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An Optimized Clustering-Based Contention-Free MAC Protocol for Vehicular Ad Hoc Networks

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Research Article

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I. INTRODUCTION

Nowadays, vehicular ad hoc networks (VANETs) have been gaining more attention in emerging intelligent transportation system (ITS) technologies, aiming to provide a wide spectrum of safety and comfort applications to drivers and passengers, and are regarded as an essential component of smart cities [1]. For ensuring reliable communications, providing an efficient medium access control (MAC) protocol is extremely vital in the VANET platform by disseminating safety messages to prevent accident-prone tragedies and causal sequences [2].

Numerous researchers have proposed distinct types of MAC protocols to meet the stringent requirements of dynamically changing traffic network topology in VANET. The preponderance of evidence suggests that the majority of MAC protocols for wireless access in vehicular environment (WAVE) are based on IEEE 1609.4 and IEEE 802.11p standards to cope with the rapid motion of vehicles, incessant topology changes, inadequate facilities, and a broad variety of quality of service (QoS) requirements [2].

Predominantly, all the MAC protocols can be categorized as contention-based and contention-free strategies [3]. Since contention-based IEEE802.11p has been developed, dedicated short-range communications (DSRC) adopts the carrier sense multiple access/collision avoidance (CSMA/CA) mechanism and enhanced distributed channel access (EDCA) to handle the major issue of rapid network topology and vehicle mobility. However, the IEEE 802.11p protocol suffers from poor scalability and involves issues with hidden and exposed terminals, which will result in the failure of real-time security message transmission [4].

In contrast, the main idea of contention-free schemes is to eliminate unnecessary collisions and back-off predicaments but they require the periodic exchange of control messages to maintain the scheduled table and network time in sync [3]. Meanwhile, time division multiple access (TDMA)-based MAC protocols are becoming an emerging topic of research to overcome the shortcomings of others in the field of VANETs, in which time is methodically divided into time slots, and only one vehicle can access the channel at any time slot that permits various vehicles to be assigned different numbers of time slots [5].

In centralized TDMA-based contention-free MAC protocols for VANETs, cluster-based approach can reduce the effect of high relative mobility, make communication architecture stable, and reduces end-to-end delays [3]. However, in high mobility scenarios of VANET, cluster instability is a challenging issue, whereas the clusters have to form and change over time and which may lead to MAC performance degradation. Meticulously, the innovative stringent algorithms are essential to improve the cluster head (CH) selection, cluster formation including cluster merging and CH dissolving, and utilization of efficient optimization algorithms.

Recently, we have proposed a cluster-based contention-free medium access control (CC-MAC) protocol [6] to mitigate inter-cluster and intra-cluster transmission collisions in VANETs. Though the performance of the CC-MAC protocol is affected by radio propagation and mobility models, no real-world map simulation is provided to enhance cluster formation efficiently. Motivated by the aforementioned issues, in this paper, we propose the Optimized Clustering-Based Contention-Free MAC (OCC-MAC) by providing a robust and well-balanced clustering structure to meet the requirements of a realistic vehicular network scenario in a dynamic VANET environment. The novelty and contributions of this paper are listed as follows:

- Custom vehicular mobility model and channel model are developed and incorporated to comply with the realistic scenarios of VANET communication.
- A metaheuristic clustering optimization algorithm is proposed based on specifications and cluster formation procedures to improve cluster maintenance and increase the network lifetime.
- Encirclement marching strategy is proposed based on selected CH in which efficient CH dissolving and cluster merging mechanisms can eliminate transient changes from causing unnecessary re-affiliation attempts and improve the cluster's stability.
- Based on the pragmatic vehicular scenarios, real-world map simulation is conducted. In both highway and urban traffic scenarios, the simulation results disclose that the optimized protocol outperforms the IEEE 802.11p and competitive protocols in terms of normalized throughput, packet delivery ratio (PDR), access delay, end-to-end delay, and collision rate.

The rest of the paper is organized as follows. Section II presents an overview of related work. Section III presents the preliminaries and custom models of vehicular mobility and channel propagation. Section IV describes the optimized clustering algorithm with the proposed encirclement marching method. The performance comparison of real-world simulation results is presented in Section V, and conclusions are given in Section VI.

II. RELATED WORK

Cluster stability is a key factor in efficient clustering and can significantly improve the performance of the vehicular network. In recent years, various clustering techniques have been developed to improve network efficiency in terms of scalability and reliability. In scalable cluster-based TDMA MAC (STCM) [7], a new entering vehicle is required to allocate two control channel (CCH) mini-slots, which may prolong the waiting time to reserve the CCH and collect a high amount of access delay involved for frequent switching from CCH to service channel (SCH). In optimized cluster-based (OCB-MAC) [8], CH is selected on the received Registration to Cluster (ReTCL) packet and the clustering algorithm is based on RTS/CTS and Short Inter Frame Space (SIFS)

interval timeout. Therefore, double-checking on leaving CM can cause scheduling overhead and impair cluster maintenance.

In clustering MAC protocols, the time required for the clustering process can contribute to end-to-end delay, especially when the network is large or vehicles frequently join or leave clusters [9]. Therefore, metaheuristic clustering algorithms are considered as a crucial computational strategy to eliminate diverse technical hurdles in VANET [10]. In K-means clustering [11], the CH is selected by weight function based on the amount of free buffer space, the speed, and the node degree. In Fuzzy C-means clustering [12], a fuzzy cluster head selection scheme is considered according to various input parameters such as vehicles' average velocity, distance, network connectivity level, lane weight and trustworthiness for the fuzzy system.

III. System Models

This section describes the preliminaries, fundamental models of vehicular mobility and channel characteristics, which are implemented to provide more realistic scenarios of VANET communication.

A. Preliminaries

It is assumed that an onboard unit (OBU) with dual transceivers is equipped in each vehicle as a core component of communication between each other, and the communication radius for all OBUs is the same. Each vehicle is assumed to have a unique identification (ID) based on its MAC address and an onboard unit that facilitates wireless communication in accordance with the IEEE 802.11p/WAVE 1609.4 standard [2].

Along the roadway, a specific number of road side units (RSUs) are deployed, and a multi-access edge computing (MEC) server is internally linked to each RSU whereas each MEC server is wired to one another to extend the network infrastructure. As shown in Fig. 1, R_S represents the RSU's communication radius and R_c represents the communication radius of the OBU of each vehicle.

B. Mobility Model

Considering that each vehicle is arbitrarily specified its origin and destination on a multi-lane roadway, let us assume that α_n is the number of vehicles/s moving on the n-th lane, and L_t is the total number of lanes on a road segment. The total number of vehicles arriving at the road per second can be expressed as

$$\alpha = \sum_{n=0}^{L_t} \alpha_n \,. \tag{1}$$

The arrival of vehicles at each road segment is distributed according to an independent homogeneous Poisson point process (PPP) [9], which can be represented as $\beta_v^{\alpha} = \{\beta_v^{\alpha_1}, \beta_v^{\alpha_2}, ..., \beta_v^{\alpha_n}\}$, and RSUs are spatially distributed according to a homogeneous PPP. For road safety, the minimum headway between all vehicles on the road follows the 2 s rule, which means that the distance for vehicle-to-vehicle (V2V) connectivity must be equal to 2 times the vehicles' velocity.

C. Channel Model

A channel model that adequately incorporates numerous recognized physical channel characteristics (such as path loss, fading and shadowing) could result in a more accurate assessment similar to real-world application scenarios in VANET. In this research, based on the Friis transmission formula [9], the SINR for V2V varies in a path-loss fading/shadowing channel as defined by:

$$SINR = \frac{P_r}{N + I\ell(x_i, x_{rx})} = \frac{P_t K_0 \ell(x_{tx}, x_{rx})}{\sum K_x \ell(x_i, x_{rx}) + N}, \tag{2}$$

where P_r represents the signal strength from the transmitting vehicle on the receiving vehicle, N is the average power of thermal noise, I is the interfering signal strength to the receiver, whereas $\ell(x_i, x_{rx})$ is the path loss between the interferer and receiver. And, P_t denotes the transmitted power of the vehicle, K_0 denotes a constant that depends on useful channel fading and antenna characteristics, $\ell(x_{tx}, x_{rx})$ is the path loss between the transmitting vehicle and receiving vehicles, K_x represents a constant that depends on the interfering channel fading for an interferer at location x, and N is the noise power of white Gaussian noise.

IV. Optimized Clustering Algorithm

Motivated and inspired by existing works, this work proposes a metaheuristic algorithm of cluster optimization based on two steps: 1) Specifications and cluster formation including CH selection strategy and cluster maintenance procedures, and 2) Encirclement marching method to reinforce the integrity of the cluster.

A. Specifications and Cluster Formation

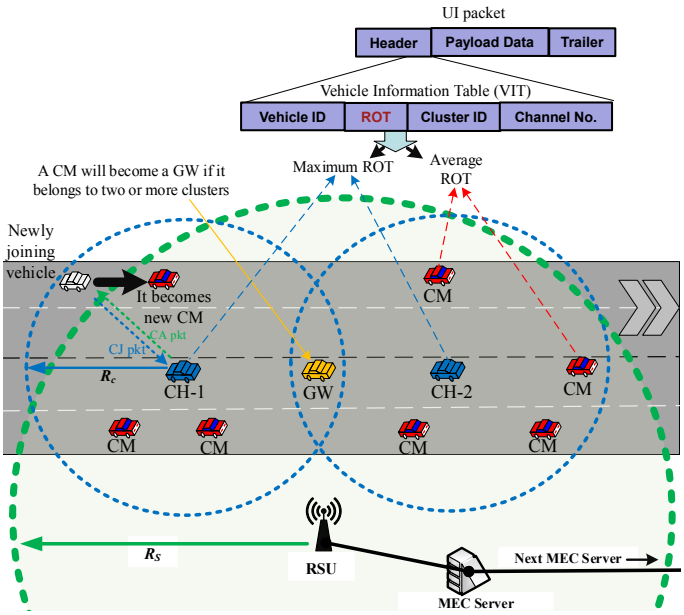


Fig. 1. Proposed optimized clustering architecture for VANETs.

A traffic network model with clustering architecture is depicted in Fig. 1. As a first step, to initialize the cluster architecture, a cluster is formed within a one-hop range of vehicles traveling in the same direction with similar speeds and multi-hop transmission is only possible for CHs [13]. Furthermore, CH is responsible for the role of cluster supervision and coordination as well as intra and inter-cluster information dissemination.

It is considered that each vehicle has a vehicle information table (VIT), which comprises information about itself and its one-hop neighbors, such as the vehicle ID, relative offset time (ROT) [6] (including position, speed, moving direction and etc.,), cluster ID and channel number. For local topology discovery, each vehicle sends all the information in its updated information (UI) packets, and all adjacent vehicles and the relevant RSU update its VIT based on their received UI packets.

In the second step, if a vehicle discovers that it has the maximum ROT among all its one-hop neighboring vehicles, it will select a free channel for intra-cluster communications and utilize a CH slot to transmit a CH packet for identifying a newly-established cluster. In this case, CH selection is also based on three factors: 1) a CH vehicle with the maximum number of successful transmission times in the past, 2) a vehicle with the least mobility in the cluster, and 3) lane weight that is identified to be center depends on the overall number of lanes on the road as well as the right-most lanes in each traffic flow.

The third step of the proposed clustering algorithm is cluster formation and maintenance which are important aspects to enable efficient communication and coordination among vehicles. As illustrated in the upper left side of Fig. 1, a new vehicle that receives this CH packet within the transmission range can sense the channel and send a cluster join (CJ) packet to the associated CH. Then, CH responds with a cluster accept (CA) or cluster reject (CR) packet in the following slot after receiving the CJ packet. The new vehicle can successfully join the channel and can become a CM with a free slot if received the CA packet. Moreover, if a vehicle discovers that it belongs to two or more clusters and there are no gateways (GWs) with a greater ROT in its coverage area, it will become a GW and send a UI packet to notify the change.

When a vehicle discovers that it is not a member of any clusters, and all its one-hop neighbors with greater ROT are members of other clusters, and they are not CHs, it will declare to become a CH. If a CH discovers that it is three hops away from another CH, it chooses a pair of vehicles with higher ROT as second-type GWs to relay data packets for these two clusters. After each vehicle in the network defined its task, the cluster maintenance procedure begins.

B. Encirclement Marching Method

After the CH is selected, the CMs position themselves around the CH, creating an encirclement region to adjust their positions by moving closer to the CH to establish an optimal communication range and connectivity. Let us consider that $\Delta X(ROT)$ indicates the difference between the coordinates of neighboring vehicle V_{n} and the current vehicle V_{x}. It is calculated as follows:

$$\Delta X(ROT) = V_x(ROT) - V_n(ROT) . \quad (3)$$

Once the encirclement is formed, CMs monitor their positions relative to the CH. Next, to escape from the precarious situation, we consider a unit distance d_{i} based on the one TDMA frame period which is the required time interval to get closer to the CH. Since all the vehicles follow the 2s rule, each CM is necessary to discontinue encircling when reaching the specified closed area of CH. And, each vehicle follows increasing path loss with 5~6 dB per octave (one octave is when the distance between two vehicles increases doubles). By having a CH encircled by CMs, the stability and connectivity of the cluster are enhanced. This prolongs the period of cluster formation, as the encirclement reinforces the integrity of the cluster, minimizing the need for frequent reformation.

C. TDMA Time Slot Allocation

Similar to [6], each time frame is composed of a set of TDMA time slots that are used to transmit safety and control messages by acquiring the vehicle's current information. Two RSU control time slots is allocated at the beginning of each frame, and then a TDMA-based time slot scheduling algorithm is employed to acquire the channel access as follows:

- If a new vehicle V_n is scheduled to join the network, first it must listen to the channel for one frame duration in order to collect and keep the information from its one hop set (OHS) neighbors, then it can detect and receive all packets in the channel.
- After one TDMA time frame has elapsed, when the channel condition is detected as free, known as IDLE, V_n can acquire one from any of the free available time slots during the next time frame.
- Afterward, V_n will disseminate its UI packet in its acquired time slot during the subsequent TDMA time frame.
- By sensing the UI packet, all other vehicles in the channel can be notified that V_n has successfully occupied the unique time slot.

Details of CCH and SCH assignment procedures, control channel interval (CCHI) slot reallocation mechanism and hidden terminal elimination technique are discussed in our previous work [6].

V. PERFORMANCE EVALUATION

By iteratively going through the simulation process and analyzing the results in real-world map road networks, the OCC-MAC protocol can evolve and adapt to better meet the reliable communication needs in VANETs, resulting in improved network performance and reliability. The performance of our proposed OCC-MAC protocol is compared with STCM [7], OCB-MAC [8], and IEEE 802.11p [4] protocols while the simulation is implemented in terms of performance metrics for normalized throughput, PDR, end-to-end delay, access delay and collision rate.

A. Simulation Configuration

For simulations, OMNeT++ utilizing the INET framework is employed [9]. Using the microscopic road traffic simulator, Simulation of Urban Mobility (SUMO), a realistic traffic scenario is created by OpenStreetMap (OSM) for identifying the road network, specifying vehicle types, generating traffic flows, and setting traffic conditions. Veins is integrated into the OMNeT++ and SUMO environment to establish communication between the simulated network and traffic scenarios. The output file is extracted by MATLAB.

SUMO is used to generate traffic models, which includes the deployment of the Intelligent Driver Model (IDM) and the minimizing overall braking induced by lane change (MOBIL) model [9]. These are intended to replicate realistic trajectories and each vehicle reacts to the stimulus from preceding vehicles. In the one-dimensional or two-dimensional environment, it is assumed that vehicles follow a homogeneous Poisson distribution and the number of inserted vehicles is binomially distributed, i.e. a vehicle is emitted randomly with the given probability each second until the end time is reached.

In our simulation configuration, the DSRC message set [6] has been used to describe the UI packet. The size of WAVE short messages (WSM) is estimated to be 250 bytes and $\tau_{c\text{-}min}$ is 0.35 ms. The channel propagation model of Nakagami-m [14] is also used to cover a wide range of multi-path fading patterns. A modified user datagram protocol (UDP) application included in the INET suite, is used to deliver unicast and multicast non-safety packets for the simulation of communication traffic on SCHs. Global address resolution protocol (ARP) is utilized in the network layer to streamline the simulation model while speeding up network setup time. The simulation network parameters are listed in [6].

The effective bitrate is normalized by adopting one of the combinations of modulation and coding scheme (MCS) of mode as depicted in Table I, when the complexity of the modulation increases, the estimated SINR threshold increases as well.

TABLE I. MODULATION AND CODING SCHEMES

Mode	Modulation Scheme	Coding Rate	Data Rate (Mbps)	Receiver Sensitivity, S_{rx} (dBm)	Minimum SINR Threshold
#0	BPSK	½, ¾	3, 4.5	−87, −85	6 dB
#1	QPSK	½, ¾	6, 9	−84, −82	10 dB
#2	16-QAM	½, ¾	12, 18	−79, −75	16 dB
#3	64-QAM	½, ¾	24, 27	−73, −71	27 dB

Considering different combinations of factors, the simulation model is set up to enable varying vehicle density, maximum vehicle speed, and data rate. To simply differentiate the traffic model, three kinds of traffic densities are defined: (1) low level (20 – 50 vehicles), medium level (80 – 100 vehicles) and high level (150 – 200 vehicles), whereas vehicles are emitted with random time-gaps that follow an exponential distribution until the specified number is reached. Maximum vehicle speed is set up at 10 – 30 m/s with an acceleration/deceleration rate of 30 – 20 m/s, i.e. speedMode parameter in Veins has been setup in different values (around with the maximumSpeed parameter) for each vehicle in order to achieve the discrete relative speed (dynamic behavior), ranging from (0x00) to (0xff). In each step time (e.g. 0, 100, 200), variable speed signs (e.g. 2.8, 47.22, -1) are defined such as [0, 2.8], [100, 47.22] and [200, -1]. Consequently, the dynamicity of the network is significantly configured. Vehicle length is roughly defined as 4m, and the minimum gap is 1 m between each other. Since the slot size $\tau_{c=0.5\ ms}$, and there are 200 slots for CCH, subsequently, 100 slots for each CCHI direction.

For the real-world map extraction, the OSM is employed to generate the simulated map and the simulation is conducted on a real map of a specific area including Xueyuan campus of Beihang University, Beijing as shown in Fig 2. By giving the GPS coordinates of the required region, a 2 km^2 area is retrieved. Using the mobility platform SUMO, the road network was recovered from the raw map by the vehicular framework Veins. While SUMO handled the road traffic simulation, Veins handled the network simulation and sumo-launched served as an interactive tool between the two modules. The traffic-related data are dynamically updated by SUMO via the Traci interface. Next, OSM generated map is converted into SUMO and relevant modules are operated simultaneously during the experiment.



Fig. 2. Real-world map generated by the OSM for a specific area.

B. Simulation Results

Fig 3 illustrates the normalized throughput of OCC-MAC protocol, STCM, OCB-MAC, and IEEE 802.11p protocols based on the number of vehicles on both CCH and SCH. In a dynamic network, when vehicle density increases, the throughput tends to increase due to increased successful data transmissions with cluster networks. As shown in Fig. 3, it is obvious that there is a considerable reduction in throughput variability with no more than 0.4 of normalized throughput at 200 vehicles in both scenarios. Moreover, STCM has a substantially rising value than OCB-MAC after 80 vehicles,

whereas there is no momentous variation in 802.11p. Considerably, OCC-MAC remains outperformance over other results. The reason is that OCC-MAC significantly reduces transmission collisions caused by hidden terminal problems by transmitting the details of time slot allocation to the adjacent clusters through GWs. Particularly, OCC-MAC can quickly adapt to rapid vehicle density changes.

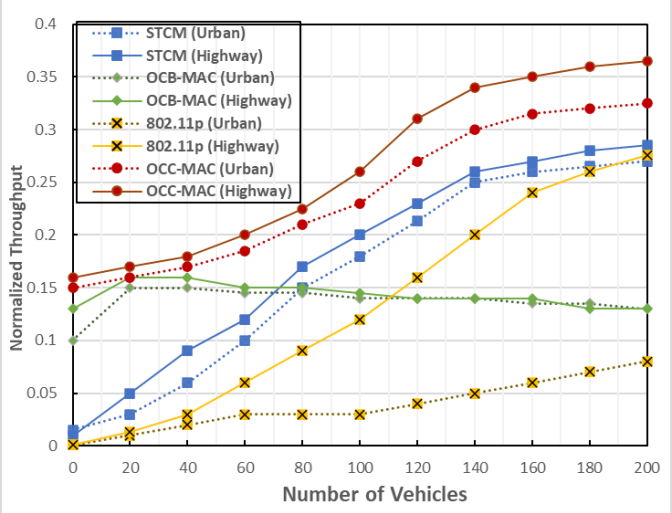


Fig. 3. Normalized throughput versus the number of verhicles.

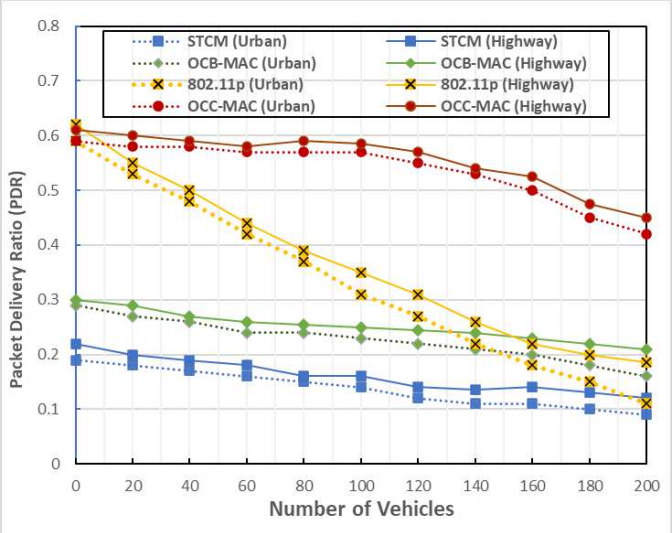


Fig. 4. PDR versus the number of vehicles

In Fig 4, it is noticeable that PDR values in all protocols perform inferior performance whereas STCM and OCB-MAC have gradual falling values because of defective packet transmission with more collisions as part of the radio wavefront is obstructed by opaque obstacles. And, there is less discrepancy between the highway and urban scenarios for all protocols. In both figures, it is worth mentioning that OCC-MAC substantially outperforms STCM, OCB-MAC, and IEEE 802.11p protocols because it successfully resolves the merging collisions to steer clear of packet loss caused by traffic congestion and successive interference.

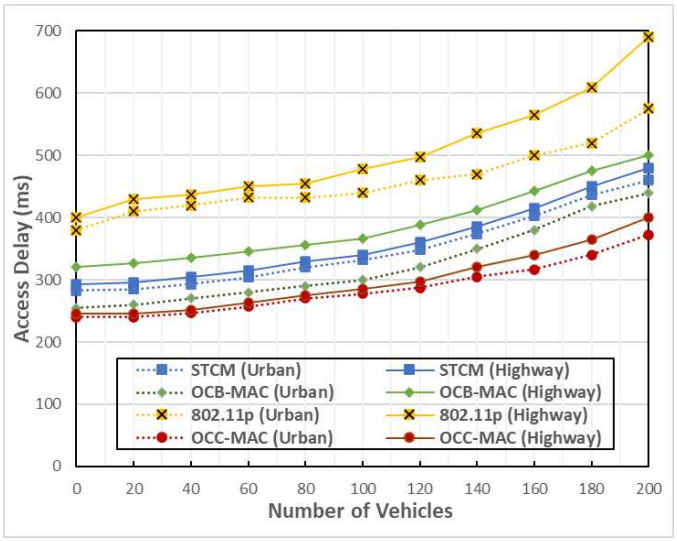


Fig. 5. Access Delay versus the number of vehicles

In Fig 5, IEEE 802.11p has an enlarging delay value at high density and OCB-MAC has a noticeable difference in both scenarios while STCM remains unchanged. On the contrary, it is evident that the proposed OCC-MAC achieves a minimal access delay and substantially outperforms others. The reason for this is that when channel accessing capability improves, it can lessen excessively long retransmission delays and is capable of providing rapid access for a newly joined vehicle.

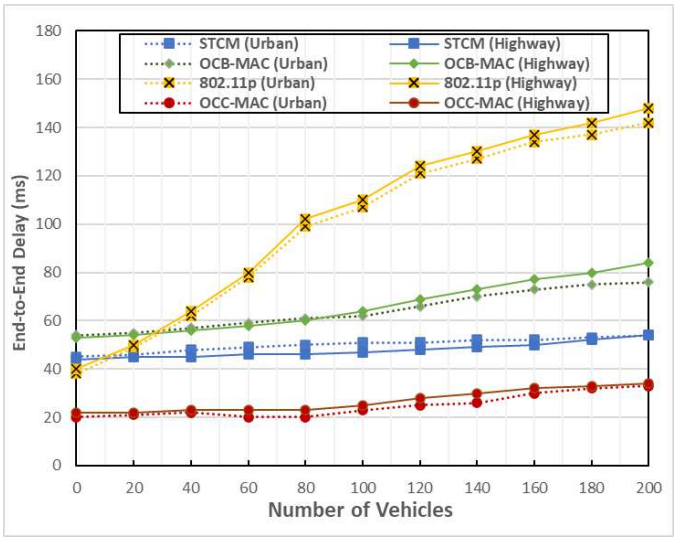


Fig. 6. End-to-End Delay versus the number of vehicles

In Fig. 6, it is noteworthy that the delay values rise vigilantly and there is a small scale difference between highway and urban traffic scenarios for all protocols. OCB-MAC has a substantial upward delay value compared to the synthetic layout because of the inefficient cluster merging and dissolving approach. Nevertheless, it is evident that OCC-MAC is substantially lower than the aforementioned three protocols in both figures achieving a minimal end-to-end delay. It is because the different kinds of delay are mitigated by that data packets will quickly follow to reach the destination

vehicle by the proposed metaheuristic optimization algorithm with the encirclement marching strategy on selected CH in which efficient CH dissolving and cluster merging mechanisms can eliminate unnecessary re-affiliation attempts and it improves overall network performance.

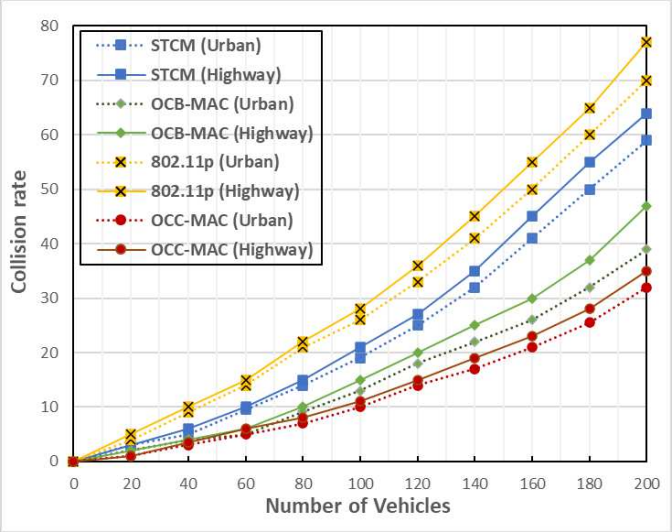


Fig. 7. Collision rate versus the number of vehicles

In Fig. 7, all protocols have an increasing collision rate than simulation with a synthetic map. It is noticeable that the proposed OCC-MAC has the lowest collision rate and remains constant or slightly increases, generally below 35 at both road networks. The main reason is that OCC-MAC's disjoint time slot-partition technique has more of a correlation to engaging channel utilization and the CCHI slot reallocation mechanism is more reliable in resolving same-direction merging collisions and hidden terminals to a certain extent.

Furthermore, it is remarkable that all compared MAC protocols perform better in the highway scenario than in the urban scenario because, in urban areas, vehicle speeds are slower, and 4-way road junctions are complex, where the vehicles inevitably stop at traffic lights for a long period of time, raising the instantaneous vehicle density in that vicinity. When the vehicles move faster and then network topology changes more frequently, the transmission collision probability due to hidden terminals and merging collisions is increased in STCM, OCB-MAC, and IEEE 802.11p protocols.

VI. Conclusions

This paper proposes a performance optimization of clustering-based contention-free MAC protocol with enhanced vehicular models of mobility and channel propagation. To develop a reliable and harmonious clustering structure, an encirclement marching strategy is proposed by the metaheuristic optimization algorithm to eliminate unnecessary re-affiliation attempts and improve the cluster's stability. Simulation results through the real-world map scenario show that OCC-MAC can guarantee great cluster stability by the reason of higher throughput, higher PDR, and substantially lower end-to-end delay than existing MAC protocols in high vehicle mobility to adapt to the rapidly changing topology of future VANETs.

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