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Enhancing Reliability in Infrastructure-Based Collective Perception: A Dual-Channel Hybrid Delivery Approach With Real-Time Monitoring

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ABSTRACT Standalone autonomous vehicles primarily rely on their onboard sensors and may have blind spots or limited situational awareness in complex or dynamic traffic scenarios, leading to difficulties in making safe decisions. Collective perception enables connected autonomous vehicles (CAVs) to overcome the limitations of standalone autonomous vehicles by sharing sensory information with nearby road users. However, unfavorable conditions of the wireless communication medium it uses can lead to limited reliability and reduced quality of service. In this paper, we propose methods for increasing the reliability of collective perception through real-time packet delivery rate monitoring and a dual-channel hybrid delivery approach. We have implemented AutowareV2X, a vehicle-to-everything (V2X) communication module integrated into the autonomous driving (AD) software Autoware. AutowareV2X provides connectivity to the AD stack, enabling end-to-end (E2E) experimentation and evaluation of CAVs. The Collective Perception Service (CPS) was also implemented, allowing the transmission of Collective Perception Messages (CPMs). Our proposed methods using AutowareV2X were evaluated using actual hardware and vehicles in real-life field tests. Results have indicated that the E2E network latency of the perception information sent is around 30ms, and the AD software can use shared object data to conduct collision avoidance maneuvers. The dual-channel delivery of CPMs enabled the CAV to dynamically select the best CPM from CPMs received from different links, depending on the freshness of their information. This enabled the reliable transmission of CPMs even when there was significant packet loss on one of the transmitting channels.

INDEX TERMS Collective perception, cooperative ITS, road-side infrastructure, V2X, autoware, vehicular networks.

I. INTRODUCTION

The development and deployment of Intelligent Transportation Systems pose one of the most critical challenges for our modern society. With rapid advances in cyber-physical system technologies, AVs and CAVs are becoming increasingly feasible. The arrival of these new mobility technologies presents us with new opportunities to drastically improve road safety, traffic throughput, and energy efficiency [1]. Effective use of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications could potentially reduce up to 80% of traffic accidents in the US alone [2].

One of the crucial modules of the autonomous driving (AD) stack is perception, which focuses on accurately perceiving the surrounding environment and extracting information necessary for navigation. The perception pipeline includes object detection, tracking, semantic segmentation, etc. Although many state-of-the-art AD solutions use only their onboard sensors to provide local perception, they face various

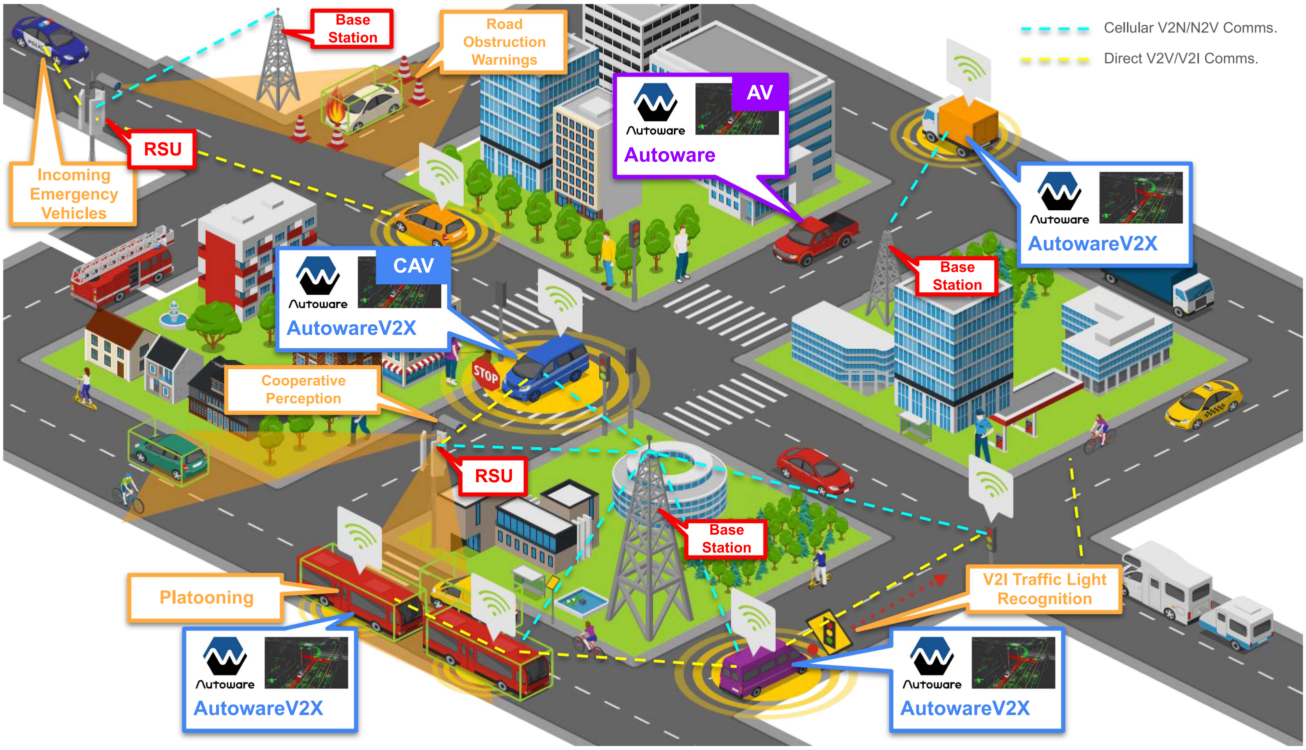

FIGURE 1. High-level Overview of AutowareV2X Applications.

limitations, many of which cannot be trivially overcome with mere improvements of individual sensors or algorithms [3].

Collective perception [4] enables AVs to overcome certain limitations of standalone driving by sharing information with nearby vehicles and infrastructure through V2X communications. It expands the perception capabilities of connected vehicles and allows for greater environmental awareness. The Collective Perception Service (CPS) [5] is a standard being developed by ETSI that specifies how an ITS-Station (ITS-S) can inform other ITS-Ss about road users and objects detected by onboard sensors. Here, the Collective Perception Message (CPM) format is also defined, which includes information such as the sender's sensory capabilities, detected objects, road-related perception regions, etc.

Collective perception is a combination of the sensing and perception strategies along with the V2X communications network capabilities, and both of these factors heavily influence its reliability [6]. Therefore, it must be analyzed and evaluated through both the sensing/perception aspect and the communications aspect [7], [8].

Research and development platforms for CAVs have been widely studied, with various implementations focusing mainly on realizing V2X communications and their application to specific use cases. Although each implementation shows promising results in its specific use case and deployment scenario, we are yet to see a comprehensive V2X communications router that is fully integrated with an AD software stack and capable of emitting different protocols through multi-radio access technology (RAT) interfaces.

In our previous work, to facilitate end-to-end development, experimentation, and evaluation of CAVs on actual testbeds, we proposed AutowareV2X [9], which is an implementation of a V2X communication module that is integrated into the open-source AD software, Autoware [10]. In addition to simulation-based evaluation, the software was implemented into actual vehicular and OBU hardware for thorough real-life testing [11]. Fig. 1 shows a high-level overview of how AutowareV2X can be used in various use cases.

This paper proposes novel methods for improving the reliability of collective perception using a hybrid radio access technology approach. Although conventional methods of collective perception focus on direct V2V or V2I communications, the reliability of this type of communication can be heavily affected by deteriorated radio conditions or large obstructions. We use a dual-channel delivery method of CPMs that utilizes cellular links to monitor packet delivery rates effectively and provide redundancy to the CPMs being delivered, all while limiting the resources used. By utilizing our V2X-enabled AD software, AutowareV2X, we conducted experiments in the field and evaluated our methods using actual vehicles and radio access equipment.

The remainder of this paper is structured as follows: Section II presents related works of collective perception, V2X router implementations, and evolving V2X network architectures. Section III outlines the problem statement and existing issues with collective perception along with the requirements set forth for a reliable implementation of collective perception. Section IV introduces our V2X router

TABLE 1 **Summary of Related Works in Both the Collective Perception and V2X Communications Aspect**

Category	Ref	Contributions
Reliable Collective Perception	[12]	Studies the effect of lossy communication on cooperative perception and proposes a lossy communication-aware repair network to mitigate the impact of packet loss.
	[13]	Investigates the trade-off between perception performance and communication bandwidth, and uses feature decoupling, spatio-temporal collaboration, and feature fusion.
	[14]	Proposes the V2X-INCOP solution that leverages historical information to recover missing information due to communication interruption. Achieved by a communication adaptive multi-scale spatial-temporal prediction model.
	[15]–[17]	Redundancy mitigation methods of Collective Perception Messages (CPMs)
	[18]	Evaluation metrics of Collective Perception performance
V2X Router Implementations	[19], [20]	OpenC2X: Open-source experimental and prototyping platform that supports ETSI ITS-G5 and runs on standard Linux.
	[21]	GeoNetworking-Stack: Open-source implementation of the GeoNetworking stack based on ETSI standard with support for single-hop broadcast and GeoBroadcast.
	[22]	Vanetza: Open-source C++ implementation of the ETSI ITS-G5 protocol suite, covering GeoNetworking, BTP, DCC, Security, and several facilities such as CAM, DEMN.
	[23]	AutoC2X: Open-source AD stack Autoware integrated with OpenC2X, enabling prototyping of CAVs
	[24], [25]	CARMA: Open-source platform providing connectivity features on top of Autoware using US-based standards. A platform for connected vehicular solutions used for the X-CAR platform.
	[26]–[31]	Proprietary V2X router solutions.
Hybrid Architectures	[32]	Analyzes the limitations of existing V2X technologies and proposes the interworking of DSRC and cellular networks.
	[33]	Proposes a service-aware radio access technology (RAT) selection algorithm that enables a heterogeneous LTE/DSRC approach. Considers service requirements and network performance to select appropriate RAT.
	[34]	Introduces the hybrid vehicular network architecture that addresses radio resource management strategies for DSRC and cellular combinations. Investigates adaptive RAT selection and vertical handover algorithms.
	[35]	Discusses the DSRC and cellular network hybrid architecture, considering the limitations of each of the technologies.
	[36]	Reviews Multi-RAT V2X networks focusing on selection mechanisms of RAT over heterogeneous VANETs.

implementation, AutowareV2X, including its architecture and collective perception application; Section V describes our proposed methods of improving the reliability of collective perception; Section VI tests the performance of our proposed implementation and methods using both simulation-based and field experiments, and Section VII discusses and concludes this paper.

II. RELATED WORKS

Table 1 summarizes related works covered in this section. We categorize the research based on their thematic relevance and discuss their implications in the context of our work.

A. RELIABILITY OF COLLECTIVE PERCEPTION

Achieving timely and robust collective perception reliably is a difficult task. It requires addressing many challenges caused by perception accuracies, fusion strategies, communication performance, environmental noise, and security. Especially with multi-agent collaboration at its core, the quality of the communication channel, measured in terms of latency or packet loss, can directly impact the reliability of collectively perceived information [37]. [12] proposes a framework that tackles the problem of lossy communication, with its Lossy Communication-aware Repair Network, to fix the damaged areas of the input features. A V2V Attention module is also introduced to consider intra-vehicle and inter-vehicle attention when fusing features from multiple sources.

The What2comm framework [13] achieves a trade-off between perception performance and communication bandwidth. It consists of a communication mechanism based on feature decoupling, a spatiotemporal collaboration module that is robust against transmission delay and localization error, and a fusion strategy that uses historical information. V2X-INCOP [14] leverages historical information in a spatiotemporal prediction model to recover missing information due to communication interruption.

B. V2X ROUTER IMPLEMENTATIONS

In addition to simulation-based evaluations, proof-of-concepts that allow for real-world experiments on actual field testbeds are crucial for understanding the capabilities and limitations of novel systems. Various implementations focus mainly on realizing V2X communications and applications of specific use cases. Open-source platforms [19], [21], [22] provide V2X software packages based on the ITS-G5 ITS Station Architecture [38]. Proprietary V2X stacks [26], [27], [28], [29], [30], [31] can be feature-rich and production-ready but could suffer from blackbox behavior, lack of customizability, and inability to share extensions openly with the community.

Efforts to integrate V2X communications software with an AD stack have also been made. The CARMA platform [24] is a reusable and extendible platform that enables cooperative driving automation. The X-CAR project [25] implemented CARMA on more affordable, high-quality hardware to increase the versatility of the entire software stack. AutoC2X [39] extended OpenC2X [19] by integrating it with the AD stack, Autoware [10], and enabled CAM [40] -based cooperative perception [41]. Objects detected by the AD stack could be transmitted by CAM messages to other connected road users.

Other studies focus only on the integration of V2X communication into a specific module of the AD stack, such as the perception [42] [43] or planning [44] pipeline. [45] proposes a V2X communication-aided autonomous driving system for vehicles and presents applications for perception, planning, and control. Although this is sufficient for evaluating the effects of V2X communication on a single module or a limited scope of the AD stack, a more versatile design of AD stack integration is needed to enable the experimentation and evaluation of the effects of V2X communication on the E2E AD software as a whole.

Although each implementation shows promising results in its specific use case and deployment scenario, we have yet to see a comprehensive V2X communications router fully integrated with an AD software stack and capable of emitting different protocols through multi-radio access technology (RAT) interfaces.

C. HYBRID COMMUNICATIONS ARCHITECTURE

Using a single V2X communications technology to achieve reliable and efficient collective perception poses limitations such as limited network bandwidth and insufficient market penetration of each technology [37]. Each communication method has advantages and disadvantages, often complementing one another. When the number of roadside ITS-Ss and CAVs increase, using only existing cellular communications infrastructure is not always scalable [46].

[32] highlights the limitations of various existing V2X communication technologies and discusses the potential for the interworking between DSRC and C-V2X [47]. The cellular network can back up vehicle data when the V2V multi-hop connection is interrupted. [35] analyzes the DSRC and cellular network hybrid architecture and considers each of their limitations. Multi-access Edge Computing (MEC)–based data offloading from a cellular network to an IEEE 802.11p V2I connection using roadside ITS-Ss is examined in [48].

[33] proposes a heterogeneous LTE/DSRC approach where vehicular nodes can select their RAT based on the service requirements. Simulation-based evaluations showed that the LTE/DSRC selective algorithm outperforms purely DSRC-based communication. [34] introduces a hybrid vehicular network architecture that combines DSRC and cellular to address radio resource management (RRM) strategies and RAT selection algorithms based on the measurements of QoS parameters and network conditions.

Multi-access connectivity and the techniques of selecting different RATs to meet certain performance requirements are studied for VANETs as well, with [36] introducing related works of selection mechanisms of RAT, the simultaneous establishment of multi-link V2X network, and resource allocations.

III. PROBLEM STATEMENT AND REQUIREMENTS

A. PROBLEM STATEMENT

The current collective perception standard [5] focuses on broadcasting CPM packets from the sender to arbitrary receivers within the broadcast range of the wireless communication medium. This raises the concern that even when packet loss occurs on the wireless channel, the sender and receiver cannot be aware of this in real-time. To use CPM-shared information reliably, the packet delivery rate of the CPM packets must be continuously monitored by both the sender and receiver ITS-Ss.

Furthermore, existing CPS works focus on sending CPMs on one radio access interface and do not deal with using multiple radio access technologies to send CPMs over various network interfaces. To increase the reliability of CPM-shared information, redundancy in the access technology used is crucial [49]. Redundancy must be provided while limiting the additional resource allocations as much as possible.

In the context of CAVs, the end user of CPM-shared information is the autonomous driving system. To this end, collective perception must be integrated into a working AV system to evaluate its full end-to-end capabilities and limitations.

B. REQUIREMENTS

One of the motivations behind our research is to realize fully connected and autonomous ITS-Ss and to utilize V2X communications to overcome the limitations of stand-alone systems. For a system to achieve its fullest potential, the following requirements are set, all of which must be fulfilled during the design, implementation, and deployment phases.

- *Scalability and Extensibility:* In existing V2X schemes, different modules within the AD stack each had their own method of connecting to external nodes through multiple Wi-Fi or cellular interfaces. This limits the scalability of V2X utilization in the AD stack because multiple modules cannot reuse the same V2X router resources. To prevent this issue, the AD stack and V2X router must be decoupled, and the interface between them must be properly designed so that various applications can reuse communication interfaces and resources. In our proposed system, the V2X communication stack and the AD stack are loosely decoupled and can be placed on different hardware. The simple Ethernet connection between them will allow multiple modules within the AD stack to access and share the same V2X communication resources.
- *Compliance with Standards and Protocols:* For a V2X router to function properly in a wide range of environments, the protocols used must comply with existing standards and must also be kept up-to-date with the newest changes. Protocols defined in the Abstract Syntax

Notation One (ASN.1) [50] format can be easily imported into our proposed system.

- *Robustness Against Packet Loss:* The safety of cooperative systems that utilize CPS information is based on the reliability of the wireless network used for transmitting the CPMs. Degradation in the network condition due to congestion, radio interference [51], and large obstacles can lead to significant packet loss for CPMs, resulting in the receiver nodes not achieving full environmental awareness. The sender and receiver of CPMs must continuously monitor packet delivery rates and detect any substantial packet losses that can affect the collective perception performance. A multi-RAT approach to provide dual-channel link redundancy to the connection used for CPM transmission is also crucial. This enables CPMs to be successfully transmitted even in the event of significant packet loss on one of the channels. We propose several methods of improving the reliability of collective perception.
- *Working Application Proof-of-Concepts (PoCs):* To verify the functionalities of the proposed system, a working prototype must be implemented and evaluated in real-life scenarios. A working implementation of CPS and its evaluation in field tests are especially necessary.
- *Open-source Development and Discussion:* With the success of Linux, the power of open-source communities has shaped the way for faster development lead times and wider acceptance of new software. The proposed system must be made open-source to align with the developer ecosystem of Autoware under The Autoware Foundation [52].
- *Safety and Security:* For any AV, the safety of the passengers and VRUs is paramount. Especially when the vehicles are connected with outside parties, possibly via multiple radio access technologies, security of not just the stand-alone intra-vehicle network but of external inter-connected networks becomes crucial.

IV. PROPOSED SYSTEM: AUTOWAREV2X

We propose AutowareV2X, an implementation of a V2X communication module integrated into the AD software Autoware, to enable the E2E development, experimentation, and evaluation of CAVs.

AutowareV2X enables a highly flexible and extensible experimental platform where V2X applications can be built on top of existing autonomous driving software modules. E2E testing of the autonomous driving algorithms and the V2X network functionalities could be conducted, providing a more comprehensive evaluation of future connected mobility applications.

AutowareV2X can be integrated easily into autonomous vehicles operating on Autoware to enable connectivity features and collection perception capabilities. CAVs equipped with AutowareV2X will be able to communicate with other connected road users using the ITS-G5 communication standards in V2V, V2I, V2P, or V2N communications. Various radio access technologies, including but not limited to Wi-Fi, DSRC/802.11p, 4G, and 5G, can be used as the underlying network interface.

As one of the many potential applications of AutowareV2X, a Collective Perception Service (CPS) application was implemented to enable the sharing of perceived objects and to enhance environmental awareness of AVs. AD systems can utilize CPS-shared information to conduct cooperative collision avoidance maneuvers.

AutowareV2X and the CPS application are fully open-sourced and can be found on GitHub: https://github.com/tlab-wide/AutowareV2X, along with the official documentation: https://tlab-wide.github.io/AutowareV2X/main/.

A. SYSTEM ARCHITECTURE

The system architecture for AutowareV2X is shown in Fig. 2. AutowareV2X is used as a V2X communication module integrated into Autoware. Autoware provides AD functionalities and uses sensing and HD map information to execute the entire AD stack from perception, localization, decision, and planning to control. Since it is based on ROS 2 [53], all internal messages are shared through a publish-subscribe architecture. AutowareV2X is connected with Autoware through an Ethernet interface, and all relevant messages from Autoware are converted and packed into V2X messages. Vanetza [22] implements basic functionalities for the ETSI ITS-G5 V2X communication stack. AutowareV2X extends the existing implementation of Vanetza to allow the seamless integration with Autoware, and the realization of reliable Collective Perception. Because both Autoware and AutowareV2X are only connected by a simple Ethernet interface, they can be loosely decoupled, and the two components can be placed on separate hardware to accommodate more use cases.

B. COMPONENTS OF AUTOWAREV2X

The components of AutowareV2X are shown in Fig. 3. The AutowareV2X Core component interfaces the ROS2-based AD software, Autoware, and the V2X router software. The *V2X Node* is a ROS 2 node that is placed in the same ROS 2 domain as Autoware, and the *V2X App* is the main V2X router app that orchestrates various applications and handles common tasks.

The Collective Perception Service is part of the *AutowareV2X Apps* collection. Other applications, such as Cooperative Awareness Messages (CAMs), can be included. The CPM Assistive Message (CPAM) App provides the basis for our methods.

Finally, the *AutowareV2X Modules* are other software components that can be optionally used to extend the functionality of AutowareV2X. We have added the TCP/IP Module to realize our proposals. Here, the ETSI-compliant messages such as CAM, DENM, or CPM can be encapsulated in TCP/IP packets. Certain messages that need to be reliably transferred or routed across the Internet can opt to use these TCP/IP modules. It is expected that this will be used in conjunction with the default direct communication link using DSRC or

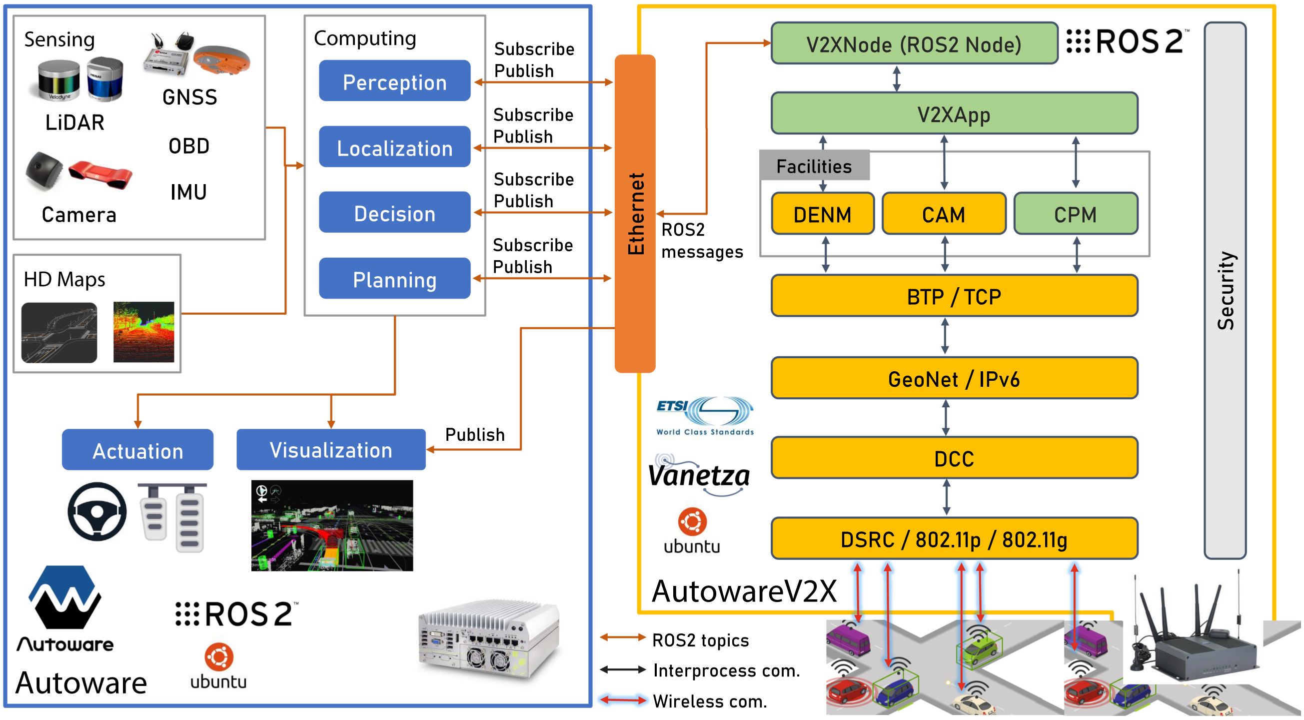

FIGURE 2. System Design and Architecture.

C-V2X, to accommodate use cases in which a more reliable transport is necessary.

V. METHODS OF IMPROVING THE RELIABILITY OF COLLECTIVE PERCEPTION

We propose methods of improving the reliability of collective perception by providing monitoring capabilities and redundant CPM delivery mechanisms. All of the methods here are implemented and integrated into our proposed system of AutowareV2X.

A. DUAL-CHANNEL HYBRID DELIVERY OF CPMS

For a more reliable realization of collective perception, we propose a multi-RAT approach to provide dual-channel link redundancy to the connection used for CPM transmission. The proposed concept, namely the "**Dual-Channel Hybrid Delivery System**", is shown in Fig. 4. We consider a scheme where roadside ITS-Ss send their perception information as CPMs to nearby connected vehicles. Here, we consider a scenario where there are two communication methods that can be utilized: the primary first channel and the secondary supporting channel. We explicitly number these channels as *Channel 1* and *Channel 2*, and they each have different characteristics. The roadside ITS-Ss communicate with the surrounding vehicles mainly over *Channel 1* with V2I communications. Access technologies are direct communication mediums such as ITS-G5, 802.11p, and DSRC. In parallel to CPM dissemination on Channel 1, the same CPMs are also sent from the roadside ITS-Ss to mobile networks through the Internet. The CPMs are disseminated to the vehicles on a more stable secondary communications channel, namely *Channel 2*. This communication structure is based on the Vehicle-to-Network (V2N) communications scheme, and cellular technologies such as 4G or 5G can be utilized.

The main advantage of this system is that even if there is significant packet loss on the direct V2I communication interface between the roadside ITS-Ss and the vehicles, the same information can be reliably delivered to the vehicles via the redundant route based on the V2N communication scheme over the mobile cellular network. This is based on the assumption that the V2N communication medium (Channel 2) has significantly lower packet loss rates than Channel 1, although the latency could be larger.

When the same CPMs are sent over multiple channels, the receiver has to decide which CPMs to accept into its system and which CPMs to discard and ignore. Thus, we introduce a new concept for the use of CPMs in the receiver, which is the "*Acceptance*" and "*Rejection*" of CPMs. In conventional CPMs, the receiver will always receive and utilize the information provided. However, when considering multiple channels, we must consider scenarios where the receiver will receive CPMs from multiple senders and will be responsible for deciding which ones to accept into its system.

Fig. 5 shows the temporal flow of CPMs between a roadside ITS-Ss and a vehicle and how the acceptance and rejection of CPMs are decided. The CPMs sent over *Channel 1* and *Channel 2* are depicted with green and red arrows, respectively. Communication latency on *Channel 2* is generally larger, represented by the slightly more slanted red arrows. The dotted green arrows represent packet loss occurring on *Channel 1*.

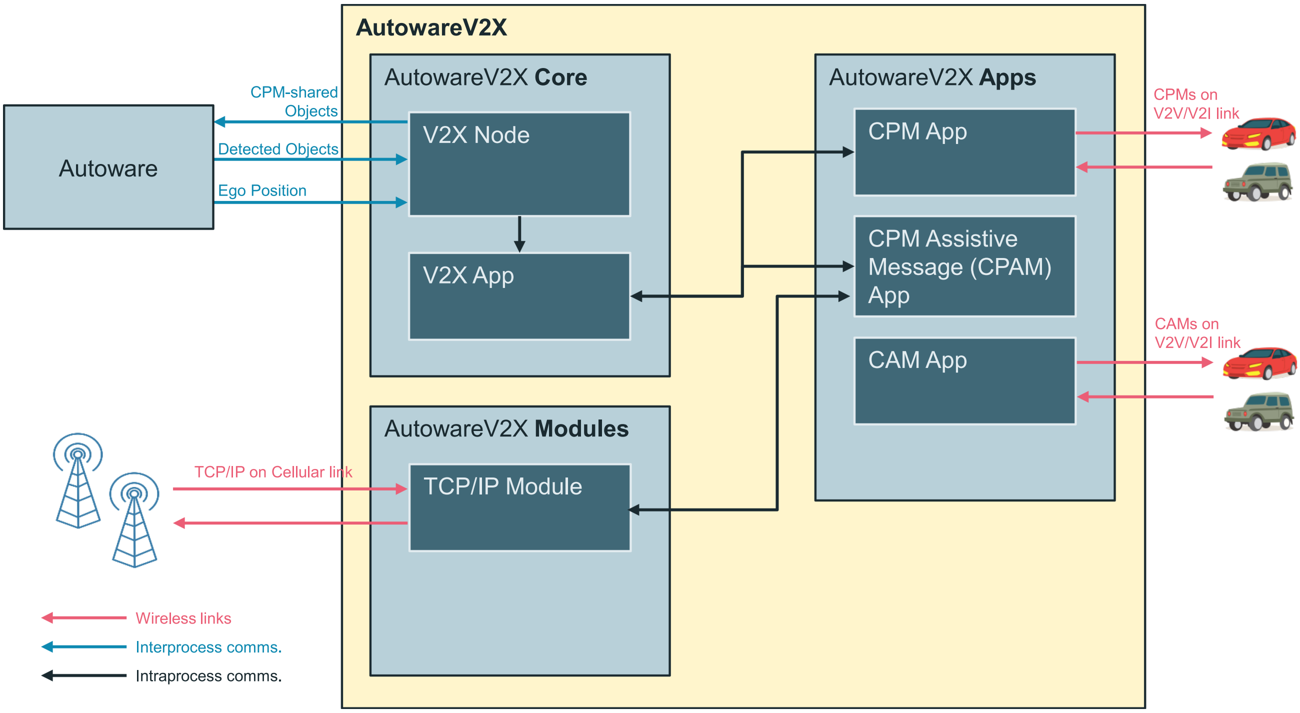

FIGURE 3. Components of AutowareV2X.

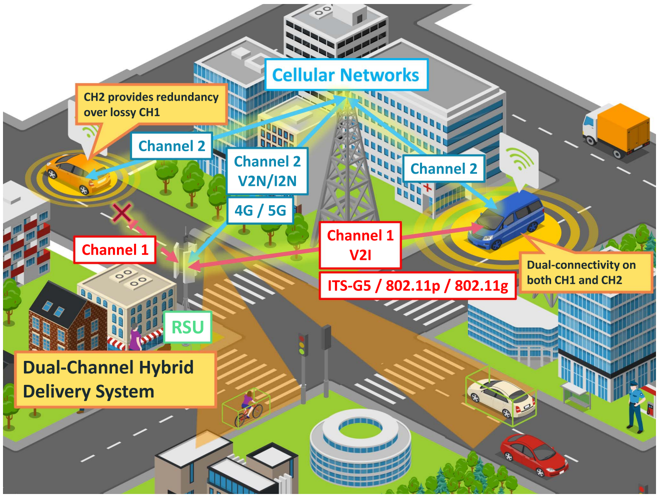

FIGURE 4. Dual-Channel Hybrid Delivery System.

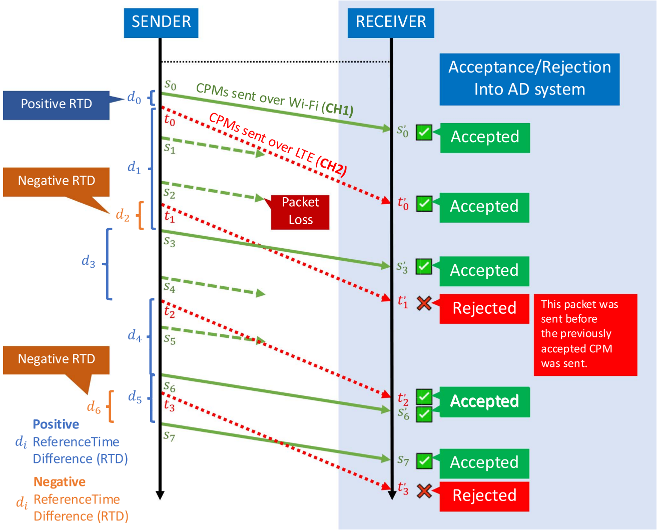

FIGURE 5. Using *ReferenceTime Difference* to accept/reject CPMs.

To decide which CPMs to accept, we utilize a field that is defined in the CPM format called the *referenceTime* [54]. The *referenceTime* value is included and encoded in all CPMs and is defined as the timestamp for when the CPM's sender ITS-S's position was decided. A larger *referenceTime* value means that the CPM was generated later, so by comparing the *referenceTime* values, we can identify which CPMs were more newly generated. Therefore, when a receiver ITS-S receives multiple CPMs from different channels, it can decide which CPMs to accept based on the difference of the *referenceTime* values.

Here, we define the *Reference Time Difference* denoted as RTD given by

$$RTD = T'_{RT} - T_{RT} \tag{1}$$

where T'_{RT} is the $referenceTime$ for the newly received CPM while T_{RT} is the $referenceTime$ for the most recently accepted CPM. Fig. 5 shows an example of how the transmission of CPMs can happen between a sender and receiver when there are two delivering channels. At t'_0, when a CPM is

Algorithm 1: CPM Acceptance and Rejection at Receiver.

```
$T_{RT} \leftarrow referenceTimeofmostrecentlyacceptedCPM$
while CPM is received do
    $T'_{RT} \leftarrow referenceTimeofnewlyreceivedCPM$
    $RTD = T'_{RT} - T_{RT}$
    if $RTD > 0$ then
        Accept(CPM)
        $T_{RT} = T'_{RT}$
    else
        Reject(CPM)
    end if
end while
```

received via LTE, the $referenceTime$ for this CPM is $T'_{RT} = t_0$, and the $referenceTime$ for the previously accepted CPM is $T_{RT} = s_0$. Therefore, $RTD = t_0 - s_0$, and we portray this as d_0. d_0 in this case shows a positive value.

A positive RTD would signify that the newly received CPM includes fresher information than the previously accepted CPM. In contrast, a negative RTD would mean that it includes older information than a previously accepted CPM. For example, in Fig. 5, when a CPM over LTE is received at time t'_1, its $referenceTime$ will be $T'_{RT} = t_1$. Meanwhile, the $referenceTime$ for the most recently accepted CPM will be $T_{RT} = s_3$. Therefore, $RTD = t_1 - s_3$, but since $t_1 < s_3$, RTD will show a negative value. This means that the CPM received at t'_1 is older than the CPM accepted at s'_3, thus can be rejected by the receiver.

In Fig. 5, the blue d values represent a positive RTD value, while the orange d values represent a negative RTD value. For each CPM that reaches the receiver, the RTD is calculated, and the CPM is accepted into the system if the value is positive.

The algorithm for accepting and rejecting CPMs in the receiver is described in Algorithm 1. When a new CPM is received from either of the dual channels, the RTD is calculated by finding the difference between the $referenceTime$ included in the received CPM and the $referenceTime$ of the previously accepted CPM. If the RTD value is positive, the new CPM is accepted, and the $referenceTime$ of the most recently accepted CPM is updated. Otherwise, the CPM is rejected and discarded.

B. REAL-TIME PACKET DELIVERY RATE (PDR) MONITORING

A CPM packet is delivered to nearby vehicles and infrastructure through single-hop broadcast (SHB) communication. Since there are no acknowledgment schemes, the sender of a CPM cannot be made aware of whether the CPM was successfully transmitted to the receiver. Similarly, since the receiver does not know how many CPMs are being sent in the first place, it cannot assess the integrity of the CPMs it receives properly.

In other words, the sender of the CPM cannot monitor the packet delivery rate (PDR) of the CPMs it has sent. Similarly, the receiver cannot calculate the PDR of CPM delivery since it does not know how many CPMs were sent in a given time interval in the first place.

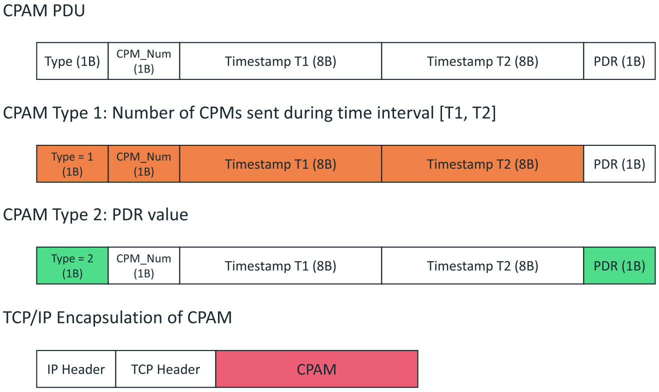

FIGURE 6. **PDU of CPM Assistive Messages (CPAMs).**

To realize reliable collective perception, the PDR of the CPMs must be monitored continuously, and both the receiver and sender must be made aware of this value. To achieve this, a relatively reliable communications channel, such as a cellular link, is used as a control plane to send information necessary for calculating the PDR.

To send the necessary information, we propose the **CPM Assistive Messages (CPAMs)**, which consists of the following two types.

- *CPAM Type 1:* Used for calculating PDR on the CPM receiver. Includes the number of CPMs the sender sent during a time interval specified by two timestamps.
- *CPAM Type 2:* Allows the CPM sender to be aware of the current PDR at the receiver. Includes the newest calculated PDR value at the receiver.

The PDU of CPAMs is shown in Fig. 6. Both types use the same PDU with the colored attributes used in each type. CPAMs are TCP/IP encapsulated and unicasted to the CPM sender and receiver for reliable transmission.

Fig. 7 shows how CPAMs are used to calculate the PDR at the receiver and monitor that value at the sender. Algorithm 2 describes this real-time PDR monitoring mechanism in detail. The CPM sender is responsible for not only sending the CPMs on the main V2X channel (Channel 1) but for periodically sending the *CPAM Type 1* packets on the secondary cellular channel (Channel 2). The *CPAM Type 1* packet is sent from the CPM sender to the CPM receiver and includes information about how many CPMs were sent within the time intervals specified in the CPAM PDU. Upon receiving this *CPAM Type 1* packet, the CPM receiver can calculate how many CPMs it has actually received within the specified time interval, and by comparing that with the number of CPMs that were sent, the PDR for that time window can be calculated. Then, once the PDR for a specific time window is calculated, the CPM receiver generates a *CPAM Type 2* packet that includes the calculated PDR value and proceeds to send the packet back to

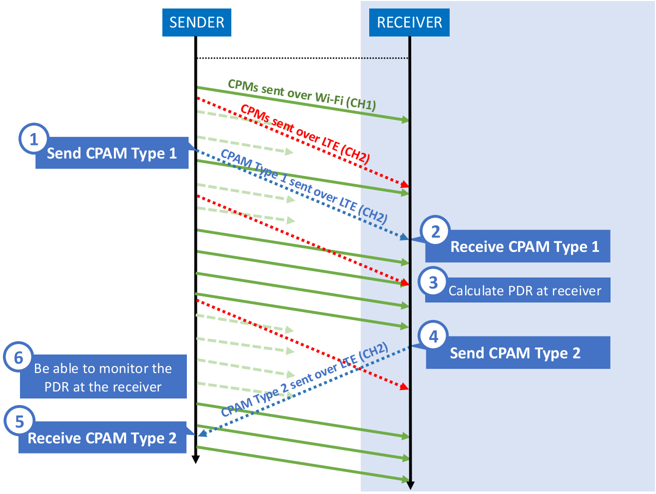

FIGURE 7. Real-time Packet Delivery Rate Monitoring using CPAMs.

Algorithm 2: PDR Calculation and CPAM Generation at the CPM Receiver.

```
$\tau$ ← Time interval for CPAM delivery
$\omega$ ← Window size for PDR calculation
count(CPMs, $\omega$) ← Number of CPMs sent in $\omega$
while CPAM(count(CPMs, $\omega$)) is received do
    $PDR_\omega$ ← Calculate PDR for time $\omega$
wnd while
For every $\tau$ milliseconds do
    Generate new CPAM($PDR_\omega$)
    Send CPAM($PDR_\omega$) to $cpm\_sender$
End For
```

the CPM sender. This way, the CPM sender can also be made aware of the PDR for a specific CPM receiver.

C. ADAPTIVE DUAL-CHANNEL CPM DELIVERY

We can further investigate a scheme where the dual-channel delivery of CPMs can be turned on and off depending on the real-time PDR values. Once the CPM sender can monitor the PDR at the CPM receiver, it can compare this PDR to a predefined threshold, and depending on the value, it can dynamically turn the dual-channel delivery of CPMs on and off. This way, bandwidth on the secondary cellular channel can be conserved, and dual-channel delivery of CPMs will not be conducted when it will not benefit the CPM receiver.

VI. EXPERIMENTS AND EVALUATION

The various features of AutowareV2X, including the dissemination and reception of ETSI-compliant CPMs and implementation of the proposed methods, were evaluated through (i) Functional Verification in Simulation-based Environments, (ii) Indoor Experiments using actual hardware in Indoor scenarios [9], and (iii) Field Test Experiments in outdoor testing facilities. Here, we mainly focus on the results from the outdoor field tests since they are the most relevant in terms of end-to-end performance evaluation.

A. FUNCTIONAL VERIFICATION IN SIMULATION-BASED ENVIRONMENTS

Functional verification of AutowareV2X was first conducted in simulation-based environments using Docker-based containers and Autoware's Planning Simulator. Two Docker networks simulated the direct V2X communications channel and the secondary cellular channel. Two Docker containers were prepared for the sender and receiver, with Autoware and AutowareV2X running on the same container. CPMs were sent on the Docker network emulating the direct V2X communication channel, while the secondary network was used to test our proposed methods.

B. EVALUATION METRICS

AutowareV2X was primarily evaluated through the packet delivery rate (PDR) between the sender and receiver routers and the E2E latency T, which we define as the time taken for the CPM-based perception information to reach from the sender perception stack to the receiver perception stack. Latency T is given by

$$T = T_{r_1} + T_{r_1 r_2} + T_{r_2} \tag{2}$$

where T_{r_1} and T_{r_2} are the execution time at the sender router r_1 and receiver router r_2, respectively, and $T_{r_1 r_2}$ is the communication latency between r_1 and r_2. $T_{r_1 r_2}$ is calculated by considering half of the round-trip time of the wireless link.

In addition to the *ReferenceTime Difference (RTD)* metric we proposed in Section V-V-A, we additionally propose the *LTE-based CPMs Acceptance Rate (LAR)*, or the acceptance rate of CPMs sent over the secondary LTE channel. The LAR value is defined as the ratio of the number of LTE-based CPMs accepted in a specific time window to the number of all CPMs accepted in the same time window, including the Wi-Fi-based CPMs. A higher LAR value would signify that the LTE-based CPMs in the dual-channel delivery scheme have an increased impact on the cooperative perception reliability at the receiver.

C. OUTDOOR FIELD EXPERIMENTS

Outdoor field experiments were conducted in the Kashiwa ITS R&R Test Field at The University of Tokyo, Japan.

The experimental setup is shown in Fig. 8. The roadside ITS-S detects surrounding objects with its LiDAR and uses AutowareV2X to send out CPMs. Meanwhile, the CAV golf cart uses AutowareV2X to receive the CPMs and accept them into its AD system. The hardware used for the CAV and roadside ITS-S is described in Table 2.

Autoware is run on hosts a_1 and a_2, while AutowareV2X is executed on routers r_1 and r_2. Host a_1 and router r_1 are connected by an Ethernet interface, and these two hosts comprise the AutowareV2X system for the roadside ITS-S. The sensing component of the roadside ITS-S is a Velodyne VLP-16 LiDAR mounted on top of a tripod. The point cloud

FIGURE 8. Experimental Setup.

TABLE 2 Hardware for CAV and Roadside ITS-S

Device	Specifications
Intel NUC Model: 11Pro	OS: Ubuntu 20.04, ROS: Galactic, Software: AutowareV2X
Netgear Model: A6210	Dual-band: 802.11b/g/n (2.4GHz), 802.11a/n/ac (5GHz)
IDY IoM 5G Gateway Model: iR730B	Bands: 3G, 4G, 5G, nano PSIM, 4x high-performance active antennas
Gigabyte PC Model: AERO-15	OS: Ubuntu 20.04, ROS: Galactic, Software: Autoware.universe
CAV Model: Yamaha G30Es-Li	Speed: $\leq$ 20 km/h, Sensor: VLP16 3D LiDAR (Rooftop)
Roadside ITS-S Sensor: VLP16 3D LiDAR	Pointclouds are processed in Autoware to output objects

packets generated by the LiDAR are sent to host a_1 through an Ethernet interface. Host a_2 and router r_2 are set up in the same configuration and on the CAV. The CAV is equipped with a Velodyne VLP-16 LiDAR on the top and can run the complete AD stack to realize autonomous driving. Routers r_1 and r_2 are equipped with an 802.11g ad-hoc mode Wi-Fi interface and an LTE interface. Due to Japanese regulations, 802.11g instead of 802.11p is used for the direct V2X communications channel.

D. BASIC SCENARIO

The roadside ITS-S is placed in one corner of the test field for the first scenario, and the CAV circles around the outer perimeter. The roadside ITS-S constantly detects nearby objects with its onboard LiDAR and generates CPMs with the perceived object information. The CAV is also constantly receiving CPMs sent by the roadside ITS-S. The CPMs are being delivered using the dual-channel hybrid delivery system on both the Wi-Fi and LTE channels. The received signal strength indicator (RSSI) values for the CPMs sent from the roadside ITS-S to the CAV on the Wi-Fi channel are mapped on a heatmap in Fig. 9. The RSSI values are significantly higher when the CAV is closer to the roadside ITS-S, with values ranging from -50 to -60 dBm. When the CAV goes further away from the roadside ITS-S, the RSSI values drop below -80 dBm. The PDR values for the CAV in the same scenario are shown in Fig. 10. It can be seen that despite the low RSSI in some areas, the PDR of the CPMs is nominal

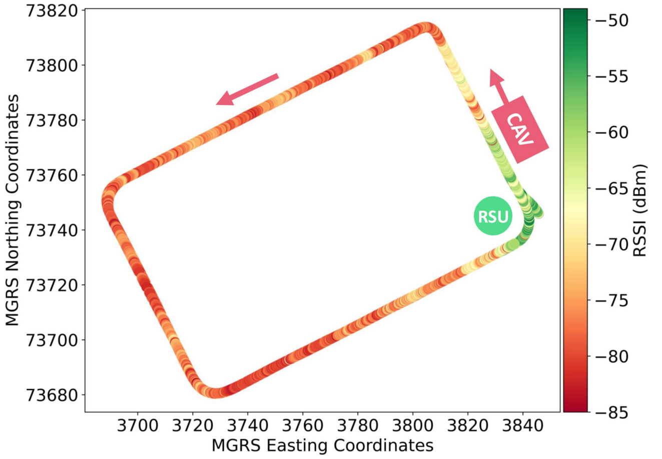

FIGURE 9. Heatmap of RSSI for Wi-Fi-based CPMs.

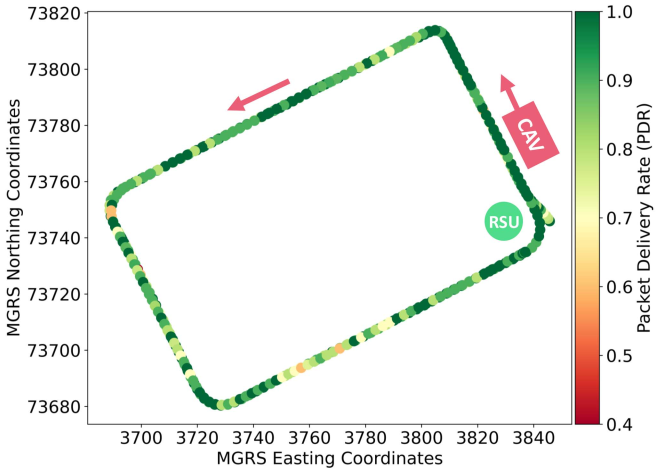

FIGURE 10. **Heatmap of PDR for Wi-Fi-based CPMs.**

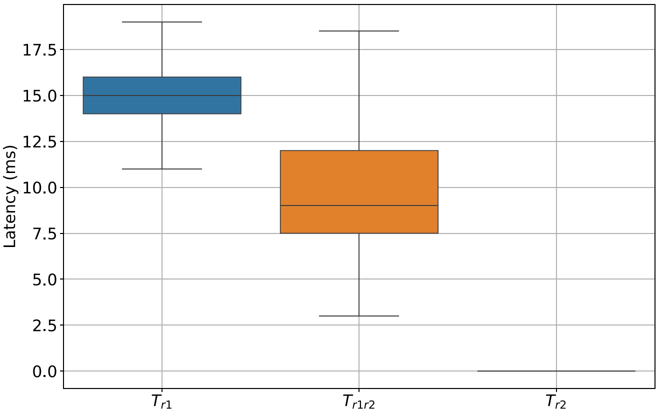

FIGURE 11. **E2E latency for Wi-Fi-based CPMs.**

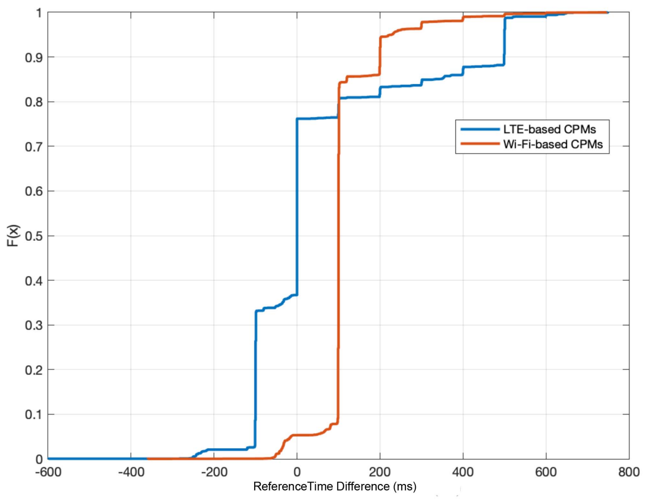

FIGURE 12. **CDF for the "ReferenceTime Difference" (RTD) of Dual-Channel CPMs.**

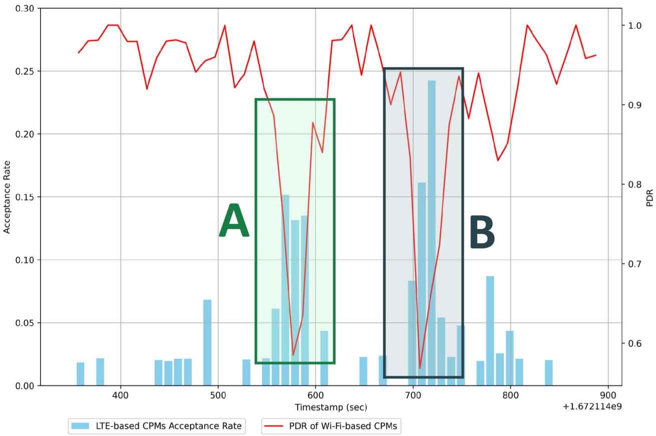

FIGURE 13. **LTE-based CPM Acceptance Rate (LAR).**

and high for most areas. However, in some places near the top-left corner and the bottom edge, the PDR has dropped to about 60%. This can be due to interference in the Wi-Fi channel, which degrades the network conditions significantly. Especially in the south edge of the perimeter, the PDR is leveling at around 70% until the CAV returns closer to the roadside ITS-S.

Each latency component for the E2E latency of the Wi-Fi-based CPMs is shown in Fig. 11. The processing time at the roadside ITS-S's AD stack T_{r1} is around 15ms, while the wireless communication latency between the roadside ITS-S and CAV T_{r1r2} is only around 9 ms. The processing time at the CAV T_{r2} is less than 1 ms because the receiver side of CPMs only needs to extract information from the CPM and publish that as a ROS2 topic to the AD stack. In total, the objects perceived by the roadside ITS-S's perception stack were delivered from the roadside ITS-S to the CAV's AD stack in less than 30 ms.

The CDF plot for the *ReferenceTime Difference* RTD is shown in Fig. 12. The CPMs sent over Wi-Fi are depicted with the orange line, and most of them have a positive RTD value of around 100 ms. This aligns with the fact that the Wi-Fi-based CPMs are sent every 100ms. Meanwhile, LTE-based CPMs that are shown with the blue line mostly have an RTD value that is negative or close to zero. With the CPMs being sent on two channels, the same CPMs are received via Wi-Fi before receiving via LTE. However, around 20% of LTE-based CPMs show positive RTD values, which shows the advantage of using the dual-channel delivery approach. In this 20%, LTE-based CPMs yield an RTD value between 200 ms and 600 ms. This signifies that when there are consecutive drops in the Wi-Fi channel, the CPM receiver benefits from the CPMs sent over LTE. Especially because LTE-based CPMs are sent every 500 ms in this experiment, when more than five consecutive CPMs are lost on the Wi-Fi channel, the LTE-based CPM will always fill in this information gap.

We also analyze the *LTE-based CPM Acceptance Rate (LAR)*. Fig. 13 shows the LAR values with the cyan bars and the PDR for Wi-Fi-based CPMs with the red line. The PDR for Wi-Fi-based CPMs decreases dramatically in the sections denoted as "A" and "B". Here, LAR increases significantly.

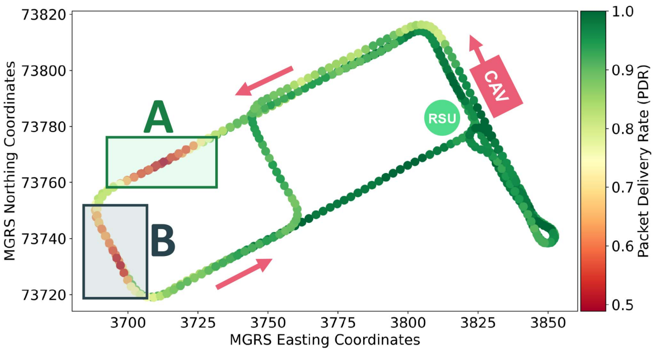

FIGURE 14. Heatmap of Packet Delivery Rate for Wi-Fi-based CPMs.

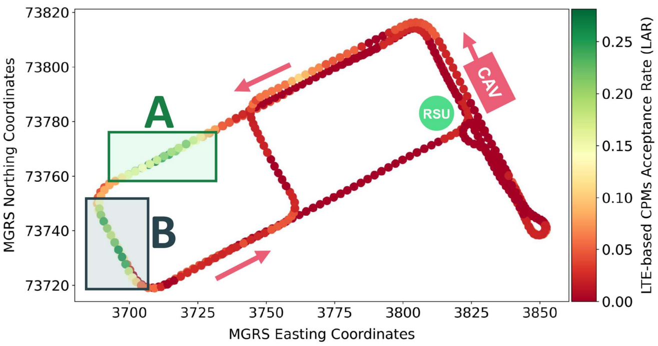

FIGURE 15. Heatmap of LTE-based CPMs Acceptance Rate (LAR).

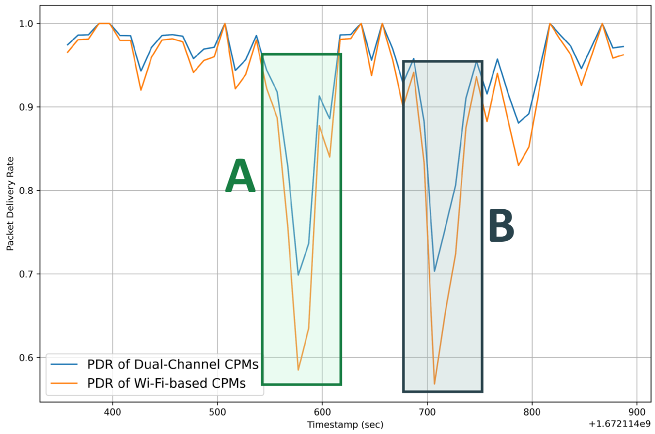

FIGURE 16. Packet Delivery Rate for Dual-Channel vs. Wi-Fi-based CPMs.

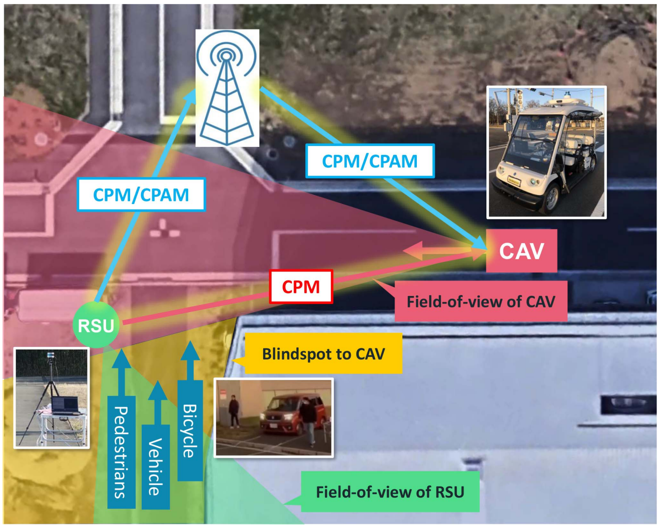

FIGURE 17. Blindspot Scenario Experiment.

This signifies that when the PDR for Wi-Fi-based CPMs decreases and the conditions for the Wi-Fi channel deteriorate, the LTE-based CPMs can provide newer information to the receiver better than the Wi-Fi-based CPMs. The interval for the LTE-based CPMs' dissemination is set to 500ms in this scenario. By changing this interval to be more frequent, we may see an increase in the *LAR* values, although this is left for future work.

A heatmap of the PDR for Wi-Fi-based CPMs and the *LAR* values are shown in Figs. 14 and 15, respectively. In the areas denoted as "A" and "B", the PDR for the Wi-Fi-based CPMs deteriorates. However, the *LAR* values in the same areas increase. In other areas where the PDR of Wi-Fi-based CPMs is high, the usage of LTE-based CPMs is extremely low.

Fig. 16 shows the PDR for Wi-Fi-based single-channel CPM delivery and the PDR for the proposed method of dual-channel CPM delivery. It can be seen that the PDR for the proposed method increases compared to the single-channel CPM delivery, signifying that the receiver ITS-S can receive more of the CPMs sent from the sender ITS-S. LTE-based CPMs usually endure no packet loss, so the perfect PDR measured here increases the PDR for the dual-channel method. Note here that the transmission rate of the LTE-based CPMs is set to be lower than that of the Wi-Fi-based CPMs in order to conserve LTE communication bandwidth. Especially in cases where the wireless radio conditions deteriorate and the PDR decreases, the extra boost of packet delivery we can obtain from the dual-channel method can increase CPM usability and reliability.

E. BLINDSPOT SCENARIO

To evaluate the E2E performance of CPMs and to see how they can benefit CAVs in collision avoidance maneuvers, we considered a blindspot scenario where objects emerge from an area that cannot be directly seen from the CAV approaching an intersection. The layout of the experiment is depicted in Fig. 17.

A roadside ITS-S in an intersection perceived nearby objects and broadcasted the information as CPMs to the approaching CAV. While the CAV approaches the intersection, it cannot locally detect the two pedestrians and vehicles approaching the intersection since they are in a blind spot behind the building wall. This blindspot is depicted as the yellow area in Fig. 17. However, the roadside ITS-S can detect the objects in this blind spot and transmit their information to the CAV through CPMs.

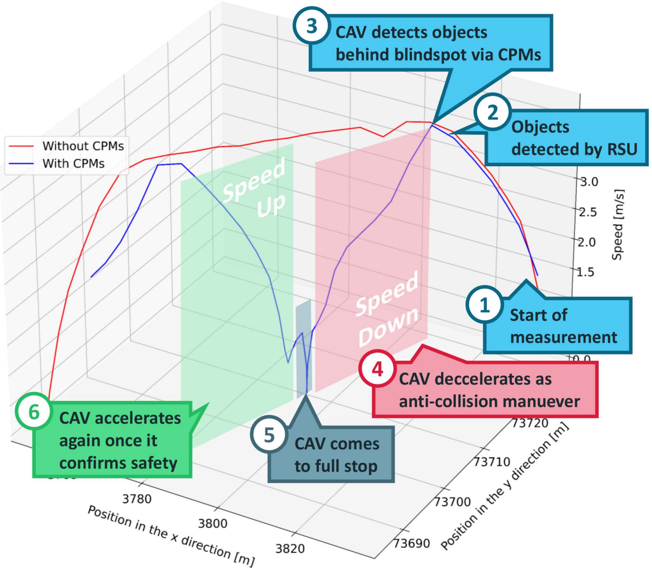

FIGURE 18. **Speed and position of CAV for Blindspot Scenario.**

The CAV was able to perceive a wider area of its surroundings (i.e., including previously unknown places such as blind spots) through both its local onboard sensors and the object information shared by CPMs [1].

The speed and position of the CAV during this experiment are shown in Fig. 18. The red line depicts the speed of the CAV when no CPMs are sent from the roadside ITS-S. The CAV is unaware of the objects in the blind spot and continues to proceed through the intersection with no deceleration. The blue line depicts the speed of the CAV when CPMs are sent from the roadside ITS-S. The CAV can perceive the objects behind the blind spot in this case. Through the information shared by AutowareV2X in the form of CPMs, the CAV can infer that the pedestrians and vehicles behind the blind spot are approaching the intersection. Therefore, it can decelerate before entering the intersection and come to a complete stop before slowly starting again once it can fully confirm the safety.

VII. CONCLUSION

For cooperative intelligent transport systems (C-ITS), V2X communication is utilized to allow autonomous vehicles to share critical information with each other. Collective perception enables CAVs to overcome the limitations of standalone AVs by sharing sensory information with nearby road users. This paper aims to analyze the requirements for reliable collective perception amongst multiple ITS stations and propose methods of improving the reliability of its utilization.

We propose three methods of increasing the reliability of collective perception: (i) dual-channel hybrid delivery of sensory information, (ii) real-time packet delivery rate (PDR) monitoring, and (iii) the adaptive dual-channel delivery of sensory information using the combination of the above two methods. To realize the proposed methods, we extended our previous work on AutowareV2X.

Simulation-based and outdoor field experiments were conducted to evaluate the performance of AutowareV2X and the effectiveness of our proposed methods. Field experiments have indicated that the E2E network latency is around 30 ms, and the AD software can use shared object data to conduct collision avoidance maneuvers. The effectiveness of the proposed methods was also confirmed, with the dual-channel delivery of CPMs enabling the CAV to dynamically select the best CPM from CPMs received from different links, depending on the freshness of their information. This enabled the reliable transmission of CPMs even where there was significant packet loss on one of the transmitting channels.

While using dual-channel delivery improves communication quality and collective perception reliability, there is a degradation in frequency utilization efficiency since the same CPMs are sent over two channels repetitively. To address this, it is necessary to implement measures such as channel switching using digital twins that consider the differences between theory and actual measurements. The communication coverage can be predicted using a digital twin environment, and ML-based approaches can be used to improve resource utilization while maintaining the same level of reliability. Another challenge is the increased power consumption from using dual channels. One possible solution is to adapt coverage for two different frequencies with varying qualities through transmission power control.

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