Optimizing mmWave Beamforming for High-Speed Connected Autonomous Vehicles: An Adaptive Approach

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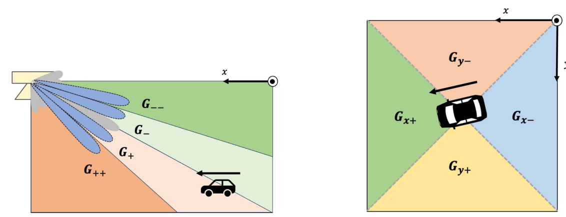
***Abstract*—The commercialization of 5G has been initiated for a while. Furthermore, millimeter wave (mmWave) has been introduced to small cells with small coverage due to its strong linearity and non-winding characteristics. On the other hand, in connected autonomous vehicles (CAVs), where various traffic systems can cooperatively perform recognition, decision-making, and execution, communication is assumed to be always connected. Therefore, to use low latency mmWave for high-speed moving CAV, existing beamforming cannot follow them at high speed. This paper proposes an improved beam tracking algorithm for high-speed CAVs, which can be evaluated in a more general environment using a traffic simulator. We proposed an adaptive algorithm for a general road environment by increasing the number of beam searches and search dimensions.**

***Index Terms*—Millimeter wave, Fast beam tracking, V2X, Connected autonomous vehicle**

I. INTRODUCTION

Cooperative automated driving is capable of recognition, judgement, and execution with various traffic systems such as roads and traffic signals [1]. High-capacity and low-latency communication functions for such cooperative infrastructure could be essential for its realization. Millimeter-wave (mmWave), introduced in the 5th generation mobile communications (5G), offers low latency and wide bandwidth. It still has the problem of a smaller coverage area than conventional systems due to its strong linearity and lack of diffraction. In Vehicle-to-Infrastructure (V2I) communications between vehicles and infrastructure such as roadside equipment, efforts on exploiting mmWave are underway to efficiently share raw sensor data such as LiDAR and high definition camera images [2]. Massive array beamforming at the network side [3] is expected to be a candidate for realizing cooperative automatic driving technology, assuming a millimeter-wave small-cell system. In the existing 5G mmWave system, 3GPP prescribes the control signal-based beam search function [4]. However, existing beam sweeping cannot track vehicles moving at high speeds because they aim to uniformly extend the coverage. Although the fast beam tracking algorithm [5] was developed, its effectiveness is limited in a simple straight-road environment. It also does not consider the real-world traffic environment. In order to deepen the preceding study above, this paper constructs a simulation environment that incorporates a traffic simulator which can reproduce realistic road environment. We also propose an extended beam tracking algorithm that increases the beam search direction and the number of dimensions to adopt to various road environments. Main contributions in this paper are summarized as follows.



(a) 4-way **(b)** 2-dimension

Fig. 1: Extended number of beam searches

- To construct a simulator environment that links a traffic simulator and a wireless communication system
- To propose an improved algorithm that enables fast beam tracking in various road environment

Reminder of this paper is as follows. Section II describes our proposed method. Section III explains the simulator conditions and results. Finally, Section IV concludes this paper.

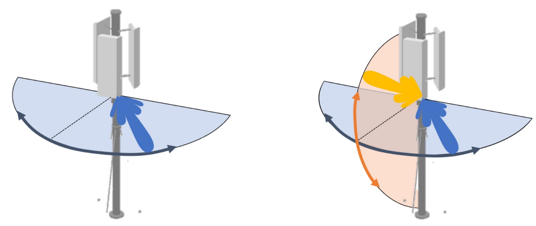
II. PROPOSED METHOD

A. Proposal I: Extension of beam searches to 4 directions

Beam tracking in beamforming must be performed properly for vehicles moving at high speed. In the existing research, the beam is irradiated in two directions, one in front of and the other behind the predicted vehicle position, and the one with the better signal-to-noise ratio (SNR) is used to update the predicted speed based on the information. However, simply setting two directions to the front and rear may result in a loss of accuracy because even if they are in the same direction, they are treated as uniform, regardless of the size of the deviation from the predicted position. Therefore, we propose an expansion method to increase the number of beam searches to 4 ways in total, as shown in Fig. 1a.

B. Proposal II: Extension of beam searches to 2-dimensions

In the conventional algorithm, the beam's direction from the base station antenna was oriented only horizontally relative to the ground, as depicted in Fig. 2a. The beam search was restricted to 1-dimensional tracking, insufficient for scenarios where vehicles moved in a 2-dimensional plane, such as on winding roads. We expanded the beam search direction to include the vertical axis to address this limitation, as illustrated in Fig. 2b. This allows the beam to be directed flexibly across the 2-dimensional plane on the road. As a result,



(a) Horizontal only (Conventional)

(b) Horizontal & Vertical (Proposal II)

Fig. 2: Beam search method

TABLE I: Simulation Parameters.

Parameters	Value
Frequency	28 GHz
Transmission bandwidth	400 MHz
Number of BS / Vehicle antennas	256 (16×16) / 10
BS/ Vehicle antenna gain	8/0 dBi
BS transmission power	40 dBm
Feeder loss	3 dB
BS antenna pattern	3GPP model (TR 38.901, V14.0.0)
Channel Model	LoS, Free space propagation
Beam Tracking Frequency	100 Hz

we anticipate more accurate communication across a broader range of scenarios, as illustrated in Fig. 1b.

III. Simulation Results

A. Building a Simulation Environment

In this study, we use Simulation of Urban MObility (SUMO) to simulate realistic vehicle movements and speed variations and incorporated MATLAB to implement beam tracking functions. We employed an API provided by SUMO, called TraCI4Matlab, to bridge the two softwares. Through this API, MATLAB can retrieve information such as the speed/position of a vehicle and the width of the road where the vehicle is currently traveling on. The simulation parameters are summarized in Table I.

B. Simulation Results

The simulation results for the straight road are presented in Fig. 3. In the figure, the black line shows the optimized theoretical value, the blue line represents the conventional method [5], the green line depicts the 4-way beam search, and the red line indicates the 2-dimensional beam search. The horizontal axis corresponds to the vehicle's position, while the vertical axis represents the received SNR. A higher SNR suggests the signal can be transmitted with fewer errors, leading to better communication quality. On the straight road, the 4-way beam search produced satisfactory SNR performance. On the other hand, there was little effect of increasing the number of search dimensions. This is quite reasonable that the movement of vehicle is 1-dimensional on the straight road.

The simulation results for the curved road are shown in Fig. 4. The curved road was created and used with a radius of curvature of 40 m. On the curved road, a 4-way beam search was less effective. This is due to the limitation of the 1-dimensional beam search domain. On the other hand, the

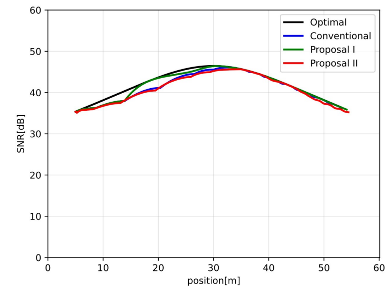


Fig. 3: Results on the straight road

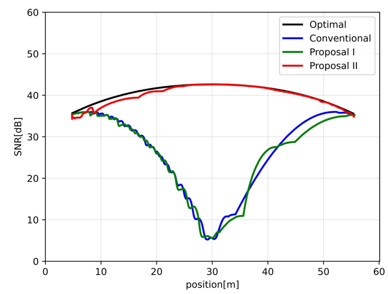


Fig. 4: Results on the curved road

2-dimensional search exhibited drastic improvement. On the curved road, the strength of 2-dimensional search becomes more apparent. Based on these results, it is expected that the combination of the two methods, 4-way and 2-dimensional beam search, can provide highly accurate mmWave V2X communications in general road environments.

IV. Conclusion

This paper proposed two types of improvements to the existing mmWave fast beam tracking algorithm; a 4-way and 2-dimensional beam search approaches. The former was particularly influential on straight roads while the latter was effective on curved roads. We jointly implemented two simulators, SUMO and MATLAB, to thoroughly verify the effectiveness of proposed beam tracking extensions in the general road environment.

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