V2I Blockage Modeling and Performance Evaluation for Connected Autonomous Vehicle

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***Abstract*—The burgeoning Intelligent Transportation System (ITS) spurs global technological advancements, notably in innovative community development through vehicle-to-everything (V2X) communication. This study focuses on the high data rates and low latency offered by a millimeter-wave (mmWave) enabled vehicular network while addressing the significant challenge of link quality degradation due to blockages, exacerbated by the mmWave band's small wavelength in high mobility and traffic conditions. We propose an RSU-assisted ITS system tailored for multi-lane, straight-road scenarios, effectively identifying blockage status for vehicles. Combining Simulation of Urban Mobility (SUMO) and MATLAB, this blockage-aware scheme lays the groundwork for future ITS enhancements. The research also delves into the effects of various frequency bands, vehicle types, and communication ranges, offering a holistic system performance analysis.**

***Index Terms*—millimeter-wave, V2X, intelligent transportation system, connected autonomous vehicle, blockage determination**

I. Introduction

Autonomous Driving (AD) is part of the Intelligent Transportation System (ITS), which has been intensively researched due to its potential to mitigate common road problems and provide solutions for issues such as traffic safety, trajectory planning, fuel consumption, etc. By utilizing sensors, such as LiDAR, radar, and cameras, the vehicles gather information around them, therefore assisting the decision during driving [1]. The Connected Autonomous Vehicles (CAVs) harness V2X communications to achieve the information exchange wirelessly for coordinated autonomous functions [2]. As standardized by the European Telecommunications Standards Institute (ETSI), the Cooperative Awareness Message (CAM) [3] and Collective Perception Message (CPM) [4] have provided ample information on the CAVs and their surroundings. The CAM message contains information about the status and attributes of the originating ITS Station (ITS-S), and the CPM message describes the perceived objects and regions. The combination of these messages allows CAVs to share their intentions and perceive others, which is enabled by communication through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) links. While vehicles communicate with other vehicles via the V2V scenario, roadside units (RSUs) exchange information with vehicles under the V2I scenario.

According to the Third Generation Partnership Project (3GPP) [5], the fifth-generation (5G) New Radio (NR)-based V2X services have targeted the connected autonomous use cases. 5G-enabled mmWave vehicular networks aim to provide solutions with high data transmission rates and ultra-reliability. However, due to high penetration loss and sensitivity to blockages, the 5G mmWave band has a small coverage area and weak connection stability [6]. As mmWave connections are highly directional, Line-of-Sight (LoS) must be maintained between the transmitter (Tx) and receiver (Rx) to ensure satisfying communication quality [7]. This has become one of the challenging problems in the physical layer of the mmWave-based CAV system since LoS connectivity is hardly a guarantee under high-mobility on-road scenarios [8]–[10].

The main contribution of this paper can be summarized as follows.

- We propose an RSU-assisted ITS system architecture with a heterogeneous network for determining the dynamic blockage under the V2I communication scenario.
- We propose a practical V2I blockage determination solution based on electromagnetic theories, requiring minimal CAV data such as position and dimensions. This approach significantly mitigates blockage effects, demonstrating its effectiveness in enhancing communication reliability.
- We investigate the impact of several V2I communication-related parameters, such as center frequencies, types of vehicles, and LoS distance.

The structure of this paper is as follows: Section II reviews the related work on RSU-assisted vehicular networks and mmWave Blockage. Section III presents the proposed system architecture design and system model. Section IV explains the simulation in detail. Finally, Section V presents the conclusion and future work.

II. Related Works

In this section, we review literature in two main related categories: first, we summarize work regarding RSU-involved vehicular systems; second, we discuss research related to mmWave blockages under the V2I scenario.

The RSU-assisted vehicular network has gained increasing attention in AD technology for its significance in improving driving safety. Hirta et al. [11] proposed a network structure for future path sharing. This work enabled CAVs to coordinate their future path plans to achieve higher safety and efficiency. Song et al. [12] developed joint vehicle tracking and RSU

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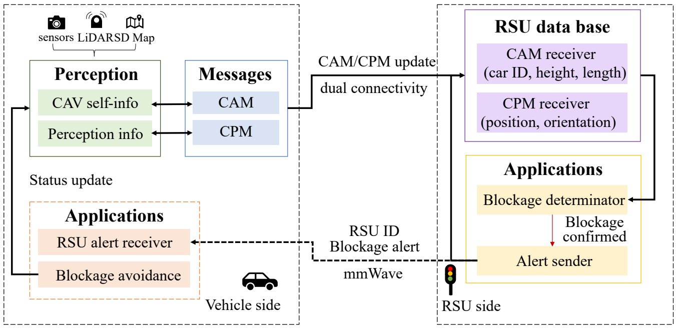

Fig. 1. Proposed system architecture

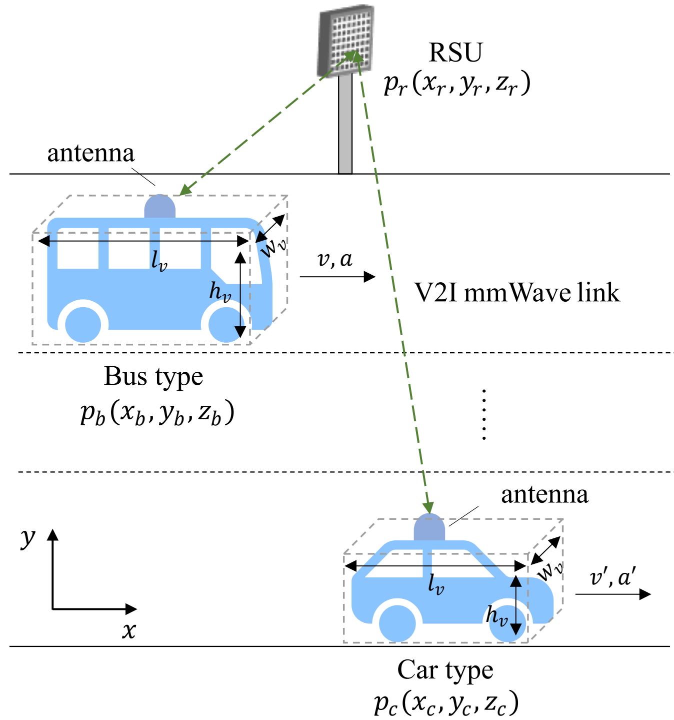

Fig. 2. Scenarios of V2I mmWave link in a straight road segment

selection algorithms suitable for V2I communications. This algorithm helps in carrying out efficient vehicle tracking. Charalampopoulos et al. [13] evaluated the performance of the RSU-based vehicular systems under two V2I scenarios over Vehicular Networks (VANETs). Chattopadhyay et al. [14] investigated the minimum RSU height required in highways to guarantee all-time 60 GHz LoS connectivity for different lanes. However, none of these works have investigated the heterogeneous network in the ITS system.

Blockage impact in V2X communication is also a research topic that is hotly debated. Dong et al. [15] modeled the blockage probabilities under the mmWave V2V communication scenario using the effective height of the First Fresnel zone ellipsoid as blockage determination criteria. However, the V2I scenario is not considered in this work. Iimori et al. [16] proposed a novel robust beam-forming scheme for mmWave Coordinated Multipoint (CoMP) systems. This method addresses the challenges of random path blockages in mmWave communications. Tunc et al. [17] analyzed the latency and reliability performance of LoS mmWave V2I communication and considered three approaches to control the blockage probability and distribution of blockage duration. They extend their work [18] that successfully captures the channel dynamics caused by blockers surrounding a moving vehicle using proposed Markov chain models. However, their studies are limited to evaluation in numerical analysis.

III. System Architecture

A. Proposed System Design

Fig. 1 shows the overview of the proposed system architecture. This system leverages the heterogeneous network that includes mmWave and macro cell frequency bands to provide a blockage-robust V2I communication link. For the macro cell, we consider the frequency bands from Long-term Evolution (LTE) and sub-6 GHz. On the vehicle side, the CAM and CPM messages will be structured by collecting CAV self-information and perception results using equipped sensors, such as cameras and LiDARs. Dual connectivity in heterogeneous networks is implemented for V2I message transfer with a broader communication range and stable connectivity. When the nearby RSU receives the messages, a database will be maintained with the updated information. The database includes the vehicle IDs, vehicle properties, current position, etc. Therefore, a series of applications can be carried out within the RSU leveraging the continuously updating database.

In this system, the RSU is designed to transverse the vehicles registered in the database and determine if the current V2I communication link on the mmWave band is blocked by other vehicles. If the blockage is confirmed, the RSU could notify the vehicles through the macro cell connection to react to the obstruction, such as acceleration, deceleration, change lanes, etc. The blockage determination process utilizes the Fresnel zone theory and the geometry calculation that will be elaborated in the following subsection. Therefore, the design of RSU in the system could assist future road planning in a blockage awareness way to coordinate traffic accordingly.

As a limitation of the current system in this paper, the RSU cannot predict or alert the target vehicle before the blockage occurrence since the system is operated on the feedback of the current vehicle situation. Therefore, the blockage prediction function and the application layer concerning blockage avoidance are expected to be implemented in future work.

B. System Model

The considered scenario is a segment of a straight road with multiple lanes. As depicted in Fig. 2, two types of CAV are considered, and they are assumed to have a cube shape with the size of $w_v \times l_v \times h_v$, details can be referred to the simulation setting described in Table I. CAVs are equipped with antennas enabling mmWave and macro cell V2I communication on the rooftop. One RSU is located on the road edges. Due to the different initial speeds, acceleration, the change of lanes, etc.,

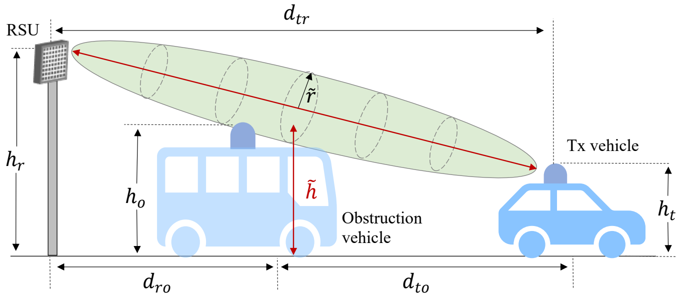

Fig. 3. First Fresnel zone blockage under V2I scenario

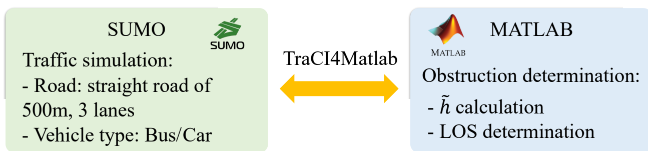

Fig. 4. Cooperation between SUMO and MATLAB

the CAVs would interfere with V2I communication between themselves or other CAVs.

From the electromagnetic perspective, serious interference occurs when 40% of the first Fresnel zone is obstructed, resulting in low communication qualities [19]. We assume that a CAV is obstructing the V2I communication as depicted in Fig. 3. The distance d_{tr} refers to the communication link distance between the RSU and the Tx vehicle. d_{ro} and d_{to} represent the distance between the RSU and Tx vehicle to the obstruction along the LoS line. The radius of the first Fresnel zone can be calculated by,

$$\tilde{r} = \sqrt{\lambda_c \frac{d_{to} d_{ro}}{d_{to} + d_{ro}}} \tag{1}$$

where λ_c stands for the carrier wavelength. With the radius being obtained, the effective height of the first Fresnel ellipsoid $\tilde{h}$ at the obstruction position can be further deducted using the knife edge theory.

$$\tilde{h} = (h_r - h_t)\frac{d_{to}}{d_{tr}} + h_t - 0.6\tilde{r} \tag{2}$$

where h_r and h_t are the height of the RSU and Tx CAV. Accordingly, the above equations indicate that the blockage occurs when the height of the obstruction h_o exceeds the effective height of the first Fresnel zone, i.e., $h_o - \tilde{h} > 0$. In addition, the blocker vehicle should be located on the LoS line between the RSU and the Tx vehicle.

IV. Simulation

A. Simulation setup

This study uses the SUMO [20] as the ITS traffic simulator and MATLAB as the data processor to realize the RSU applications. In SUMO, a realistic linear road with three lanes was created. SUMO emitted the vehicles following binomial distribution to provide a traffic flow. We set the emission probability differently for bus-type and car-type vehicles. After generating a configuration file, the traffic model is built and available for further calculation. The RSU is represented by MATLAB to model its data processing ability. For the synchronization during the simulation process, this study leverages the Application Programming Interface (API) provided by SUMO, which is TraCI4Matlab [21] as shown in Fig. 4. TraCI4Matlab allows users to retrieve parameters or modify the simulation objects within the defined domains. Therefore, the following assumptions were made due to the usage of the API.

- The CAM and CPM are structured and sent on the vehicle side through dual connectivity.
- The RSU is assumed as the center data handler and the data processing is simulated by MATLAB.
- The path loss, link budget, and package error rate are not considered during this simulation due to the direct parameter retrieval from SUMO to MATLAB. That is, the channel is assumed to be ideal.

As SUMO models the traffic by step, MATLAB can retrieve the required parameters within each step and complete the calculation. The pseudo-code of the blockage determination algorithm in MATLAB is presented in Algorithm 1. Firstly, we generated a 500 m straight road in SUMO and start emitting vehicles. At each simulation step, vehicle information was tethered by MATLAB through TraCI4Matlab. Finally, MATLAB transverses all vehicles at each step, calculates the effective height $\tilde{h}$ of the first Fresnel zone, and determines the geometric position of the Tx vehicle, blocker, and RSU. This code realized the proposed system model for its performance evaluation. The position of RSU pos_r is defined

Algorithm 1: Blockage determination algorithm

$traci.start()$;
Parameters Initialization;
RSU position definition;
while $step < step_{total}$ **do**
  $traci.simulationStep()$;
  $IDList = traci.getIDList$;
  for $i = 1 : length(IDList)$ **do**
    $pos_t = traci.getPostition('vehicleID(i)')$;
    $h_t = traci.getHeight('vehicleID(i)')$;
    for $j = 1 : length(IDList)$ **do**
      $pos_o = traci.getPostition('vehicleID(j)')$;
      $h_o = traci.getHeight('vehicleID(j)')$;
      $l_o = traci.getLength('vehicleID(j)')$;
      $w_o = traci.getWidth('vehicleID(j)')$;
      /* proposed algorithm */
      $Blockage(pos_r, pos_t, pos_o, h_t, h_o, l_o, w_o)$;
    end
  end
  plot();
end
$traci.close()$;

TABLE I
SIMULATION CONFIGURATION.

Parameter	Value
RSU position	$(53, 0, 5)$
Bus-type CAV dimension	$2.5 \times 12 \times 3$
Car-type CAV dimension	$1.8 \times 3 \times 2$
Center frequency (GHz)	28/40/60
Lane number	3
Bus emission probability	0.8
Car emission probability	0.6
Road length (m)	500
Channel status	ideal

within MATLAB. The configurations of the simulation are summarized in Table I. In the simulation, we adopted three frequency bands, 28 GHz, 40 GHz, and 60 GHz for the V2I mmWave simulation.

B. Simulation result

To verify the blockage determination method, we first implemented a simulation to calculate and analyze the influence on the first Fresnel zone radius from three aspects: obstacle position on the LoS line, LoS distance, and different center frequencies.

As depicted in Fig. 5, the obstacle is located on different portions of the LoS line. The x-axis represents the LoS distance between the transmitter and the receiver in meters, the y-axis denotes the radius of the first Fresnel zone. As the LoS distance increases, the radius is enlarged. In addition, it can also be observed that the radius reaches a maximum when the obstacle is located at the center of the LoS line. The simulation also demonstrates that the first Fresnel zone radius might be the minor influence for $\tilde{h}$ at higher frequency bands when the LoS distance is small. However, even to a high frequency, such as 60 GHz, the average distribution of radius lies within 1 m to 2 m at a short LoS distance of 300 m. This makes the term $\tilde{r}$ in Eq. 2 meaningful and therefore should not be neglected. Considering the autonomous driving scenario, conclusions can be drawn that it is contributed to taking the influence from $\tilde{r}$ into account considering the assigned frequency band for ITS system and also the relatively large communication distance between CAVs in the real world.

In the following simulation, we implemented the simulation setup mentioned in the previous subsection. With the retrieved vehicle information at each step, the first Fresnel zone could be easily calculated, and therefore to determine the effective height according to the configuration predefined in SUMO. Combining the vehicle geometry determination, the blockage situation for every vehicle within one simulation step could be calculated. Fig. 6 exhibits the simulation process in SUMO Graphical User Interface (SUMO-GUI). SUMO-GUI is the application that extends SUMO functions with a graphical user interface that displays SUMO configuration. Special attention should be taken that the RSU position is marked on SUMO-GUI for a better understanding of the geometry relation. The RSU-concerned settings and functions are realized in

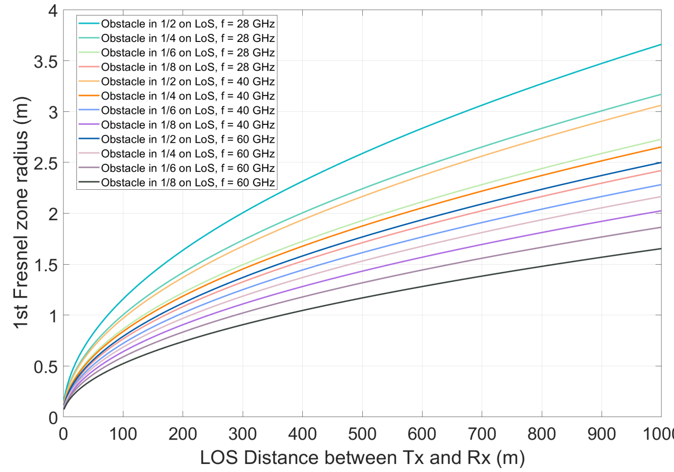

Fig. 5. First Fresnel zone radius

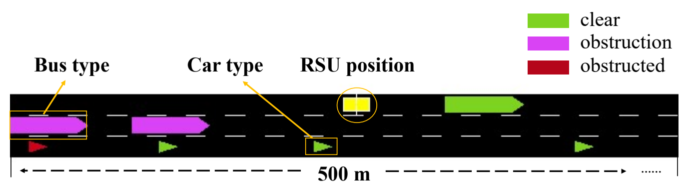

Fig. 6. Number of blockage vs. total number of vehicles on the road under V2I scenario

MATLAB. After the blockage algorithm is carried out, we set different colors to denote the vehicles' blockage status. Green, red, and purple represent the vehicles that are currently clear of obstruction, being obstructed, and being an obstruction to other vehicles respectively.

The simulation results are shown in Fig. 7. The x-axis represents the simulation steps in SUMO; 200 steps in total were taken as a sample in this simulation. The y-axis shows the number of vehicles. In this figure, the blue line has recorded the total number of vehicles within the SUMO scenario. Due to the limitation of the road length, vehicles would eventually exit the segment of the road. Therefore, the total number of vehicles fluctuates with simulation steps. We also adopted three frequency bands in the blockage determination algorithm to offer a further understanding of the blockage rate under different use cases. It can be observed that the total number of blockages varies among frequencies, and the blockage rate is becoming higher at lower frequency bands. The reason can be analyzed by digging into the blockage determination algorithm. It depends on two criteria: the effective height of the first Fresnel ellipsoid and whether the obstruction is located within the LoS line. The geometry relation does not change with frequency settings for the same SUMO configuration. Besides, it is known that the higher center frequency leads to a smaller ellipsoid radius, as depicted in Fig. 5. Hence, the smaller radius leads to the increase of the effective height regarding higher frequency bands. Ultimately, the blockage rate decreases regarding the same obstacle with higher center frequencies.

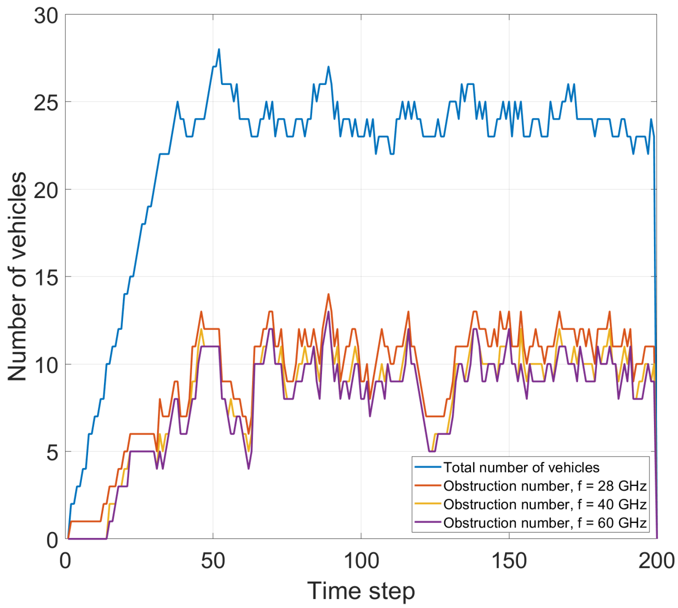

Fig. 7. Number of blockage vs. total number of CAVs on the road under V2I scenario

V. Conclusion and Future work

In this paper, we have discussed the issue of blockage determination under the high mobility road in the RSU-assisted ITS system. We proposed the system architecture of CAM and CPM message sharing by a heterogeneous V2I communication network. The RSU is considered a calculation center that carries out dynamic blockage determination for the current on-road vehicles. Eventually, it notifies the CAVs of their blockage status. With the combination of SUMO and MATLAB, the system performance for blockage determination is validated by considering three different mmWave center frequencies, two types of vehicles, and different LoS distances. SUMO-GUI supports the validation by visualizing the blockage status. The result has presented that the first Fresnel zone radius increases with LoS distance but decreases for higher frequencies. Hence, the blockage rate rises at the lower frequency bands.

This work is promising in stabilizing V2I communication under high mobility real-world scenarios by identifying the blockage status of CAVs for further applications. In future work, we will integrate the blockage determination function into the vehicle side by obtaining the RSU information through maps. In addition, the model will be further developed in a real-world communication environment by considering path loss models. Also, different traffic scenarios will be implemented to explore the algorithm performance even further.

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