Millimeter-Wave Fast Beam Tracking Enabled by RAN/V2X Cooperation

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***Abstract*—Automated driving has the same limitations as human drivers because it functions as a replacement for humans and operates based on local information using onboard sensors and computers. Cooperative automated vehicles (CAVs) are expected to achieve both safety and efficiency, which could not be achieved by imitating human driving, by sharing sensor information from roadside equipment and other vehicles. Since such sensor information is enormous, it is desirable to utilize mmW, which are capable of high-capacity transmission. However, wireless communication systems for CAV have the challenge of radio quality degradation due to vehicle movement. Our research project aims to realize stable millimeter-wave transmission by incorporating open radio access network (O-RAN) and vehicle-to-everything (V2X) functions. This paper presents the overall proposed concept and an example of validation; we show the results of evaluating our previously proposed fast beam following scheme in a handover environment with multiple roadside units.**

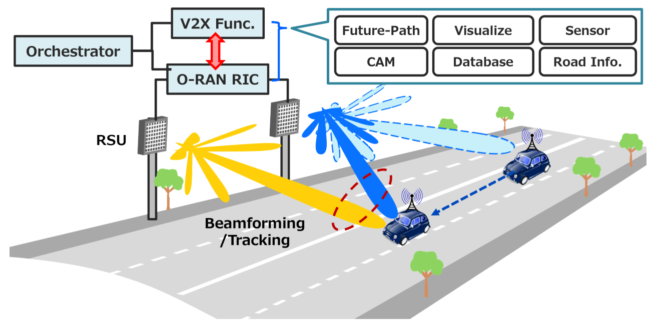


Fig. 1: System overview.

I. Introduction

Society 5.0 has been proposed as a vision of future society in Japan. This is a concept that aims to create a prosperous society as a whole by utilizing advanced technologies such as artificial intelligence (AI), robotics, big data, and the Internet of Things (IoT) to achieve both economic development and solutions to social issues [1]. Automated driving is considered to be one of the technologies that will play an important role in the realization of forthcoming society/industry. Although automated driving is currently under active research and development, its autonomous driving functionality currently replaces the driver, i.e., it drives based on local information, and thus has the same limitations as the driver. In contrast to such basic self-driving, "cooperative automated vehicle (CAV)" is expected to be realized. Infrastructure equipped with communication functions and various transportation systems will work together to enable cooperative recognition, decision-making, and steering execution. Traffic conditions are acquired from various sensors such as high-definition cameras and Light Detection And Ranging (LiDARs) installed in roadside units (RSUs) and shared with automated vehicles [2]. A digital twin infrastructure that enables wireless communication systems and CAV to interoperate with each other is necessary to realize such safer automated driving [3].

From the perspective of wireless communications, in addition to the narrowing of base station (BS) coverage (small cell) as a means of efficiently accommodating increasing mobile traffic under limited frequency resources, there is a background of a shift to millimeter-wave (mmW) bands ensuring a wide bandwidth. In the 5th generation mobile communications (5G), frequencies in the 4-5 GHz band (Sub6) and 28 GHz band (mmW) have been newly allocated. Because of their higher frequencies, the range of radio waves is shorter than in conventional systems [4]. While the small cells are highly compatible with small cells, the deployment of mmW small cell BSs has not yet progressed after introducing 5G in 2020 due to installation cost considerations [5].

The CAV is also equipped with high-definition sensors, and these acquired information is shared with surrounding vehicles via wireless communication links and networks. However, many issues must be solved to provide stable mmW communications with narrow coverage to vehicles in a constantly moving environment. Array antenna beamforming is a useful fundamental technology that contributes to solving this problem. By controlling the amplitude and phase of signals input to and output from a large number of antenna elements, a beam can be formed in a specific direction to increase radio wave strength, i.e. signal gain. However, when the communication target changes dynamically, it is necessary to control the beam direction adaptively. It is not always possible to maintain line-of-sight (LoS) between BS and the vehicle in the mobility environment. Particularly in dynamic shielding scenarios, such as when large vehicles like buses and trucks change lanes or make left/right turns at intersections, mmW suffer from significant attenuation of the radio signal.

In this study, we propose an interoperable infrastructure for CAV that is equipped with an open radio access network (O-RAN) and a vehicle-to-everything (V2X) interface that encompasses vehicle-to-vehicle (V2I)/vehicle-to-infrastructure (V2V). Fig. 1 shows the overall concept of the proposed CAV system. V2X messages are stored on a dynamic map, based on which Open Centralized (O-CU) and Distributed Unit (O-DU) are controlled in cooperation via the RAN intelligent controller (RIC) of O-RAN. Here, a dynamic map can handle dynamic information such as vehicle information on top of static information such as map information. We also target Near-Realtime RIC (Near-RT RIC), which can operate from 10 msec to 1 second, as standardized in O-RAN. By defining an interface that enables xAPP of this function to work with V2X App, V2X information is used to control the beamforming of O-DUs. This mechanism also enables seamless handover management. We have previously proposed an algorithm that can achieve fast beam tracking based on some geographic information [6]. In conjunction with the above proposed concept, this paper clarifies the effectiveness of the fast beam tracking scheme in a multi-RSUs environment.

The rest of this paper is organized as follows. Section II provides an overview of CAV. Sections IV and III present the proposed system architecture and the fast beam tracking approach. The simulation result is presented in Section V. Section VI concludes this paper.

II. Cooperative Automated Vehicle

Automated driving is expected to improve safety and efficiency by assisting or replacing human drivers, and is being actively researched, developed, and implemented in society worldwide. This is called autonomous driving [7], in which the vehicle itself collects data on its surroundings using its own sensors, and uses this data to plan routes and operations. Therefore, there is a limit to the range of recognition that can be achieved in the same way as in the case of conventional human driving. CAVs are attracting attention to overcome this limitation and realize safer and more efficient automated driving [8]. In CAV, a wide range of highly reliable data can be obtained by exchanging information with other vehicles (V2V) and with infrastructure facilities such as RSU (V2I) [9]. Several standards currently exist for V2X in CAV. For instance, ITS-G5, standardized by ETSI [10], and DSRC, standardized by the FCC in the US [11], both utilize IEEE 802.11p. Meanwhile, C-V2X [12], developed by 5GAA, is a standard that employs mobile networks. While these specifications may not directly apply to Japan's CAV system due to differences in available frequency bands, they do lay the groundwork for such a system. For instance, ITS defines messages for vehicle-to-ITS station communication, including those for road event detection, cooperative awareness messages (CAMs) for broadcasting a vehicle's status (position, movement) and characteristics (size, type), and messages for managing sessions. Each ITS station compiles the road data gathered from these messages into a local dynamic map (LDM). This map can then be accessed or subscribed to by applications for purposes like route planning, allowing them to utilize this information.

In mobile networks, mobility control is indispensable to realize stable communication with moving targets, and especially in mmW, beam control and handover are essential from the viewpoint of transmission range. The current beamforming approach is sweeping [13], in which BS transmits a pre-scheduled pattern of beams at regular intervals and the terminal reports the received signal strength results to BS to select the optimal beam direction. Handover refers to the process where a user's connection is switched to another cell upon exceeding the communication range of the currently connected cell. As mobile networks evolve with higher frequency bands to increase communication capacity, cells are becoming smaller and more densely packed. This change is due to the shorter propagation distance of these higher frequencies and the goal of efficiently connecting numerous devices. Consequently, the frequency of handovers inevitably rises, necessitating more efficient handover methods. In the current 5G NR handover method, a terminal receives a downlink reference signal from a nearby BS. It reports the measured reception strength (RSRP) back to the BS, determining whether a handover is needed. Key parameters in this process include the time to trigger (TTT) and the measurement gap (MG), which are crucial for optimizing handover efficiency.

Handover performance has several evaluation axes such as frequency, failure rate, ping-pong rate, energy consumption, success rate, data delay, and communication interruption time, etc. The challenge in the current 5G NR is to reduce the failure rate and terminal energy consumption, especially due to high-frequency handovers [14]. In existing research, some methods use Markov chains to make handover decisions before the signal strength actually decreases to reduce the failure rate and delay, [15] and some of them use deep learning. Other methods include handover skipping to reduce the frequency of handovers and the pin-pong rate and connecting to multiple cells simultaneously to eliminate communication downtime. In another direction, some studies use camera input and other methods to predict in advance the communication interruption caused by obstacles and perform handover [16]. The challenges of mobility control are more pronounced for fast-moving vehicles, and there is a lot of research focused on handover for vehicles [17]. The issues to be solved and the methods used in such research are not so different from those used in normal handover research. Vehicle handover often focuses on accurate estimation of the vehicle's self-position, speed-based decision making, and the use of geographic information obtained from car navigation systems and other unique information such as the vehicle's own path. For example, a method for estimating the relative position to the base station based on the result of receiving a reference signal from the base station [18] and a method for changing the handover policy according to its own speed and 5G QoS identifier (5QI) [19] have been proposed.

III. Proposed Architecture

Existing research on beamforming and handover control of mobile networks for vehicles assumes realistic scenarios in

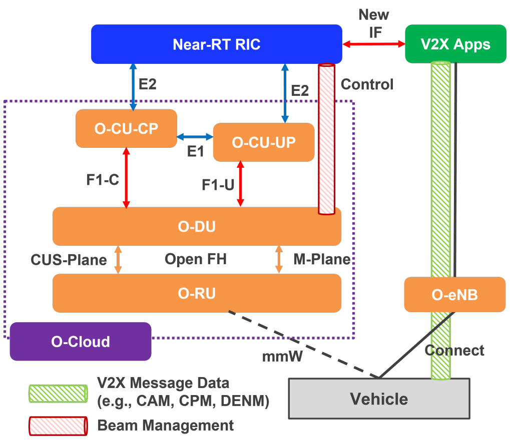


Fig. 2: Proposed architecture.

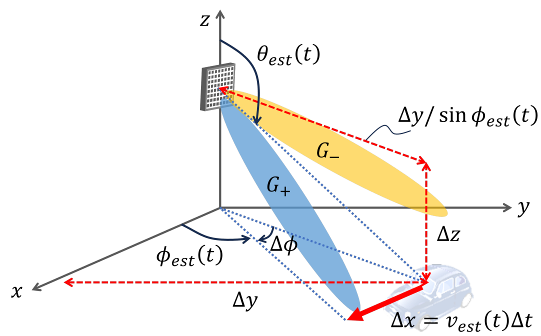


Fig. 3: Overview of fast beam tracking.

the current society and is limited by the limited information that can be obtained. If CAV is assumed, mobility control with more information is possible by closely coordinating the wireless communication system with the CAV system. In such system, RSU maintains information such as the size, position, and speed of vehicles on the road using dynamic map [20], etc. This information is expected to enable more stable and efficient communication by controlling beamforming and handover.

Fig. 2 visualizes the O-RAN-based proposed architecture. This architecture assumes that messages primarily maintained by the CAV system are transmitted via microwave macrocells. Meanwhile, mmW is reserved for large-volume data communications, such as sensor information. For CAM that include vehicle position and speed, and collective perception messages (CPMs) that contain sensor recognition information, a wide coverage area is crucial to ensure stable transmission at all times. These messages are consistently transmitted through an Open eNodeB (O-eNodeB) on the macro frequency side, which provides the broad coverage. The open radio unit (O-RU), intended for use with high-definition sensors like LiDAR and cameras, is envisioned to be installed in the RSU. The O-RU operates in conjunction with the open distributed unit (O-DU) and adheres to the O-RAN specification [21]. The O-DU and the Open Central Unit (O-CU) are also based on the O-RAN specification [22]. RICs are categorized into near-realtime RICs (Near-RT RICs), manageable within a range of 10 msec to 1 sec, and Non-Near RT RICs, controllable over 1 sec. This paper primarily discusses Near-RT RICs in the context of beamforming and handover scenarios. Within Near-RT RIC, two main functions are the focus: the xAPP, which facilitates integration with external applications, and the configuration manager (Config Mgr), responsible for managing settings on the O-DU side.

CAMs and CPMs transmitted via macrocells are dynamically updated on the dynamic map. This map represents a V2X App installed beyond the user plane function (UPF). On this map, static information like the layout is established, with dynamic information superimposed over it [23]. An interface compatible with the RAN is essential to effectively use dynamic information on the Radio Access Network (RAN) side. Presently, two standardized interfaces are designed for connecting with external xAPP functions. These are primarily defined for interacting with orchestrators and publishing RAN analysis information to internal and external functions. Consequently, this paper suggests transmitting vehicle position and speed data from the CAM, as collected by the dynamic map, to the xAPP of the Near-Realtime Radio Intelligent Controller (Near-RT RIC) through a new interface. The xAPP of the Near-RT RIC would then use this vehicle data to manage beamforming control on the Open Distributed Unit (O-DU) side. This approach is anticipated to facilitate more seamless handover control.

IV. Fast beam tracking

In this paper, we examine the effectiveness of our previously proposed location-based fast beam tracking algorithm [6] in an environment with multiple RSUs. The proposed scheme assumes that some position information is obtained by CAM. It limits the number of candidate beam searches to the area around the vehicle's direction of movement while estimating its speed. BS maintains the initial beamforming weight at the beginning of the road's observation range. When a vehicle's approach is identified through signal strength, the BS initiates speed estimation $v_{\text{est}}(t)$ from a predefined starting value. It then periodically adjusts the azimuth and elevation angles, using a specific formula at each time interval Δt.

$$\begin{aligned}\phi_{\text{est}}(t) &= \phi_{\text{est}}(t-\Delta t) - \Delta\phi \\ &= \phi_{\text{est}}(t-\Delta t) - \tan^{-1}\left(\frac{v_{\text{est}}(t)\Delta t}{\Delta y}\right), \end{aligned} \tag{1}$$

$$\theta_{\text{est}}(t) = \tan^{-1}\left\{\frac{\Delta z \sin\phi_{\text{est}}(t)}{\Delta y}\right\} + 90^\circ. \tag{2}$$

As illustrated in Fig. 3, Δy represents the vehicle's position relative to the normal direction of the road from RSU, and Δz indicates the vertical distance between RSU and vehicle. Each of these values is individually established. The elevation angle $\theta_{\text{est}}(t)$ is exclusively defined by $\phi_{\text{est}}(t)$.

The estimated speed $v_{\text{est}}(t)$ undergoes modification based on the variance between the present signal strength (or SNR),

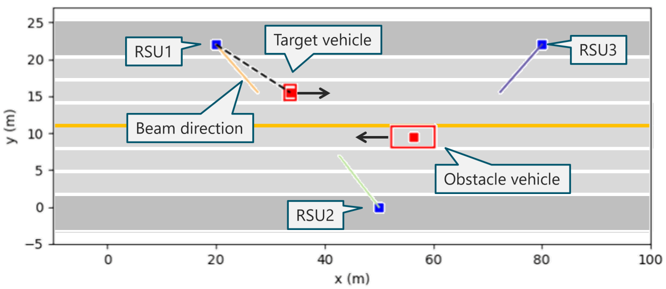


Fig. 4: Simulation environment.

$G(t)$, and its preceding level, $G(t-\Delta t)$. Moreover, two beam search patterns are established in the $\pm\Delta\phi$ directions, with SNR assessments conducted for each. These measurements are referred to as G_+ and G_-, respectively. The update of v_{est} is then determined by the direction of the beam where an increased gain is noted;

$$v_{\text{est}}(t) = v_{\text{est}}(t-\Delta t) + \text{sgn}\left(\log \frac{G_+}{G_-}\right) \frac{\alpha G(t)}{G(t-\Delta t)}. \quad (3)$$

In this context, $G(t)$, G_+, and G_- can be fed-back from the vehicle through uplink. As depicted in Fig. 3, a scenario where $G_+ > G_-$ suggests that the beam tracking lags behind, necessitating an increase in the estimated speed, and the reverse is true for the opposite scenario. This updating mechanism also incorporates the proportion of received signal strength as a factor for adjusting speed, enabling agile adaptation to variations in the vehicle's movement speed. The parameter α is utilized to regulate this sensitivity. This approach allows for rapid tracking by considerably narrowing the search scope to just two alternatives triggered by a decline in signal strength.

V. Computer Simulation

A. Simulation setting

The simulation environment is illustrated in Fig. 4, and parameters are summarized in Table I. We have chosen the 28 GHz band as mmW band for 5G applications. Three RSUs are installed at a height of $h_{\text{bs}} = 10$ m. The road comprises three straight lanes on each side, with widths of 3.0 m for the road and 5.0 m for the sidewalk. A vehicle, standing 2.0 m in height, travels in each of the opposite lanes. We observe the downlink received Signal-to-Noise Ratio (SNR) at the vehicle as our primary evaluation metric. RSU is equipped with a 16×16 planar array, featuring half-wavelength spacing. The vehicle utilizes a 10-element linear array to enable maximal ratio combining (MRC) reception. The sweep angle for adapting v_{est}, denoted as $\Delta\phi$, is set to 7°. We assume there is no co-channel interference from adjacent RSUs and vehicles. The beam tracking's update time interval is established at $\Delta t = 10$ msec. Finally, the sensitivity coefficient in (3) is set to $\alpha = 3$. Consider a scenario where a road has three lanes on each side, with one vehicle traveling in the opposite direction. In this initial study, 50 msec is considered the processing delay required for handover.

TABLE I: Simulation parameters

Parameters	Values
Carrier frequency	28 GHz
Transmission bandwidth	400 MHz
Number of RSU / vehicle antennas	256 (16×16) / 10
Height of RSU / vehicle antenna	10 / 2 m
RSU / vehicle antenna gain	8 / 0 dBi
RSU transmission Power / Feeder loss	40 dBm / 3 dB
Receiver (vehicle) Noise power	−80 dBm

B. Results

As shown in Fig. 5, the orange, green, and blue lines represent the direction of the beam from RSU1, RSU2, and RSU3 respectively, and plot the time variation of the received SNR for each beam. The fixed beam is shown for reference. Beam sweeping [13] causes the SNR to vary irregularly due to the discrete change of the beam direction. The proposed method can improve the stability of SNR in multiple RSUs environments. When an obstacle blocks the signal, SNR is treated as 0dB. In particular, we can confirm that the SNR recovers after shielding when compared to the ideal performance. This is because RSU1 can track the beam and switch to it temporarily. In some cases, it may be possible to approach the ideal beam gain by configuring the RSUs.

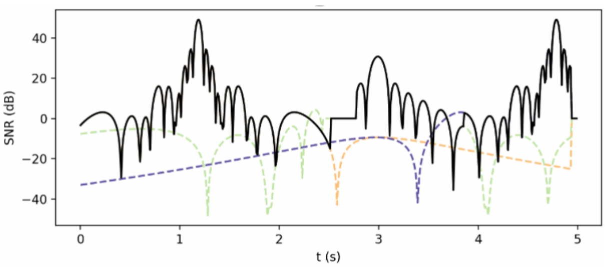
Our future work is to proceed with a more realistic analysis, considering the delay required for beam search and the detailed processing delay derived from the system architecture described above. Under such constraints, we expect that our proposed method, which significantly reduces the number of beam candidates while cooperatively utilizing various side information, will work more effectively.

VI. Conclusion

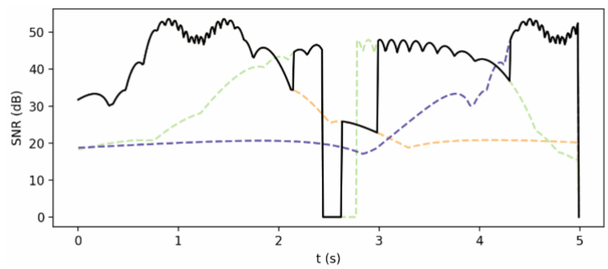
This paper presents the concept of a millimeter-wave beam tracking technology that supports the realization of CAV and examples of preliminary studies of the proposed approach. Our research includes a more sophisticated beam sweeping [24] and tracking algorithm [25] as well as driving parameters estimation [26] to adapt to various road geometries. We are also investigating multi-user spatial multiplexing transmission in which a single RSU supports multiple vehicles [27]. In a mobility environment, CSI will become outdated due to variations in channel timing, which impedes the effective suppression of inter-user interference. Our proposed scheme offers a robust solution to this challenge. We plan to further validate its effectiveness through outdoor field demonstrations using practical implementations in our future studies.

Acknowledgments

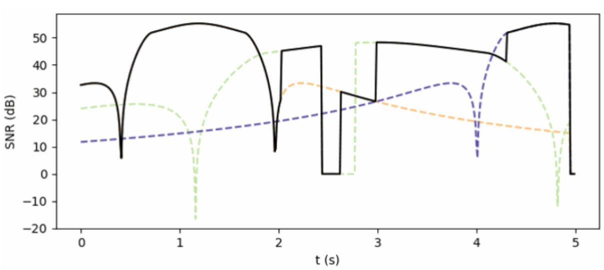
This research is supported by the Strategic Information and Communications R&D Promotion Programme (SCOPE) by Ministry of Internal Affairs and Communications, Japan (receipt number JP235003002). The authors are sincerely grateful to Mr. Osamu Morita, Mr. Akinori Saeki, Mr. Satoshi Ogura and Mr. Kazuyoshi Ohnishi of MORITA TECH CO., LTD. for their technical support/contribution on this work.



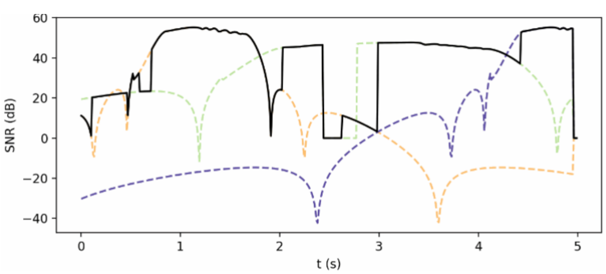
(a) Fixed beamforming



(b) Beam sweeping



(c) Proposal



(d) Ideal

Fig. 5: Received SNR with running time.

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