A Modified TC-MAC Protocol for Multi-hop Cluster Communications in VANETs

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***Abstract*—One of the challenges for Vehicular Ad-hoc Networks (VANETs) is the design of the Medium Access Control (MAC) protocol. When exchanging messages between vehicles, there are network issues that must be addressed, including the hidden terminal problem, high density, high node mobility, and data rate limitations. A cluster-based MAC scheme is needed in VANETs to overcome the lack of specialized hardware for infrastructure and the mobility to support network stability and channel utilization. This paper presents a multi-hop cluster MAC protocol for vehicular ad-hoc networks using a modified TC-MAC, which is a method for TDMA slot reservation based on clustering of vehicles. Our protocol aims to decrease collisions and packet drops in the channel, as well as provide fairness in sharing the wireless medium, minimizing the effect of hidden terminals, and increasing the network scalability.**

***Keywords*—Ad-hoc network; Medium Access Control; Vehicular Ad-hoc Network;**

I. Introduction

According to the World Health Organization (WHO) [1], approximately 1.3 million people die each year on the world's roads and between 20 and 50 million sustain non-fatal injuries. Road traffic injuries are the leading cause of death among young people, aged between 15 and 29. Many accidents may be avoided by having vehicles communicating with each other to exchange messages to warn the drivers about unsafe situations on the road. Moreover, the Texas Transportation Institute [2] reported that in 2009 the cost of traffic congestion in the US was about $115 billion. This cost based on the wasted time and fuel. The total hours wasted in traffic congestion in the US alone is about 4.8 billion hours, and about 3.9 billion gallons of fuel is wasted. Besides the economic cost, traffic congestion leads to more pollution in our cities.

The impact of traffic accidents and traffic congestion on the economy and the environment motivated the research and development of Intelligent Transportation Systems (ITS). Vehicular Ad Hoc Networks (VANETs) are an important component ITS [3]. VANETs enable the exchange of messages between vehicles and between vehicles and infrastructure. Such communications aim to increase safety on the road, improve transportation efficiency, and provide comfort to drivers and passengers. Figure 1 shows a typical vehicular communications scenario of the future.

Since safety applications of vehicular communication have stringent reliability and delay requirements, giving each vehicle the time to send safety messages without interfering with other vehicles is required. Also, safety messages are based on broadcast transmission, so, using the IEEE 802.11 RTS/CTS mechanism for collision avoidance is not feasible in VANETs.

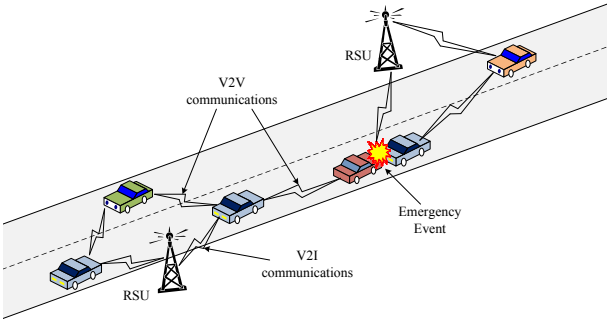

Fig. 1. Safety and non-safety communications over DSRC. It shows Vehicle-to-Vehicle communication (V2V) and Vehicle-to-Infrastructure communication (V2I)

Time Division Multiple Access (TDMA) is a technique used to enable multiple nodes to transmit on the same frequency channel. It divides the signal into different time *frames*. Each frame is divided into several time *slots*, where each node is assigned to a time slot to transmit. The length of the time slot may vary, based on the needs of the node assigned to it. The goal of any assignment scheme is to make the process of assigning slots easy and straightforward. For VANET, safety messages are more important, but non-safety messages need to be delivered even if there are a lot of safety messages.

In this paper, we propose a new MAC protocol for VANETs based on TC-MAC protocol [4]; a cluster-based MAC protocol for VANETs. The proposed work, modified TC-MAC, is taking advantage of the light weight TDMA slot assignment and the clustering algorithms. The main objective of our work is to improve TC-MAC by developing a multi-cluster intra-cluster communication for VANET. We also modified the TDMA frame size of TC-MAC for better use without any impact on the delivery of safety/update messages.

The remainder of the paper is organized as follows. Section 2 provides background about communications in VANETs and reviews related work. Section 3 describe our scheme in detail. Section 4 discusses the simulation evaluation. Finally, Section 5 concludes the paper and presents future work.

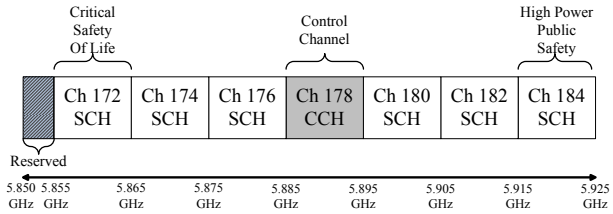

Fig. 2. US DSRC spectrum allocation

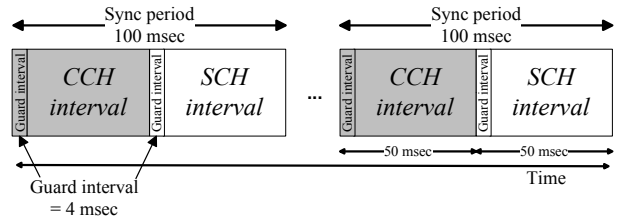

Fig. 3. Division of time into CCH intervals and SCH intervals, IEEE 1609.4 standard

II. Background and Related Work

A. IEEE Standards for MAC protocols for VANET

In the US, the Federal Communication Commission (FCC) has allocated 75 MHz of spectrum at 5.9 GHz for Dedicated Short-Range Communications (DSRC) [5], which provides high-speed communication between the vehicles and road-side units (RSUs). DSRC is divided into 7 channels, each 10 MHz wide, as shown in Figure 2. Channel 178 is the control channel (CCH), which is used for beacon messages, event-driven emergency messages, and service advertisements. The remaining six service channels (SCHs) support non-safety applications provided by RSUs. The IEEE has completed the 1609 family of standards for the Wireless Access in Vehicular Environments (WAVE) standard [6] for vehicular communications. Here we briefly explain the WAVE standard as well as the challenges.

1) IEEE 1609 WAVE Standards: IEEE 1609 WAVE is family of standards for vehicular communication encompassing vehicle-to-vehicle as well as vehicle-to-infrastructure communications [6]. WAVE specifies the following standards:

- IEEE 1609.1 specifies the services and interfaces of the WAVE Resource Manager application, [7].
- IEEE 1609.2 defines secure message formats and processing [8].
- IEEE 1609.3 presents transport and network layer protocols, including addressing and routing, in support of secure WAVE data exchange [9].
- IEEE 1609.4 specifies MAC and PHY layers [10], which are based on IEEE 802.11. This is the main focus of this paper.

2) IEEE 1609.4 Standard: In WAVE, the IEEE 1609.4 trial standard [10] operates on top of the IEEE 802.11p in the MAC layer. IEEE 1609.4 focuses mainly on dealing with multi-channel operations of DSRC radio. There is a sync interval (SI) that consists of a CCH interval (CCHI) and a SCH interval (SCHI), each separated by a guard interval, as shown in Figure 3. All radio devices are assumed to be synchronized using Global Positioning System (GPS). During the CCHI, all radios must be tuned to the CCH to broadcast updates and listen for messages from neighbors and RSUs. During the SCHI, vehicles may tune to the SCH of their choice depending on the services offered.

3) Challenges and issues of WAVE: As currently envisioned, WAVE allows for the communications of safety and non-safety applications through a single DSRC radio. Unfortunately, it has been shown that DSRC cannot support both safety and non-safety applications with high reliability at high traffic densities. Either safety applications or non-safety applications must be compromised. To maintain the 100 msec requirement of safety applications and ensure reliability, the CCHI must be lengthened and the SCHI shortened. Wang and Hassan [11] studied this scenario, requiring 90% and 95% reliability for CCH messages with different traffic densities. Their results indicate that as traffic density increases, ensuring CCH reliability requires compromising SCH throughput. At high densities, to avoid compromising non-safety applications, the SI would need to be lengthened. This would result in fewer beacon messages sent per second, compromising safety.

B. Alternative MAC Protocols

A significant amount of research has been devoted to developing new cluster-based MAC protocols, [12]–[15]. Gunter et al. [12] proposed schemes where the *CH* takes on a managerial role and facilitates intra-cluster communication by providing a TDMA schedule to its *CMs*. Based on the amount of data the *CMs* have to send, the *CH* assigns a bandwidth and time slots to the *CMs* in each TDMA frame. Su and Zhang [15] proposed a scheme where adjacent clusters are assigned different CDMA codes to avoid interference between clusters. This work shows a substantial reduction in probability of message delivery failure, when compared to the traditional 802.11 MAC. The disadvantages of this work are that it uses two transceivers. It also reserves channels for specific tasks; so if there is no activity on these channels, the channels will be wasted.

III. Our Scheme

We propose a multi-hop communications scheme for VANETs using a modified TC-MAC protocol [4]. In this section, we will give an explanation of TC-MAC with our modifications, and then we will explain the intra-cluster communication using a two-hop cluster.

A. Modified TC-MAC Protocol

TC-MAC is a dynamic TDMA slot assignment technique for cluster-based VANETs. TC-MAC, unlike WAVE, allows vehicles to exchange non-safety messages while maintaining a high reliability level for exchanging safety messages. In this technique, the collision-free intra-cluster communications are managed by the Clusterhead (CH) using TDMA. The TC-MAC protocol is based on the multi-channel DSRC layout, with 1 CCH and 6 SCHs.

The length of the TDMA frame in TC-MAC is based on the number of vehicles in the cluster. So, if we have two different clusters with different numbers of vehicles, the TDMA length

may vary. We modified the length of the TDMA frame in TC-MAC to be 100 msec. In this case, we guarantee that every vehicle in the cluster sends one update/safety message every 100 msec to meet the safety message requirements. Moreover, all clusters on the road will have the same TDMA frame start time, which will make it easy for future inter-cluster communications.

To explain TC-MAC with our modifications, we assume an N-vehicle cluster. The number of vehicles in the cluster must be less or equal to N_{max}; where N_{max} is the maximum number of vehicles in the cluster. The transmission time is partitioned into consecutive, non-overlapping logical TDMA frames. The length of the TDMA frame in TC-MAC is equal to 100 msec, to meet the safety/update messages requirements. We assume the existence of k slotted SCHs numbered from 0 through k-1[1]. In each SCH, the logical TDMA frames are aligned, i.e. begin and end at the same time. Each logical frame contains S number of slots, where $S = \lfloor \frac{N_{max}}{k} \rfloor + 1$ slots. The slots are numbered from 0 through $\lfloor \frac{N_{max}}{k} \rfloor$. All slots are the same size, and the slot size τ is fixed, based on the data rate and the maximum packet size.

As in TC-MAC, we also assume one CCH, channel k, is used by the vehicles and *CH* for disseminating status and control messages as is done with WAVE. As with the SCHs, the TDMA frame on channel k is divided into slots of size τ. Each time slot on the CCH is divided into k mini-slots used to disseminate status information, such as periodic beacon updates used in safety applications.

By virtue of synchronization, the vehicles know the frame and slot boundaries. The number of vehicles N may change dynamically, and the *CH* is responsible for updating N and for informing all vehicles in the cluster of the new value of N.

Each vehicle in the cluster will receive a local ID. This local ID is a number from 0 to N. The *CH* will always have ID 1. We do not expect all N vehicles in the cluster to be communicating, or active, simultaneously. The *CH* keeps a list of all the currently-active vehicles and disseminates this list to all the members of the cluster.

In each logical frame, vehicle j, $(0 \leq j \leq N-1)$, owns:

- channel j *mod* k during time slot $\lfloor \frac{j}{k} \rfloor$; we also say that vehicle j owns the ordered pair (j *mod* k, $\lfloor \frac{j}{k} \rfloor$)
- the j-th mini-slot of slot $(\lfloor \frac{j}{k} \rfloor - 1) mod \lfloor \frac{N}{k} \rfloor$, on channel k, as illustrated in Figure 4; we use the convention that $(-1 mod \lfloor \frac{N}{k} \rfloor)$ is the $\lfloor \frac{N}{k} \rfloor$-th slot of the previous logical frame.

The basic idea is that in each logical frame, while idle, vehicle j listens to channel j *mod* k in slot $\lfloor \frac{j}{k} \rfloor$.

For an illustration of the modified TC-MAC protocol, let N=61 and k=6. Assume we have the network settings in Table I, the number of TDMA slots on the SCHs will be 65; $N_{max} =$ 389. As shown in Figure 5, vehicle with local ID 39 owns channel (39 *mod* 6)=3 during slot $\lfloor \frac{39}{6} \rfloor$=6, as well as 4-th mini-slot on the control channel in slot 6-1=5. We note that for any given N, there are $N_{max} - N$ unused slots in the frame.

[1]In practice we use k=6 to match DSRC, but we will describe it in general

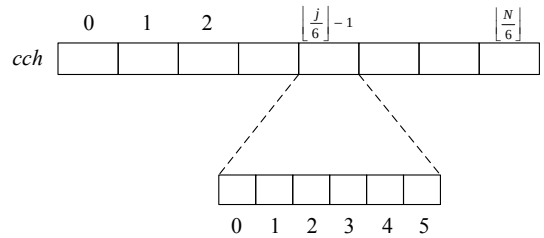

Fig. 4. Mini-slots on channel k (k=6); vehicle j owns a mini-slot in the slot preceding its own slot.

TABLE I. NETWORK SETTINGS

Parameters	Values
Max Safety Packet Size	200 bytes
Max Non-Safety Packet Size	1200 bytes
Data Rate	6 Mbps
Mini Slot Size	0.26 msec
SCH Slot Size	1.6 msec
TDMA Frame Size	100 msec

For communication between two vehicles, the vehicles will use their time slots on the SCHs to exchange messages. For communication with *RSUs*, if the *RSU* is communicating with one vehicle, the *RSU* will be treated as if it is a vehicle. If the *RSU* is trying to communicate with more than one vehicle, the *RSU* and the other vehicles will use their time slots to communicate. The communications of the *RSUs* are considered as any other vehicle in the cluster.

B. intra-cluster communication

For intra-cluster communication, we look at single-hop and multi-hop clusters. TC-MAC explained a lightweight communication protocol for a single-hop cluster. We extended this protocol and propose intra-cluster communication using multi-hop cluster. As a single-hop cluster, all vehicles in the cluster can communicate directly; while vehicles in the multi-hop cluster need to rely on other vehicle(s) in the cluster to communicate with all vehicles.

Each vehicle uses its own mini-slot to disseminate status information. The first byte of the mini-slot can be used to encode $2^8 = 128$ different situations; a few of them are listed below:

- **0** indicates that the vehicle is not communicating on its own slot on the *SCH* at the moment.
- **1** indicates that the vehicle is involved in communicating with some other vehicle in the cluster on the *SCH*; the binary encoding of the ID of the interlocutor follows in the second byte.
- **2** indicates that the vehicle is involved in communicating with a multicast group in the cluster; the binary encodings of the IDs of the members of the multicast group follow in the next bytes.

	← ---------- 1 TDMA FRAME (100 msec) ----------→																	
	S0	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**…**	**…**	**…**	**…**	**S60**	**S61**	**S62**
SCH 5	5	11	17	23	29	35	41	47	53	59	…	…	…	…	…	…	…	…
SCH 4	4	10	16	22	28	34	40	46	52	58	…	…	…	…	…	…	…	…
SCH 3	3	9	15	21	27	33	39	45	51	57	…	…	…	…	…	…	…	…
SCH 2	2	8	14	20	26	32	38	44	50	56	…	…	…	…	…	…	…	…
SCH 1	1	7	13	19	25	31	37	43	49	55	61	…	…	…	…	…	…	…
SCH 0	0	6	12	18	24	30	36	42	48	54	60	…	…	…	…	…	…	…
CCH	6-11	12-17	18-23	24-29	30-35	36-41	42-47	48-53	54-59	60-65	…	…	…	…	…	…	…	0-5

Fig. 5. Logical frames in TC-MAC for N=61 and k=6

- **3** indicates that the vehicle is involved in communicating with a vehicle or *RSU* outside the cluster.
- **4** indicates that the *CH* is leaving the cluster and a new *CH* is picked by the current *CH*; the binary encoding of the old ID of the new *CH* follows in the second bytes.
- **5** indicates that the vehicle is leaving the cluster.
- **6** indicates that the *CH* election process need to be performed.
- **7** indicates that the vehicle wants to join the cluster, "Handshake". This will be sent by the new comer vehicle to the any cluster member in the targeted cluster.
- *8* is the confirmation of the "handshake" message that sent by the new comer.
- **9** indicates that the vehicle will transmit during its upcoming slots; the binary encodings of the number of frames that the vehicle will be using on its own slot on the *SCH*.
- **10** indicates that the vehicle will use its upcoming slot to transmit.

Certain messages need to be transmitted inside the cluster. These messages are safety, governance, and non-safety messages. Also, the messages could be broadcasted or unicasted. We explain our scheme for multi-hop cluster below.

1) Disseminating Intra-Cluster Safety/Governance Messages: The *CH* is responsible for disseminating safety and governance messages to nearby cluster members and will pick a vehicle to be a relay node to other cluster members that are not in the range of the *CH*. As in TC-MAC, the *CH* will use its mini-slot on the *CCH* to broadcast the message. Also, the *CH* will repeat the same safety message in any available mini-slot on the *CCH* of the same TDMA frame. The reason for repeating the same safety messages is to achieve the effect of broadcasting to the entire cluster. The *CH* may decide to disseminate safety messages to a subset of the vehicles, in which case it will also broadcast an *N*-bit vector, indicating which vehicles are targeted by the message; if all bits are set, the message is a cluster-wide broadcast. In addition to safety messages, the previously-described mechanism is employed for cluster governance messages including, such as the updated value of *N*.

In Figure 6, we have a three-hop cluster with a transmission range of 300 m. When the *CH* wants to disseminate safety/governance messages, vehicles up to 300 m behind and

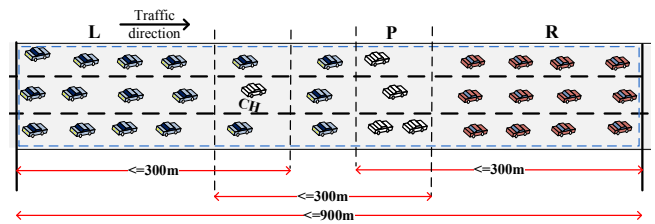

Fig. 6. Disseminating of safety messages by the *CH* in a multi-hop cluster. The *CH* sends the safety messages to vehicles in group *L* and group *P*. The *CH* will pick a vehicle from group *P* to be a relay node to vehicles in group *R*

300 m ahead of the *CH* will receive the messages directly. However, the vehicles that are located more than 300 m away from the *CH* in group *R* will not be able to receive the messages. In this case, the *CH* will find a vehicle that is in range of the *CH* and other vehicles in *R* to be a relay node. This can be done by the *CH* requesting one of the farthest vehicles ahead to disseminate the safety message to other vehicles in range. As show in Figure 6, any vehicle in group *P* can be a relay node to vehicles in group *R*.

2) Intra-Cluster Unicast Communication: Unicast (a.k.a. point-to-point) communications in a multi-hop clusters are set-up through negotiation with some cluster members to find a path. Due to the paper length limitation, we will describe only the two-hop case. From Figure 7, we have a two-hop cluster where each vehicle in group *L* can communicate directly with other vehicles in group *L*, as well as vehicles in group *P*. Also, vehicles in group *R* can communicate directly with other vehicles in group *R* and group *P*. If vehicle *A* from group *L* wants to send a non-safety message to vehicle *B* from group *R*, vehicle *A* will try to find a vehicle from group *P* to be a proxy node for the communication between *A* and *B*. Finding vehicle in *P* is done by vehicle *A* sending a request on the *CCH* during *A*'s mini-slots seeking a vehicle in the range of *B*. If there is a vehicle in *P* willing to be a relay node between *A* and *B*, vehicle *P* will reply to *A* during *A*'s time slot on the SCH. Once the *P* vehicle is determined, the path is defined and vehicles can start transmission. The transmission will be done during the time slots for the three vehicles in the path, *A*, *P* and *B*.

3) Intra-Cluster Multicast Communication: Multicast (a.k.a. point-to-multipoint) communications may be set up with or without *CH* intervention. Suppose vehicle *j* wishes to establish a multicast group involving vehicles $i_1, i_2, ..., i_p$. If the multicast group is small, vehicle *j* will attempt to send a handshake message to each of the remaining vehicles in the multicast group. Once the group has been set up, vehicle *j*

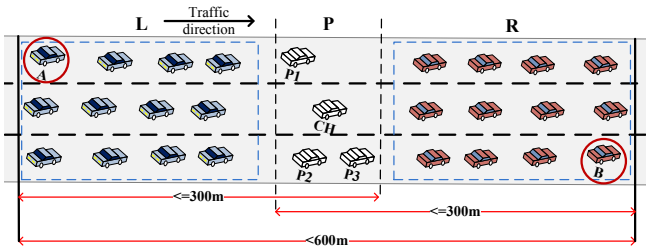

Fig. 7. Unicast of non-safety messages in a two-hop cluster, where vehicle *A* from group *L* is trying to send a non-safety message to vehicle *B* from group *R*. Vehicle *A* needs to find a vehicle in group *P* to be a relay node to vehicle *B*

will transmit on channel *j mod k* during time slot time $\lfloor \frac{j}{k} \rfloor$ and all the other vehicles will listen to the channel. If the size of the multicast group is large, vehicle *j* will send the *CH* a multicast group request consisting of its own ID along with an *N*-bit vector with the bits corresponding to the multicast group set. Once received by the *CH*, this multicast group set-up request will be disseminated by the *CH* in the next available logical frame, by all the modalities discussed above. Once the multicast group has been set up, vehicle *j* will transmit to the group on channel *j mod k* during slot $\lfloor \frac{j}{k} \rfloor$. For a multi-hop cluster, if the vehicles are not in the range of vehicle *j*, vehicle *j* will find a vehicle in P1 or P1 and P2 to act as a proxy(s) to the other vehicles in multicast group.

IV. Evaluation

To evaluate our proposed scheme, we measured the percentage of the successful delivery of safety/update messages for both the modified TC-MAC and WAVE. For the modified TC-MAC, we did the measurement in two ways, direct and indirect messages. The direct safety/update messages are the messages that are received without being rebroadcasted by the *CH*, while the indirect safety/update messages are the ones that are received after being rebroadcasted by the *CH*.

A. Simulation Model

The modified TC-MAC protocol was evaluated through detailed simulation using ns-3 network simulator [16], which is a follow-on to the popular ns-2 simulator. For VANET, we used modules [17] that added well-known traffic mobility models, the Intelligent Driver Model (IDM) [18] and the MOBIL lane change model [19]. The goal was to create a vehicular network on highways with different number of lanes and different number of vehicles.

The network parameters used to evaluate the modified TC-MAC as compared to WAVE are listed in Table II. In the modified TC-MAC, all vehicles in the cluster are using their own time slots to communicate with other vehicles. These slots are assigned to them by the *CH*, to communicate with other vehicles. For WAVE, all vehicles are using CSMA/CA mechanism to access the medium.

The scenarios implemented for the highway are with different number of lanes and different density levels. We evaluated scenarios with 2, 3, and 4 lanes. For the traffic density levels, we used four different levels; they are Low, Med, High, and Very High. Table III shows the number of vehicles per lane for each density level, as well as the gap between vehicles. Since we are limited with the maximum number of vehicles in the cluster, based on the network parameters, we used 372 vehicles in the cluster instead of 400 vehicles when the traffic density is very high and the number of lanes is 4. The highway length is set to 5,000 *m* and vehicles are set to different speed limits. The speed limits are set to maintain particular density of the vehicles in the road.

TABLE II. Network parameters used in the simulation

Parameter	Values for WAVE	Values for the modified TC-MAC
TX Range	300 m	300 m
Max. Safety Message size	200 bytes	200 bytes
Max. Non-Safety Message size	1200 bytes	1200 bytes
Data Rate	6 Mbps	6 Mbps
CCHI	0.05 sec	N/A
SCHI	0.05 sec	N/A
Mini Slot Size	N/A	0.267 ms
SCH Slot Size	N/A	1.6 ms

TABLE III. Density levels in the highway

Density Level	Number of Vehicles per Lane	Gap between Vehicles
Low	5	60 m
Med	12	20 m
High	20	10 m
Very High	50	1 m

The time interval SI for both the modified TC-MAC and WAVE is 100 *msec*. Ideally, the vehicle in the modified TC-MAC will be tuned to the CCH during the time interval; unless its own SCH slot time on the SCHs. In the case of WAVE, all vehicles will be tuned to the CCH during CCHI and to the SCHs during SCHI.

B. Simulation Results

Before running the scenarios, we calculated the communication density (*CD*) [20] on the road. *CD* is used to measure the channel load in vehicular communications. This is done by calculating the number of carrier sensible events per unit of time. In the two-hop clusters, the *CD* of the vehicles that are in the middle and in range of all the cluster members is calculated as if they all were in a single-hop cluster. For example, if we have a two-hop cluster of the size of 372, and we have a vehicle that can hear every vehicle in the cluster, the *CD* would be 3720.

The simulation results show that the modified TC-MAC performed better than WAVE in delivering safety/update messages. The modified TC-MAC does not experience any collisions during the transmission of safety/update messages, but Figure 8 shows the percentage of collisions experienced with WAVE using two-hop cluster comparing to the communication density during the CCHI. From the figure, it is clear that as the Communication Density goes high, the percentage of traffic collision on the CCH goes high. The main reason for this issue is that every vehicle in the cluster is trying to compete to send its safety/update messages during the CCHI.

We also measured the percentage of direct safety/update messages that were missed comparing to the communication

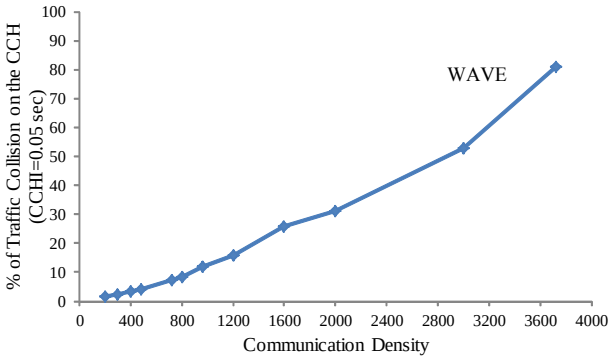

Fig. 8. Percentage of collisions safety/update messages during the *CCHI* for WAVE using a two-hop cluster

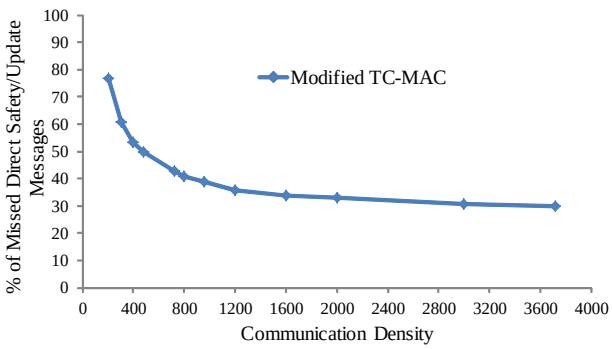

Fig. 9. Percentage of missed direct safety/update messages for the modified TC-MAC in a two-hop cluster based on the communication density. Assuming that half of the vehicles in the cluster are engage in any sort of communications during their own slot time on the *SCHs*

density in two-hop cluster using the modified TC-MAC. From Figure 9, it shows that the modified TC-MAC has higher missed direct safety/update messages percentage in the two-hop cluster compared to the single-hop cluster in TC-MAC [4]. The reason for that is when calculating the percentage, all vehicles in the two-hop cluster are included even if they are out of range of other vehicles in the cluster. If the missed messages are safety messages, the *CH* will rebroadcast them to all vehicles in the cluster including the vehicles that missed them. On the other hand, if the missed messages are update messages, this should not be an issue because these messages are from vehicles that are more than one hop away.

V. Conclusion

In this paper, we presented the modified TC-MAC as a cluster-based TDMA scheduling protocol for VANETs, in which the collision-free intra-cluster communications were organized by the CH using a TDMA scheme. This protocol is based on the light weight slot reservation algorithm proposed in TC-MAC protocol. We changed the length of the TDMA frame to be 100 msec. In this way, we make it simple for all cluster members by have the same TDMA frame start, and still meeting the 100 msec safety/update messages requirement. We also extended TC-MAC to be used in multi-hop cluster. The modified TC-MAC showed that it can support higher reliability of safety/update messages than WAVE standard, even in high density scenarios. On the other hand, WAVE suffered from high traffic density. For WAVE, as the traffic density increases, the collision on the CCH increases.

In the future, we will further develop our protocol to address inter-cluster communications. We are also focusing addressing the dynamic nature of VANET clusters.

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