TDMA Cluster-based MAC for VANETs (TC-MAC)

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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 MAC algorithm for vehicular ad-hoc networks using a new method for TDMA slot reservation based on clustering of vehicles. Our algorithm aims to decrease collisions and packet drops in the channel, as well as provide fairness in sharing the wireless medium and minimizing the effect of hidden terminals.**

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

I. Introduction

According to the Texas Transportation Institute [9], in 2009 the cost of wasted time and fuel due to traffic congestion in the US was about $115 billion. Besides the economic cost, traffic congestion leads to more pollution in our cities.

The impact of 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 of ITS and are useful for a wide variety of applications, including both safety applications and non-safety applications [6]. The emergence of vehicular networking has encouraged researchers to study how such communications could be used to enhance travellers' comfort. In the past several years, government agencies have partnered with car manufacturers to design and prototype different types of non-safety-related vehicular applications. Most of these applications rely on communication in the vehicular environment.

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.

Time-Division Multiple Access (TDMA) is used to enable multiple nodes to transmit on the same frequency channel. It divides the signal into different time frames. Each time frame is divided into several time slots, where each node is assigned to a time slot to transmit [10]. 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 TDMA cluster-based MAC (TC-MAC) that can be used for intra-cluster communications in VANETs. This protocol integrates the centralization approach of cluster management and a new scheme for TDMA slot reservation. The main objective of this work is to allow vehicles to send and receive non-safety messages without any impact on the reliability of sending and receiving safety messages, even if the traffic density is high.

The rest of the paper is organized as follows. Section 2 gives a background about communications in VANETs and reviews the related work. Section 3 describe TC-MAC in detail. Section 4 discusses the simulation result. Finally, Section 5 concludes the paper and presents future work.

II. Background and Related Work

A. IEEE Standard for MAC protocols for VANET

In the US, VANETs use 75 MHz of spectrum in the range of 5.850 to 5.925 GHz band specially allocated by the U.S. Federal Communications Commission for Vehicle-to-Vehicle communication (V2V) and Vehicle-to-Infrastructure communication (V2I) using Dedicated Short Range Communication (DSRC) technology [11]. The spectrum band is divided into seven 10 MHz channels (Figure 1). Channel 178 is the control channel (CCH), which is used for beacon messages, event-driven emergency messages, and service advertisements. The other six channels are service channels (SCH) to support non-safety applications. The IEEE has completed the 1609 family of standards for the Wireless Access in Vehicular Environments (WAVE) standard [4] for vehicular communications. Here we briefly explain the WAVE standard as well as the challenges.

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1) IEEE 1609 WAVE Standards: IEEE 1609 WAVE is the family of standards for vehicular communication encompassing vehicle-to-vehicle as well as vehicle-to-infrastructure communications [4]. WAVE specifies the following standards:

- IEEE 1609.1 specifies the services and interfaces of the WAVE Resource Manager application [2].
- IEEE 1609.2 defines secure message formats and processing [3].
- IEEE 1609.3 presents transport and network layer protocols, including addressing and routing, in support of secure WAVE data exchange [5].
- IEEE 1609.4 specifies MAC and PHY layers [1], which are based on IEEE 802.11. This standard is the main focus of this paper.

2) IEEE 1609.4 Standard: In WAVE, the IEEE 1609.4 trial standard [1] operates on top of IEEE 802.11p in the MAC layer. IEEE 1609.4 focuses on multi-channel operations of a 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 2. All radio devices are assumed to be time-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 road-side units(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 [19] 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

The main concept of TDMA, where nodes are assigned to times for collision free transmission, attracted researchers to develop new TDMA schemes for VANETs. Several protocols have been proposed in VANETs using TDMA to provide fairness and reduce interference between vehicles.

Yu and Biswas [20] proposed Vehicular Self-Organized MAC (VeSOMAC). They designed a self-configuring TDMA slot reservation protocol capable of inter-vehicle message delivery with short and deterministic delay bounds. To achieve the shortest delay, vehicles determine their TDMA time slot based on their location and movement on the road. Also, the TDMA slot assignment is designed to be in the same sequential order with respect to the vehicles' physical location. The process of assigning time slots is done without using infrastructure or virtual schedulers such as a leader vehicle. However, the assumption of forwarding messages without processing time or propagation delay is unrealistic. In reality, if the message needs to be delivered from the tail to the head of the platoon, it will need a time frame for each hop.

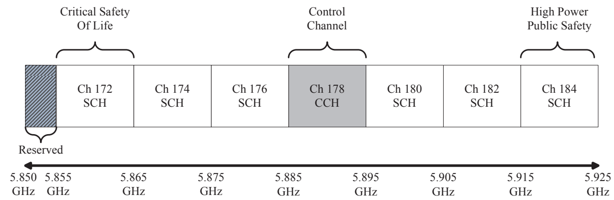

Figure 1. US DSRC spectrum allocation

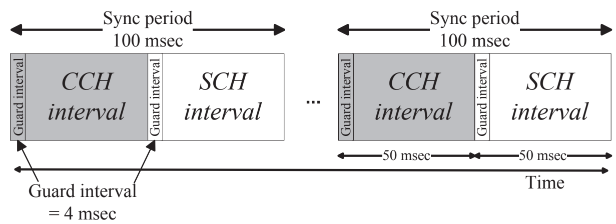

Figure 2. Division of time into CCH intervals and SCH intervals, IEEE 1609.4 standard

Omar et al. [16] proposed a multichannel MAC protocol for VANETs, called VeMAC, to reduce interference between vehicles and reduce transmission collisions caused by vehicle mobility. VeMAC is based on a TDMA scheme for inter-vehicle communication. Vehicles in both directions and RSUs are assigned time slots in the same TDMA time frame. Also, VeMAC is designed based on having one control channel and multiple service channels in the network (as with DSRC/WAVE). VeMAC assumes that there are two transceivers on each vehicle and that all vehicles are time-synchronized using GPS. The first transceiver is assigned to the control channel, while the second transceiver is assigned to the service channels.

Gunter et al. [14] proposed schemes where the clusterhead (CH) takes on a managerial role and facilitates intra-cluster communication by providing a TDMA schedule to its cluster members. The TDMA frame is divided into multiple slots. The first slot is a HELLO message from the CH followed by another slot from the CH announcing the actual assignment of the remaining slots in the frame. The issue of this protocol is that it depends on the CH every time a new TDMA frame starts, which will lead to increased communication overhead.

III. TC-MAC

We propose TC-MAC as a new dynamic TDMA slot assignment technique for cluster-based VANETs. TC-MAC, unlike DSRC, will allow vehicles to exchange non-safety messages while maintaining a high reliability level of exchanging safety messages. In this technique, the collision-free intra-cluster communications are managed by the CH using TDMA. As a result, we must address three important challenges: cluster formation, TDMA slot reservation and intra-cluster communication.

A. *Cluster Formation*

Stable clustering methods reduce the overhead of re-clustering and lead to an efficient hierarchical network topology. During the creation of VANET clusters, cluster members select one member to be the CH. Fewer CH changes result in a more stable cluster. To achieve this goal, cluster members must select a member that has the potential to be a CH longer than other cluster members.

There are several CH selection algorithms. One of the algorithms is Lowest-ID [13]. The Lowest-ID clustering algorithm is based on selecting as the CH the member with the lowest ID, assuming each node has a fixed ID. The Highest-Degree algorithm [17] selects the CH based on the node connectivity to the other nodes in the same cluster. Another algorithm is the Utility Function algorithm [12]. This algorithm considers the characteristics of VANET in CH selection, such as speed, velocity and position.

In our previous work [7], we developed a CH selection algorithm using traffic flow. Besides the characteristics of VANET, the lane where the vehicle resides is part of the process of the CH selection. This algorithm produced longer CH lifetimes than the previously mentioned algorithms above. Therefore, TC-MAC uses the traffic flow algorithm for cluster formation.

B. *TDMA Slot Reservation in TC-MAC*

To explain our technique, we assume an *N*-vehicle cluster. The transmission time is partitioned into consecutive, non-overlapping logical TDMA frames. We assume the existence of *k* slotted SCHs numbered from 0 through *k*-1. In each SCH, the logical TDMA frames are aligned, i.e. begin and end at the same time. Each logical frame contains $\lfloor\frac{N}{k}\rfloor + 1$ slots numbered from 0 through $\lfloor\frac{N}{k}\rfloor$. All slots are the same size, and the slot size τ is known to all vehicles in the cluster.

We also assume one CCH, channel *k*, is used by the vehicles and CH for disseminating status and/or control messages. 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

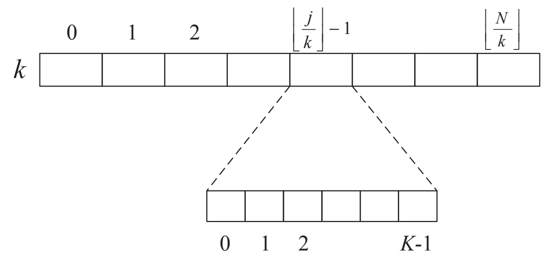

Figure 3. Mini-slots on channel *k*; vehicle *j* owns a mini-slot in the slot preceding its own slot

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*-1. The CH will always have ID 1, while ID 0 is reserved for a virtual vehicle. 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 using one of the mechanisms discussed below.

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 3; 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 $\lfloor\frac{j}{k}\rfloor$ and sets the corresponding byte in the CCH in order for other vehicles to be aware. Notice that the Integer Division Theorem guarantees that if $i \neq j$ then either:

- $\lfloor\frac{i}{k}\rfloor \neq \lfloor\frac{j}{k}\rfloor$ or
- *i mod k* $\neq$ *j mod k*, or both.

This confirms that no two vehicles own the same ordered pair. For an illustration, let *N*=61 and *k*=6. As shown in Figure 4, 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:

$$(\lfloor\frac{N}{k}\rfloor + 1) * k - 1 - N$$
$$= \lfloor\frac{N}{k}\rfloor * k + k - 1 - N$$

channel\slot	0	1	2	3	4	5	6	7	8	9	10
5	5	11	17	23	29	35	41	47	53	59	unused
4	4	10	16	22	28	34	40	46	52	58	unused
3	3	9	15	21	27	33	**39**	45	51	57	unused
2	2	8	14	20	26	32	38	44	50	56	unused
1	1	7	13	19	25	31	37	43	49	55	**61**
0	reserved	6	12	18	24	30	36	42	48	54	60
mini-slot ownership	[6-11]	[12-17]	[18-23]	[24-29]	[30-35]	**[36-41]**	[42-47]	[48-53]	[54-59]	[60-65]	[1-5]

Figure 4. Logical frames in TC-MAC for N=61 and k=6

$= N + k - 1-$ *(N mod k)* $-N$

$= k - 1-$ *(N mod k)* unused channels in slot $\lfloor \frac{N}{k} \rfloor$; in the previous example, there were 6-1-(61 mod 6)=5-1=4 unused channels in slot 10. These unused slots/mini-slots will be put to work in various ways that depend on the specific clustering regimen under investigation.

C. Intra-cluster Communication

For intra-cluster communication, we look at the single-hop cluster case in this paper; multi-hop cluster intra-cluster communication will be investigated in future work. Our goal is to design lightweight communication protocols that avoid, to the largest extent possible, the involvement of the CH in setting up connections between vehicles. As a single-hop cluster, all vehicles in the cluster can communicate directly. Consequently, the vehicles do not need to discover their neighbors.

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 at the moment.
- **1** indicates that the vehicle is involved in communicating with some other vehicle in the cluster; 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 63 bytes.
- **125** is the confirmation of the “Hello” message.
- **126** indicates that the vehicle will transmit a request during its upcoming slot (i.e., next slot).
- **127** indicates that the car 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 below.

1) Disseminating intra-cluster safety/governance messages: The CH is responsible for disseminating control messages. When a safety message needs to be broadcast to the cluster, the CH interrupts the transmission/reception of non-safety data. Then, the CH will change the status of its mini-slot to 127. Using the CHs receiving slot, the CH will broadcast the safety message to other vehicles in the cluster. This will be repeated on other available slots of the next logical frame to achieve the effect of broadcasting to the entire cluster. Other vehicles, in each logical frame, will be tuned to one of these channels to pick up potential safety messages. 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:

- The updated value of *N* and multicast group setup requests.
- Channels and slot times during which the CH has “office hours” and will listen to individual requests.

2) Disseminating intra-cluster non-safety: For non-safety messages, the CH uses its own slot for non-safety data exchanges, behaving as a normal vehicle.

3) Setting up intra-cluster unicast communication: Unicast (a.k.a. point-to-point) communications are set up without CH intervention. Suppose vehicle *i* wishes to talk with vehicle *j*; setting up a connection between them is done as follows:

- By tuning in to vehicle *j*ś own mini-slot, vehicle *i* determines whether or not vehicle *j* is available.
- If so, vehicle *i* transmits a handshake packet on channel *j mod k* during time slot $\lfloor \frac{j}{k} \rfloor$.

Assuming no collision (i.e. some other vehicle may also want to talk to *j*), *j* will pick up the handshake packet and will negotiate with vehicle *i* the parameters of the data exchange by replying on channel *i mod k* during time slot $\lfloor \frac{i}{k} \rfloor$; again, assuming no collision, the connection between vehicles *i* and *j* has been set up. Now, both vehicles set up the first byte of their mini-slots to indicate the status change. Once the connection has been set up, the two vehicles can communicate either in *i*ś slot, *j*ś slot, or both, if possible. If vehicles *i* and *j* need more than the basic amount of bandwidth, they may seek permission from the CH to use one or several extra unused time slots.

4) Setting up 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 will transmit on channel $j \bmod k$ 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 setup 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 $j \bmod k$ during slot $\lfloor \frac{j}{k} \rfloor$.

IV. Evaluation

A. Simulation Settings

TC-MAC was evaluated through detailed simulation. We used the ns-3 network simulator [15], which is a follow-on to the popular ns-2 simulator. For VANETs, we used modules [8] that added well-known traffic mobility models, the Intelligent Driver Model (IDM) [18] and the MOBIL lane change model.

The simulation parameters for the network are listed in Table I. The scenarios implemented were for a highway with different number of lanes (2, 3 and 4). The length of the highway is 2000 *m*, and the simulation time is 100 *sec*. For the traffic density, four different levels of traffic density were tested, as shown in Table II. As the gap between vehicles increases, the number of vehicles in the lane decreases, which will effect the density level on the road. In each scenario, we tested our TC-MAC as well as DSRC.

The time interval SI for both TC-MAC and DSRC is 100 *msec*. Ideally, the vehicle in 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 DSRC, all vehicles will be tuned to the CCH during CCHI and to the SCHs during SCHI.

B. Simulation Results

The simulation results show that TC-MAC performed better than DSRC in delivering safety/update messages. TC-MAC does not experience any collisions during the transmission of safety/update messages, but Figure 5 shows the percentage of collisions experienced with DSRC.

We also measured the percentage of direct safety/update messages that were missed, based on the number of vehicles in the cluster. The direct messages are the messages that are received directly from the source of the message, without being re-broadcast by any other vehicle in the cluster, including the CH. So, if the cluster size is 15 vehicles, the number of direct safety/update messages should be 14 messages for each vehicle per 100 *msec*. The result in Figure 6 shows the performance of TC-MAC and DSRC under different traffic densities. We observed that when the density

Table I
Simulation Parameters

Parameters	Values for DSRC	Values for TDMA
Cluster Length	300 m	300 m
TX Range	300 m	300 m
Safety Packet Size	200 bytes	200 bytes
Data Rate	6 Mbps	6 Mbps
CCHI	0.5 sec	N/A
SCHI	0.5 sec	N/A
Mini Slot Size	N/A	0.032 msec
SCH Slot Size	N/A	0.19 msec
Speed Limit	29 m/sec	29 m/sec

Table II
Traffic Density

Density Level	Number of Vehicles/Lane	Gap between Vehicles
Low	5	60 m
Med	12	20 m
High	21	10 m
Very High	50	1 m

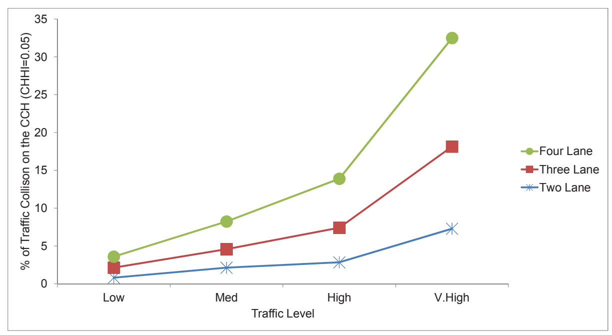

Figure 5. Percentage of collisions during the CCHI for DSRC

is low, the percentage of the missed direct messages between vehicles is high in TC-MAC. The reason for that is switching to the SCH. If we have 15 vehicles in a single-hop cluster, every vehicle may miss up to 6 safety/update messages from other vehicles sending on the CCH during the vehicle's SCH time slot. This happens only when we have all vehicles engage in any sort of communication during their own SCH time slot. TC-MAC has addressed this issue by having the CH resend the needed safety messages during the *unused* slots. On the other hand, for DSRC, the percentage of missed direct messages increases as the traffic density increases. The reason for this is the increase of packet collisions and missed opportunities to send during CCHI.

V. Conclusion

In this paper, we presented 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. We also explained a

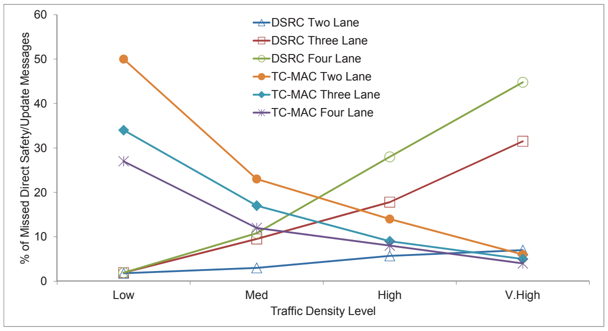

Figure 6. Percentage of Missed Direct Messages for TC-MAC and DSRC

light weight slot reservation algorithm. Our work is based on guaranteeing that vehicles receive non-safety messages without affecting safety messages. We also changed the concept of having two intervals by having vehicles listening to the control channel and the service channels during the same time cycle. This scheme should be easy and fast to maintain. The simulation results show that TC-MAC is able to deliver non-safety messages, as well as meeting the requirements of the safety messages.

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

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