maximized based on the HARQ retransmission limit that represents the outage probability and delay limit, conditioned on packet reception, and we calculate the throughput according to equation (16).

$$\text{Throughput} = \frac{k}{n} \times \frac{1 - p_e}{p_0 + \sum_{i=1}^{m-1} (p_i \sum_{j=0}^{i} \tau_j) + p_e \sum_{j=0}^{m-1} \tau_i} \tag{16}$$

Here, (n, k) denotes the channel code used by the transmitting VUE for encoding during IR-HARQ, and packet encoding is assumed to be performed using the channel code. The packet reception interval is set as τ_1 at the initial transmission, and τ_n denotes the packet reception interval at the n-th additional packet transmission if the receiving vehicle fails to decode the packet. Additionally, p_0 represents the probability of successful packet transmission in a single transmission, and p_e represents the probability of packet transmission failure.

We fix the channel code (n, k) based on the MCS level presented in Section III and conduct retransmissions using

IR-HARQ to increase the throughput value through improved PER performance. However, as the number of packet retransmissions exceeds the fixed resource limit, the throughput gain from IR-HARQ saturates and requires many packet retransmissions, resulting in increased delay overhead. Therefore, to maximize the throughput value while satisfying the target PER with IR-HARQ, we consider the queue delay time and minimize the resulting τ_n.

The proposed constraints enable the selection of the retransmission count when using IR-HARQ to maximize the target PER's throughput and reduce the queue delay through optimal packet reassignment for retransmission.

$$\max_{\tau_1} \eta$$
$$s.t. 0 < \boldsymbol{\tau} \leq 1, p_e \geq \delta \tag{17}$$

In equation (17), the given constraints to maximize throughput η impose limitations on the retransmission waiting time and that the PER should not exceed a certain threshold δ. This ensures reliability through the PER value and optimizes τ_1, the retransmission coefficient with high SNR for achieving high throughput. Moreover, in the proposed priority-based groupcasting method which broad /uni/groupcast mixed scenario, as the group size increases, PRR decreases and the throughput value decreases. This is mainly because the same packet retransmission delay increases as the required packet transmission amount between the first transmission and the retransmission increases. The proposed constraints increase the retransmission restrictions and throughput at the same PRR and PER by selecting the optimal τ value. The proposed throughput optimization method is applied to priority-based groupcast scheduling and evaluated through simulation. The selection of transmission technology and the throughput optimization process in this approach are depicted in Figure 4.

VI. PERFORMANCE EVALUATION

In this section, we will implement simulations to evaluate the mixed use of broad/uni/groupcast based on the proposed priority based groupcast scheduling and the delay-limit throughput optimization method. We will use the link and system-level environment described in Sections III and IV. The simulations will consider factors such as the number of retransmissions and packet reception probability.

A. EVALUATION OF CASTING STRATEGIES USING IR-HARQ

To emphasize the reliability enhancement performance of IR-HARQ, we present simulation results that show the PRR values based on the number of retransmissions in the broadcast casting strategy. Figure 5 illustrates the PRR values according to the number of retransmissions with IR-HARQ applied in the broadcast casting strategy. The PRR value is calculated from the SLS assuming that the received SINR value for each vehicle according to each of the previously presented casting methods is greater than or equal to the SINR threshold value that satisfies the Target PER $= 10^{-1}$ derived from the LLS results. Additionally, in the IR-HARQ approach, the same MCS and packet size were applied, and the RV value was increased with each retransmission, based on the initial transmission RV0 defined in the circular buffer, performing retransmissions at regular intervals. Based on these assumptions, the reception status of packets for all vehicles in the entire simulation is calculated, and the average PRR values are derived and presented in Figure 5. To compare the performance following the application of IR-HARQ, we determined the broadcast IR-HARQ performance according to each transmission count at a PRR value of 90%. For the case of broadcast without IR-HARQ, it satisfies the PRR value of 90% at a inter vehicle distance of 260m. However, when IR-HARQ is applied, and the maximum number of transmissions is limited to 2, 3, or 4 times (1, 2, or 3 retransmissions), the inter vehicle distances that satisfy a PRR value of 90% are 390m, 430m, and 460m, respectively. This shows a range gain of 130m, 170m, and 200m compared to the case without IR-HARQ. Through this, we verify that the packet reception rate with the increase in the number of retransmissions, and we confirm a significant increase in reception distance between packets through the application of IR-HARQ. Moreover, range gains increase as the maximum number of retransmissions increases. In particular, the reason for the increase in reception rate due to the IR-HARQ method is because each retransmitted packet contains different additional redundancy information than the previous packet, which increases the probability of correctly decoding the received information when combined with the previously received packet, and this was verified through the experimental results in Figure 5.

We also confirm the PRR values according to the application of IR-HARQ in the broad/uni/groupcast casting strategy using the same method. Figure 6 shows the PRR values according to the application of IR-HARQ in each casting strategy. In Figure 6, we presented the PRR values according to the number of retransmissions with IR-HARQ applied in the broadcast casting strategy. The solid line graphs in the figure represent the curves of each PRR for broad/uni/groupcast without applying IR-HARQ, while the dotted line graphs represent the PRR curves for IR-HARQ applied, satisfying a maximum of 4 transmissions (3 retransmissions). For unicast and groupcast, the inter vehicle distances satisfying PRR value of 90% are 510m and 340m, respectively. It can be confirmed that the inter vehicle distances satisfying the target PRR value are significantly increased compared to broadcast when using unicast and groupcast. Moreover, when applying IR-HARQ in the unicast/groupcast and increasing the number of retransmissions, it can be confirmed that the inter vehicle distances satisfying the PRR value are increased by about 210m and 180m to 720m and 520m, respectively, and the packet reception probability is significantly increased. These results demonstrate that unicast and groupcast methods can secure a much wider communication range compared to the traditional broadcast method. Moreover, when IR-HARQ is applied to each casting method, the unicast and groupcast methods show a greater

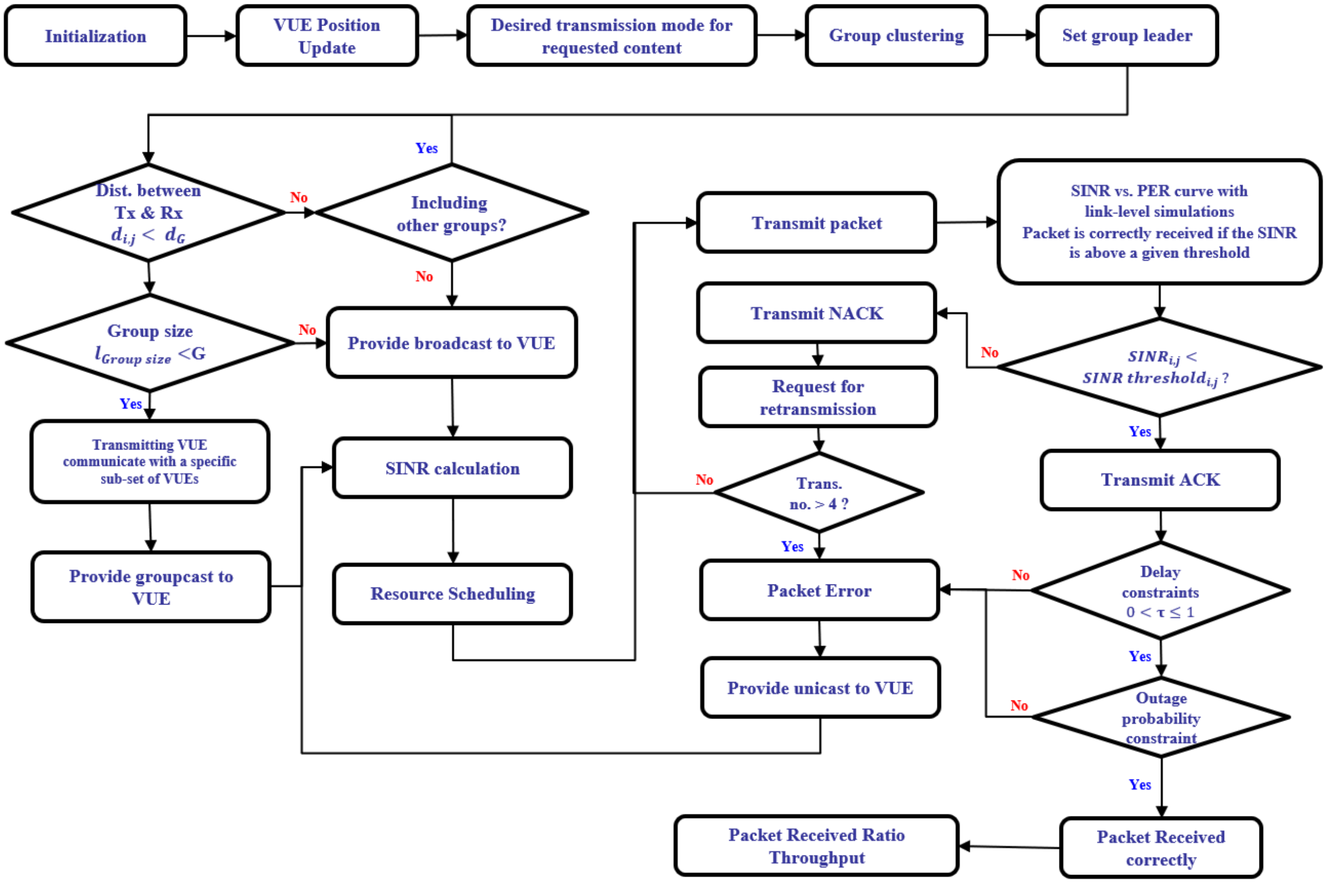

FIGURE 4. Procedure for broad/uni/groupcast selection and throughput optimization supported by 5G-NR V2V networks.

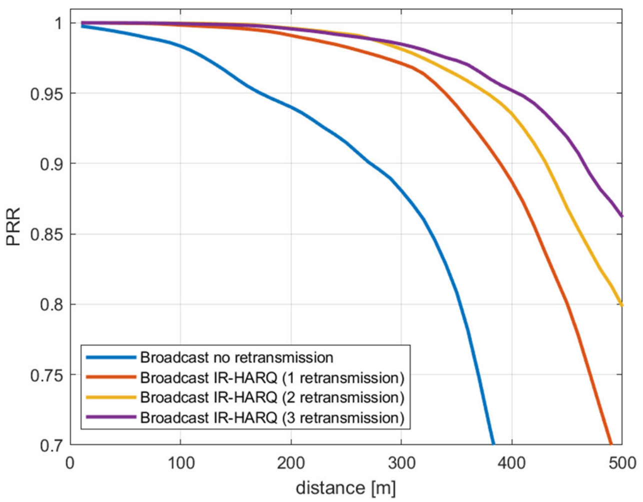

FIGURE 5. Impact of transmission attempts on PRR in a broadcasting with IR-HARQ.

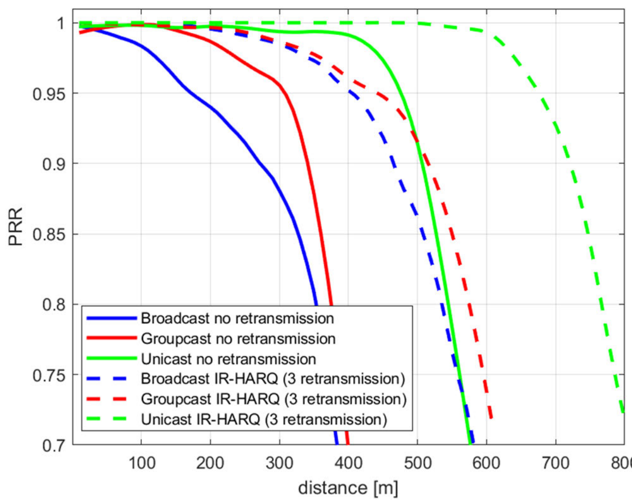

FIGURE 6. PRR for IR-HARQ applied to uni/groupcasting strategies.

increase in the distance that satisfies 90% PRR, which verifies the efficiency of implementing the IR-HARQ method. Consequently, the IR-HARQ method proves to significantly enhance reliability in the proposed scenarios.

B. EVALUATION OF PRIORITY-BASED GROUPCASTING

In the simulation, all VUEs use the broad/uni/groupcast casting strategies to transmit and receive packets and share the same RP. To maximize the reliability of V2V communication, the IR-HARQ method is applied to all casting strategies.

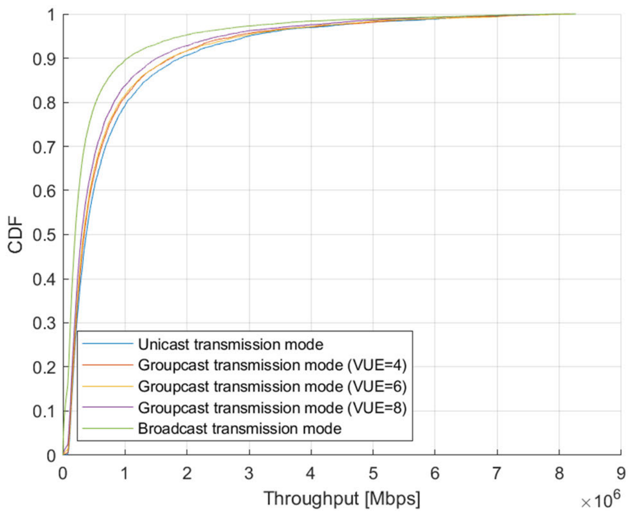

FIGURE 7. Throughput based on group size with IR-HARQ applied to broad/uni/groupcasting strategies.

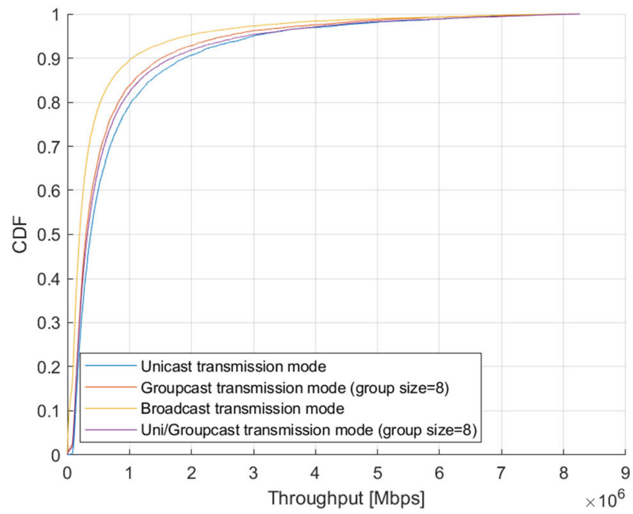

FIGURE 8. Throughput using priority-based groupcasting strategies.

The goal is to maximize the throughput value processed in the limited RP while leveraging the advantages of each casting strategy mentioned in the previous sections. First, we analyze the throughput values for each communication method. Figure 7 illustrates the throughput values when using the broadcast, unicast, and groupcast casting strategies for group sizes of 4, 6, and 8 in the simulation. We evaluate the performance at the 90% interval of the throughput cumulative distribution function (CDF) values for comparison. According to the graph, the broadcast has a value of 1.05 [Mbps], and the groupcast has values of 1.75 [Mbps], 1.74 [Mbps], and 1.52 [Mbps] for group sizes of 4, 6, and 8, respectively, when used as a single method. In addition, the unicast has the highest throughput value of 1.88 [Mbps]. The graph shows that the throughput value tends to decrease as the group size increases in the groupcast method. When the group size is 8, the groupcast has about a 45% performance improvement from 1.05 [Mbps] to 1.52 [Mbps] compared to the broadcast. Furthermore, the unicast increases the throughput value by 0.83 [Mbps] and 0.36 [Mbps] compared to the broadcast and groupcast methods, respectively, indicating a significant performance improvement of 79% and 23% for unicast in terms of data transmission compared to other casting strategies.

Based on these results, we propose a scenario where a mixture of broad/uni/groupcast casting strategies is used, with groupcast prioritized based on the proposed scheduling approach. Figure 8 compares the throughput values achieved when this proposed approach is applied under groupcast conditions with a group size of 8 to those achieved when single casting strategies of broad/uni/groupcast are used. The proposed approach achieves a throughput value of 1.71 [Mbps], which is lower than the throughput value achieved when using unicast only, but represents a 13% improvement over the single groupcast casting strategy, increasing from 1.52 [Mbps] to 1.71 [Mbps]. Simulation results demonstrate that using

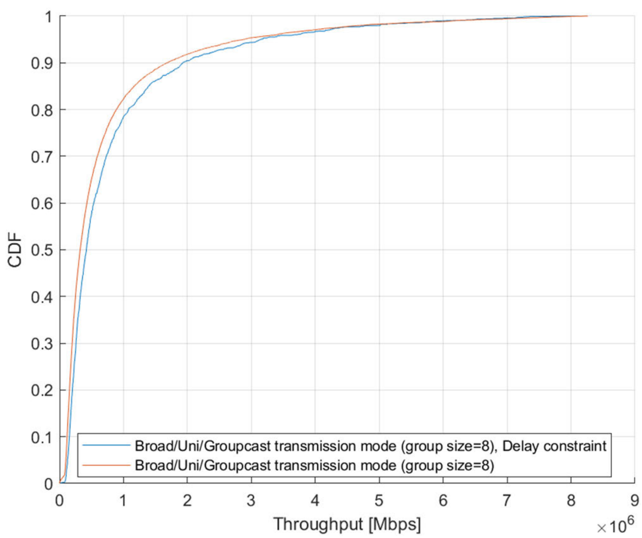

FIGURE 9. Maximizing throughput using delay constraints.

unicast results in the highest PRR and throughput performance. However, if the data exchange is conducted only via unicast, network overload can occur depending on vehicle density. Therefore, we propose and verify a mixed casting strategy, utilizing broad/uni/groupcast with a priority on groupcast, in order to maximize throughput.

Finally, we propose a method for optimizing throughput in highway environment using a mixed method of broad/uni/groupcast, along with IR-HARQ and delay-limited conditions. Figure 9 presents the resulting throughput values when using IR-HARQ to maximize VUE's PER throughput processing based on the optimal retransmission length, minimizing queue delay time, and maintaining PER values at the desired level to maximize throughput. Through simulation, we show that this proposed method achieves a 22% improvement in performance, increasing throughput from 1.71 [Mbps] to 2.08 [Mbps], which represents a

0.37 [Mbps] increase. In summary, we evaluate the performance of three casting strategies, broad/uni/groupcast, when using IR-HARQ, and verify that our proposed priority based groupcast scheduling approach for a mixed methods of broad/unicast/groupcast and the delay-limited condition.

VII. CONCLUSION

This paper proposes a method to enhance the reliability and throughput by combining IR-HARQ with various casting strategies in 5G NR V2X mode 2 environments. The proposed method utilizes the priority-based groupcasting strategy that selects the casting method based on VUE information and available resources. In addition, we maximize throughput by adjusting the amount of retransmitted data through constraints on delay and outage probability. To validate the method, we implement and simulate LLS and SLS based on 3GPP technical document of V2X methodology. Simulation results indicate that applying IR-HARQ to each casting strategy increases the maximum distance that satisfies the target PRR. Additionally, the priority-based groupcasting method improves the throughput by 13%, from 1.52 [Mbps] to 1.71 Mbps, while maintaining the maximum distance that satisfies the target PRR. Furthermore, maximizing throughput by constraining delay and outage probability increases it up to 2.08 [Mbps], which is a 98% improvement compared to conventional broadcasting. These results confirm that the proposed methods significantly improve the reliability of V2V links.

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