Beyond Vision: Hidden Car Detector With On-Demand Relaying in Vehicular Communications

Sunwook Hwang, Seongwon Kim, *Member, IEEE*, Hoyoung Yoon, Byungjun Kim, Sunghyun Choi, *Fellow, IEEE*, and Saewoong Bahk, *Senior Member, IEEE*

***Abstract*—Cellular Vehicle-to-Vehicle (C-V2V) communications take autonomous driving technology to the next level by allowing a Vehicular User Equipment (V-UE) to receive Cooperative Awareness Messages (CAMs) from other V-UEs, and enable the V-UE to see beyond what is detectable by vision-based sensors, thereby preventing accidents and ensuring user safety. However, there remains a fundamental limitation in the conventional CAM broadcasting since a transmitter (TX) V-UE cannot confirm whether its CAM is successfully received at other V-UEs. Without a feedback process, a significant uncertainty arises in CAM reception, posing a critical threat to user safety. To address this threat, we propose Beyond-Vision, an effective C-V2V on-demand relay system that allows CAMs that are not well received at nearby V-UEs to be better received. Through simulation that reflects realistic vehicle mobility and road environments in urban scenarios, we verify the superiority of Beyond-Vision over the conventional C-V2V, which improves performance by up to 215% in terms of message reception ratio (MRR) within a communication range under Non-Line-Of-Sight (NLOS) channels.**

***Index Terms*—C-V2V, cooperative awareness message (CAM), relaying, vehicular communications.**

I. Introduction

AUTONOMOUS driving technology has evolved over time from lab-based "future technology" to "real-world technology" visible on the roads. However, commercialization of the technology requires autonomous vehicles to understand their surroundings to prevent accidents and ensure user safety. Peripheral object recognition is well known as one of the essential functions required for safety in autonomous driving. Until now, autonomous vehicles have mainly relied on sensors such as Light Detection And Ranging (LiDAR), radar, and cameras to detect objects on the roads [1]. However, vehicles face a serious challenge if they solely rely on these vision-based sensors because peripheral sensing is not possible in a Non-Line-Of-Sight (NLOS) environment and external factors such as weather may degrade sensing accuracy.

In an effort to overcome these limitations, studies have been conducted on vehicular communications that can be effective even in NLOS situations and are less vulnerable to external factors. In addition, Cellular Vehicle-to-Vehicle (C-V2V) communications have been standardized based on Long Term Evolution (LTE) [2], [3] since Release 14 of 3GPP organization. Also, interest in C-V2V has grown recently as it is one of the core services in 5 G concerning the safety of autonomous vehicles.

In C-V2V communications, a Vehicular User Equipment (V-UE) periodically broadcasts Cooperative Awareness Messages (CAMs) including its status information for nearby V-UEs.[1] Upon receiving CAMs, V-UEs can detect the existence of other V-UEs transmitting CAMs. The reception of CAMs helps a V-UE to detect other V-UEs beyond the detectable range of vision-based sensors or those invisible due to NLOS positions. In addition, the V-UE can use received CAM information for various driving assistance applications such as collision avoidance, accident warning, and intelligent navigation [4].

However, the conventional CAM broadcasting has a fundamental problem because it has no feedback process to confirm whether a CAM is received or not. In other words, there is no way for a transmitter (TX) V-UE to know whether receiver (RX) V-UEs have received a CAM since the CAM does not contain any feedback information and no feedback message is defined in C-V2V. In particular, in a NLOS situation where vision-based sensors are unable to detect an object, the uncertainty of CAM reception becomes a fatal threat to users.

In this paper, we propose an effective C-V2V on-demand relay system, termed `Beyond-Vision`, that enables V-UEs to identify which nearby V-UEs fail to receive which CAMs. To achieve this goal, we focus on the specific information that a CAM should contain. According to the ETSI standard [5], a

[1]The CAM contains the V-UE's status information including CAM generation time, V-UE's location obtained from GPS, V-UE's speed, and V-UE's ID, etc.

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Sunwook Hwang, Hoyoung Yoon, and Saewoong Bahk are with the Department of ECE and INMC, Seoul National University, Seoul 08826, Korea (e-mail: swhwang@netlab.snu.ac.kr; hyyoon@mwnl.snu.ac.kr; sbahk@snu.ac.kr).

Seongwon Kim is with the Vision AI Labs, SK Telecom, Seoul 04539, Korea (e-mail: s1kim@sktair.com).

Byungjun Kim is with the Department of Electrical and Computer Engineering, University of California, San Diego, CA 92092 USA (e-mail: byk004@ucsd.edu).

Sunghyun Choi is with the Samsung Research, Seoul 06765, Korea (e-mail: sunghyunc.research@gmail.com).

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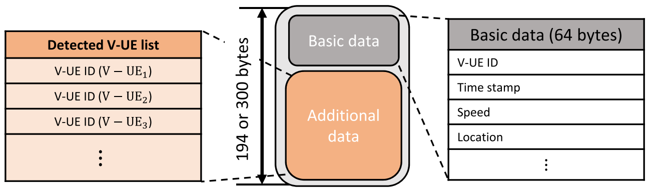


Fig. 1. Proposed CAM configuration.

CAM contains the TX V-UE's status information which occupies approximately 64 bytes of data. However, given the fact that the size of data used for actual CAM transmission is 194 or 300 bytes [4], the size of basic data, including the TX V-UE's status information, is even smaller. As shown in Fig. 1, the novel CAM configuration we propose contains additional information of nearby V-UEs detected during the CAM generation period.

Then the V-UE exploits received information of detected V-UE lists to identify which V-UEs have received which CAMs and which V-UEs are hidden to which V-UEs. This novel relay system effectively contributes to finding hidden V-UEs without any subsidiary feedback process, and relaying CAMs of hidden V-UEs, which helps to improve Message Reception Ratio (MRR) in C-V2V communications.

The merits of `Beyond-Vision` and the contributions of this paper are as follows:

- We propose a novel C-V2V relay system that improves MRR with no overhead by utilizing previously unused bytes in the conventional CAM.
- We evaluate `Beyond-Vision` performance via simulation which reflects realistic vehicle mobility and road situations based on Simulation of Urban MObility (SUMO) [6].
- We verify the superiority of `Beyond-Vision` with the latest C-V2V protocol defined in 3GPP and other relay systems.

The rest of this paper is organized as follows. We first present the related work and motivation of the work in Section II. Section III introduces the basic operation of the conventional C-V2V protocol. Then, we present our proposed relaying scheme, `Beyond-Vision`, in Section IV, and evaluate `Beyond-Vision` through system-level simulation under various scenarios in Section V. Finally, we conclude the paper in Section VI.

II. Related Work

In this section, we summarize previously studied relaying schemes in V2V communications and present the motivation of our proposed scheme.

A. Relaying Schemes for V2V

Previous relaying studies on V2V communications have been performed primarily under the IEEE 802.11p-based system called Dedicated Short Range Communications (DSRC) [7], [8].

The farthest-first dissemination is the most commonly used strategy to disseminate safety data in V2V communications. This strategy allows the vehicle farthest from the sender to be selected as a relay node for disseminating safety data. For example, Street Broadcast Reduction (SBR) scheme, proposed by Martinez *et al.* [9], utilizes the farthest-first dissemination scheme to reduce the warning message notification time in urban setting scenarios with multiple intersections and obstacles. Urban Multihop Broadcast (UMB) scheme, proposed by Korkmaz *et al.* [10], maximizes its one-hop dissemination performance by selecting a vehicle in the road segment farthest from the sender. Li *et al.* [11] came up with OppCast, a safety data dissemination scheme with enhanced scalability. OppCast operates in two phases. First, farthest-first dissemination takes place to disseminate data as far as possible. Second, make-up dissemination completes the process while ensuring high reliability.

Another method is probability-based broadcasting. In this method, stochastic relaying limits the number of relaying events [12], [13], thereby preventing redundant re-transmissions in V2V communications. Specifically, vehicles are prioritized by their assigned relaying probabilities. Slotted p-Persistence Broadcasting proposed in [12], assigns a relay probability to each relaying according to its distance from the original TX; The farther the vehicle is from the original TX, the larger relaying probability it is assigned. Considering the density level of nearby vehicles, AutoCast proposed in [13] determines the relaying probability.

There are more studies that propose different relaying schemes. For example, Packet-value-based dissemination scheme (PVCast) [14] presents a novel way to determine relay priority considering both spatial and temporal preferences of each received CAM. In [15], the authors propose a cooperative transmission scheme employing a signal superposition technique. Under this scheme V-UEs superpose other V-UEs signals that they have received onto their own transmission signals. In [16], the authors propose Reliable Broadcasting of Life Safety Messages (RBLSM) where vehicles nearer to the sender suffer shorter wait time and packets delivered to nearby vehicles experience smaller latency. In [17], the authors compare DSRC and C-V2V communication performance in several aspects. Furthermore, in [18], the authors propose a relay system focusing on hybrid V-UEs, i.e., V-UEs equipped with both DSRC and C-V2V modules. In [19], the authors propose a relaying scheme with Road Side Units (RSUs) in vehicular communications. Unlike the studies on the above relaying protocols, J. Heo *et al.* explore the utility and trade-off of using buses as mobile RSUs through mathematical analysis, simulation, and real-world experiments [20]. Also, B. Kang *et al.* study the traffic steering scheme to extend the operation of D2D communications to both licensed and unlicensed bands as well as propose a transmission power adaptation algorithm for C-V2X Mode 4 [21], [22].

B. Motivation of Proposed Beyond-Vision

The previous studies on the relaying scheme described above are as follows. To determine CAM selection priority for relaying, these relaying methods take into account: 1) The distance between TX V-UEs and RX V-UEs, 2) the number of V-UEs that can receive CAMs, and 3) temporal and spatial preferences of each CAM. However, these methods are limited in improving MRR performance because they do not take a sophisticated

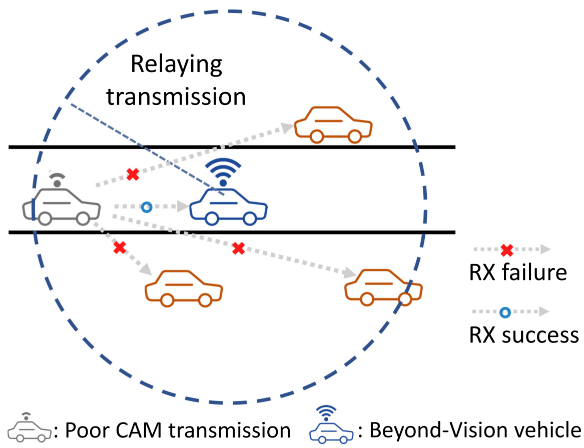


Fig. 2. Motivation: Finding and relaying CAMs that are not well received at nearby V-UEs.

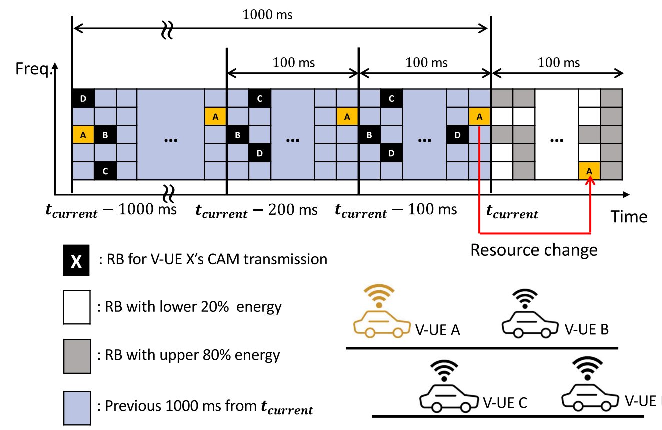


Fig. 3. C-V2V resource allocation.

approach to examine how successfully nearby vehicles receive CAMs when selecting a CAM for relaying.

Our proposed Beyond-Vision ensures effective CAM relaying by addressing the limitation. Specifically, Beyond-Vision finds 'hidden V-UEs' that are not detected because CAMs transmitted by those V-UEs cannot be received within the communication range. As shown in Fig. 2, Beyond-Vision enables V-UEs to selectively choose and relay hidden V-UEs' CAMs. Beyond-Vision enables this process simply by adding some information to each CAM, without additional transmission for confirming the reception of CAMs.

III. PRELIMINARIES

A. C-V2V

In this section, we describe C-V2V communications defined in the 3GPP standard Release 14 [2], [3], for which our proposed scheme applies. In C-V2V communications, each V-UE exchanges accurate information such as its ID, location, velocity, and acceleration [5], [23], which contributes to improving traffic safety.

C-V2V was originated from LTE sidelink, called LTE Device-to-Device (LTE-D2D) communications which 3GPP first introduced in Release 12 for public safety. As LTE-D2D was designed to lower battery consumption rather than latency, it is not suitable for C-V2V which requires low latency and high reliability [24], [25]. A significant difference between C-V2V and LTE-D2D is in how to allocate dedicated resources. While LTE-D2D systems rely on specific LTE uplink resources, C-V2V systems utilize separate resources.

C-V2V communications using a single-carrier frequency division multiple access support one or two channels of 10 MHz in the 5.9 GHz spectrum which many countries already dedicate to vehicular communications [26]. The minimum resource unit that C-V2V utilizes in the 5.9 GHz spectrum is Resource Block (RB).[2] It has a frequency width of 180 kHz (12 subcarriers of 15 kHz) and consists of one subframe (= 1 ms). In the 10 MHz channel, there are 50 RBs available on the frequency axis for C-V2V communications. Also, C-V2V defines subchannel as a group of multiple RBs. Multiple V-UEs can transmit simultaneously by using subchannels in the same subframe.

C-V2V selects a subchannel, which is a resource for transmission in two ways: Sidelink Modes 3 and 4 [3]. Under sidelink Mode 3, Evolved Node B (eNodeB) allocates resources for V-UEs in a centralized manner. Under sidelink Mode 4, in contrast, V-UEs select resources independently. This means that a V-UE under Mode 4 allocates resources regardless of the cellular coverage of the eNodeB. In this paper, we assume that the Beyond-Vision operating environment is controlled in a distributed manner, i.e., sidelink Mode 4.

When selecting a resource for transmission in Mode 4, a V-UE uses the sensing-based Semi-Persistent Scheduling (SPS) scheme, which is defined in 3GPP Release 14. As shown in Fig. 3, the V-UE in Mode 4 analyzes energy levels detected during the previous 1000 ms. Based on average sensed Received Signal Strength Indicator (RSSI) analysis, the V-UE extracts a pool of candidate resources from the current time to 100 ms later and selects new resources. In doing so, the V-UE randomly chooses one of the subchannels as a resource with the lowest 20% energy level to avoid possible collisions with adjacent V-UEs that select the same subchannel [3]. With a period of 100 ms, the V-UE repeatedly occupies the resource as many times as a randomly selected counter between 5 and 15. When the counter expires, the V-UE selects a new resource and counter with the same procedure.

B. Challenge of Relaying Protocols in C-V2V

The operation of relaying protocols in C-V2V should consider the following characteristics of CAMs. First, conventional CAM broadcasting has no feedback process to confirm whether a CAM is received. For this reason, relay transmission may cause unnecessary transmissions by repeatedly relaying already received CAMs. To reduce unnecessary transmissions, the relaying V-UE should find a proper CAM that needs to be relayed under this constraint. Second, a V-UE generates a CAM periodically, and updates its CAM information every 100 ms of the typical option

[2]Since C-V2V is defined based on LTE, users in LTE system utilize RBs for the minimum resource unit as well.

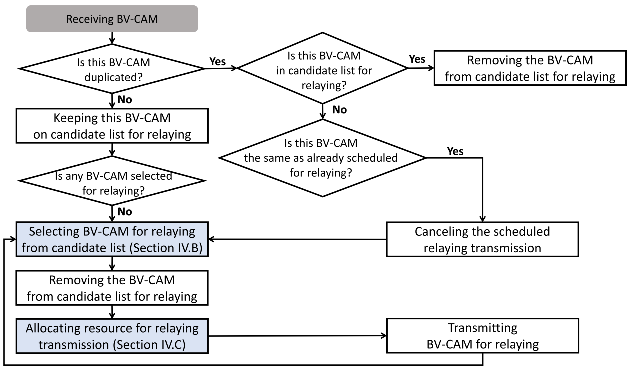


Fig. 4. Overall `Beyond-Vision` operation.

in C-V2V [3]. If the CAM information becomes invalid 100 ms after its generation, the CAM is no longer eligible for relaying. Thus, the V-UE should seek to relay valid CAMs before new ones are created. Third, there is a communication range for CAM transmission, defined differently according to the average speed of the V-UE in the road environment. Specifically, the communication range is defined as 150 m for urban environments [27]. For effective transmission, relaying protocols should be designed to ensure a high reception rate of CAMs within the communication range.

IV. Beyond-Vision: Proposed C-V2V Relay System

A. Overview

We propose `Beyond-Vision` to overcome the defects of the CAM relaying schemes previously studied. As described, the primary goal of `Beyond-Vision`, which uses a newly proposed CAM configuration, is to select CAMs that are not successfully transmitted to V-UEs within the communication range and to relay them efficiently.[3] `Beyond-Vision` achieves this goal with the following two features:

- CAM selection algorithm that utilizes novel CAM configuration for relaying
- Standard-compliant relaying that minimizes redundant re-transmissions

Before explaining the details, we present the overall operation of `Beyond-Vision` described in Fig. 4. We define a novel CAM used for the `Beyond-Vision` as BV-CAM in this paper. A V-UE periodically broadcasts a BV-CAM. Upon receiving a BV-CAM, a V-UE checks whether it is an original BV-CAM or a relayed duplicate BV-CAM.

If the BV-CAM is original, the V-UE forwards the BV-CAM information to the V-UEs in the candidate list for relaying and keeps this information until the BV-CAM becomes invalid. In other words, the candidate list only has information of the received original BV-CAM within 100 ms of its creation. If there is no BV-CAM selected for relaying, then the V-UE selects one from the candidate list for relaying according to the selection algorithm, which will be specified in Section IV-B. After the selection, the V-UE removes the BV-CAM from the candidate list, duplicates the BV-CAM, and marks the duplicate on the BV-CAM using one flag bit. Finally, the V-UE allocates resources for relaying transmission. Once a duplicate BV-CAM is transmitted, BV-CAM selection algorithm is invoked to select a new BV-CAM for next relaying.

If the BV-CAM is a duplicate, on the other hand, the V-UE does not need to relay the BV-CAM. Such duplicate BV-CAMs are removed from the candidate list for relaying and excluded in the selection for BV-CAM relaying. When a BV-CAM equal to the received duplicate has been already scheduled for relaying, the V-UE cancels the scheduled BV-CAM relaying to prevent redundant re-transmissions and selects a new BV-CAM for relaying.

B. BV-CAM Selection for Relaying in Beyond-Vision

As we mentioned, the conventional CAM carries only the information of the TX V-UE itself and CAM generation time.

In this paper, we define a novel CAM configuration for `Beyond-Vision`. A conventional CAM carries 194 or 300 bytes of data that contains vehicle information, consisting of 64 bytes of basic information. In `Beyond-Vision`, a V-UE utilizes the vacant space in the conventional CAM to contain Detected V-UE List (DVL), a newly defined list of detected V-UE IDs within the TX V-UE's communication range.

As described in Fig. 5(a), BV-CAM of V_x contains DVL as well as its basic information. In the DVL, V_x includes the detected V-UE IDs: V_a, V_b, V_c, except for V_d which is detected but exists out of the communication range of V_x.[4] In the process of DVL creation, a V-UE uses only valid BV-CAMs since they present the current state of their TX V-UEs. By doing so, the V-UE not only sends its own status information via BV-CAM, but also notifies the successful reception of valid BV-CAMs transmitted by V-UEs within its communication range.

Each V-UE uses received valid BV-CAMs and their DVLs as the basis of its BV-CAM selection for relaying. The selection process consists of the following components.

1) Development of Observation Table: A V-UE creates its own Observation Table (OT) with the received valid BV-CAMs. The OT shows the relationship between V-UEs that are detected through valid BV-CAMs. As shown in Fig. 5(b), assume that there are four valid BV-CAMs received at V_x, and each V-UE's ID is V_a, V_b, V_c, and V_d, respectively. Since each valid BV-CAM contains location information about its TX V-UE, V_x calculates the distance between each V-UE. If the distance between two V-UEs, say $d(V_a, V_b)$, is shorter than the communication range (D_{range}), the relationship between the two is denoted as '1' on the OT. If the distance between the two is longer than D_{range}, on the other hand, their relation is denoted as '0'.

[3]We interchangeably use the terms 'the communication range of a CAM' and 'the communication range of a V-UE' to represent the communication range of a V-UE at the moment of the CAM generation.

[4]According to the ETSI standard [5] the data size of a V-UE ID is 4 bytes. A 300-byte CAM contains approximately 60 V-UE IDs. If a V-UE utilizes data compression techniques such as hash, its CAM can contain more V-UE IDs.

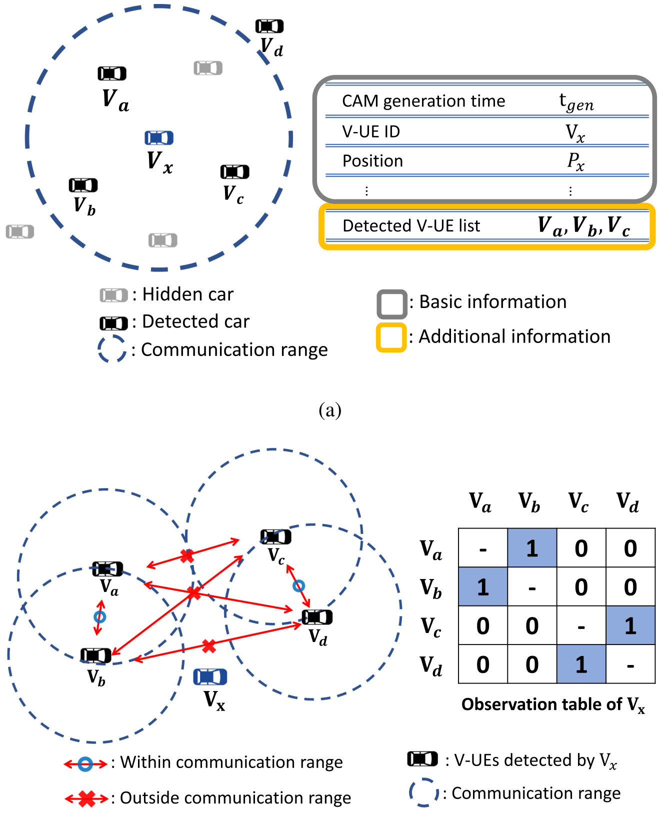


Fig. 5. Proposed configuration: (a) BV-CAM configuration and (b) observation table.

In short, with the information of detected V-UEs, we create the OT by using

$$OT(V_a, V_b) = \begin{cases} 1, & d(V_a, V_b) \leq D_{\text{range}}, \\ 0, & d(V_a, V_b) > D_{\text{range}}. \end{cases} \quad (1)$$

2) Calculation of Estimated Message Reception Rate: Estimated Message Reception Rate (eMRR) is a metric that indicates the ratio of the number of V-UEs that received a specific BV-CAM to the number of all V-UEs within the BV-CAM's communication range. V-UEs calculate eMRR for each received valid BV-CAM, which is calculated using two components: Failure Counter (FC) and Success Counter (SC).

Failure Counter is defined as the number of V-UEs not receiving a BV-CAM within the communication range of the BV-CAM. A V-UE calculates the FC for each received valid BV-CAM using its OT and the BV-CAMs' DVLs. For example, Fig. 6 shows that V_x recognizes which V-UEs are within V_a's communication range from an observer's perspective based on its OT. We define the list of such V-UEs as Target V-UE List (TVL) of V_a, denoted by TVL_a. At the same time, when receiving a BV-CAM from V_a, V_x becomes aware of V_a's DVL (DVL_a). By comparing TVL_a in the OT with DVL_a, V_x identifies a list of V-UE(s) that V_a did not detect, which is the Hidden V-UE List (HVL) of V_a, denoted by HVL_a. In this case, according to V_x's OT, TVL_a contains V_b, but DVL_a does not contain V_b. This means that even though V_a is within V_b's communication range, it failed to receive a valid BV-CAM of V_b. Thus, V_b's FC, denoted as FC_b, is increased by 1. By comparing the OT and DVL of the received valid BV-CAMs' TX, V_x yields its FC for all TXs of the received valid BV-CAMs.

Algorithm 1: Calculation of eMRR in `Beyond-Vision`.

Require: Observation of BV-CAM information
V_i, V_j, V_k: Presenting V-UE's ID
l_{ID}: The V-UE's ID list of valid BV-CAMs
Initialize :
Initializing Failure Counter (FC) and Success Counter (SC) for all ID to 0
CountingFCandSC
for V_i **in** l_{ID} **do**
  Create TVL_i based on OT
  Extrcat DVL_i from BV-CAM of V_i
  $HVL_i \leftarrow TVL_i \cap DVL_i^C$
  for V_j **in** HVL_i **do**
    $FC_j \leftarrow FC_j + 1$
  end for
  for V_k **in** DVL_i **do**
    $SC_k \leftarrow SC_k + 1$
  end for
end for
CalculatingeMRR
for V_i **in** l_{ID} **do**
  $eMRR_i \leftarrow \frac{SC_i}{FC_i + SC_i}$
end for

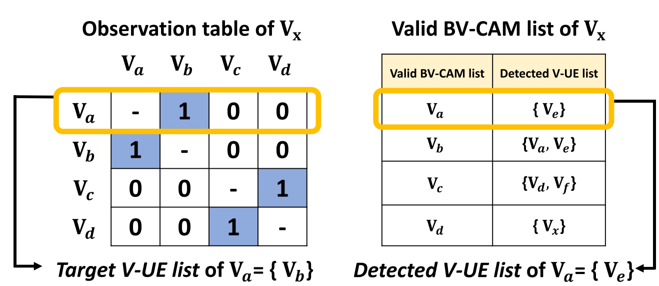


Fig. 6. `Beyond-Vision`: BV-CAM selection for relaying.

Success Counter is defined as the number of V-UEs receiving a BV-CAM within the communication range of the BV-CAM.

When a V-UE generates its own BV-CAM, it records the V-UEs' IDs in its DVL that are contained in the received valid BV-CAMs in its communication range. Therefore, we obtain the SC of a V-UE by counting the number of valid BV-CAMs containing a DVL that records the V-UE's ID.

According to the values of FC_i and SC_i, where i is the BV-CAM's ID of V_i, we calculate the eMRR as

$$eMRR_i = \frac{SC_i}{FC_i + SC_i}. \quad (2)$$

To select a BV-CAM for relaying in `Beyond-Vision`, a V-UE needs to find out the eMRR of each received valid BV-CAM and identify which BV-CAM has a low eMRR.

Algorithm 1 shows the pseudo code to calculate eMRR from OT and DVL.

3) Weighted Random Selection: A V-UE selects a BV-CAM for relaying in `Beyond-Vision` based on the eMRR of each received valid BV-CAM. However, to prevent the same BV-CAM from being selected by multiple adjacent V-UEs at the same time, the V-UE does not simply select the BV-CAM with the lowest eMRR. Instead, the V-UE selects a BV-CAM according to the selection probability using its eMRR as a weight parameter. The probability of selecting a BV-CAM is calculated as

$$P_i = \frac{1 - eMRR_i}{\sum_{i' \in c_{\text{id}}} (1 - eMRR_{i'})} \tag{3}$$

where P_i is the probability of selecting V_i's BV-CAM for `Beyond-Vision` relaying and c_{id} is the set of V-UE IDs in the candidate list for relaying.

C. Resource Selection for Beyond-Vision Relaying

When a V-UE selects a BV-CAM for `Beyond-Vision` relaying, it selects RBs to send the selected BV-CAM. To comply with the standard C-V2V defined in 3GPP, RBs for `Beyond-Vision` relaying are allocated according to the sense-based SPS operation. The V-UE analyzes energy levels for the duration of 1000 ms before the BV-CAM is selected for relaying. Through the process, the V-UE extracts candidate RBs from resources with the lowest 20% received energy levels. However, for the relayed BV-CAM to be valid, it must be sent before it expires with the generation of a new BV-CAM. Therefore, the V-UE randomly chooses RBs within the BV-CAM's generation time plus 100 ms ($t_{\text{gen}} + 100$ ms) for BV-CAM relaying within a valid period.

We design `Beyond-Vision` to take this aspect into account as it is necessary to inhibit redundant re-transmission of BV-CAMs through relay operation. When transmitting in `Beyond-Vision`, a V-UE duplicates the BV-CAM selected for relay and records its flag bit to indicate that the BV-CAM is duplicated. Through this flag bit, the other V-UEs receiving the BV-CAM can find out whether it is the original or a duplicate. To prevent unnecessary re-transmissions, a V-UE removes a duplicate BV-CAM from the candidate list where the BV-CAM is chosen for relaying transmission. Furthermore, if the V-UE has already scheduled the BV-CAM for relaying transmission before receiving its duplicate, it cancels its transmission schedule and selects a new BV-CAM for relaying again.

V. Performance Evaluation

In this section, we evaluate the performance of `Beyond-Vision` with the comparison schemes, through the simulation that reflects realistic vehicle mobility and the road environment in urban scenarios.

A. Simulation Environments

Table II shows the parameters for simulation environments.

TABLE I
ACRONYMS AND TERMS

V_x	ID of V-UE
DVL_x	Detected V-UE List of V_x
TVL_x	Target V-UE List of V_x
HVL_x	Hidden V-UE List of V_x
FC_x	Failure Counter of V_x
SC_x	Success Counter of V_x

TABLE II
SIMULATION ENVIRONMENTS

Carrier frequency	5.9 GHz
System bandwidth	10 MHz (50 RBs)
Topology	Manhattan grid [27] and Berlin
Target communication range	150 m
No. of total V-UEs	500, 200 (Manhattan, Berlin)
Vehicle mobility model	SUMO [6]
Link performance model	LTE error model [28]
Channel model	Fast fading + shadowing + pathloss + in-band emission [27] + out-of-band emission [29]
Modulation	QPSK
Code rate	0.529
TX power of V-UE	23 dBm
Noise figure	9 dB
Noise power	-174 dBm/Hz
CAM size	300 bytes
CAM generation period	100 ms
Simulation time	50,000 subframes (50 s)

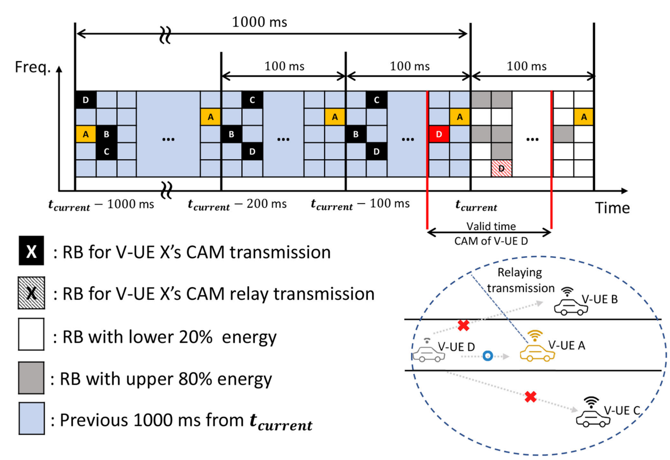
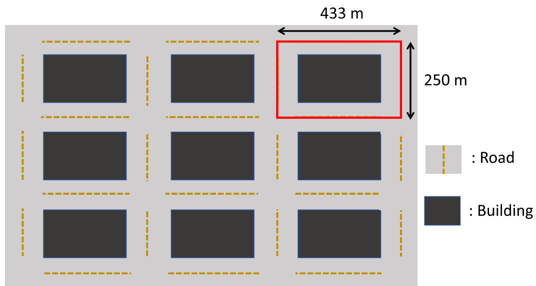
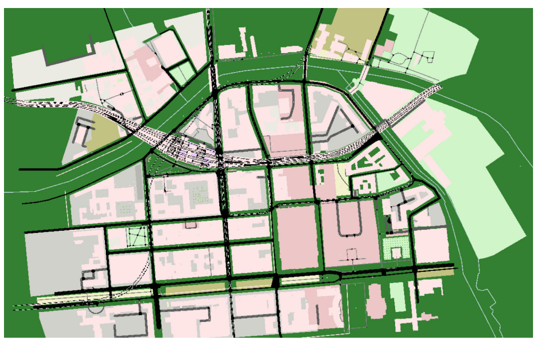


Fig. 7. Relaying resource allocation in `Beyond-Vision`.

Topology and vehicle mobility model: As shown in Fig. 8, we consider Manhattan grid and Berlin topologies for simulation in this paper. Manhattan grid topology, which is typically used for urban scenarios [27], includes a total of nine 433 m $\times$ 250 m-sized grids. We adopt Berlin topology to reflect the actual mobility of vehicles. SUMO provides OpenStreetMap (OSM) [30], which applies realistic map information to our simulator. Manhattan grid and Berlin topologies have traffic lights installed at each intersection, and use SUMO-generated mobility models [6]. SUMO helps to create real road environments, including vehicles' movement considering traffic lights linked to the actual map information provided by OSM. The number of V-UEs determined as the medium traffic case in [27] is 500 in the Manhattan grid scenario while it is 200 in the Berlin scenario to achieve the equal density level of V-UEs.



(a)



(b)

Fig. 8. Simulation topology: (a) Manhattan grid and (b) Berlin.

Channel model: The simulator adopts WINNER+ B1 model as the pathloss model [31] and the shadowing model in [27], which follows a log-normal distribution with 3 dB and 4 dB standard deviations for LOS and NLOS, respectively. ITU-R IMT UMi model in [32] is used for fast fading. For in-band emission, undesired emission to subchannels under the same channel and time slot, we adopt the model in [33].

Link performance model: We choose a proven error model of LTE data transmission from [28], which is also used by an established open-source simulator in the network and communications field, ns-3 [34]. The conversion of Signal-to-Interference-plus-Noise Ratio (SINR) based on the channel model to Transmission BLock Error Rate (TBLER) enables the simulator to determine whether the message reception is successful.

Configuration CAM resources in C-V2V: In DSRC, Quadrature Phase-Shift Keying (QPSK) and code rate of 0.5 are the optimal option [35] for CAM transmission. Since we use QPSK and code rate of 0.529 (i.e., closest to the optimal rate in the LTE environment), one RB can contain 177 bits. Therefore, to transmit a CAM size of 300 bytes, 15 RB pairs form one subchannel. Assuming that there are 50 RBs in the 10 MHz bandwidth, $3(= \lfloor 50/15 \rfloor)$ subchannels are available.

B. Comparison Schemes

This paper adopts various comparison schemes to prove the excellence of `Beyond-Vision`. They are 802.11p-based DSRC protocols which are modified to operate in the C-V2V standard for fair comparison. The comparison schemes

First, Farthest-First Relaying (FAR) is the most representative relaying scheme, studied in several papers [9]–[11]. It allocates

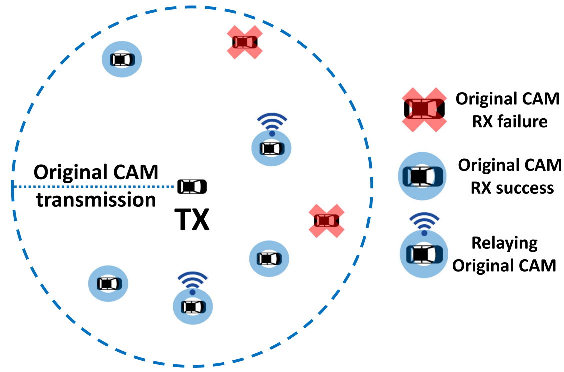


Fig. 9. Message reception rate and relaying ratio.

wait time for relaying transmission to be inversely proportional to the distance between the TX V-UE and the RX V-UE. As a result, a V-UE relays the CAM received from the farthest first. To prevent unnecessary re-transmission, the V-UE waits until the wait time ends and transmits the CAM unless it receives a relayed CAM during this period.

Second, another scheme is Probability-based Relaying (PR). This method, proposed in [13], considers the density of nearby V-UEs in determining the relaying probability.

The relay probability is calculated in the number of V-UEs around a TX V-UE and as the number of the V-UEs increases, the relay probability decreases. The V-UE does not cancel the scheduled relaying when it receives an already-relayed CAM, but it prevents redundant transmission by stochastic relay transmission.

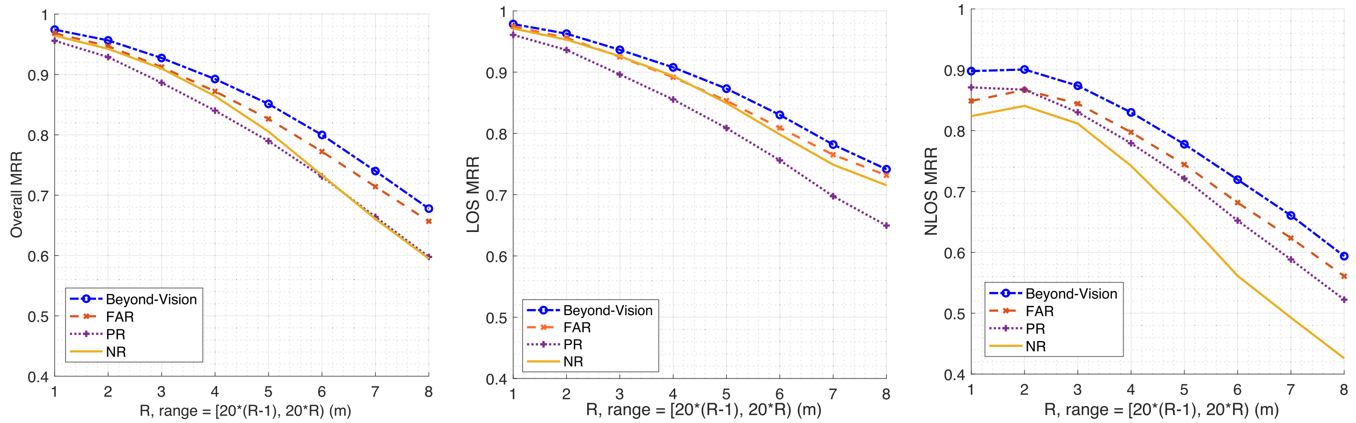
Finally, no relaying scheme (NR) is the baseline protocol of C-V2V in the 3GPP standard [2], [3]. In NR, V-UEs or any other objects such as Road Side Units (RSUs) do not relay CAMs.

C. Performance Metrics

Message reception ratio: The MRR is a basic metric for performance evaluation which indicates CAM reception ratio of V-UEs within the communication range of the TX V-UE. In Fig. 9, for example, the MRR is 5/7 because five V-UEs succeeded while two V-UEs failed in receiving the CAM. To reflect various MRR indexes, we consider not only overall MRR performance, but also MRR performance in NLOS. Since we evaluate performance in urban environments, we set the communication range at 150 m.

Average value of lower MRR: We obtain the MRR of each CAM and calculate the average the lowest 10% and 20% MRRs. In this way, we can see whether the MRR of each CAM that was not successfully transmitted via relaying protocols improves. This paper reveals the average of lower MRR in each comparison scheme.

Relaying ratio: Relaying ratio is defined as the ratio of the number of V-UEs that relayed the original CAM to the total number of V-UEs that received it. To relay a CAM, a V-UE first should receive the original CAM. The V-UE that succeeded in receiving the original CAM becomes a relaying seed. In the case of Fig. 9, five V-UEs become relaying seeds since they received



(a) (b) (c)

Fig. 10. Ranged MRR performance in Manhattan grid topology: (a) Overall MRR, (b) LOS MRR, and (c) NLOS MRR.

the original CAM. On the other hand, the number of V-UEs relaying the original CAM is 2. Thus, the relaying ratio is $2/5$. In this paper, we verify the relaying ratio relative to the MRR of original CAM transmission under each scheme.

D. Simulation Results

Fig. 10 shows MRR performance in the Manhattan grid topology. The graphs in the figure show how MRR performance varies with the distance between the TX V-UE and the RX V-UE, denoted as R. Fig. 10(a) represents overall MRR which incorporates all MRR values, when the TX V-UE and RX V-UE are in the LOS or NLOS position. Fig. 10(b) and 10(c) show LOS MRR and NLOS MRR, respectively. These graphs show that MRR performance degrades with the distance. `Beyond-Vision` outperforms the other schemes in terms of MRR performance.

In Fig. 10(b), LOS MRR shows a similar pattern to overall MRR. In particular, the MRR performance of PR is lower than that of NR for the following reason. Although the V-UE under PR does not cancel the scheduled relaying when receiving the same duplicate CAM, it relays duplicate CAMs by the probabilistic manner as to prevent redundant transmission. Therefore, in high MRR environments, as in the case of LOS, redundant relaying of original CAMs is more likely to occur. Such unnecessary relaying causes resource collision, degrading MRR performance.

On the other hand, we can see in Fig. 10(c) that NR shows the worst performance and its performance significantly deteriorates with R. In the NLOS case, the relaying schemes improve MRR, and `Beyond-Vision` is the most effective of all. FAR shows better performance than PR since it does not relay the same CAM it has received before.

Fig. 11 shows the MRR performance in the Berlin topology. As confirmed previously, the MRR performance decreases with the distance between the TX V-UE and RX V-UE. Given that 3GPP sets the communication range in the urban environment as 150 m, we verify the MRR performance in the range [140 m, 160 m). As in the Manhattan grid topology, we can confirm that NR shows severe MRR performance degradation in the NLOS

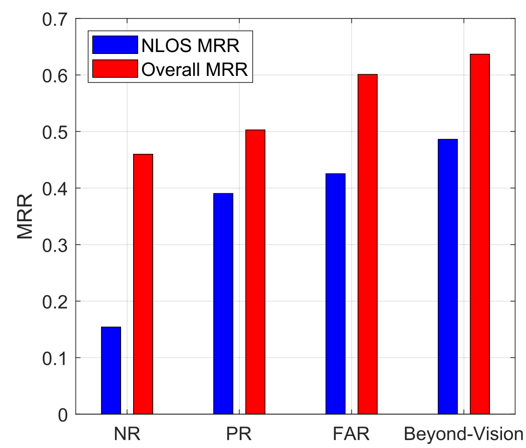


Fig. 11. MRR performance in a range close to the communication range in Berlin topology.

case while the relaying schemes improve MRR performance. Again, `Beyond-Vision` outperforms its competitive schemes in MRR improvement.

Unlike the previous evaluation, Fig. 12 compares MRR performance regardless of the distance between the TX V-UE and RX V-UE. It shows the average MRR of CAMs for the lowest 5%, 10%, 20%, and 40% MRR levels regardless of the distance. From the results, we see how much improvement `Beyond-Vision` makes for CAMs with low MRR. Fig. 12 summarizes the simulation outcomes for all cases under the two topologies, where we observe the same patterns. Note that the average MRRs in the lowest 5%, 10%, and 20%-MRR-CAM group are lower under the schemes of PR and FAR than under NR. Only after exceeding the lowest 20%-MRR-CAM group, FAR shows performance similar to or greater than NR. This indicates that the other comparison schemes do not efficiently improve MRR performance for low-MRR-CAM groups. We confirm that `Beyond-Vision` is the only relaying scheme that improves MRR performance for the low-MRR-CAM groups by selectively relaying CAMS with low MRR.

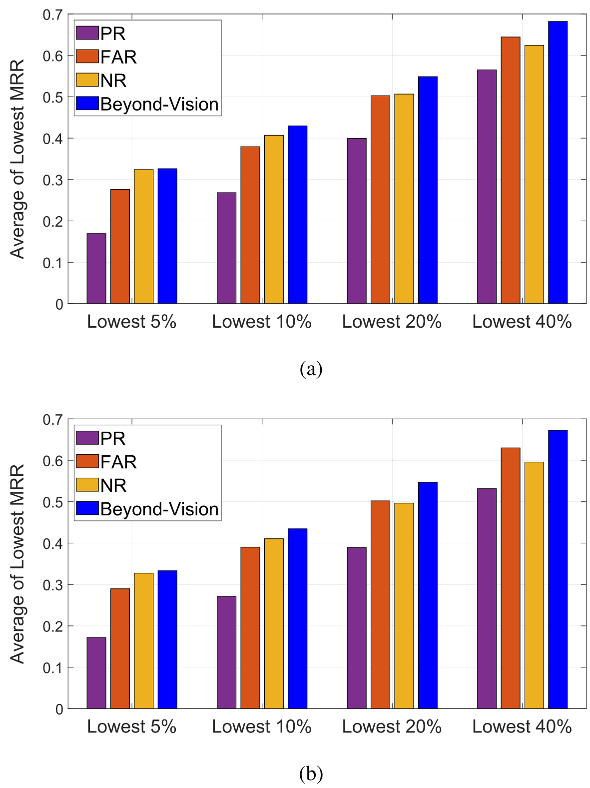


Fig. 12. Lowest MRR Average: (a) Manhattan grid and (b) Berlin topology.

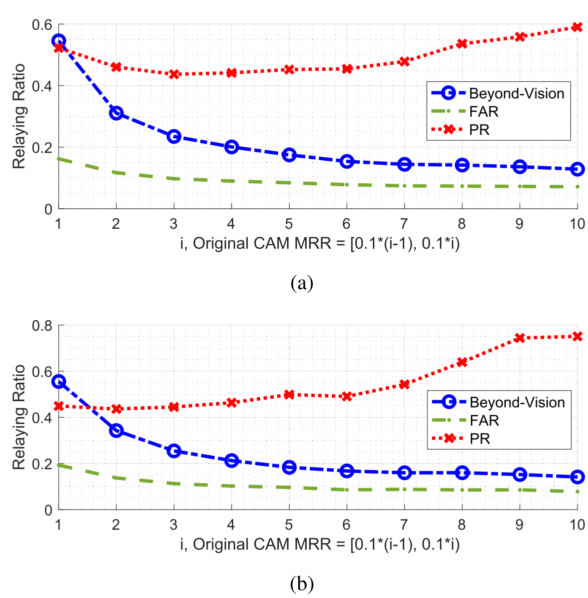


Fig. 13. Relaying ratio: (a) Manhattan grid and (b) Berlin topology.

Fig. 13 represents the relaying ratio relative to original CAM MRR. The original CAM MRR indicates the MRR for original CAM transmission before any relaying occurs. As described before, V-UEs that received original CAMs become relaying seed V-UEs enabled to relay CAMs. Thus, the relaying ratio represents the ratio of V-UEs that relayed CAMs to relaying seed V-UEs. In Fig. 13, x-axis indicates that the range of MRR for the original CAM. In `Beyond-Vision`, the probability that a V-UE relays a CAM is higher when the CAM is less likely to be received at surrounding V-UEs. In addition, the V-UE does not relay duplicated CAMs. Therefore, even when there are many relaying seeds due to high original CAM MRR, the relaying operation in other relaying seeds is effectively suppressed.

On the other hand, the relaying ratio of PR is the highest in almost all sections of x-axis. In particular, the graphs in Fig. 13(a) and 13(b) show that PR is more likely to relay CAMs with a higher MRR of the original CAM. Redundant relaying can occur in PR that determine relay operation in a stochastic manner. As a result, the higher the original CAM MRR, the greater the proportion of V-UE available for relaying, resulting in more redundant relaying.

Finally, FAR yields the lowest relaying ratio in all ranges of CAM MRR for two reasons. First, in FAR, the V-UE does not relay duplicate CAMs if it has already received the same CAMs before. Second, in our adoption of FAR to C-V2V, the V-UE sometimes fails to schedule CAM relaying due to lack of available subchannels within a determined wait time. Compared with `Beyond-Vision`, FAR shows less significant inverse-proportional relation between relaying ratio and original CAM MRR, which demonstrates that `Beyond-Vision` relays CAM more effectively from the perspective of MRR improvement.

VI. Conclusion

In this paper, we have presented `Beyond-Vision`, a standard-compliant relay system in C-V2V, that aims to guarantee stable MRR in vehicular communications. To ensure effective relaying performance, each V-UE should be able to distinguish CAMs that are not likely to be received at nearby V-UEs. `Beyond-Vision` enables V-UEs to examine eMRR of received CAMs with no overhead by utilizing previously unused bytes in the conventional CAM. By doing so, `Beyond-Vision` relays CAMs more efficiently than the other comparison schemes. Based on our realistic simulation results, we have verified the performance of `Beyond-Vision` in various environments, demonstrating that `Beyond-Vision` significantly improves MRR performance compared with the other comparison schemes and that its relaying transmission is very effective.

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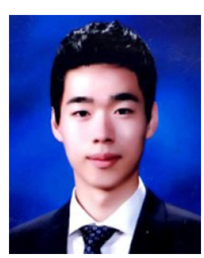
Sunwook Hwang received the B.S. degree in electrical engineering from the Pohang University of Science and Technology (POSTECH) in 2016. He is currently working toward the Ph.D. degree with the Department of Electrical and Computer Engineering, Seoul National University (SNU), Seoul, South Korea. His research interests include coexistence for IEEE 802.11 WLAN and LTE in unlicensed spectrum, Vehicle-to-Everything (V2X) communications, and next-generation wireless networks.

Seongwon Kim (Member, IEEE) received the B.S. degree in electrical engineering from the Pohang University of Science and Technology (POSTECH) in 2011, and the M.S. and Ph.D. degrees in electrical and computer engineering from SNU, in 2013 and 2017, respectively. He is a Research Engineer with AIX Center, SK Telecom, Seoul, South Korea. Before joining SK Telecom, he was a Postdoctoral Researcher with Seoul National University (SNU), Seoul, South Korea, from 2017 to 2019. He was also a Visiting Research Scholar with the Department of Electrical and Computer Engineering, Rice University, USA, from 2017 to 2017. His current research interests include applied AI, IoT connectivity, and next-generation wireless networks.



Hoyoung Yoon received the B.S. degree in electronic and electrical engineering (EEE), from the University of Seoul, South Korea, in 2014. He is currently working toward the Ph.D. degree with the Department of Electrical and Computer Engineering, Seoul National University (SNU), South Korea. His research interests include wireless networks, Device-to-Device (D2D) communication, and Vehicle-to-Everything (V2X) communications.

Byungjun Kim received the B.S. degree in electrical engineering from the Pohang University of Science and Technology (POSTECH) in 2017, and the M.S. degree from Seoul National University in 2019. He is currently working toward the Ph.D. degree with the Department of Electrical and Computer Engineering, University of California, San Diego (UCSD). His research interests include Vehicle-to-Everything (V2X) communications and next-generation wireless networks.

Sunghyun Choi (Fellow, IEEE) received the B.S. (*summa cum laude*) and M.S. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), in 1992 and 1994, respectively, and received the Ph.D. degree from the Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor in 1999. He is a Senior Vice President and Head of Advanced Communications Research Center with Samsung Research, Seoul, South Korea. He was a Professor with the Department of Electrical and Computer Engineering, Seoul National University , Seoul, South Korea from 2002 to 2019. Before joining SNU in 2002, he was with Philips Research USA, Briarcliff Manor, New York, USA, as a Senior Member Research Staff for three years. He was also a Visiting Associate Professor with the Electrical Engineering Department, Stanford University, USA, from 2009 to 2010.

He is currently heading Center for Next-Generation Communication Research with Samsung Research working on the researches for 6G, 5G, and IoT connectivity. He coauthored more than 230 Technical Papers and a book "Broadband Wireless Access and Local Networks: Mobile WiMAX and WiFi," Artech House, 2008 (with B. G. Lee). He holds over 160 patents, and numerous patents pending. He was a General Co-Chair of COMSWARE 2008, a Program Committee Co-Chair of IEEE DySPAN 2018, ACM Multimedia 2007, and IEEE WoWMoM 2007. He has also served on program and organization committees of numerous leading wireless and networking conferences including ACM MobiCom, IEEE INFOCOM, IEEE SECON, and IEEE WoWMoM. He is a Division Editor of *Journal of Communications and Networks*, and was an Editor for IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, IEEE TRANSACTIONS ON MOBILE COMPUTING, *IEEE Wireless Communications Magazine*, *ACM SIGMOBILE Mobile Computing and Communications Review, Computer Networks, and Computer Communications*. He was a Guest Editor for IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, IEEE WIRELESS COMMUNICATIONS, IEEE TRANSACTIONS ON COGNITIVE COMMUNICATIONS AND NETWORKING, and *ACM Wireless Networks*. From 2000 to 2007, he was an Active Contributor to IEEE 802.11 WLAN Working Group.

He was the recipient of the numerous awards including KICS Dr. Irwin Jacobs Award (2013), Shinyang Scholarship Award (2011), Presidential Young Scientist Award (in 2008), IEEK/IEEE Joint Award for Young IT Engineer (2007), Outstanding Research Award (2008), and Best Teaching Award (2006), both from the College of Engineering, Seoul National University, the Best Paper Award from IEEE WoWMoM 2008, and Recognition of Service Award, from 2005 to 2007 from ACM. He was the recipient of the Korea Foundation for Advanced Studies (KFAS) Scholarship and the Korean Government Overseas Scholarship during 1997–1999 and 1994–1997, respectively. He was named IEEE fellow in 2014 for the contribution to the development of WLAN protocols.

Saewoong Bahk (Senior Member, IEEE) received the B.S. and M.S. degrees in electrical engineering from Seoul National University, in 1984 and 1986, respectively, and the Ph.D. degree from the University of Pennsylvania in 1991. He is a Professor with Seoul National University (SNU). He was Director of the Institute of New Media and Communications during 2009–2011. Prior to joining SNU, he was with AT&T Bell Laboratories as a member of Technical Staff from 1991 to 1994 where he had worked on network management. He received KICS Haedong Scholar Award in 2012. He has been leading many industrial projects on 3G, 4G, and 5G and IoT connectivity supported by Korean Industry, and authored or coauthored more than 200 Technical Papers and holds more than 100 patents. He is President of the Korean Institute of Communications and Information Sciences (KICS), and serving as an Editor for *IEEE Network Magazine*. He was Chief Information Officer (CIO) with SNU, General Chair of IEEE DySPAN 2018 (DYNAMIC SPECTRUM ACCESS AND NETWORKS), General Chair of IEEE WCNC 2020 (Wireless Communication and Networking Conference), and Director of Asia-Pacific region of IEEE ComSoc. He was TPC Chair for IEEE VTC-Spring 2014, General Chair of JCCI 2015, and Co-EIC of the *Journal of Communications and Networks* (JCN). He was on the Editorial Board of Computer Networks Journal (COMNET) and IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS. He is a member of the National Academy of Engineering of South Korea (NAEK), a member of Whos Who Professional in Science and Engineering.