Received 16 December 2020; accepted 2 January 2021. Date of publication 8 January 2021;
date of current version 17 February 2021. The review of this article was arranged by Associate Editor Shuaishuai Guo.

Digital Object Identifier 10.1109/OJVT.2021.3049783

Towards Safe Automated Driving: Design of Software-Defined Dynamic MmWave V2X Networks and PoC Implementation

ZONGDIAN LI (Student Member, IEEE), TAO YU (Member, IEEE), RYUICHI FUKATSU (Student Member, IEEE), GIA KHANH TRAN (Member, IEEE), AND KEI SAKAGUCHI (Senior Member, IEEE)

Electrical and Electronic Enginneering, Tokyo Institute of Technology, Tokyo 152-8552, Japan

CORRESPONDING AUTHOR: ZONGDIAN LI (e-mail: lizd@mobile.ee.titech.ac.jp)

This work was supported in part by the European Commission H2020 programme (5G-MiEdge project), in part by the Ministry of Internal Affairs and Communications, Japan (5G-MiEdge project), and in part by the Ministry of Internal Affairs and Communications, (MiEdge+ project).

ABSTRACT The technical exploration of safe automated driving has evolved from single vehicle intelligence to vehicular networking. Therefore, to a certain extent, the safety requirements have been translated into the requirements for network performance. Although Vehicle-to-Everything (V2X) communication technologies have developed decades of years, from the Dedicated Short-Range Communication (DSRC) to the Long Term Evolution V2X (LTE-V2X), the introduction of millimeter wave (mmWave) in the 5G era will achieve an unprecedented leap in V2X performance by empowering multi-gigabit data transmission with ultra-low latency. Meanwhile, the emergence of Software Defined Networking (SDN) enables centralized network management and allows flexible scheduling of communication resources to match V2X capacities. Their benefits for vehicular networks have been revealed by plenty of studies respectively. Nevertheless, no researchers investigate their combination to improve the safety of automated driving, especially lack of scalable prototype systems for proof-of-concepts (PoCs), not to mention the field test with real traffic. In this paper, we firstly propose a novel architecture, i.e. software-defined dynamic mmWave V2X network, to support cooperative perception. And then, necessary hardware and software platforms are introduced to compose prototype systems. Step by step, we conduct PoCs from the indoors to the outdoors, which demonstrate the network functions, the prototype scalability and most importantly, the significant enhancement to the vehicle perception for safe automated driving.

INDEX TERMS Cooperative perception, millimeter wave, proof-of-concept, prototype, SDN, V2X communication.

I. INTRODUCTION

Since the term ITS which stands for "Intelligent Transport System" was coined in 1994, global governments, industry and academia have spent tremendous efforts to create a new era of safer, greener, smarter, more efficient and connected transportation. Automated driving is one of the key ITS enablers. It started with the Advanced Driver-Assistance System (ADAS) which expects to halve traffic congestion on major roads and reduce fatalities to fewer than 2500 (4166 fatalities in 2018) by 2020 [1]. Towards higher levels of driving automation and safety as laid out by the Society of Automotive Engineers (SAE) international, automakers (Tesla, Volvo, etc), device vendors (Qualcomm, Intel, etc) and leading Information Technology (IT) companies (Google, Baidu, etc) continue to invest heavily in the manufacture of intelligent Automated Driving System (ADS) and generic On-Board Unit (OBU). In order to enhance network accessibility and provide Vehicle-to-Everything (V2X) services referring to the use cases in the Third Generation Partnership Project (3GPP) Release 14/16 [2], [3], authorized telecom operators will deploy a number of Roadside Units (RSU). The government's role in this marathon is to open test fields for automated vehicles before commercial rolling-out, issue licenses and call on a group of researchers to perfect standards and address existing technical bottlenecks.

The primary public concern regarding automated driving is safety, especially after the first road traffic death caused by a test automated vehicle in 2018. V2X communication is considered a promising solution against the unsafe factors of current automated vehicles, i.e. limited Non-Line-of-Sight (NLOS) perception and data processing capability, by sharing sensing information among each other (Vehicle-to-Vehicle, V2V), with nearby RSUs (Vehicle-to-Infrastructure, V2I) or smart devices on road users (Vehicle-to-Pedestrian, V2P) [4]. The technical evolution of V2X standards accommodates demands on the data rate growth (larger than assumed 1320% for machine-to-machine/Internet of Things (M2M/IoT) from 2016 to 2021) and latency reduction [5]. The IEEE 802.11p based ITS-G5 [6]/Dedicated Short-Range Communication (DSRC) [7], operating in the licensed ITS 5.9 GHz band, can hardly exceed 6 Mbps with high mobility, although it ensures low latency less than 10 ms. As an alternative, 3GPP-conducted cellular V2X (C-V2X) has concluded the design of Long Term Evolution V2X (LTE-V2X) in Release 14. It supports higher throughputs using LTE radio interface (Uu) and side-link interface (PC5) [8]. However, the peak data rate is still lower than 28.8 Mbps and the end-to-end latency cannot go below 100 ms [9]. In order to fulfill the stringent quality of service (QoS) of safety-critical V2X applications, for instance, cooperative perception which requires a data rate of over 1 Gbps, end-to-end latency of less than 10 ms, communication range of larger than 50 m and reliability of above 99.99%, evolutions for DSRC and C-V2X, known as 802.11bd and New Radio (NR) V2X respectively, are underway, taking millimeter wave (mmWave) into account due to its abundant spectrum resources for significant throughput enhancements [10].

Remarkably, massive V2X linking will reshape the traditional Vehicular Ad Hoc Network (VANET) with new characteristics of huge capacity, high dynamicity and instantaneity, which increases the complexity of network resource management and protocol or application renewal. Software Defined Networking (SDN) appears as a revolutionary network paradigm that breaks the inherent coupling of data plane (D-plane) and control plane (C-plane). This paradigm surpasses the conventional one in terms of flexibility, programmability, global awareness and centralized management. In order to diffuse its advantages into the vehicular networks, preliminary attempts have been made by some researchers in architecture design and performance analysis. Nevertheless, most of the architecture works focus on the technical combination with other emerging technologies like fog computing [11] and Multi-access Edge Computing (MEC) [12] to satisfy the general quality of service (QoS) requirements of V2X, rather than orienting a specific safety service like cooperative perception. Besides, nearly all the performance evaluations are based on network simulators (ns-2, ns-3) and emulation tools (Mininet, Mininet-WiFi) [13], thus lack of field tests with real testbeds.

This paper reviews the literature of mmWave V2X and SDN-based vehicular networks, but the ultimate goal is fusing these two promising technologies to reach safe automated driving. The contributions of this paper are sound and distinctive in two fronts. Firstly, we explain the necessity of mmWave V2X from the perspective of safety for automated driving. In order to meet the safety requirements and tackle the inevitable challenges using mmWave, we propose a software-defined dynamic mmWave V2X network, which not only achieves real-time context tracking in fast changing topologies, but also enables flexible radio resource management (RRM) for mmWave fronthauling/backhauling. Secondly, we conduct indoor and outdoor proof-of-concepts (PoCs) that demonstrate the proposed network can serve the cooperative perception with a better performance. The testbeds are constructed by latest commercial hardware (e.g. mmWave routers, 2D/3D LiDARs, mobile robots, etc) [14]–[17], and the functionalities are implemented upon developer-friendly software platforms, e.g. OpenDaylight (ODL), Open vSwitch (OVS), Robot Operating System (ROS), etc [18]–[20]. As for the system networking, we have used 2.4/5 GHz IEEE 802.11n/ac (Wi-Fi) and 2.5 GHz IEEE 802.16 (WiMAX) for C-plane, instead of DSRC and LTE-V2X, because Wi-Fi and WiMAX are easily available. In D-plane, IEEE 802.11ad (WiGig) using 60 GHz is adopted. Our previous work has presented some preliminary results of the field trial [21], nonetheless, the requirements for safe automated driving and the adaptive vehicular network architecture were not clarified. Also, the scenario design and indoor PoC implementation were not disclosed. Therefore, this paper yields original information to readers.

The remainder of the paper is organized as follows. Section II summarizes related works to help readers understand the state-of-the-art of mmWave V2X and software-defined vehicular networks. Section III presents the overall architecture we proposed and includes more details of the D-plane and C-plane design. Section IV and Section V introduce our testbeds, implementation of indoor and outdoor PoCs as well as the important results showing matched performances based on the safety requirements. Finally, Section VI provides concluding remarks of this paper.

II. RELATED WORKS AND MOTIVATION

This section provides an introduction of current academic work on extending mmWave and SDN, two key technologies of the fifth generation (5 G) mobile communication and beyond, to the V2X network with their benefits.

A. MMWAVE TECHNOLOGIES FOR V2X

The high-rate, low-latency and massive-connectivity requirements corresponding to 5G use cases such as the enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC) and massive machine type communications (mMTC) motivate the exploration of mmWave spectrum (30-300 GHz) due to the bandwidth shortage in Sub-6 GHz. As one of the dominant applications of 5 G, automated driving will incorporate mmWave with conventional V2X technologies to support advanced services. Shimizu *et al.* described some attractive ones like cooperative perception, sensor data upload, high-speed mobile broadband internet access, etc., to show the throughput and delay benefits that mmWave can bring about [22]. Regarding the spectrum selection, Sakaguchi *et al.* summarized the candidate bands identified for 5G and beyond by four different organizations, i.e. the World Radiocommunication Conference 2015 (WRC-15) in International Telecommunication Union Radiocommunication Sector (ITU-R) [23], the European Conference of Postal and Telecommunications (CEPT) in EU [24], the Federal Communications Commission (FCC) in US [25], the Fifth Generation Mobile Communication Promotion Forum (5GMF) in Japan [26] and nominated four frequency candidates for mmWave V2X: (1) 31.8-33.4 GHz, (2) 40.5-42.5 GHz, (3) 47.0-50.2 GHz, and (4) 66.0-71.0 GHz [27]. Although 28 GHz and 60 GHz are out of this scope, they have drawn considerable attention since the former is the most likely choice for 5G deployment in the South Korea, US and Japan, and is hopefully applied to 3GPP NR V2X, the latter currently used by IEEE 802.11ad/802.11ay can be the basis for the design of IEEE 802.11bd [10].

So far, the channel characteristics of mmWave V2X have been known better, because considerable propagation measurements at 28/30/60/63/73 GHz were carried out under different vehicular scenarios (urban/highway) [28]–[30]. The influences by blockage, shadowing, foliage effect, etc were individually or jointly investigated [31]–[34]. Va *et al.* surveyed the state-of-the-art in modeling for mmWave vehicular channels [35]. The 3GPP also summarized the mmWave V2X channel modeling for 5G NR-V2X systems [36]. Besides, researchers have explored various reliable solutions to assist the beam alignment of mmWave V2X, a generally recognized difficulty due to the narrow beamforming, directional antennas and the high vehicle mobility. A consensus is forming that the out-of-band information from sensors or DSRC is valuable, which can be leveraged to achieve dynamic beam tracking and reduce recovery overhead [37]–[40]. To associate the most appropriate beam pairs, novel schemes like the fingerprint database and machine learning were taken into account [41], [42]. Obviously, these works set up the fundamentals for the practical use of mmWave in vehicular scenarios.

Recently, impressive research that further improves the reliability of mmWave V2X is emerging. For example, Sugihara *et al.* proposed a mmWave massive analog relay MIMO system, which generates artificial propagation paths to avoid blockage attenuation and can be used to increase the channel capacity of V2X [43]. Although the effectiveness was presented via numerical simulation, implementation methods (e.g. SDN) of organizing those relay paths for a moving vehicle were not discussed. Yin *et al.* attempted to mitigate the interference of mmWave V2V by designing a ZigZag antenna configuration method [44]. Its improvement on the signal-tonoise ratio (SNR) was remarkable. However, vehicle antennas should be controllable for dynamic switching based on vehicle roles (relays, transmitters, receivers) in ZigZag transmission, which was hard to be implemented without network control.

B. SDN APPROACH FOR VANETS

SDN was first proposed to revolutionize wired networks by separating the underlying D-plane and C-plane, providing network management in a centralized manner with well-defined southbound protocols such as OpenFlow and NETCONF [45], [46], as shown in Fig. 1. Due to its remarkable promotions on flexibility and programmability compared to the conventional network, the idea of SDN has been transplanted to wireless networks and mobile networks, i.e. Software-Defined Wireless Networks (SDWNs) [47] and Software-Defined Mobile Networks (SDMNs) [48]. One of the prospective applications is context-based dynamic meshed backhaul construction for 5G heterogeneous networks [49]. In order to compensate for the drawbacks of VANETs, research pioneers start throwing their eyes at the adaptation of SDN for vehicular networks, which is so-called Software-Defined Vehicular Networks (SDVNs).

To the author's knowledge, the first studies considering SDN as a key technology enabler for advanced vehicular networks appeared around 2014. Ku *et al.* were early researchers who declared the components and requirements needed to deploy SDN in VANETs and discussed the benefits and services that can be provided [50]. As new features of global awareness and centralized control were introduced in SDVNs, it is able to implement comprehensive resource management. Zheng *et al.* proposed a multi-layer Cloud-RAN architecture for heterogeneous SDVNs, where multi-domain resources including communication and computing/storage resources can be exploited as needed for vehicle users [51]. Besides, by integrating with 5G cloud technologies, the QoS of most on-board services will be satisfied. Zhang *et al.* presented a fog-computing-based SDVN with efficient access handover and resource allocation schemes, which guarantee vehicles' QoS and provide significantly better performances [52]. Liu *et al.* proposed a SDVN architecture assisted by MEC and validated that it can provide desired data rates and reliability in V2X communication simultaneously [53]. Moreover, driving safety of intelligent vehicles (IVs) is possible to be enhanced. Cheng *et al.* proposed a 5G-enabled cooperative IV framework, in which SDN achieves the remote control of IVs and arranges storage and processing resources for high-precision localization and real-time route planning [54].

C. PROTOTYPING

Other than the studies above, prototyping is carrying on. Regarding the hardware implementation of mmWave V2X, Wooseong Kim tested the applicability of the WiGig technology to V2V communications at 60 GHz, where commercial off-the-shelf WiGig devices were used, and inter-vehicle connectivity was measured on campus and city roads with different vehicle speeds [55]. Besides, projects such as the Lightpole Site by Ericsson/Philipps [56], the Smart Pole Pilot in

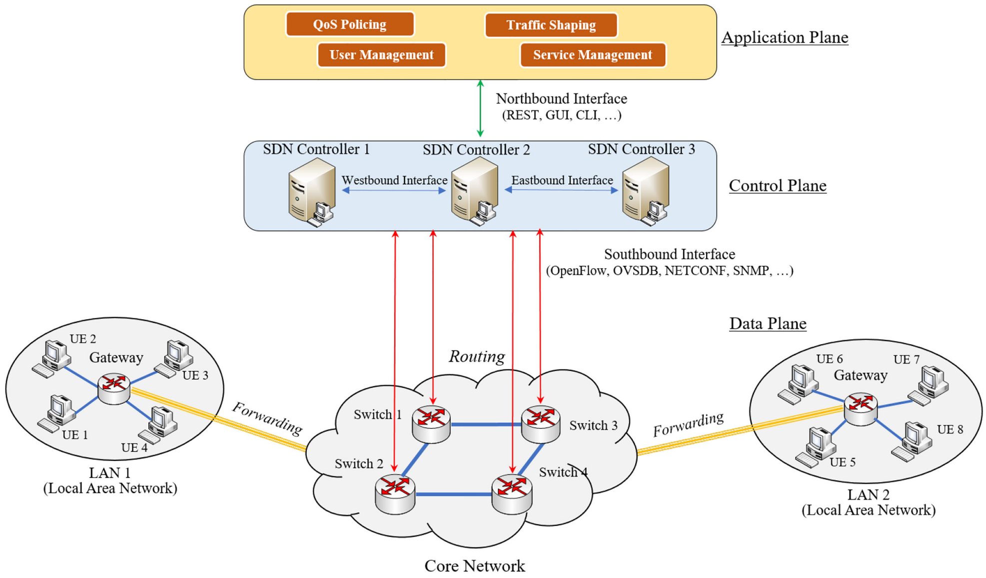


FIGURE 1. Original SDN paradigm in wired networks.

San Jose [57], the 5G BERLIN initiative [58] and the LuxTurrim5G project in Finland [59], the ITS Connect in Japan [60], and the SSS project in Tokyo [61], are working to integrate mmWave V2X infrastructures into the urban landscape. These works contribute to the real applications and deployments of mmWave V2X. Nevertheless, a systematical construction of vehicular networks is absent, especially lack of the design of backhaul and the selection of network infrastructures, let alone the management schemes for mmWave V2X services.

As for the SDVN, due to its complex compositions, it is very costly to establish a testbed that incorporates all facilities like vehicles, OBUs, RSUs and control servers. Besides, finding appropriate test fields is not easy in some countries with strict regulations like Japan and Europe. Fontes *et al.* took a flexible approach by implementing the SDVN in a wireless SDN network emulator (Mininet-WiFi), and tested a scenario of technology handover for video streaming [62]. By contrast, Seçinti *et al.* made a step forward, deploying testbeds with Raspberry Pi to enable OpenFlow soft-switches in both RSUs and OBUs [63]. However, only flow management was implemented since the Raspberry Pi works as a mobile Wi-Fi access point (AP) in their architecture. More recently, Sadio *et al.* designed a complete SDVN prototype consisting of a SDN-based backbone and a SDN-based radio access, in which multiple SDN controllers are used to implement routing algorithms and manage mobility schemes [64]. But there is still room for improvement. For example, the Wi-Fi APs used for V2X limited the access throughput and the optical cables used in the backbone produced huge cost.

This work intends to fill in the gaps by designing prototype systems from a network perspective. A SDN-based vehicular network is established to support advanced V2X services with mmWave V2X.

III. SYSTEM DESIGN

In this section, mmWave and SDN are integrated to compose a software-defined dynamic mmWave V2X network based on the requirements of safe automated driving.

A. SAFETY REQUIREMENTS

The common idea to improve the safety of automated vehicles is attaching multiple and multi-type sensors, e.g. cameras and Light Detection and Rangings (LiDARs) on board, which however exerts much pressure on the processing capability of a single vehicle. The sensor detection performance is also highly constrained by frequent blockage and extreme weather. To ensure the reliability of information acquisition, delivering alarm messages via V2X then becomes a new safety demand. Either DSRC or LTE-V2X can support this application for use cases like pre-crash warning [2]. Nonetheless, alarm messages discard many environmental details due to the restricted message size. Complete safety is hard to meet with the limited context information. In this regard, raw sensor data retains full environmental details, but meanwhile its dissemination desires higher performances of vehicular networks. The requirements on three different network layers are summarized as follows:

1) *High-rate V2X access layer:* The high-definition (HD) dynamic maps composed by sensor data are crucial for the ADSs to safely maneuver vehicles, in particular as a means to provide decimeter localization that consumer-grade GPS cannot achieve. For a LiDAR-generated HD map, the total data volume collected for the duration of one hour is about 1 TB, which corresponds to a 2.2 Gbps data output [65]. The required data rate for cooperative perception is analyzed based on an overtaking scenario, which reveals that over 1 Gbps LiDAR information per is needed on V2V links to ensure safety for vehicle

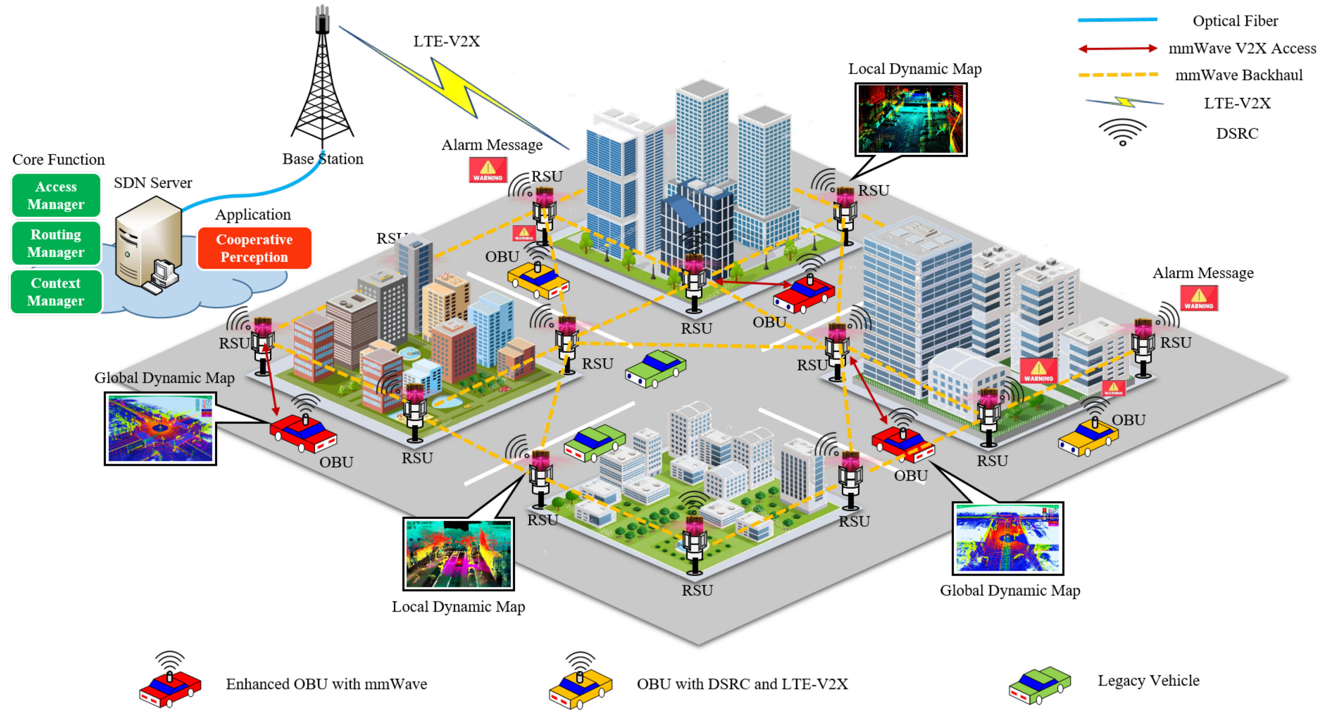


FIGURE 2. Software-defined dynamic mmWave V2X network for cooperative perception.

velocities above 70 km/h [66]. Hence, an estimation of 1 Gbps can be reasonably considered as the typical data rate requirement for exchanging HD information via V2X links.

2) *Low-latency and economical backhaul layer:* Vehicular backhaul refers to the associations from the source OBU to the destination OBU or RSU. The backhaul carries huge amounts of user traffic and should guarantee the QoS correspondingly, of which the latency is the most significant metric for safety-related services. For example, an end-to-end latency of less than 20 ms is tolerable for remote driving [3]. But HD map exchanging requires a more strict latency of less than 10 ms [65]. Besides, since a considerable number of RSU are being deployed to facilitate the penetration of automated vehicles, cost-efficient alternatives for optical fibers are much preferred to reduce the budget of vast backhaul construction.

3) *Ubiquitous and reliable control layer:* Inadequate challenges are posed to the vehicular network when transmitting alarm and other context information embedded in the Cooperative Awareness Message (CAM) [67] and the Decentralized Environmental Notification Message (DENM) [68]. However, the dissemination of raw sensor data or HD map can cause traffic congestion, load imbalance, etc that degrade the network performances. Therefore, a control layer with wide coverage should be supplied to manage global network resources and coordinate multi-hop flow transmission. Moreover, it is necessary to monitor the real-time vehicle status reliably in high dynamic contexts for safe automated driving.

B. ARCHITECTURE DESCRIPTION

Figure 2 gives an overview of the software-defined dynamic mmWave V2X network where cooperative perception is performing at urban intersections. In a mixed traffic environment, legacy vehicles and vehicles with OBUs coexist. For driving safety, alarm messages are broadcasted by OBUs and RSUs via LTE-V2X and DSRC. The contexts of legacy vehicles are captured by nearby RSUs which then send proxy notifications. As is mentioned above, HD dynamic maps measured by versatile sensors (e.g. LiDAR) are critical for automated vehicles to ensure safety. They can be basically divided into two types: the local dynamic map and the global dynamic map. The former indicates the single HD map captured by self-sensors connected with an OBU or a RSU. This sort of maps can provide the context information of surroundings, but it only covers LOS regions and is subject to the visual range of equipped sensors. In other words, the local dynamic map only helps with local environmental perception, which is inadequate for 100% driving safety. The latter indicates the merged multi-source HD map. Besides its own HD map, a certain automated vehicle can acquire more than one local dynamic maps from vehicles ahead or fixed RSUs that monitor particular areas at high views. The received maps is then merged into a global dynamic map that provides extra information of NLOS regions and enables proactive risk awareness and reaction.

The proposed architecture is intended to ensure global HD dynamic maps available for each OBU in demand. Cooperative perception of HD dynamic maps is running on the application plane. It utilizes the functions of SDN controller in the C-plane via the Northbound Interface (NBI) to distribute local dynamic maps according to the context information (velocity, location, destination, etc) collected from the participants, i.e. OBUs and RSUs via the Southbound Interface (SBI). The role of three major elements in this architecture is described in detail:

- *SDVN RSU:* Existing infrastructures like street lamps or traffic lights can be easily retrofitted into RSUs by mounting sensing, computing and communication modules. A RSU can directly share its raw/processed HD map with vehicular OBUs via V2I communications or simply forward map data via the backhaul network as relays. In the SDVN, RSUs belong to the D-plane, handling network traffic according to the decisions made by the C-plane and performing resource/mobility management (e.g. power allocation, channel/RAT handover, etc) under the instruction of SDVN controller.
- *SDVN OBU:* The OBU is commonly used to represent the automated vehicle but originally it refers to the platform of automated driving system, which takes raw sensing data coming from various on-board sensors (LiDAR, camera, GPS, gyro, etc) as input, develops dynamic path planning as intermediate results and finally maps to the appropriate action of the vehicular engine system as output. For the compatibility of cooperative perception, V2X module is added to receive external information. Multi-source data fusion is implemented before the path planning. In the SDVN, OBUs also belong to the D-plane and are controllable by the SDVN controller in terms of network selection, data relay and handoff.
- *SDVN controller:* As the core of the proposed architecture, SDVN controller locates at the C-plane and is responsible for tracking the network status including the dynamic topology and the resource distribution. It also accepts control edicts from the applications and applies them to the environment using specific protocols (OpenFlow, NetConf, SNMP, etc). In the scenario of cooperative perception, SDVN controller implements corresponding NBIs and SBIs for three key function components, i.e. context manager, access manager and routing manager. The context manager periodically requests the D-plane elements to upload their context information to the C-plane. Based on the context information, the access manager associates OBUs with the most appropriate RSUs. And then the routing manager pushes flows to promote the data sharing.

In order to meet the safety requirements from the aspect of vehicular network performances, mmWave as well as legacy V2X technologies are exploited:

1) *MmWave V2X access layer:* The broadband mmWave is the only means to support cooperative perception of HD maps, because the conventional V2X technologies, i.e. DSRC and LTE-V2X can not provide multi-gigabit data rates due to the limited bandwidth. In the proposed architecture, the access of mmWave V2X is under the coordination of SDN controller. With a global network view, the SDN controller can monitor the V2X status (e.g link stability) and help vehicles create dynamic V2X accordingly. Therefore, the negative impacts of severe path loss, blockage and fast fading on mmWave V2X can be timely noticed and minimized.
2) *MmWave backhaul layer:* The mmWave meshed network is a cost-efficient architecture that can be adopted to compose the vehicular backhaul. It can make full use of the network capacity enhanced by mmWave V2X. With SDN, the backhaul can be dynamically constructed in adaptation to the context information of the OBUs (e.g. position). Moreover, the QoS requirements such as optimum latency or bandwidth can be flexibly met by implementing various routing algorithms on the C-plane. Fast failover is another feature of such backhaul networks, since the SDN controller monitors the global link status in real time and can quickly handle any network failure.
3) *LTE-V2X/DSRC control layer:* Though the legacy V2X technologies cannot support the safety information (e.g. HD map) exchange which requires gigabit data rates and millisecond latency, they have demonstrated their adaptability and reliability of supporting a number of V2X services (e.g. pre-crash warning) in highly mobile environments. Hence, they are qualified to provide stable control signals for the SDVN C-plane. Since the LTE base station has a high penetration rate both in urban and rural areas, it can provide extensive user coverage. Meanwhile, free control resources will be usable as more and more DSRC modules are deployed in smart cities.

IV. INDOOR PROOF-OF-CONCEPT

In this section, initial proof-of-concept work with an indoor prototype system is presented to demonstrate the safety benefit of the proposed vehicular network architecture.

A. PROTOTYPE DETAILS

The deployment of the software-defined dynamic mmWave V2X network is initiated by the indoor implementation based on a prototype system. Table 1 lists the hardware components. The OBU consists of one 2D/3D LiDAR, a pair of WiGig antennas and one control PC. And it is built on the Kobuki Turtlebot II, a low-cost mobile robot for education and research. The equipped 2D/3D LiDARs are used to create dynamic HD maps for automated driving. And the WiGig antennas enable ultra-high rate mmWave V2X communications for map sharing. As the brain of the OBU, the control PC processes the input data, plans the navigation route and interacts with the engine of the robot based on the ROS, an open-source robotics software project that commonly utilized by application developers of automated driving. The RSU is

TABLE 1. **Indoor Prototype Hardware**

Hardware Name	Specifications
2D LiDAR	Model: Hokuyo UST-10LX Scan angle: 270° Resolution: 0.25° Rotation rate: 40Hz Accuracy: ±40mm
3D LiDAR	Model: Velodyne Lidar VLP-16 Scan angle: 30°(vertical), 360°(horizontal) Resolution: 2°(vertical), 0.1°-0.4°(horizontal) Rotation rate: 5-20Hz Accuracy: ±30cm
Wi-Fi AP	Model: Cisco Aironet 1850 Series Standards: IEEE 802.11n, 802.11ac MIMO: 4x4 Antenna: 2.4GHz/3dBi, 5GHz/5dBi, omni
WiGig $Antenna_1$	Model: Intel Lens Antenna Scan angle: ±4.5°(vertical), ±17°(horizontal) 3dB bandwidth: 7°(vertical), 3.5°(horizontal) Gain: 25.97dBi
WiGig $Antenna_2$	Model: Intel Lens Antenna Scan angle: ±7°(vertical), ±13.5°(horizontal) 3dB bandwidth: 6.4°(vertical), 2.9°(horizontal) Gain: 25.4dBi
Mobile Robot	Model: Kobuki Turtlebot II Maximum translational velocity: 70cm/s Payload: 5kg(hard floor), 4kg(carpet)
PC/Laptop	OS: Ubuntu 16.04 Wireless LAN: IEEE 802.11a/b/g/n/ac

composed of one 3D LiDAR, a pair of WiGig antennas and one management PC. One of the WiGig antenna is used for mmWave access, the other is used for mmWave backhaul. The management PC deploys application agents for C-plane registration and map merging, or simply forwards raw sensor data to the next hop through the OVS, an open-source implementation of a distributed virtual multilayer switch that supports OpenFlow protocols. The SDN controller is running on a PC with the ODL framework, which is the most pervasive open-source SDN controller that provides abundant native features and well-defined APIs for network monitoring and traffic management. In addition, ODL supports flexible deployments of customized applications or protocols, which contributes to the extension of control functions for the software-defined vehicular network.

Figure 3(a) and Fig. 3(b) present the architecture of the prototype system from the perspective of hardware configuration and software platform respectively. Since Wi-Fi is widely used indoors, it can replace DRSC and LTE-V2X in the PoC. As seen in Fig. 3(a), wireless C-plane is constructed by a cluster of Wi-Fi APs that are deployed on the corridor roof. Basically, the out-band control channel carries two types of messages. One is the context messages collected from D-plane elements (OBUs, RSUs) periodically. The other is the control messages (access control, routing control) sent from the SDN controller once cooperative perception is activated. WiGig antennas establish mmWave V2X links for D-plane, where big LiDAR traffic is transmitted through the organized path to the target OBU. According to the specifications, on the one hand, 2D LiDARs have shorter detection range but higher accuracy comparing with 3D LiDARs, so they are preferred to be used for the indoor PoC. On the other hand, 3D LiDARs generate more data volumes, which is suitable to highlight the performances of mmWave V2X transmission. Therefore in this PoC, 2D LiDAR maps will only be utilized for self-navigation while 3D LiDAR maps are shared to ensure better safety.

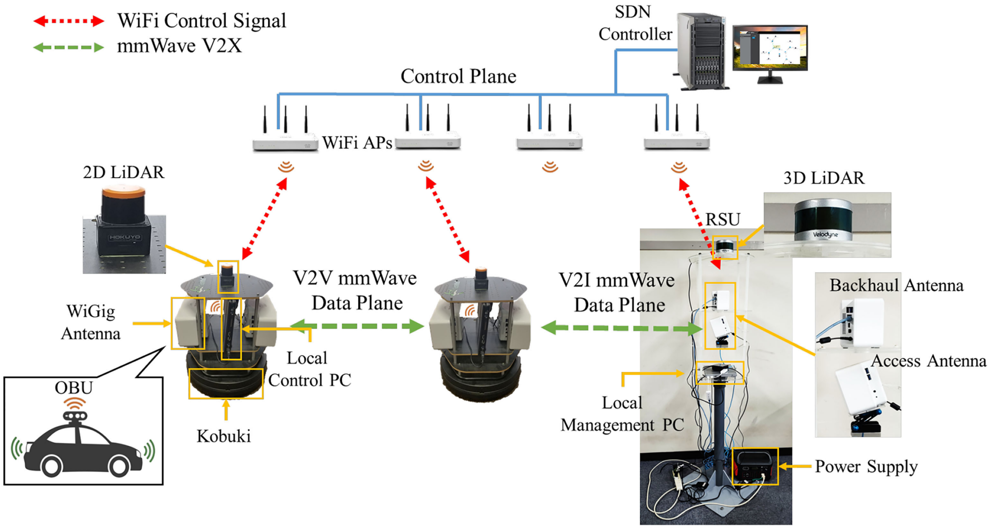
Open-source software also plays an important role in this prototype system. The three representatives are ODL, ROS and OVS, as shown in Fig. 3(b). SDN control relies on the ODL platform, in which both native and customized components are implemented. Native components such as the metrics collector and OpenFlow plugins provide basic network information and configuration tools. Upon them, customized components, i.e. context manager, access manager and routing manager in this case, achieve extensive functions for cooperative perception in the mmWave V2X networks. Automated driving of OBUs depends on the ROS, which provides hardware abstraction for robotics motion control by applications or algorithms, and device drivers for 2D/3D LiDARs. Based on these fundamentals, Simultaneous Localization And Mapping (SLAM) is implemented to create static and dynamic maps for automated navigation. In addition, OVS enables the map sharing among D-plane elements. Through the OpenFlow SBI, OVS updates flow tables that decide the data forwarding according to the dynamic routing decisions made by SDN controller.

B. COOPERATIVE PERCEPTION OVER MMWAVE V2V

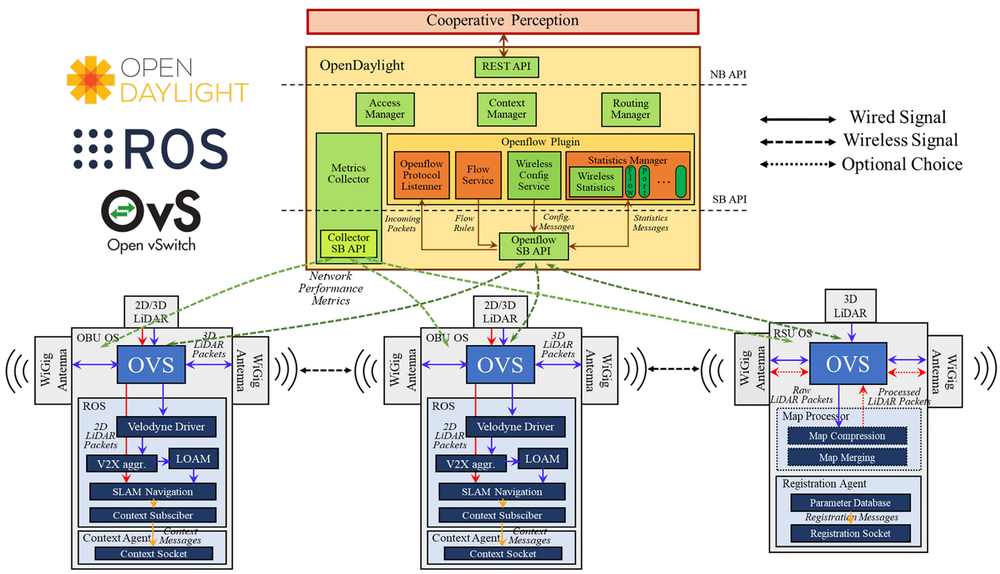
Although on-board sensors are replacing human drivers' eyes, the vision of automated vehicles can still be blocked by obstacles while driving. For example, when inter-vehicle distance becomes too short, the front vehicle may decrease the LOS area of the behind vehicle, as shown in Fig. 4. This will lead to potential traffic hazards if the behind vehicle tries to overtake without the notification of oncoming vehicles or passes through a busy intersection without the information of both sides. Therefore, in order to acquire a boarder view for safe driving, cooperative perception is necessary between the front vehicle and the behind vehicle over mmWave V2V. Under the proposed architecture, SDN controller periodically collects the context information of the two vehicles. Context information such as vehicle position, Received Signal Strength Indicator (RSSI), and etc can be the reference for mmWave access configuration. As soon as the V2V link is established, routing configuration messages are distributed to both vehicles to direct the data flows from OBUs.

To demonstrate the performance of our prototype system in above-mentioned scenario, an indoor PoC[1] is carried out. The test field is a long corridor over 50 meters with a single fork. Two OBUs are deployed to represent the vehicle front and the vehicle behind. Since the corridor width is narrow, about 2 meters, it is hard for the OBU to detect the region behind the fork before the OBU comes very close. Therefore, the OBU front will take responsibility to transmit its 3D LiDAR map which contains the information of this NLOS

[1] https://www.youtube.com/watch?v=a5fd5oXv4qI



(a) Hardware configuration



(b) Software platform

FIGURE 3. **Prototype details of indoor proof-of-concept.**

area for the OBU behind. As Fig. 5(a) indicates, the Wi-Fi APs on the roof provide wireless C-plane. SDN controller activates cooperative perception via mmWave V2V according to the vehicle's relative distance (e.g. 5 m), which can be determined by different safety requirements based on the speed or the degree of visual obstruction. Fig. 5(b) shows the map transmission process. The received 3D LiDAR map is presented at the top right of the figure. Apparently, the perception of the OBU behind is greatly enhanced that it can touch the field beyond LOS, as circled in Fig. 5(c), which highlights the benefit of mmWave V2V for large LiDAR data transmission. Besides, with software-defined mmWave V2V communications, the timing for cooperative perception can be flexibly modified by applications depending on specific safety requirements.

C. COOPERATIVE PERCEPTION OVER MMWAVE V2I

Besides V2V communications, another sensible method to improve the driving safety is to communicate with RSUs, of which wider deployments can be envisioned in the future ITS. To save costs, RSUs are probably installed on the existing road infrastructures like street lamps and traffic lights. Meanwhile, their higher altitude than OBUs' brings them bird's eye views for broader monitoring. This contributes to the early warning in blind areas when a vehicle tries to pass the intersection with heavy traffic, as shown in Fig. 6. By cooperative perception

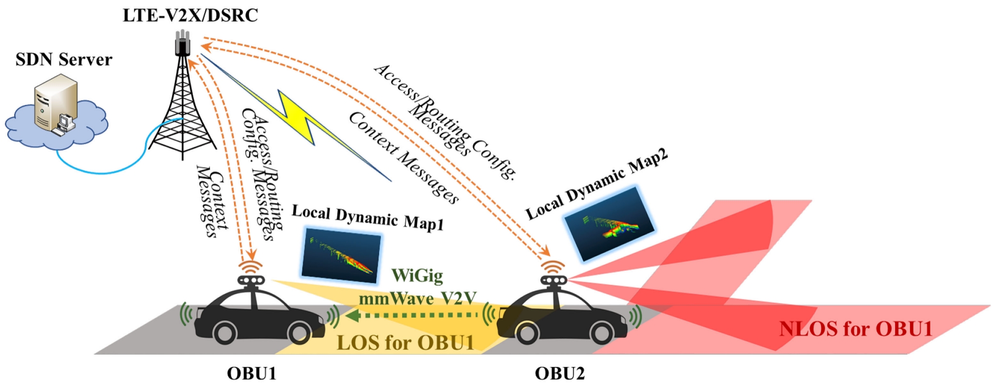


FIGURE 4. Scenario of cooperative perception over mmWave V2V.

over mmWave V2I, dynamic HD maps from the RSU can be exploited to compensate for the loss of vehicle perception in NLOS regions. Under the proposed architecture, this process is also managed by SDN controller. Once a RSU is built, its location and coverage will be record to the global topology. When vehicles move towards the RSU, their real-time positions are collected and used for control. If the relative distance is within the coverage, SDN controller starts mmWave access and routing configurations to perform cooperative perception.

To demonstrate our prototype system also adapts to this scenario, an indoor PoC is implemented. The test field keeps the same as previous mmWave V2V demonstration, where a fork of the corridor results in a NLOS region for upcoming vehicles. In this case, one OBU is deployed on the Kobuki robot and one RSU is installed on a multilayer bracket. The bracket is placed near the fork, but at the opposite side for global LiDAR monitoring. The communication coverage of RSU is an importance parameter that should be predefined and registered to the SDN controller. Although transmission throughput suffers from severe reflections in indoors, it remains higher than 1 Gbps up to 35 m. Moreover, transmission latency fluctuates slightly within the whole distance of the corridor (approximately 2.5 ms/packet). Considering the NLOS distance from the fork, the coverage value is set to 5 m. Fig. 7(a) shows the scenario when the OBU is moving out of the coverage. In the top right of the figure, the merged LiDAR map only contains the static map (grey points) and the OBU map (red points), which means the cooperative perception is still off. Since the indicated NLOS region is uncovered with dynamic point clouds, automated driving is under risks. Instead, Fig. 7(b) shows the scenario when the OBU moves into the coverage. At this moment, cooperative perception is initiated by SDN controller. In the top right of the figure, the RSU map (green points) appears in the merged LiDAR map and its dynamic point clouds already cover the NLOS region before the OBU arrives at the fork. Hence, with software-defined mmWave V2I communications, the driving safety is greatly improved.

TABLE 2. Outdoor Prototype Hardware

Hardware Name	Specifications
WiGig AP	Model: NETGEAR X10 R9000 Standards: IEEE 802.11ac, 802.11ad Bands: 800Mbps@2.4GHz, 1733Mbps@5GHz, 4600Mbps@60GHz
WiMAX Card	WAN interface: WiMAX 2+@2.5GHz Speed: Uplink$\leqslant$30Mbps, Downlink$\leqslant$440Mbps Size: 111$\times$62$\times$13.3mm
PC/Laptop	Model: Acer TravelMate Series OS: Ubuntu 16.04 USB ports: 4 WLAN interface: 802.11ac, 802.11ad, Bluetooth
Vehicle	Model_1: Toyota Estima (grey) w OBU Model_2: Toyota Ractis (blue) w/o OBU

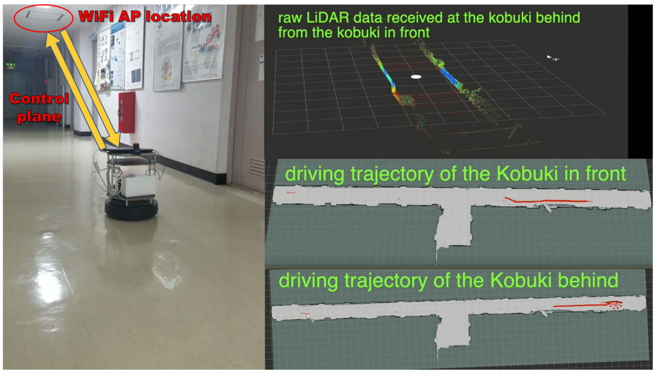
V. OUTDOOR PROOF-OF-CONCEPT

In this section, outdoor proof-of-concept work is conducted with additional hardware. The scenario of field trial is introduced and the safety improvement is reflected from the results.

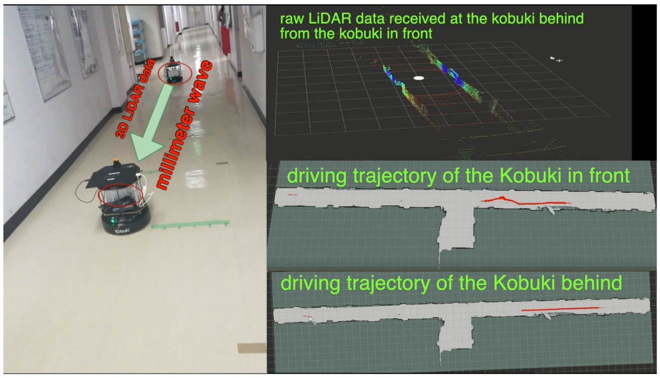
A. PROTOTYPE HARDWARE

The indoor prototype system has achieved the network functions for software-defined mmWave V2X, and the indoor PoC has demonstrated its effectiveness for safety enhancement under two typical modes of cooperative perception, i.e. mmWave V2V and mmWave V2I communications. In order to test the robustness and reliability of our network in real environments, an outdoor PoC[2] will proceed by replacing or adding some hardware for the new outdoor prototype system. Table 2 lists the additional hardware. In this case, the OBU is directly deployed to a real vehicle rather than the mobile robot. A 3D LiDAR with the same type as indoors is fixed on the top of the vehicle. The model of the control PC is substituted by Acer, which builds in 802.11ad chipsets. It comes with the 32-element phased antenna array. Therefore, it's not necessary for the OBU to equip another WiGig

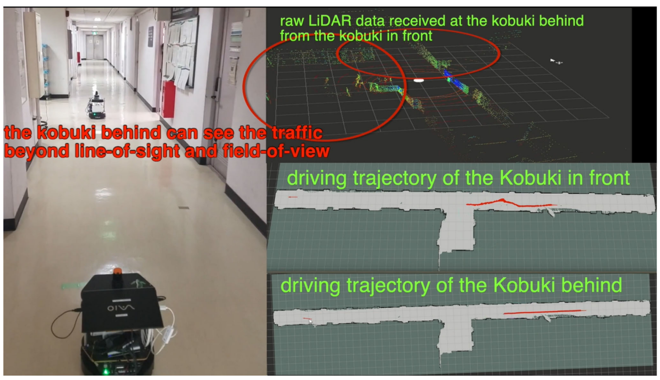
[2]https://www.youtube.com/watch?v=di1GUaA5Q4I



(a) SDN control through Wi-Fi signal



(b) Cooperative perception via mmWave V2V



(c) Enhanced driving safety

FIGURE 5. Scenario and demonstration for software-defined mmWave V2V.

antenna as indoors so the volume can be more compact and the power consumption can be less. As for the RSU, one of its antennas that serves for mmWave access is replaced by NETGEAR X10 R9000, which uses 802.11ad module and can switch to the AP mode. Saha *et al.* completed a review of the connection performances between Acer and NETGEAR X10 R9000 using WiGig, showing that the maximum transmission range in outdoors is about 20 m when the average throughput is above 1 Gbps, and the Gbps communication is possible for client angles in $[-60^\circ, 75^\circ]$ or AP angles in $[-45^\circ, 30^\circ]$ [69]. Since the outdoor field is too wide to be covered by Wi-Fi signals, WiMAX cards are utilized to provide wireless C-plane at 2.5 GHz, performing the same roles of DSRC and LTE-V2X as the system design. The supported speeds for uplink and downlink transmission are adequate because the context messages and control messages won't occupy so much bandwidth.

Figure 8 gives an overview of the hardware configuration for the outdoor prototype system, which includes one OBU, two RSUs and one SDN control server. Since the demonstrations of indoor prototype system doesn't take mmWave backhaul capacity into account, the new prototype system will incorporate one mmWave backhaul link between the RSUs for dynamic map routing. Therefore, the network performances of mmWave V2X access, mmWave backhaul and SDN management can be all confirmed in the outdoors. Note that each D-plane and C-plane element is equipped with a WiMAX card for stable interconnections. And the only OBU appears twice in Fig. 8 just in order to highlight the association handover with RSU1 and RSU2. Considering the limited perception range of 2D LiDARs, they will not be used in the outdoor PoC.

B. SCENARIO DESCRIPTION

The test field is selected at a L-shaped bend. In addition to the test vehicle with OBU, non-test vehicles in the lane are also passing normally. The driving route of the OBU has been marked on the photo of Fig. 9. To set up a dangerous scene artificially, a blue vehicle without OBU is hidden as an oncoming vehicle at the other end of the L-shaped bend, which belongs to the NLOS region of the OBU. In Fig. 9, the locations of the two RSUs are indicated by red points. They are deployed at each side of the bend, so their LiDAR views can fully cover the dynamic environments of the whole area. Because the WiMAX base station has very wide coverage, the SDN controller can be placed even miles away. In order to test cooperative perception through the software-defined dynamic mmWave V2X network, along the driving route, network functions will be implemented by four steps. ① **Leave the start point:** When the test vehicle begins to move from the start point, the OBU is still out of the communication coverage of any RSU, which is set to 20 m in outdoors. At the moment, SDN controller will not activate cooperative perception but continuously collects and judges the context information (i.e. position) from the OBU via WiMAX C-plane. ② **Associate with RSU1:** When the test vehicle approaches RSU1. As soon as it enters the communication coverage, SDN controller will send configuration messages for V2X access and backhaul routing, by which the local dynamic maps from RSU1 and RSU2 are simultaneously forwarded to the OBU via mmWave D-plane. Then the OBU can create a global dynamic map using map merging techniques. ③ **Handover to RSU2:** After the test vehicle passes RSU1, for the OBU, its dynamic map will not benefit the driving safety any more. When the OBU enters the coverage of RSU2, SDN controller will send configuration messages for mmWave V2X handover. In this case, only the dynamic map of RSU2 will be forwarded to the OBU without utilizing the mmWave backhaul. ④ **Pass the bend:**

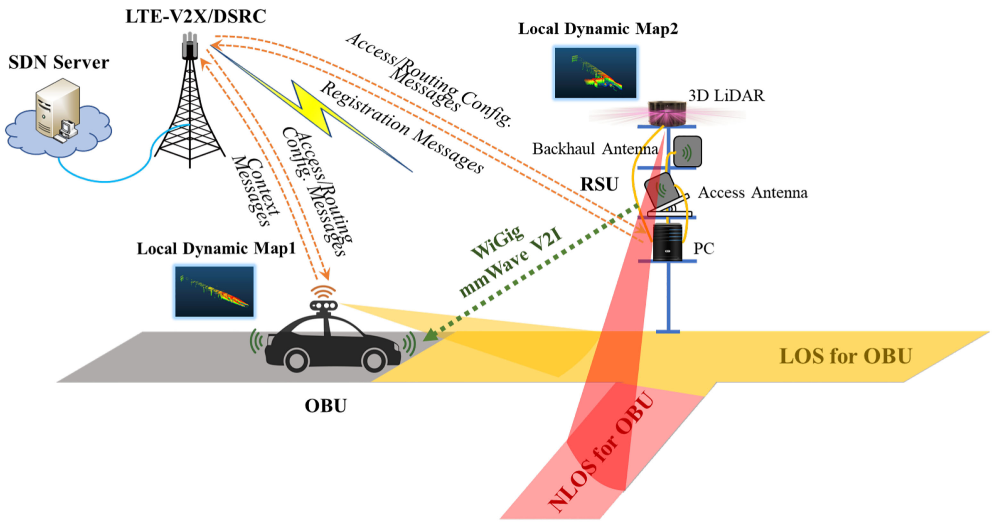
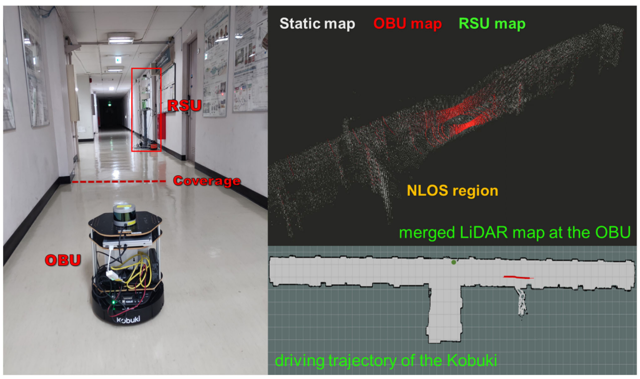
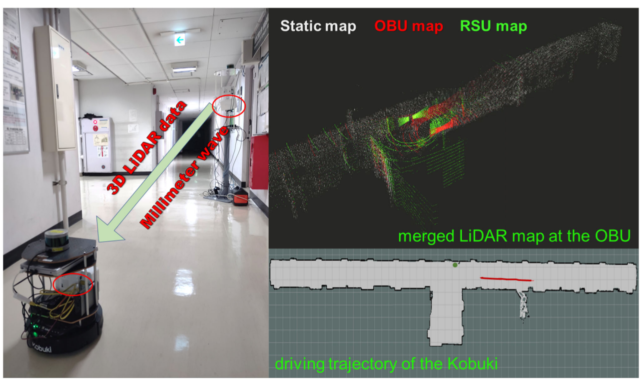


FIGURE 6. **Scenario of cooperative perception over mmWave V2I.**



(a) Driving without cooperative perception



(b) Cooperative perception via mmWave V2I

FIGURE 7. **Scenario and demonstration for software-defined mmWave V2I.**

With cooperative perception, the test vehicle is expected to drive through the bend safely. After it leaves the coverage of RSU2. SDN controller will deactivate cooperative perception.

As a matter of fact, it is the interactions of C-plane and D-plane that achieves the SDN control in above mentioned scenario. The details are described in Fig. 10. The process starts from the registration of RSUs as soon as they are deployed. The registration information includes ID numbers, locations, AP parameters and etc. This information is integrated on the C-plane and used to generate a backhaul network topology for V2X. From the SLAM, the OBU subscribes the context information (vehicle position) and uploads to SDN controller almost in real time. When the trigger condition is reached, i.e. within the communication coverage, SDN controller will activate cooperative perception by firstly distributing new flow tables to all D-plane elements for map data routing. Secondly, mmWave V2X access will be established or handover under the coordination of SDN controller. Note that the MEH which indicates the mobile edge host plays a role of map merging and can be located both in RSU and OBU.

C. RESULTS OF FIELD TRIAL

The Graphical User Interface (GUI) of OBU presents the received and merged LiDAR point clouds from dynamic cooperative perception, which are important resources for SLAM-based navigation. In Fig. 11, the three sub-figures correspond to the three critical steps of safe automated driving mentioned in the last subsection. Fig. 11(a) shows the dynamic HD map of OBU when it starts to move. In the map, the white point clouds form the static map and will be updated in a long period. Besides, the green point clouds from the OBU LiDAR compose the dynamic vehicle map. Except the static map and the vehicle map, no RSU maps appear in the GUI since cooperative perception is not activated yet, i.e. the OBU has not reached the communication coverage of RSU1. In this case, the perception range of OBU is too limited to detect the potential risk at the other side of the bend.

Figure 11(b) and Fig. 11(c) show the dynamic HD maps of OBU when mmWave V2X association and handover are implemented by dynamic cooperative perception. In Fig. 11(b), RSU1 map (red point clouds) and RSU2 map (yellow point

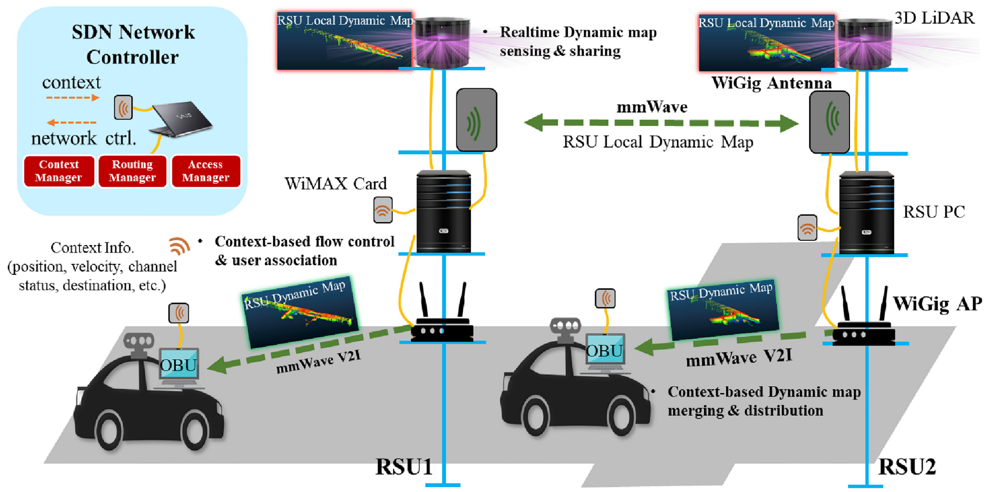


FIGURE 8. Hardware configuration for the outdoor prototype system.

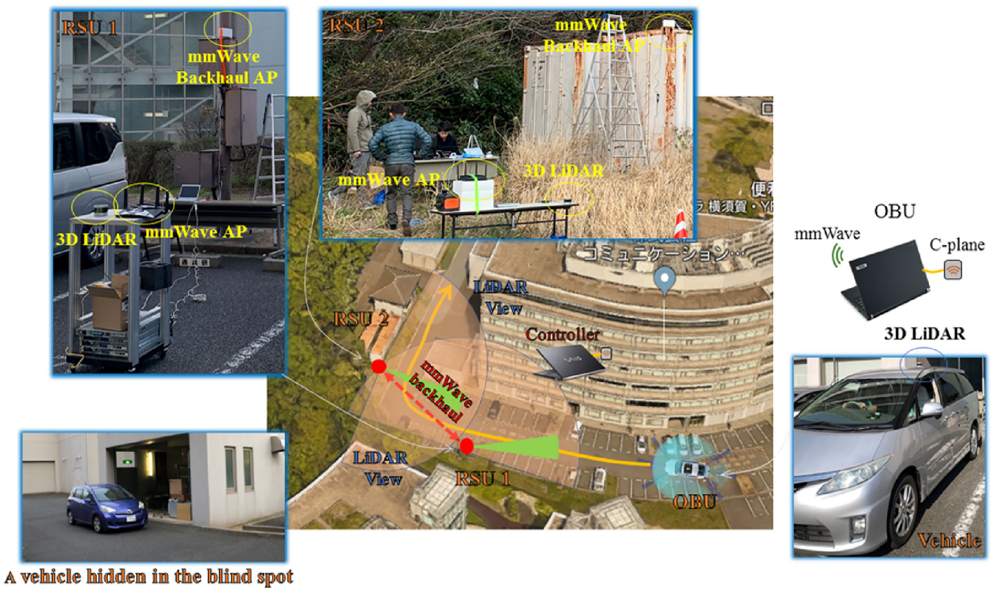


FIGURE 9. Photos of field trial.

clouds) both appear. This is in accordance with the mechanism, that all local dynamic maps of RSUs will be forwarded to the OBU through the mmWave backhaul and V2X links under SDN control. The merged global dynamic map greatly extends the perception range of OBU as it can detect an oncoming vehicle in the NLOS region (56.86 m away, 5.12 s in advance when vehicle velocity equals 40 km/h), and then take earlier measures (e.g. emergency brake) to avoid the collision. If there is no terrain restriction, this perception performance can be further enhanced. The deployed mmWave backhaul antennas support a communication range over 200 m, thus a vehicle at 80 km/h will get more than 10 s to respond. Furthermore, Fig. 11(c) presents the handover scene, in which the mmWave V2X switches to the RSU2 since the RSU1 map no longer provides safety-related information. At the moment, the global map only consists of the static map, the vehicle map and the RSU2 map. Although the red point clouds remain in the GUI, they already became static. On the contrary, the yellow point clouds fully cover the moving vehicle, which indicates that the RSU2 map is dynamically transmitting to the OBU.

Figure 12 presents critical network performance indicators measured while the vehicle is staying within the RSU coverage (i.e. 20 m). As Fig. 12(a) shows, with mmWave V2X, both of the Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) throughputs exceed 1 Gbps. A peak value of 2.01 Gbps appears when using TCP and keeping the LOS distance of 5 m between RSU and OBU. Even at the coverage edge, the throughputs of TCP and UDP still sustain at a relatively high level, i.e. 1.65 Gbps and 1.52 Gbps

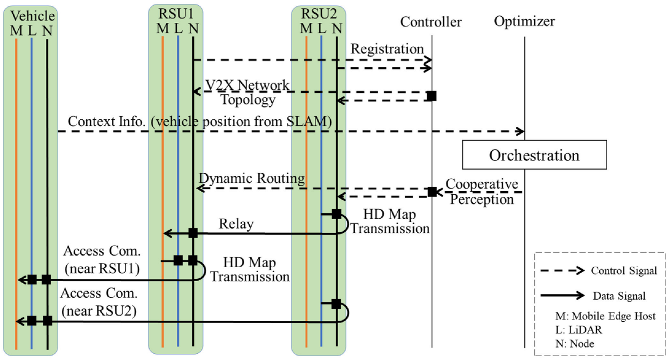
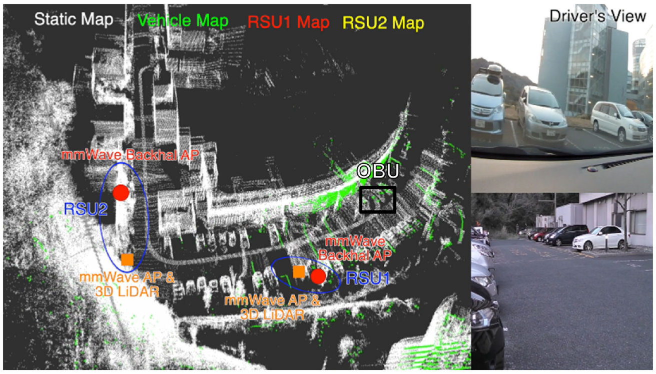
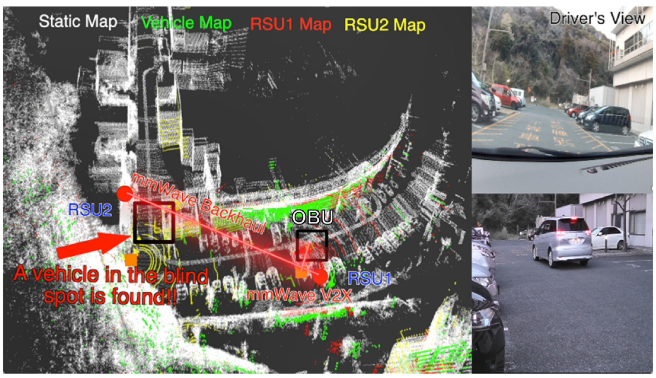


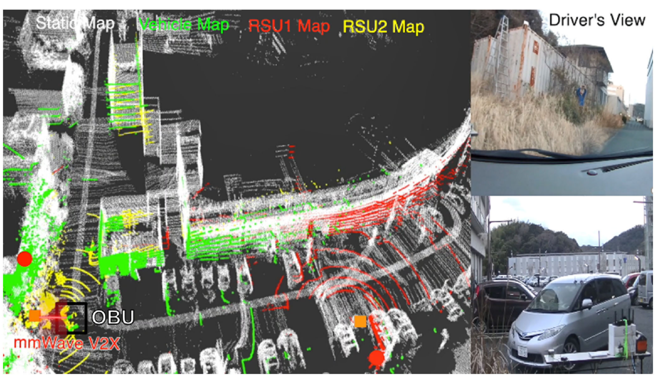
FIGURE 10. Interactions between C-plane and D-plane.



(a) Leave the start point



(b) Associate with RSU1



(c) Handover to RSU2

FIGURE 11. Point clouds of OBU from dynamic cooperative perception.

respectively, which far surpass the maximum theoretical values of legacy V2X (e.g. 27 Mbps of DSRC and 28.8 Mbps of LTE PC5). Since the LiDAR utilized in the field trial generates UDP packets with a size of 1248 bytes, the latency performance of mmWave V2X for one LiDAR packet transmission is evaluated. As shown in Fig. 12(b), the average Round-Trip Time (RTT) at 5 m and 20 m are 1.116 ms and 1.048 ms respectively. It does not reveal any appreciable performance degradation as the LOS distance increases. Besides, all measured latency within the RSU coverage is less than 3 ms which is already the toughest latency requirement for sensor information sharing claimed in the 3GPP Technical Specification (TS) 22.186 [70]. In addition, the packet loss rate of UDP transmission via mmWave V2X is recorded to characterize its reliability. As Fig. 12(c) shows, although the packet loss rate slightly grows as the LOS distance increases, the highest value is 0.043% at 20 m. It keeps below 0.05%. Therefore in this network, mmWave V2X can ensure a reliability of at least 99.95% for LiDAR map transmission within the RSU coverage.

Throughout the entire process of automated driving, SDN management does endow efficiency and flexibility to mmWave association and backhaul routing, and also provides remarkable safety enhancements to the OBU, which demonstrates the benefits of our proposed network architecture.

VI. CONCLUSION

The commercial roll-out of 5G will create a new era for ITS. As two key technologies of 5 G, SDN and mmWave communications have many use cases in vehicular networks to promote safe automated driving. The benefits of mmWave V2X and SDVN have been revealed by plenty of state-of-the-art works respectively. However, research concerning to their integration is still a vacancy, especially lack of prototype systems to do proof-of-concepts. In this contribution, we discuss the requirements on vehicular network performance towards safe automated driving. Based on the discussion, a software-defined dynamic mmWave V2X network is proposed for cooperative perception. Beyond that, we introduce the necessary hardware and software platforms to build prototype systems for indoor and outdoor PoCs. In the indoor PoC, the two modes of software-defined cooperative perception are implemented over mmWave V2V/V2I communications, showing that the indoor prototype system can achieve the network functions of the proposed architecture. Furthermore, with additional hardware, the outdoor PoC is carried out in real road environments. Under the management of SDN controller, dynamic cooperative perception for HD map distribution in a challenging bend scenario is successfully performed, which reflects not only the prototype scalability in outdoors but also the great enhancement to vehicle perception for driving safety.

In the future work, we will design a service-oriented performance evaluation model for this system, and carry out performance tests in various outdoor scenarios. The prototype system shall be further enhanced by enabling MEC for

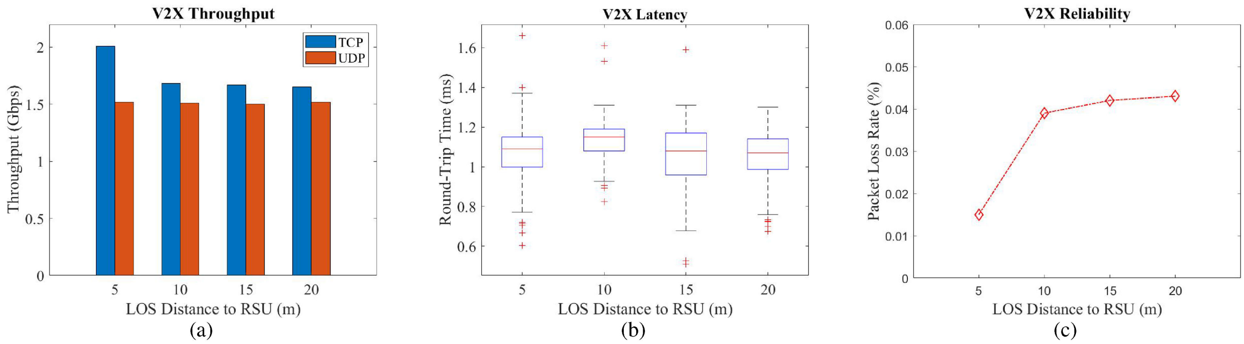


FIGURE 12. Network performance with mmWave V2X. (a) Transmission throughput between RSU and OBU within the coverage; (b) Transmission latency for one LiDAR packet of 1248 bytes; (c) Packet loss rate of UDP transmission.

delay-sensitive/safety-critical services and deploying artificial intelligence (AI) for complex network management.

REFERENCES

[1] Strategic Headquarters for the Advanced Information and Telecommunications Network Society, "Public-Private ITS Initiative/Roadmaps 2019," Strategic Conference for the Advancement of Utilizing Public and Private Sector, Data National Strategy Office of Information and Communications Technology, Cabinet Secretariat, Tokyo, Japan, Jun. 2019, [Online]. Available: http://japan.kantei.go.jp/policy/it/2019/2019_roadmaps.pdf

[2] 3GPP TR22.885, "Study on LTE support for vehicle-to-everything (V2X) services," 3rd Generation Partnership Project (3GPP), Sophia Antipolis Valbonne, France, Tech. Rep. 22.885, Version 14.0.0, Dec. 2015.

[3] 3GPP, "Study on enhancement of 3GPP support for 5G V2X services," 3rd Generation Partnership Project (3GPP), Sophia Antipolis Valbonne, France, Tech. Rep. 22.885, Version 16.2.0, Dec. 2015.

[4] M. Boban, A. Kousaridas, K. Manolakis, J. Eichinger and W. Xu, "Connected roads of the future: Use cases, requirements, and design considerations for Vehicle-to-Everything communications," *IEEE Veh. Technol. Mag.*, vol. 13, no. 3, pp. 110–123, Sep. 2018.

[5] CISCO Whitepaper, "CISCO visual networking index: Globalmobile data traffic forecast update, 2016–2021," Feb. 2017.

[6] ETSI, "Intelligent transport systems (ITS), access layer specification for intelligent transport systems operating in the 5 GHz frequency band," Eur. Standard ETSI EN 302 663 (V1.2.0), Eur. Telecommun. Standards Inst., Sophia-Antipolis, France, Nov. 2012. [Online]. Available: https://www.etsi.org/deliver/etsi_en/302600_302699/302663/01.02.00_20/en_302663v010200a.pdf

[7] J. B. Kenney, "Dedicated short-range communications (DSRC) standards in the United States," *Proc. IEEE*, vol. 99, no. 7, pp. 1162–1182, Jul. 2011.

[8] 3GPP, "Vehicle-to-everything (V2X) related items," 3rd Generation Partnership Project (3GPP), Tech. Rep. 21.914, Sophia Antipolis Valbonne, France, V14.0.0, May 2018, pp. 21–28.

[9] E. Uhlemann, "Connected-vehicles applications are emerging," *IEEE Veh. Technol. Mag.*, vol. 11, no. 1, pp. 25–96, Mar. 2016.

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

[11] A. A. Khan, M. Abolhasan and W. Ni, "5G next generation VANETs using SDN and fog computing framework," in *Proc. 15th IEEE Annu. Consum. Commun. Netw. Conf.*, Las Vegas, NV, USA, pp. 1–6, 2018.

[12] L. Nkenyereye, L. Nkenyereye, S. M. R. Islam, C. A. Kerrache, M. Abdullah-Al-Wadud and A. Alamri, "Software defined network-based multi-access edge framework for vehicular networks," *IEEE Access*, vol. 8, pp. 4220–4234, 2020.

[13] R. R. Fontes, S. Afzal, S. H. Brito, M. A. Santos, C. E. Rothenberg, "Mininet-WiFi: Emulating software-defined wireless networks," in *Proc. 11th Int. Conf. Netw. Serv. Manage.*, pp. 384–389, Sep. 2015.

[14] Netgear Nighthawk X10 Smart WiFi Router. [Online]. Available: https://www.netgear.com/landings/ad7200/

[15] UST-10LX 2D Hokuyo LiDAR. [Online]. Available: https://hokuyo-usa.com/products/lidar-obstacle-detection/ust-10lx

[16] Velodyne Lidar PUCK^{TM}. [Online]. Available: https://www.amtechs.co.jp/product/VLP-16-Puck.pdf

[17] K. Turtlebot II. [Online]. Available: https://www.turtlebot.com/turtlebot2/

[18] OpenDaylight Project. [Online]. Available: https://www.opendaylight.org/

[19] Open Vswitch Documentation. [Online]. Available: https://docs.openvswitch.org/en/latest/

[20] ROS Framework. [Online]. Available: http://wiki.ros.org/

[21] Z. Li, T. Yu, R. Fukatsu, G. K. Tran and K. Sakaguchi, "Proof-of-concept of a SDN based mmWave V2X network for safe automated driving," in *Proc. IEEE Global Commun. Conf.*, Waikoloa, HI, USA, 2019, pp. 1–6.

[22] T. Shimizu, V. Va, G. Bansal and R. W. Heath, "Millimeter wave V2X communications: Use cases and design considerations of beam management," in *Proc. Asia-Pacific Microw. Conf.*, Kyoto, Japan, 2018, pp. 183–185.

[23] ITU-R, "Final Acts WRC-15 World Radiocommunication Conference," Int. Telecommun. Union, Geneva, Switzerland, Nov. 2015, [Online]. Available: https://www.itu.int/dms_pub/itu-r/opb/act/R-ACT-WRC.12-2015-PDF-E.pdf

[24] European Commission, "5G for Europe: An action plan," Sep. 2016, pp. 1–11. [Online]. Available: https://ec.europa.eu/transparency/regdoc/rep/1/2016/EN/1-2016-588-EN-F1-1.PDF

[25] FCC, "Report and order and further notice of proposed rulemaking," Fed. Commun. Commiss., Washington, DC, USA, Jul. 2016. [Online]. Available: https://docs.fcc.gov/public/attachments/FCC-16-89A1.pdf

[26] 5GMF White Paper, "5G mobile communications systems for 2020 and beyond," Jul. 2016.

[27] K. Sakaguchi *et al.*, "Where, when, and how mmWave is used in 5G and beyond," *IEICE Trans. Electron*, vol. E100-C, no. 10, pp. 790–808, Oct. 2017.

[28] E. Ben-Dor, T. S. Rappaport, Y. Qiao and S. J. Lauffenburger, "Millimeter-wave 60 GHz outdoor and vehicle AOA propagation measurements using a broadband channel sounder," in *Proc. IEEE Glob. Telecommun. Conf.*, Houston, TX, USA, pp. 1–6, 2011.

[29] L. Wang *et al.*, "Vehicle-to-infrastructure channel characterization in urban environment at 28 GHz," *China Commun.*, vol. 16, no. 2, pp. 36–48, Feb. 2019.

[30] M. Boban *et al.*, "Multi-band vehicle-to-vehicle channel characterization in the presence of vehicle blockage," *IEEE Access*, vol. 7, pp. 9724–9735, 2019.

[31] A. Yamamoto, K. Ogawa, T. Horimatsu, A. Kato and M. Fujise, "Path-loss prediction models for intervehicle communication at 60 GHz," *IEEE Trans. Veh. Technol.*, vol. 57, no. 1, pp. 65–78, Jan. 2008.

[32] J. Park, J. Lee, J. Liang, K. Kim, K. Lee and M. Kim, "Millimeter wave vehicular blockage characteristics based on 28 GHz measurements," in *Proc. IEEE 86th Veh. Technol. Conf.*, Toronto, ON, Canada, 2017, pp. 1–5.

[33] X. Cai, C. Han and K. Sarabandi, "Phenomenology of foliage effect on 5G millimeter-wave V2V communications," in *Proc. IEEE Glob. Commun. Conf.*, Abu Dhabi, United Arab Emirates, 2018, pp. 1–6.

[34] M. Giordani, T. Shimizu, A. Zanella, T. Higuchi, O. Altintas and M. Zorzi, "Path loss models for V2V mmWave communication: Performance evaluation and open challenges," in *Proc. 2nd IEEE Connected Autom. Veh. Symp.*, Honolulu, HI, USA, 2019, pp. 1–5.
[35] V. Va, Takayuki Shimizu, Gaurav Bansal, RobertW. Heath Jr., "Millimeter wave vehicular communications: A survey," *Foundations Trends Netw.*, vol. 10, no. 1, pp. 1–118, Jun. 2016, doi: 10.1561/1300000054.
[36] 3GPP TR37.885, "Study on evaluation methodology of new vehicle-to-everything V2X use cases for LTE and NR," V15.0.0, Jun. 2018.
[37] J. Choi, V. Va, N. Gonzalez-Prelcic, R. Daniels, C. R. Bhat, R. W. Heath, "Millimeter-wave vehicular communication to support massive automotive sensing," *IEEE Commun. Mag.*, vol. 54, no. 12, pp. 160–167, Dec. 2016.
[38] N. González-Prelcic, R. Méndez-Rial and R. W. Heath, "Radar aided beam alignment in MmWave V2I communications supporting antenna diversity," in *Proc. Inf. Theory Appl. Workshop*, La Jolla, CA, USA, 2016, pp. 1–7.
[39] N. Gonzalez-Prelcic, A. Ali, V. Va and R. W. Heath, "Millimeter-wave communication with out-of-band information," *IEEE Commun. Mag.*, vol. 55, no. 12, pp. 140–146, Dec. 2017.
[40] I. Mavromatis, A. Tassi, R. J. Piechocki, A. Nix, "Beam alignment for millimetre wave links with motion prediction of autonomous vehicles," in *Proc. IET Colloq. Antennas Propag. RF Technol. Trans. Auton. Platforms*, Birmingham, U.K., 2017, pp. 1–8, doi: 10.1049/ic.2017.0023.
[41] V. Va, J. Choi, T. Shimizu, G. Bansal and R. W. Heath, "Inverse multipath fingerprinting for millimeter wave V2I beam alignment," *IEEE Trans. Veh. Technol.*, vol. 67, no. 5, pp. 4042–4058, May 2018.
[42] Y. Wang, A. Klautau, M. Ribero, M. Narasimha and R. W. Heath, "MmWave vehicular beam training with situational awareness by machine learning," in *Proc. IEEE Globecom Workshops*, Abu Dhabi, United Arab Emirates, pp. 1–6, 2018.
[43] Y. Sugihara, K. Sakaguchi, "mmWave massive analog relay MIMO for improvement of channel capacity," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Seoul, Korea, May 2020.
[44] Y. Yin, H. Chen, Z. Li, T. Yu, and K. Sakaguchi, "Design of antenna configuration for interference control in mmwave V2V communication systems," in *Proc. 92nd IEEE Veh. Technol. Conf.*, Victoria, BC, Canada, Oct. 2020, pp. 1–6.
[45] D. Kreutz, F. M. V. Ramos, P. E. Veríssimo, C. E. Rothenberg, S. Azodolmolky and S. Uhlig, "Software-defined networking: A comprehensive survey," *Proc. IEEE*, vol. 103, no. 1, pp. 14–76, Jan. 2015.
[46] N. McKeown *et al.*, "Openflow: Enabling innovation in campus networks," *SIGCOMM Comput. Commun. Rev.*, vol. 38, no. 2, pp. 69–74, 2008.
[47] S. Costanzo, L. Galluccio, G. Morabito and S. Palazzo, "Software defined wireless networks: Unbridling SDNs," presented at the *2012 Eur. Workshop Softw. Defined Netw.*, Darmstadt, Germany, pp. 1–6, 2012.
[48] T. Chen, M. Matinmikko, X. Chen, X. Zhou and P. Ahokangas, "Software defined mobile networks: Concept, survey, and research directions," *IEEE Commun. Mag.*, vol. 53, no. 11, pp. 126–133, Nov. 2015.
[49] G. K. Tran *et al.*, "Context-based dynamic meshed backhaul construction for 5G heterogeneous networks," *J. Sens. Actuator Netw.*, vol. 7, no. 4, Oct. 2018, Art. no. 43.
[50] I. Ku, Y. Lu, M. Gerla, R. L. Gomes, F. Ongaro and E. Cerqueira, "Towards software-defined VANET: Architecture and services," in *Proc. 13th Annu. Mediterranean Ad Hoc Netw. Workshop*, Piran, Solvenia, pp. 103–110, 2014.
[51] K. Zheng, L. Hou, H. Meng, Q. Zheng, N. Lu and L. Lei, "Soft-defined heterogeneous vehicular network: Architecture and challenges," *IEEE Netw.*, vol. 30, no. 4, pp. 72–80, Jul./Aug. 2016.
[52] Y. Zhang, H. Zhang, K. Long, Q. Zheng and X. Xie, "Software-defined and fog-computing-based next generation vehicular networks," *IEEE Commun. Mag.*, vol. 56, no. 9, pp. 34–41, Sep. 2018.
[53] J. Liu, J. Wan, B. Zeng, Q. Wang, H. Song and M. Qiu, "A scalable and quick-response software defined vehicular network assisted by mobile edge computing," *IEEE Commun. Mag.*, vol. 55, no. 7, pp. 94–100, Jul. 2017.
[54] X. Cheng, C. Chen, W. Zhang and Y. Yang, "5G-Enabled cooperative intelligent vehicular (5GenCIV) framework: When Benz meets Marconi," *IEEE Intell. Syst.*, vol. 32, no. 3, pp. 53–59, May-Jun. 2017.
[55] K. Wooseong, "Experimental demonstration of MmWave vehicle-to-vehicle communications using IEEE 802.11ad," *Sensors*, vol. 19, no. 9, May 2019, Art. no. 2057.
[56] E. Netw. Lightpole Product (2017): "Ericsson Lightpole Site," [Online]. Available: https://www.ericsson.com/ourportfolio/networks-products/lightpole-site?nav=fgb_101_0561%7Cfgb_101_0516%7Cfgb_101_0526
[57] M. Kanter, "Philips and city of San Jose partner to deploy philips smart-poles pilot project combining energy efficient led street lighting with wireless broadband technology from ericsson," 2015. [Online]. Available: http://www.businesswire.com/news/home/20151207005934/en/
[58] 5G Berlin innovation cluster. [Online]. Available: https://www.5g-berlin.org
[59] LuxTurrim5G project, [Online]. Available: https://www.luxturrim5g.com/
[60] ITS Connect. [Online]. Available: https://www.itsconnect-pc.org/en/
[61] SSS Promotion Consortium. [Online]. Available: Available: https://sss.e.titech.ac.jp/
[62] R. Dos Reis Fontes, C. Campolo, C. Esteve Rothenberg, and A. Molinaro, "From theory to experimental evaluation: Resource management in software-defined vehicular networks," *IEEE Access*, vol. 5, pp. 3069–3076, 2017.
[63] G. Secinti, B. Canberk, T. Q. Duong, and L. Shu, "Software defined architecture for VANET: A testbed implementation with wireless access management," *IEEE Commun. Mag.*, vol. 55, no. 7, pp. 135–141, Jul. 2017.
[64] O. Sadio, I. Ngom and C. Lishou, "Design and prototyping of a software defined vehicular networking," *IEEE Trans. Veh. Technol.*, vol. 69, no. 1, pp. 842–850, Jan. 2020.
[65] H. G. Seif and X. Hu, "Autonomous driving in the Icity - HD maps as a key challenge of the automotive industry," *Engineering,* vol. 2, no. 2, pp. 159–162, Jun. 2016.
[66] R. Fukatsu and K. Sakaguchi, "Millimeter-wave V2V communications with cooperative perception for automated driving," in *Proc. 89th IEEE Veh. Technol. Conf.*, 2019, pp. 1–5.
[67] ETSI, "Intelligent transport systems (ITS); vehicular communications; basic set of applications; part 2: Specification of cooperative awareness basic service," ETSI TS 102 637–2, Eur. Telecommun. Standards Inst., Sophia-Antipolis, France, Mar. 2011.
[68] ETSI, "Intelligent trans- port systems (ITS); vehicular communications; basic set of applications; part 3: Specifications of decentralized environmental notification basic service," ETSI TS 102 637–3, Eur. Telecommun. Standards Inst., Sophia-Antipolis, France, Sep. 2010.
[69] S. K. Saha *et al.*, "Fast and infuriating: Performance and pitfalls of 60 GHz WLANs based on consumer-grade hardware," in *Proc. 15th Annu. IEEE Int. Conf. Sens., Commun., Netw.*, Hong Kong, pp. 1–9, 2018.
[70] 3GPP TS21.886, "Enhancement of 3GPP support for V2X scenarios," V16.2.0, Jun. 2019.

ZONGDIAN LI (Student Member, IEEE) received the B.E. degree in communication engineering from the Beijing University of Posts and Telecommunications, Beijing, China, in 2018 and the M.E. degree in 2020 in electrical and electronic engineering from the Tokyo Institute of Technology, Tokyo, Japan, where he is currently working toward the Ph.D. degree with the Department of Electrical and Electronic Engineering. His current research interests include SDN, millimeter-wave V2X, and dynamic radio resource management.

TAO YU (Member, IEEE) received the M.E. degree in signal and information processing from the Communication University of China, Beijing, China, in 2010, and the Dr.Eng. degree in electrical and electronic engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 2017. He is currently working as a Postdoctoral Researcher with the Tokyo Institute of Technology. His current research interests include 5G, mmwave, wireless sensor networks, and wireless energy transmission. He is a Member of the IEICE.

RYUICHI FUKATSU (Student Member, IEEE) received the B.E. and M.E. degrees in electrical and electronic engineering in 2017 and 2019, respectively, from the Tokyo Institute of Technology, Tokyo, Japan, where he is currently working toward the Ph.D. degree. His research interests include V2V and automated driving.

GIA KHANH TRAN (Member, IEEE) received the B.E., M.E., and D.E. degrees in electrical and electronic engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 2006, 2008, and 2010, respectively. Since 2012, he has been a Faculty Member with the Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, where he is currently working as an Associate Professor. His research interests include MIMO transmission algorithms, multiuser MIMO, MIMO mesh network, wireless power transmission, cooperative cellular networks, sensor networks, digital predistortion RF, and mm-waves. He was the recipient of the IEEE VTS Japan 2006 Young Researcher's Encouragement Award from the IEEE VTS Japan Chapter in 2006 and the Best Paper Awards in Software Radio from the IEICE SR Technical Committee in 2009 and 2012, respectively. He is a member of the IEICE.

KEI SAKAGUCHI (Senior Member, IEEE) received the M.E. degree in information processing and the Ph.D. degree in electrical and electronics engineering from the Tokyo Institute of Technology, Tokyo, Japan, in 1998 and 2006, respectively. He is currently working with Tokyo Tech Academy for Super Smart Society, Tokyo Institute of Technology as the Dean and as a Professor with the School of Engineering. He is currently a Consultant with Fraunhofer HHI, Germany. His current research interests include 5G cellular networks, millimeter-wave communications, wireless energy transmission, V2X for automated driving, and super smart society. He was the receipent of the Outstanding Paper Awards from the SDR Forum and the IEICE in 2004 and 2005, respectively, three Best Paper Awards from the IEICE Communication Society in 2012, 2013, and 2015, respectively, and the Tutorial Paper Award from the IEICE Communication Society in 2006. He is a fellow of the IEICE.