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Vehicular Multi-Access Edge Computing With Licensed Sub-6 GHz, IEEE 802.11p and mmWave

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ABSTRACT With the rapid increase of vehicular Internet of things applications, it is urgent to design a mobile edge computing architecture, which is possible to distribute and process a large amount of contents with vehicles on the road. From a communication perspective, the current cellular technology faces challenges due to the limited bandwidth in a dense vehicle environment. In this paper, we propose a multi-access edge computing framework and the corresponding communication protocol which integrates licensed Sub-6 GHz band, IEEE 802.11p, and millimeter wave (mmWave) communications for the content distribution and processing in vehicular networks. The proposed protocol uses a cluster-based approach, where a fuzzy logic-based algorithm is employed to select efficient gateway nodes which bridge the licensed Sub-6 GHz communication and the mmWave communication in order to maximize the overall network throughput. IEEE 802.11p vehicle-to-vehicle communication is used to share information among vehicles in order to achieve efficient clustering. We conduct extensive simulations to evaluate the performance of the proposed protocol under various network conditions. Simulation results show that the proposed protocol can achieve significant improvements in various scenarios compared with the existing approaches.

INDEX TERMS Multi-access edge computing, vehicular networks, mmWave, Sub-6 GHz band, IEEE 802.11p, and fuzzy logic.

I. INTRODUCTION

With the emergence of various vehicular Internet of Things (IoT) applications, such as camera sensor data exchange, driving behavior analysis, speech recognition, real time traffic information update, and software downloading, a new architecture which can achieve ultra-low delay and high throughput is highly required. The current wireless communication technologies show their incompetence in the throughput performance due to the following two reasons. Firstly, the vehicles could be deployed in a highly dense manner at some urban road segments. Secondly, for rural areas, the current technologies are not designed to support a large number of user terminals. In cellular networks, the spectrum efficiency drops drastically along with the increase of the user density. The vehicular mobile edge computing (MEC) could satisfy this need as it conducts the computational tasks and data caching near the end users, such as the passengers and the pedestrians, by integrating the communication and computational capability of vehicles on the road. In this paper, we propose a vehicular MEC architecture which integrates different types of wireless communication technologies.

The use of millimeter wave (mmWave) communications is considered to be one of the main approaches to improve the throughput in 5G. However, there are several challenges to deploy mmWave in vehicular networks. First, mmWave requires a line-of-sight transmission path between the sender and the receiver. Although unlicensed 60GHz mmWave communications can provide up to 2.5Gbps for 1.7Km, the real

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transmission range in vehicular networks would be much lower as many obstacles such as other vehicles and buildings could block the signals. Second, a directional transmission technology, specifically directional antenna or beamforming, is required to overcome pathloss. The sender node needs to know the information (position etc.) of the receiver in order to design efficient beamforming. The corresponding information can be exchanged with Sub-6 GHz communications which are promising to provide larger transmission range and seamless connectivity.

The main drawback of Sub-6 GHz communications is the limited bandwidth as compared to mmWave. Sub-6 GHz communications include licensed infrastructure-based communications and unlicensed distributed communications. The benefit of using licensed Sub-6 GHz spectrum is the large coverage, and the possibility to ensure strict quality-of-service (QoS) provisioning. IEEE 802.11p [1] is the default standard for distributed vehicle-to-vehicle (V2V) communications. Vehicular ad hoc networks (VANETs) utilizing IEEE 802.11p have attracted tremendous attentions in recent years. In addition to safety applications which can be achieved by V2V communications, VANETs could also be an important part of vehicle-to-cloud communications by integrating IEEE 802.11p-based V2V with other communication technologies.

The integration of Sub-6 GHz with mmWave communications becomes a necessity to ensure QoS in vehicular networks. Recent works on V2V communications mainly focus on the use of IEEE 802.11p or mmWave V2V communications [2]–[12]. There are some studies on collaborative downloading through combining LTE with IEEE 802.11p [13]–[16]. However, the integration of licensed Sub-6 GHz, IEEE 802.11p, and mmWave communications has not been extensively in the recent studies. There are two main technical obstacles for the integration of these three communication technologies. Firstly, the selection of gateway nodes should take into account the overall network performance which is determined by both the allocated licensed Sub-6 GHz bandwidth and the V2V throughput. Secondly, the route creation from a vehicle to a gateway is challenging due to the vehicle mobility and the varying node density. The vehicle mobility and inter-vehicle wireless link quality should be taken into account in the selection of the cluster head nodes. For certain hours or road segments, vehicles are densely deployed, and the number of concurrent sending nodes can thus be huge. In IEEE 802.11p, the increase in the number of sending nodes leads to the performance degradation due to the exponential backoff based contention scheme at the MAC layer. Therefore, an efficient information exchange protocol is important for disseminating required control messages with limited bandwidths.

In this paper, we first propose a vehicular MEC architecture which utilizes the computation capability of vehicles, and then propose a cluster-based communication protocol by integrating licensed Sub-6 GHz band, IEEE 802.11p, and mmWave communications for the multi-access edge computing in vehicular networks. This paper is an extended version of our previous conference paper [23]. While [23] only discussed the communication aspects of integration of Sub-6 GHz and mmWave, the work in this paper describes a use of these technologies for MEC. In addition, we have carried out more new simulations to demonstrate the performance benefits from our proposed studies. The main contributions are briefly summarized in the following.

- We propose a vehicular multi-access edge computing architecture, where two different types of vehicular edges are defined and used for different purposes.
- We propose an approach which integrates licensed Sub-6 GHz band, IEEE 802.11p, and mmWave communications with distributed information exchange through IEEE 802.11p V2V communications. To the best of our knowledge, this is the first study addressing the integration of three different wireless technologies for MEC in vehicular networks.
- We employ a fuzzy logic-based algorithm to select efficient cluster head nodes by taking into account the vehicle velocity, the vehicle distribution, and the antenna height. The clusters are generated in a distributed way with low overhead, which ensures that the required information can be exchanged through IEEE 802.11p link.
- The proposed protocol tunes the number of cluster head nodes based on the bandwidth of licensed Sub-6 GHz band. IEEE 802.11p is also used for data transmissions when other wireless technologies are not enough to provide sufficient bandwidths.
- We launch extensive simulations to evaluate the proposed protocol by comparing with other baselines.

The remainder of the paper is organized as follows. Section III proposes a vehicular multi-access edge computing architecture. In section IV, we describe the proposed communication protocol in details. Simulation results are presented in section V. Finally, we draw our conclusions in section VI. The terms "vehicle" and "node" are used interchangeably throughout the paper.

II. RELATED WORK

Recent related studies cover communication protocols, and the design of mobile edge computing framework. However, the integration of licensed Sub-6 GHz, IEEE 802.11p, and mmWave in vehicular edge computing is an under-explored research problem.

A. COMMUNICATION PROTOCOLS FOR VEHICULAR NETWORKS

There have been many studies discussing the efficient use of IEEE 802.11p in vehicular networks. Study in [2] is an investigation of the geographic routing protocol for multilevel scenarios such as viaducts, tunnels, and ramps. A survey on clustering technologies is provided in [3]. In [4], a concept of using moving zone to improve the data dissemination process is discussed, and the formation of dynamic moving zone using pure IEEE 802.11p-based V2V communications is proposed. The incentive mechanism for stimulating the cooperation between vehicles is proposed in [5]. Research in [6] discusses the data storing problem in VANETs.

In the past few years, mmWave communication technologies have attracted a growing interest in satisfying the requirement of exponentially increasing mobile data traffic. Kong *et al.* [7] have explored the benefit of using mmWave communications for autonomous vehicles, and then proposed a design of a vehicular mmWave system combining the advantages of IoT and cloud computing. Mastrosimone and Panno [8] have introduced the concept of combining LTE and mmWave technologies for vehicular networks, and compared their approach with a pure LTE mobile femtocell approach. Perfecto *et al.* [9] have addressed the problem of how to share contextual sensed information among vehicles using many-to-one mmWave V2V links, and proposed a distributed matching game- based approach. Based on matching theory and swarm intelligence, a distributed association and beam alignment framework for mmWave V2V networks has been proposed in [10]. Cui *et al.* [11] have discussed the vehicle positioning problem using 5G mmWave signals. Cui *et al.* [11] have proposed an effective interference coordination mechanism to cognitively limit the interference between the base stations (BSs) and users in ultra-dense mmWave networks.

There have been some studies focusing on the integration of LTE with IEEE 802.11p. A scheduler for cooperative data transmissions in a hybrid infrastructure-to-vehicle and V2V communication environment has been proposed in [13]. In the hybrid networks with LTE and IEEE 802.11p, some vehicles work as gateways in order to provide routing services to other vehicles and improve the efficiency of wireless resource utilization. For this purpose, Zhioua *et al.* [14] have proposed a protocol which takes into consideration of QoS traffic class constraints for the gateway selection. The performance degradation problem in terms of increased error probability with vehicle mobility has been discussed in [15]. Ucar *et al.* [16] have combined IEEE 802.11p-based multi-hop V2V with LTE by using a clustering algorithm accounting for vehicle mobility and cluster formation overhead.

B. MOBILE EDGE COMPUTING IN VEHICULAR NETWORKS

A recent survey on the emerging 5G network edge cloud architecture can be found from [17]. In [17], Taleb *et al.* have analyzed the MEC reference architecture and main deployment scenarios, and conducted an overview of the current standardization activities. Liu *et al.* [18] have proposed an SDN-enabled MEC architecture for vehicular networks. An integration of IEEE 802.11p, cellular communication, and wired communication is used to provide vehicle-to-everything (V2X) communications. Zhang *et al.* [19] have proposed a cloud-based MEC off-loading framework in a vehicular environment. They have presented two different offloading schemes, namely direct uploading and predictive relay transmissions, which are selected depending on the time consumption and the corresponding cost. Kumar *et al.* [20] have discussed the use of vehicular delay tolerant network technologies for MEC targeting mainly at smart grid applications. The computing and communication aspects are jointly considered to evaluate the impact of MEC. Hou *et al.* [21] have presented the utilization of moving or parked vehicles as communication and computation infrastructures. They have pointed out the appearance of more advanced developments with the increase of the communication and computational capacities. Basudan *et al.* [22] have proposed a privacy-preserving road surface condition monitoring system based on fog computing. All these existing works do not sufficiently address the integration of different communication technologies especially for mmWave which is a main approach for providing high throughput transmissions in the next generation wireless networks.

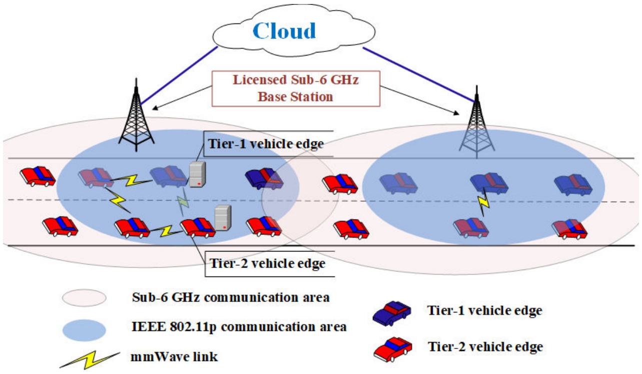

FIGURE 1. Vehicular multi-access edge computing with integration of licensed Sub-6 GHz, IEEE 802.11p, and mmWave.

III. VEHICULAR MULTI-ACCESS EDGE COMPUTING ARCHITECTURE

To meet the rapidly increasing need of latency-sensitive vehicular IoT applications such as vehicular video data analytics, autonomous driving, and intelligent navigation, a MEC architecture which can provide an ultra-low latency and high bandwidth is required. Here, we propose a hierarchical vehicular multi-access edge computing architecture which efficiently utilizes the computational resources of vehicles to perform MEC in order to provide better QoS to end users. As shown in Fig.1, three different types of communications, namely licensed Sub-6 GHz, IEEE 802.11p, and mmWave, are utilized for information exchange. We define two different types of vehicle edges specifically tier-1 edges and tier-2 edges (see Table 1). Tier-1 edges are used to conduct content caching, data aggregation, and data analysis (such as video analytics). Tier-2 edges are connected to the BS through tier-1 edges. By performing data caching and data aggregation at the Tier-1 edges, a more efficient use of the wireless resources can be achieved. A vehicle works either as a tier-1 or tier-2 edge server depending on the surrounding environment including available wireless resources and node density, which will be explained in the next section.

TABLE 1. **Tier-1 and Tier-2 vehicular edges.**

	Tier-1 edge	Tier-2 edge
Functions	Provide services to Tier-1, Tier-2 vehicular edge servers, and other non-edge terminals such as cell-phones	Provide services to non-edge user terminals such as cell-phones
Roles	Data caching, data aggregation, data analysis	Data analysis
Commun. method	Tier-1 edge ⟷ BS: licensed Sub-6 GHz, Tier-2 edge ⟷ BS: no direct commu., Tier-1 edge ⟷ Tier-2 edge: mmWave or IEEE 802.11p	

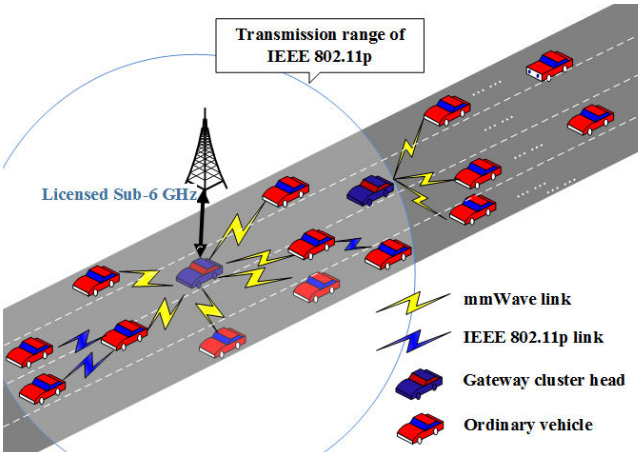

FIGURE 2. **Content distribution with licensed Sub-6 GHz, IEEE 802.11p, and mmWave.**

IV. PROPOSED PROTOCOL

A. ASSUMPTIONS

Each node is equipped with a positioning device and three wireless interfaces, namely, licensed Sub-6 GHz interface, IEEE 802.11p interface, and mmWave interface. All nodes know the road map information and the average transmission range for IEEE 802.11p-based V2V communications. Each node sends its own location information, neighbor information (the number of vehicles driving toward the same direction as in Subsection IV-C), velocity information, and antenna height information using beacon messages with a predefined interval, which is 1 second by default. We assume a connected network topology where at least one multi-hop path exists between any two nodes. As a reliable transmission is the most important requirement of content distribution, which is from a licensed Sub-6 GHz BS to a vehicle, we consider unicast communications for V2V communications which are easier to conduct retransmissions as compared to broadcast communications. As shown in Fig.2, the contents are transmitted from a licensed Sub-6 GHz BS to a gateway node, and then transmitted to multiple vehicles in vicinity simultaneously using mmWave, and IEEE 802.11p communications.

B. COMMUNICATION PROBLEM DEFINITION AND PROTOCOL OVERVIEW

We consider the problem of sending data from the cloud to vehicles which is very important for vehicular IoT applications. More specifically, the problem can be simplified as the transmission from a licensed Sub-6 GHz BS to vehicles. We utilize one-hop mmWave communications while the multi-hop mmWave communication is considered to be impractical due to the complexity of establishing a long path for mmWave communications.

In the proposed protocol, as shown in Fig.2, instead of each vehicle connecting to a BS, only the gateway vehicles utilize Sub-6 GHz interface and communicate with other vehicles through mmWave V2V communications. Control messages are exchanged with IEEE 802.11p V2V communications. The IEEE 802.11p V2V communications could be multi-hop, and could be used for data (content) exchange depending on the network conditions. The gateway nodes are selected using a fuzzy logic-based algorithm considering vehicle mobility, vehicle distribution, and antenna height. The fuzzy logic algorithm ensures the selected cluster head nodes are stable. The number of gateway nodes is tuned by an adaptive algorithm according to the bandwidth of licensed Sub-6 GHz communication, the node density, and the quality of V2V links.

C. DISTRIBUTED CLUSTER HEAD SELECTION BASED ON IEEE 802.11p V2V COMMUNICATIONS

We use an approach where cluster heads are selected in a distributed way. Cluster joining/leaving procedure is conducted with low overhead as we do not use any cluster joining/leaving messages for the maintenance of cluster member information. After cluster heads being determined, each cluster head announces the number of cluster members using the hello messages. We evaluate the suitability of a vehicle acting as cluster head by using a fuzzy logic-based approach. In the evaluation, we take into account three different factors: 1) the moving speed of vehicles, 2) the density of vehicles that are moving toward the same direction as the current vehicle, and 3) the antenna height. The first two factors are used to ensure that the generated cluster heads are stable. The third factor is to fully utilize mmWave communications as high antenna height could improve the line-of-sight distance. We use a fuzzy logic-based approach for the evaluation by combining these three factors.

The cluster heads are selected based on the information shared with hello messages. Each node attaches the information about its velocity and antenna height information. Upon reception of a hello message, each node calculates a competency value (in other words, the value for being a cluster head) for itself and each one-hop neighbor. The node which has the largest competency value in its vicinity declares itself as a cluster head using hello messages. We generate the cluster heads by considering the connectivity between cluster heads. Each node calculates a competency value for its neighbors which are within the range of R_{ref} which is smaller than $\frac{1}{2}R$ where R is the average transmission range for IEEE 802.11p V2V communications in meters. R is determined by the wireless transceivers installed at vehicles. A vehicle declares itself as a cluster head if its competency value is

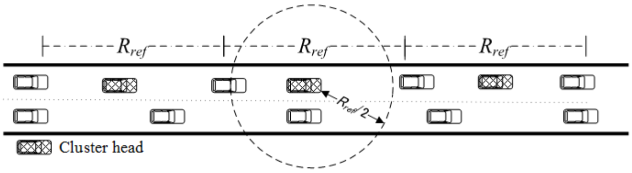

FIGURE 3. Cluster head and cluster size.

the largest in the $\frac{1}{2}R_{ref}$ region. This means that there would be at least two cluster head vehicles at R_{ref} distance, ensuring the reliable connection between two neighboring cluster head vehicles. If the vehicles are uniformly distributed, there would be one cluster head for each R_{ref} region (see Fig.3).

D. FUZZY LOGIC-BASED COMPETENCY CALCULATION

The competency value calculation consists of three steps. First, the velocity factor, the leadership factor, and the antenna height factor are calculated for each one-hop neighbor who is within the range of R_{ref}. Next, the factors are converted to fuzzy values, and then calculated by predefined rules to get the final fuzzy value. Last, the fuzzy value is converted to a numerical value (i.e., the competency value) based on fuzzy output membership function.

1) FIRST STEP – CALCULATING THREE FACTORS

The velocity factor, leadership factor, and antenna height factor are calculated based on the hello messages received from neighbors.

a: Velocity factor (VF)

Upon reception of a hello message from node m, node s calculates $VF(s, m)$

$$VF(s,m) = \frac{|\upsilon(m)| - \min_{y \in N_s} |\upsilon(y)|}{\max_{y \in N_s} |\upsilon(y)|}, \tag{1}$$

where N_s is the neighbor set of node s, and $\upsilon(\cdot)$ denotes the velocity. A smaller VF indicates a lower velocity. The update of VF is conducted periodically with the interval of one second based on a weighted exponential moving average,

$$VF_i(s,m) \leftarrow (1-\alpha) \times VF_{i-1}(s,m) + \alpha \times VF_i(s,m), \tag{2}$$

where $VF_{i-1}(s, m)$ and $VF_i(s, m)$ denote the previous value and current value of VF respectively. VF is initialized to 1, and α is set to 0.7 based on our simulation results.

b: Leadership factor (LF)

$LF(s, m)$ is calculated as

$$LF(s,m) = \frac{c(s)}{\max_{y \in N_s} c(y)}, \tag{3}$$

where $c(s)$ shows the number of vehicles moving toward the same direction as the node s. A higher LF means that the node is more suitable for being a cluster head node. The initial value of LF is 0. For every hello message reception, LF is updated using a weighted exponential moving average as

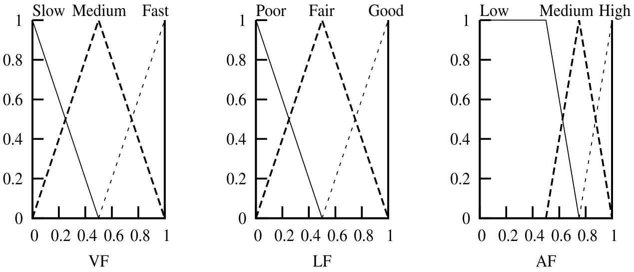

FIGURE 4. Fuzzy membership functions (left: *VF*, middle: *LF*, right: *AF*).

TABLE 2. Rule base.

	Velocity	Leadership	Antenna height	Rank
Rule1	Slow	Good	High	Perfect
Rule2	Slow	Good	Medium	Good
Rule3	Slow	Good	Low	Unpreferable
Rule4	Slow	Fair	High	Good
Rule5	Slow	Fair	Medium	Acceptable
Rule6	Slow	Fair	Low	Bad
Rule7	Slow	Poor	High	Unpreferable
Rule8	Slow	Poor	Medium	Bad
Rule9	Slow	Poor	Low	VeryBad
Rule10	Medium	Good	High	Good
Rule11	Medium	Good	Medium	Acceptable
Rule12	Medium	Good	Low	Bad
Rule13	Medium	Fair	High	Acceptable
Rule14	Medium	Fair	Medium	Unpreferable
Rule15	Medium	Fair	Low	Bad
Rule16	Medium	Poor	High	Bad
Rule17	Medium	Poor	Medium	Bad
Rule18	Medium	Poor	Low	VeryBad
Rule19	Fast	Good	High	Unpreferable
Rule20	Fast	Good	Medium	Bad
Rule21	Fast	Good	Low	VeryBad
Rule22	Fast	Fair	High	Bad
Rule23	Fast	Fair	Medium	Bad
Rule24	Fast	Fair	Low	VeryBad
Rule25	Fast	Poor	High	Bad
Rule26	Fast	Poor	Medium	VeryBad
Rule27	Fast	Poor	Low	VeryBad

$$LF_i(s,m) \leftarrow (1-\alpha) \times LF_{i-1}(s,m) + \alpha \times LF_i(s,m). \tag{4}$$

c: Antenna height factor (AF)

Node m attaches its AF in the hello messages. AF of node m is calculated as

$$AF(m) = \frac{h(m)}{\max_{y \in N_m} h(y)}. \tag{5}$$

2) SECOND STEP – FUZZIFICATION AND FUZZY RULES

The fuzzy membership functions are defined as shown in Fig. 4.

In Table 2, Rule1 is expressed as follows.

IF *Velocity* is Slow, *Leadership* is High, and *antenna height* is Good **THEN** *Rank* is Perfect.

We use the Min-Max method in the case that multiple rules apply at the same time.

3) LAST STEP – DEFUZZIFICATION

We use a membership function defined by Fig. 5 to defuzzify the result in order to get the competency value of the node. By comparing the competency values, the cluster head nodes are determined.

E. ADAPTATION OF R_{ref}

We use an adaptive algorithm to tune the size of clusters (which is determined by R_{ref}) in order to maximize the

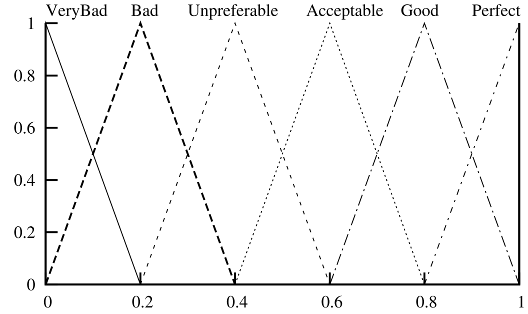

FIGURE 5. Output membership function.

average throughput. If all the vehicles are served with mmWave communications, the best action could be maintaining the current allocation or increasing the size of R_{ref}. The increase of the size R_{ref} could result in a smaller number of gateway nodes, which means a large bandwidth for each gateway. In contrast, if there are some nodes which cannot be connected by mmWave (these nodes will be served by IEEE 802.11p), the reduction of R_{ref} could possibly achieve a better performance as it provides a higher chance of utilizing high-throughput mmWave communications. Algorithm 1 shows the procedure of determining R_{ref}. This algorithm is executed before selecting cluster head nodes. B_{11p} and B_{licn} are the achievable bandwidth for licensed Sub-6 GHz spectrum (in case of serving as a gateway) and IEEE 802.11p, respectively. Γ is set to 10 by default.

Algorithm 1 Algorithm for Determining R_{ref}

```
Check the number of nodes served by IEEE 802.11p communications ($NUM_{11p}$) in the previous round.
if ($NUM_{11p} == 0$) then
    $\Delta \leftarrow \frac{B_{11p}}{B_{licn}+B_{11p}}$
    $R_{ref} \leftarrow \min(R_{ref} + \frac{\Delta}{2}R,\ R)$
else
    if ($B_{licn} > \frac{B_{11p}}{2NUM_{11p}}$) then
        $\Delta \leftarrow \frac{1}{\Gamma}$
        $R_{ref} \leftarrow \max(R_{ref} - \Delta R,\ \Delta R)$
    else
        $\Delta \leftarrow \frac{1}{2\Gamma}$
        $R_{ref} \leftarrow \min(R_{ref} + \Delta R,\ R)$
    end if
end if
```

V. SIMULATION RESULTS

We used ns-2.34 [24] to conduct simulations in freeway scenarios (see Table 3). We used a freeway which had two lanes in each direction [25]. The distance between any two adjacent lanes was 5m. Nakagami propagation model was used to simulate channel fading [26]. The parameters of Nakagami Model are shown in Table 4, where parameter names are the variable names in ns-2.34. Based on parameters given in [26], we set the average transmission range for IEEE 802.11p V2V communications as 250m. Although the transmission range can be up to 1000m in IEEE 802.11p, we believe this setting is plausible for evaluating unicast protocols as longer distance could be difficult to use an efficient modulation and coding scheme. Each vehicle blocks mmWave signal with the probability of 75%. In the simulations, 15% percent of vehicles were equipped with higher antennas, and these vehicles can provide 40% more vehicles with mmWave communications.

TABLE 3. Simulation environment.

Topology	2000m, 4lanes
Number of nodes	100–500
Maximum velocity	100 km/h
Mobility generation	Ref. [25]
MAC	IEEE 802.11p MAC (27 Mbps)
Propagation model	Nakagami model
Simulation time	1500 s

TABLE 4. Parameters of Nakagami model.

gamma0_	gamma1_	gamma2_	d0_gamma_	d1_gamma_
1.9	3.8	3.8	200	500

m0_	m1_	m2_	d0_m_	d1_m_
1.5	0.75	0.75	80	200

The proposed protocol was compared with "LIC Sub-6 GHz", and "LIC Sub-6 GHz + mmWave". "LIC Sub-6 GHz" denotes that every vehicle uses licensed Sub-6 GHz communications for the content distribution (all vehicles work as gateways). In "LIC Sub-6 GHz + mmWave", some vehicles work as gateways and others are connected to the gateways. Here gateway nodes are responsible for providing contents to non-gateway nodes. In addition to mmWave, the proposed protocol also uses IEEE 802.11p communications to provide last one-hop connections when the mmWave cannot cover all the vehicles.

The number of licensed Sub-6 GHz BSs was 1, which means that all the vehicles could be connected to the same BS. The data were sent from the BS to vehicles, and all the vehicles in the network were the intended receivers. We evaluated the performance for various vehicle densities, and licensed Sub-6 GHz bandwidths. In the following simulation results, the error bars indicate the 95% confidence intervals.

A. PERFORMANCE FOR VARIOUS VEHICLE DENSITIES

Fig.6 shows the TCP throughput for various vehicle densities. The bandwidth of LIC Sub-6 GHz communications that can be allocated for the whole vehicular network was 200 Mbps. We can observe that when the vehicle density is large, "LIC Sub-6 GHz" cannot achieve high throughput because the bandwidth allocated for each vehicle is small. This explains the importance of utilizing mmWave communications. "LIC Sub-6 GHz + mmWave" is unable to achieve satisfactory throughput as the number of gateway nodes is high (see Fig.7), resulting in the bandwidth available for each gateway is lower. The proposed protocol selects the nodes which have higher antennas by considering the antenna

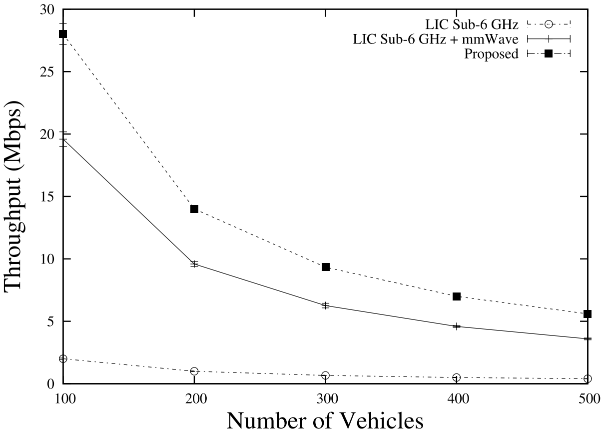

FIGURE 6. Throughput for various numbers of vehicles.

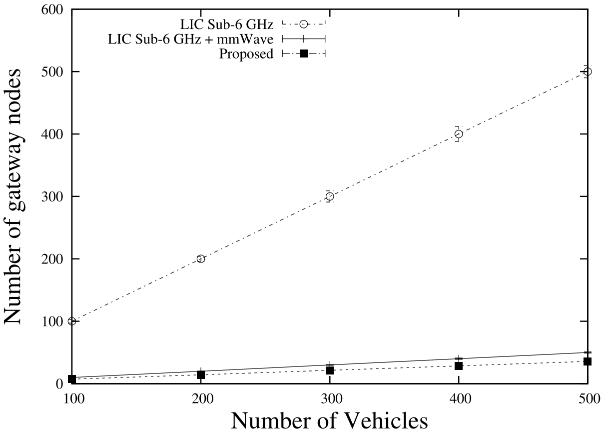

FIGURE 7. Number of gateway nodes for various numbers of vehicles.

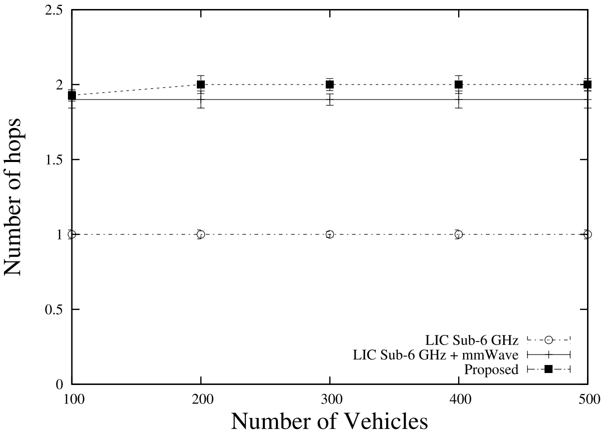

FIGURE 8. Number of hops to BS for various numbers of vehicles.

height in the gateway selection. This increases the number the vehicles served by mmWave communications and therefore achieves lower number of gateway nodes. As shown in Fig.8, there is a little increase in the number of hops for the proposed protocol. This is because the proposed protocol intends to use IEEE 802.11p links which result in 3-hop communications to a gateway node.

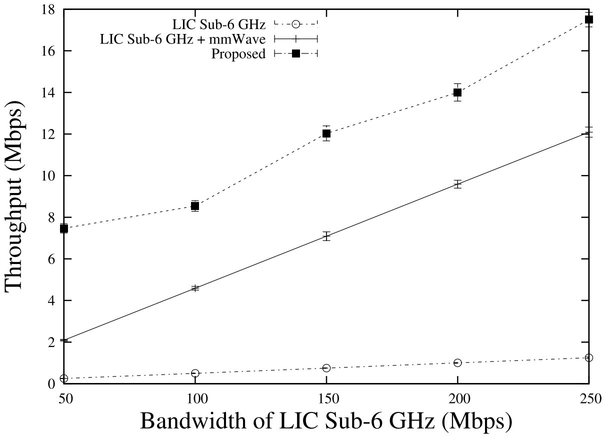

FIGURE 9. Throughput under various bandwidths of LIC Sub-6 GHz communications.

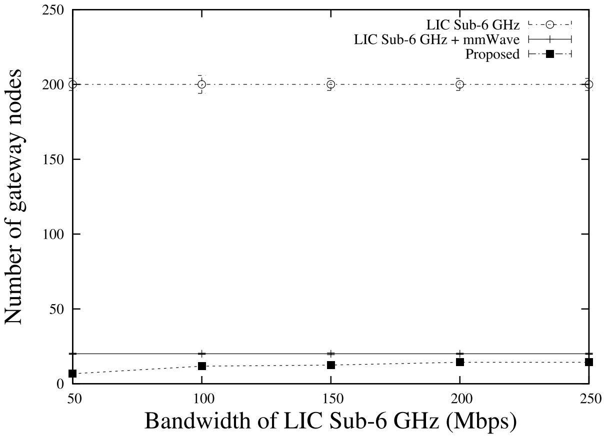

FIGURE 10. Number of gateway nodes under various bandwidths of LIC Sub-6 GHz communications.

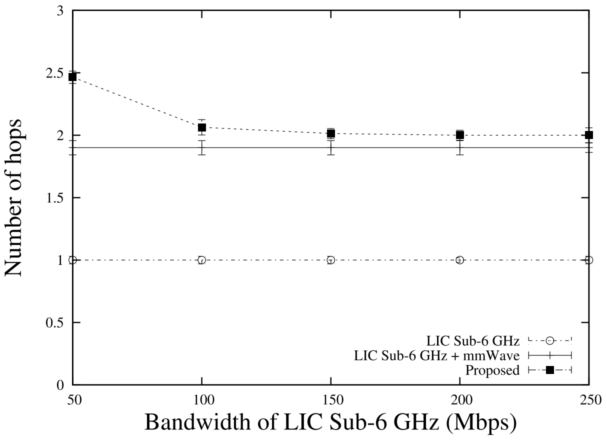

FIGURE 11. Number of hops to BS under various bandwidths of LIC Sub-6 GHz communications.

B. PERFORMANCE FOR VARIOUS LTE BANDWIDTHS

Fig.9 shows the throughput for various bandwidths of LIC Sub-6 GHz communications. The number of vehicles was 200. The throughput advantage of the proposed protocol over "LIC Sub-6 GHz + mmWave" is more significant when the

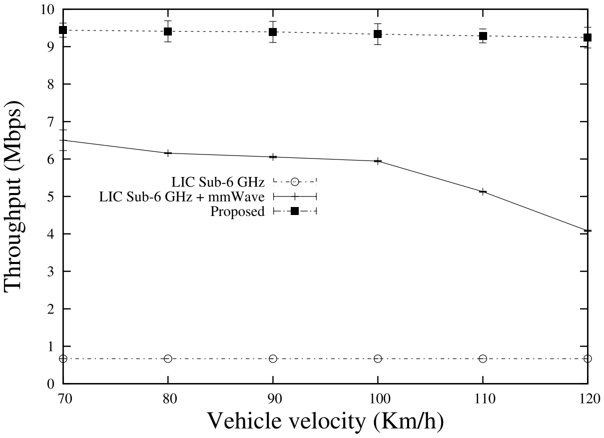

FIGURE 12. Throughput for various vehicle velocities.

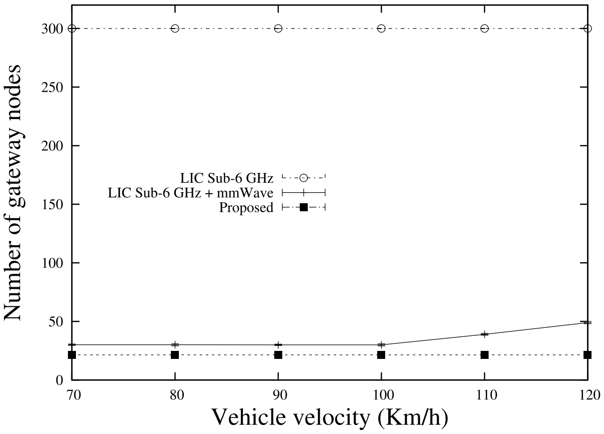

FIGURE 13. Number of gateway nodes for various vehicle velocities.

bandwidth of LIC Sub-6 GHz communications is smaller. When the bandwidth for LIC Sub-6 GHz communications is low, the proposed protocol intends to further utilize the IEEE 802.11p communications by using multi-hop transmissions. More specifically, some nodes will find it is more beneficial for them to connect to a neighbor node instead of working as a gateway by itself (see Fig.10). However, when the LTE throughput is enough, the proposed protocol uses mmWave communications for inter-vehicle data exchange. This is achieved through efficiently tuning the number of gateway nodes with dynamic adaptation of R_{ref} (see Fig.11). By integrating licensed Sub-6 GHz communications, mmWave, and IEEE 802.11p-based V2V communications, the proposed protocol can provide the best performance for various conditions.

C. PERFORMANCE FOR VARIOUS VEHICLE VELOCITIES

Fig.12, Fig.13, and Fig.14 show the throughput, number of gateway nodes, and number of hops for various vehicle velocities respectively. The number of vehicles was 300. The available bandwidth of LIC Sub-6 GHz communications was 200 Mbps. The throughput of "LIC Sub-6 GHz + mmWave" decreases with the increase of vehicle velocity. This is because in "LIC Sub-6 GHz + mmWave", the vehicles with high mobility could be selected as gateways. It is difficult for these vehicles to provide stable gateway services to other vehicles. The vehicle mobility results in a larger number of gateway vehicles and lower Sub-6 GHz bandwidth allocated for each gateway. The proposed protocol solves the problem by 1) selecting the vehicles with lower velocity as the gateway nodes, and 2) using IEEE 802.11p as the last one-hop communication approach which ensures a lower number of gateway nodes. Regarding the route length, since the proposed protocol takes into account the vehicle mobility and the leadership factor in the cluster head selection, the number of hops does not increase drastically with the increase in vehicle velocity.

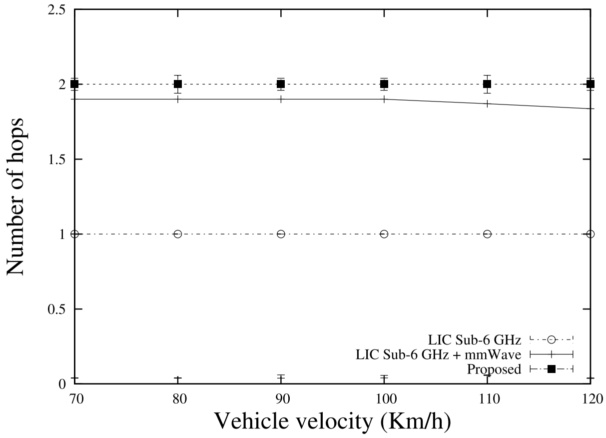

FIGURE 14. Number of hops for various vehicle velocities.

VI. CONCLUSIONS

We proposed a cluster-based protocol for the content distribution in vehicular networks by integrating licensed Sub-6 GHz band, IEEE 802.11p, and mmWave communications. In the proposed protocol, the licensed Sub-6 GHz communication is used to provide Internet connectivity to the vehicles which serve as gateway nodes providing connections to other vehicles. The mmWave communication is employed to provide high throughput connection between a vehicle and a gateway node. IEEE 802.11p-based V2V communication is used to exchange control messages for an efficient integration of different wireless technologies. We used a fuzzy logic algorithm to generate efficient cluster head nodes by taking into account vehicle velocity, vehicle distribution and antenna height. We further employed an algorithm to tune the number of gateway nodes in order to achieve high overall network performance under various network conditions. Through computer simulations, we confirmed that the proposed protocol can provide a better performance than the existing baselines in various scenarios, especially in low bandwidth and highly dense scenarios.

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