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TDMA scheduling strategies for vehicular ad hoc networks: from a distributed to a centralized approach

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Abstract— Vehicular Ad hoc NETWORKS, known as VANETs, are deployed to reduce the risk of road accidents as well as to improve passenger comfort and safety by allowing vehicles to exchange different kinds of data. Medium Access Control protocols, namely those that are based on TDMA technique play a primary role in providing bounded transmission delay while minimizing data packet loss. However, due to mobility constraints and frequent changes in topology, slot scheduling is a more challenging task in VANETs than in other networks. Many MAC protocols based on TDMA for vehicular networks have been proposed to date. Among them, CTMAC is a centralized scheduling mechanism, while DTMAC, VeMAC and ADHOCMAC are three distributed TDMA based MAC protocols. In this paper, we evaluate and analyze the performance these four protocols. The scenarios used in the simulation experiments take into account density variation factor that influences protocol performance. We use the MOVE and SUMO tools to generate realistic mobility scenarios. Performance metrics such as access collision, merging collision rate, packet loss and overhead are evaluated using NS-2.34.

I. INTRODUCTION AND MOTIVATION

Vehicular Ad hoc NETWORKS, known as VANETs, are a promising communication technology that can meet various requirements of Intelligent Transportation System (ITS) applications which aim to improve traffic safety and efficiency [1]. Through Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications, each vehicle can exchange information to warn other vehicles about the current state of the traffic flow or the existence of a potentially dangerous situation such as an accident. Road safety and traffic management applications require a reliable broadcast scheme with minimal transmission delays and collisions, which increases the need for an efficient MAC protocol [2]. Recently, Contention-free MAC protocols, notably those that are based on the TDMA technique, have attracted a lot of attention and many protocols have been proposed in the

literature in order to handle network access and transmission with minimum packet loss.

A number of TDMA-based MAC protocols have been proposed and evaluated for VANETs. In the last few years, several such protocols have been published to offer reliable and real-time communications in VANETs while attenuating the effect of the merging collision and access collision problems [2]. Each protocol has been designed for a specific problem considering a particular mobility scenario. As an example, in [3], Borgonovo et al. propose ADHOCMAC protocol (AD HOC Medium Access Control) to insure an efficient broadcast mechanism for V2V communications and cope with some medium access channel issues, like the hidden-exposed node problem. By doing so they aim to guarantee a certain Quality of Service. The ADHOC MAC protocol is a contention-less medium access protocol based on a dynamic TDMA technique which provides fast access to the channel. This mechanism can be seen as an extension of the Reliable ALOHA technique (R-ALOHA [4]). Each car is able to access the channel in every frame in a random manner to choose a time slot as its Basic CHannel (BCH). The car is guaranteed to access the channel at least once in a given frame.

In [5] Omar et al. design and study a protocol called VeMAC. VeMAC proposed for VANETs is a contention-free MAC protocol adapted to the V2V multi-channel radio system that offers efficient one-hop and multi-hop broadcast services on the control channel and eliminates the hidden node problem arising from by vehicle mobility. In addition, VeMAC [5] is able to attenuate the merging collision rate by allocating different sets of time slots to cars traveling in different directions (Right; Left) and to RSUs (RoadSide Units). As VeMAC is a fully distributed protocol, an access collision problem may frequently occur between among cars attempting to gain access to the same time slots in high traffic density situations. Another completely distributed TDMA scheduling scheme, named DTMAC which benefits from the

linear topology of VANETs is proposed and presented in [6]. This scheme is based on the assumption that the road is partitioned into equal small size areas and the time slots in every TDMA frame are divided into three sets which correspond to cars in three successive areas. In DTMAC, slot allocation and reuse procedures are designed to reduce the effect of collisions that stem from the hidden node problem.

An efficient solution to mitigate the access collision rate while reducing the scheduling overhead consists in using RSUs as primary coordinators to set up and adjust time slot allocation for the cars in their communication range. For instance, in [7] the authors propose an Adaptive Collision Free MAC (ACFM) protocol based on a centralized and dynamic time slot assignment mechanism. Each frame in ACFM is partitioned into a predefined number of time slots: one RSU time Slot (RS) is dedicated to an RSU to transmit control messages to the cars located in its vicinity and within its communication range. In addition, 36 Data time Slots (DS) can be used by the cars to transmit their data packets to their immediate neighboring vehicles. An RSU periodically diffuses a control message containing the DS allocation schedule for the cars within its radio range along with the time synchronization information. Unfortunately, the protocol does not handle communications between vehicles belonging to two different RSU coverage areas. In [8], the authors have propose a Unified TDMA-based Scheduling Protocol (UTSP) especially designed for Vehicle-to-Infrastructure communications. The main purpose of this research work is to maximize the useful bandwidth for user-related applications in VANETs. Hence, each RSU gathers the required information such as the channel occupancy information, the vehicle velocity, and the Access Category (AC) properties of the cars located in its coverage area. Then it allocates the time slots to the cars according to a weight function that takes into account three elements: speed weight factor, AC (Access Category) weight factor and channel-quality weight factor. However, the authors do not take into consideration the interference problem that may occur between cars in overlapping areas where each area is covered by a different RSU.

This paper compares our protocols DTMAC [6] and CTMAC [9], with the contention-free MAC protocol (VeMAC) and AD HOC Medium Access Control (ADHOCMAC) in a highway traffic environment under different conditions. To model realistic vehicular motion patterns, we use the Simulation of Urban Mobility (SUMO) tool. The comparison is made in terms of access collision, merging collision rate, packet loss and overhead. The rest of the paper is organized as follows. Sections 2 and 3 describe respectively the DTMAC and the CTMAC protocols. Section 4 presents the simulation results and performance comparison. Finally, conclusions are reported in Section 5.

II. DISTRIBUTED AND INFRASTRUCTURE-FREE TDMA-BASED MAC PROTOCOL

We begin by presenting our DTMAC protocol where the slot assignment decision is distributed among all the vehicles.

In DTMAC, as Figure 1 shows, the road is divided into N small fixed areas, denoted by x_i ; $i = 1, \dots, N$, of length equal to R , where R is the communication range. Area IDs can be easily derived using a map and GPS information. The time slots in each TDMA frame are partitioned into three sets S_0 , S_1 and S_2 associated with vehicles in three contiguous areas: x_i , x_{i+1} and x_{i+2} , respectively. Each frame consists of a constant number of time slots, denoted by M and each time slot is of a fixed time duration, denoted by s . Each vehicle can detect the start time of each frame as well as the start time of a time slot.

To acquire this information, messages are exchanged between neighboring vehicles. Furthermore, specific information, called Frame information (FI) is added to each transmitted packet to notify the neighboring vehicles of a time slot assignment. The FI consists of a set of ID Fields (IDFs) of size equal to the number of time slots per frame. Each IDF is dedicated to the corresponding time slot of a frame and it is composed of three fields VC_ID, SLT_STS and PKT_TYP. The VC_ID field contains the ID of the vehicle that is accessing this slot. Each vehicle is identified by its MAC address. The SLT_STS field contains the status of each slot which indicates whether the slot is Idle, Busy or in Collision. Finally, the PKT_TYP field indicates the type of packet transmitted by the vehicle, i.e., periodic information or event-driven safety messages.

Let us suppose that an active vehicle v moving within the area x_i needs to acquire a time slot on the transmission channel. Vehicle v starts listening to the channel during the set $S_j(v)$ of time slots reserved for the area in which it is traveling, where $j = (i + 2) \bmod 3$.

- Initially, the status of each slot in the FI is free.
- Each vehicle that hears exactly one node transmission in a time slot reserved for its location, will set the status of the slot to "busy" and record the ID of the vehicle accessing the channel in this time slot in the corresponding VC ID field.
- If a vehicle does not hear anything during a specific time slot, it will set its status to "free" in the FI.
- If a vehicle can not decode the data during a specific time slot, it will set its status to "collision" in the FI.
- When a vehicle A has sent data in a given slot, it looks in the field information of the next slots to discover whether its neighbors have correctly received its data. If a neighbor of A reports collision for this slot (in the FI) or even if this slot is reported to be "busy" but being sent by another node (say B in the VC_ID), A considers that its transmission has led to a collision. Actually a node A considers that its transmission is a success if and only if all its

neighbors report a success in the FI of their slots specifying that the data was sent by node A.

When an access collision occurs among the vehicles that are moving in the same area, the probability of access collision in the next reservation is increased since the choice of available slots will be limited in the new set. In order to ensure channel access continuity, each vehicle should determine the expected available time slots in the set of time slots associated with the next area before leaving the area in which it is currently traveling. In fact, when a vehicle is using a given time slot in the set S_j , it should acquire an available time slot in the set $S_{(j+1) \bmod 3}$ as its future time slot before leaving its current area.

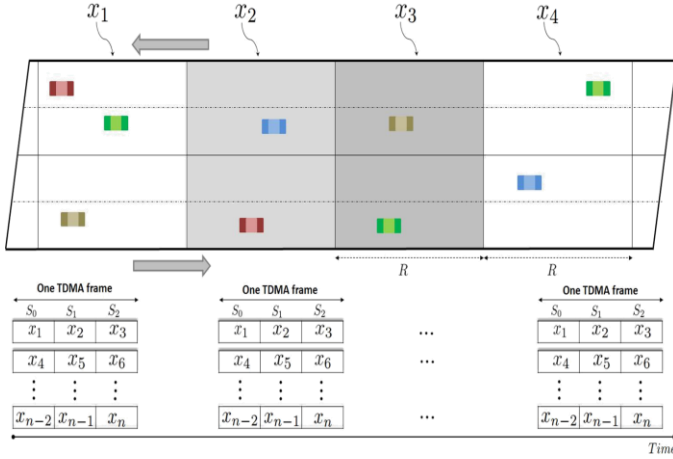


Figure 1. TDMA slots scheduling principle.

III. CENTRALIZED TDMA-BASED MAC PROTOCOL

The key idea of the CTMAC protocol [9], a TDMA-based protocol, is the use of a collision free scheduling mechanism over adjacent areas. CTMAC prevents vehicles traveling in two adjacent areas from using the same time slot to access the radio channel. In CTMAC, the road is partitioned into several contiguous areas, where each of them is covered by one *RSU* located in the middle of it. The radio range of an *RSU* is denoted by R , and the length of an area is equal to $2R$. Like traditional TDMA access channel based protocols, the time is divided into successive time frames. In addition, each time frame is divided into two sets of time slots denoted by S_1 and S_2 . These two sets are repeatedly used along the road so that no vehicles located in the same set of two-hop neighbors are using the same time slot. Figure 2 shows a highway divided into several adjacent areas where in each of them, one *RSU*, having a radio range equal to R , is located in its center. According to CTMAC rules, vehicles traveling in the area covered by *RSU1* and those covered by *RSU2* are accessing non overlapping sets of time slots. The set S_1 of time slots is used by the vehicles that are moving within the coverage area of *RSU1*, while the set S_2 is used by the vehicles that are moving within the coverage area of *RSU2*.

The major benefit of CTMAC is the limited effect of

interference between each two successive *RSUs*. Consequently, the scheduling mechanism is able to reduce the collision rate for vehicles accessing the radio channel without using any complex bandwidth allocation technique. Each time a vehicle enters a new area, it gets a new time slot (see next paragraph for more details). This time slot will be used by the vehicle to access the channel and transmit its data as long as it is traveling within the same area. Each *RSU* builds and updates a Frame Information (FI) composed of τ fields, τ being the number of time slots in the frame. Each field, denoted as IDF (ID Field) describes the corresponding time slot in the frame. Three subfields are used for this purpose: SLT_STS, VC_ID and PKT_TYP. The SLT_STS subfield indicates whether the slot is being used (occupied), in Collision, or Idle. The VC_ID subfield stores the ID of the car that is using this slot. Whereas the PKT_TYP subfield gives information about the type of packet transmitted: i.e. event-driven safety messages or periodic packets. In CTMAC and unlike the ADHOC MAC and VeMAC protocols, the frame information is periodically broadcasted only by the *RSU* and each vehicle updates its local FI based on the FI broadcasted by its *RSU*. Nevertheless, if an access collision is detected, a vehicle is allowed to broadcast its frame information to its neighbors (and the *RSU*) to warn them about this event.

An *RSU* u is able to identify the set of available time slots at the end of each frame. This set is denoted by $F(u)$. When free slots are available a Slot Announcement (SA) message along with the FI message are broadcasted during the first slot of the corresponding *RSU* time slots subset (notice that the first slots of sets S_1 or S_2 are reserved for *RSU* transmissions). Based on this information, a vehicle v traveling in that area that wishes to access the channel is able to pick one of the available slots at random. It then broadcasts a Slot REQuest message (SREQ) during the selected slot to attract the attention of the *RSU* and express its intention. When the *RSU* gets the SREQ message, it checks whether a time slot is available or not. The *RSU* will send its Slot REPLY message (SREP) containing its allocation decision including the allocated time slot index. The decision is simply integrated within the next FI announcement. Either the vehicle v can start using the assigned time slot to transmit its data, or v will reiterate the same reservation steps if a predefined timer expires and no reply has been received from the *RSU*. An *RSU* considers that a given vehicle v has left its communication range when it does not receive a packet from v during its time slot.

As stated before, v will keep using the same time slot while traveling in the same area and without any collision. When a collision occurs, the vehicle will try to get a new time slot as described above. If the moving vehicle v detects different *RSU* announcements than the current one, it will start a handover procedure to get a new time slot from the newly detected *RSU*. The vehicle will send an SREQ message to be allocated a new time slot and if it receives an SREP message from the *RSU* it will free its current time slot and it will resume its transmissions during the time slot newly allocated by the new *RSU*.

IV. SIMULATION RESULTS AND PERFORMANCE EVALUATION

In this section, we provide the simulation results to evaluate and compare the performance of four TDMA based MAC protocols by varying the number of vehicles.

A. Simulation scenarios and parameters

We use MOVE [10] to generate vehicular traffic scenarios and SUMO [11] to perform real vehicular mobility simulations (see Figure 2).

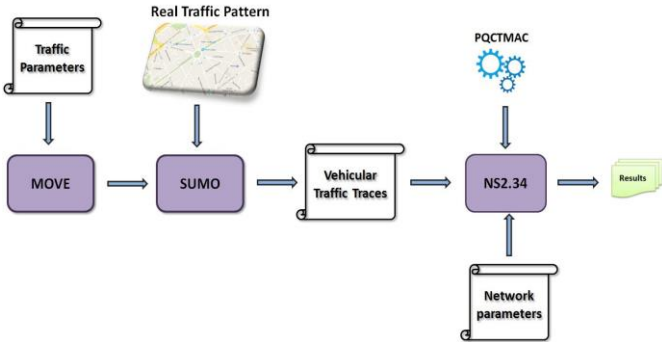


Figure 3. Simulation framework.

In our simulations, we consider a real highway area digital map to generate a VANET environment close to real highway configurations taking into account different lane directions. In Figure 3 we can see a metropolitan area taken from a Map of San Jose (California) of size 3000m 100m. This map was exported from OpenStreetMap (OSM) and adapted with the help of OpenStreetMap Editor (JOSM). The resulting roads are then populated with vehicles traveling in all directions. Each flow of vehicles is characterized by a set of parameters which consist of the starting and ending time of the flow, the initial point and the destination of the flow and the maximum number of vehicles. In this environment, each vehicle is assigned a random speed between 120km/h and 150km/h. The resulting traffic traces generated by MOVE were injected into the Network Simulator ns2:34. Table I summarizes the simulation parameters that we use in our scenarios.

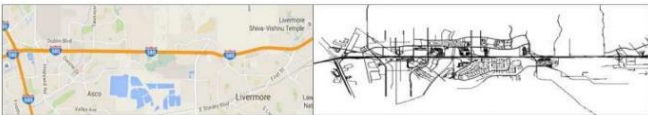


Figure 3. VANET network topology captured from Google MAP.

Table 1. Simulation parameters

Parameter	Value
Simulation duration	120 (s)
Speed	120 (km/h)
Speed standard deviation	30 (km/h)
Number of slots per frame	100
Slot duration	0:001 (s)
Highway length	2.5 (km)
The number of lanes per direction	2
The radio range (R)	310 (m)

B. Simulation results

In this section, we compare the performance of DTMAC and CTMAC with VeMAC and ADHOCMAC protocols in terms of merging and access collisions rate and the overhead (the control messages needed to establish and maintain a collision-free schedule). We have used a parameter, called the area occupancy (AO) [5]. The protocols are evaluated based on the following metrics:

The access collision rate: is defined as the average number of access collisions per slot per RSU cover-age area.

The merging collision rate: is defined as the average number of merging collisions per slot per RSU coverage area.

Overhead: which is the rate of control packets used to allocate a time slot as well as to maintain the TDMA schedules.

Figure 4 shows the rate of merging collisions for DTMAC, CTMAC, ADHOCMAC and VeMAC. We can note from this figure that DTMAC prevents more merging collisions than ADHOCMAC, VeMAC and CTMAC, especially for a high Area Occupancy ($AO = 0.4$). Moreover, we can note that CTMAC achieves a considerably lower rate of merging access collisions compared to VeMAC and ADHOCMAC. These results can be explained by the fact that DTMAC and CTMAC separates neighboring RSU areas by assigning disjoint sets of time slots to vehicles traveling in these areas. However, in VeMAC, the vehicles that cannot access a time slot from the set of slots reserved for its direction, will attempt to access any available time slot reserved for vehicles moving in the opposite direction. As a result, the merging-collisions occur frequently in VeMAC when traffic density is high, especially when the number of vehicles in each direction is not equal. However, these results might well be expected for the ADHOCMAC protocol since all vehicles randomly acquire a time slot in the frame without considering which direction they are moving in, which could make it susceptible to the merging collisions problem in highway scenarios where the vehicles are moving in opposite directions.

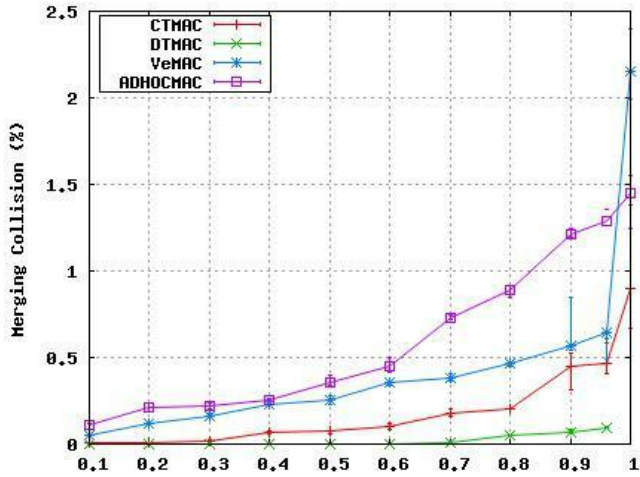


Figure 4. Merging collision rate vs. Area Occupancy (AO)

The rate of access collisions under different traffic densities is shown in Figure 5. We can note that the CTMAC protocol generates a lower rate of access collisions than the three other protocols, especially for a high traffic load. For instance, at a $AO = 0.96$, the CTMAC protocol achieves an access collision rate of 0.21%, in contrast to DTMAC, VeMAC and ADHOCMAC which show a rate of 0.352%, 0.4317% and 1.158%, respectively. The reason is that the assignment of time slots to vehicles is performed by the RSUs in a centralized manner. Moreover, CTMAC implements an Access Collision Avoidance mechanism that can prevent the access collision problem occurring more than twice between the same vehicles that are trying to access the channel at the same time. On the other hand, we can note that DTMAC and VeMAC achieve a considerably smaller rate of access collisions than ADHOCMAC, especially for a high $AO (\geq 0.5)$. These results can be explained by the fact that ADHOCMAC has achieved a higher rate of merging collision compared to DTMAC and VeMAC. Indeed, upon detection of merging-collisions, the nodes in collision should release their time slots and request new ones, which can reproduce access-collisions.

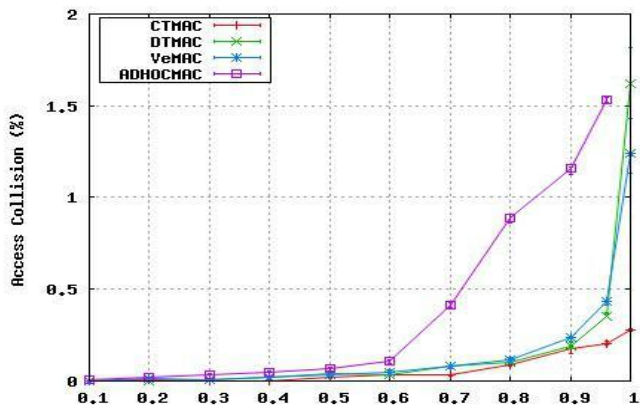


Figure 5. Access collision rate vs. Area Occupancy (AO)

Figure 6 shows the amount of overhead (in Mega octets) generated by DTMAC, CTMAC, ADHOCMAC and VeMAC. We see that DTMAC, ADHOCMAC and VeMAC have more scheduling overhead than CTMAC for all AO values. These results can be explained by the number of control messages (e.g. frame information) broadcasted by each vehicle in these protocols in order to establish and maintain its schedule table. Moreover, we can also note that the overhead increases for all protocols when the number of vehicles increases.

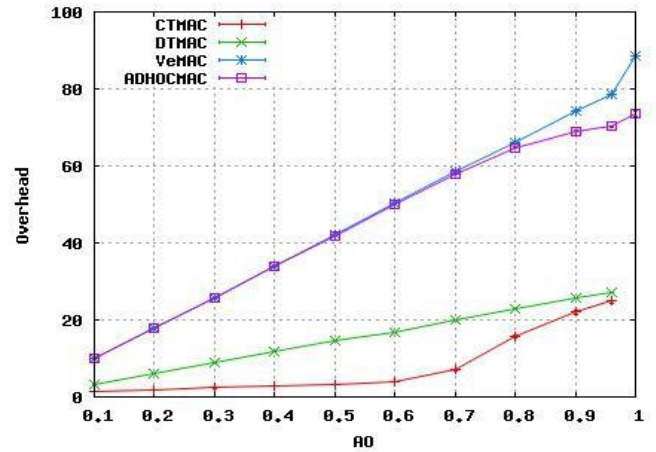


Figure 6. Overhead in Mega octets

V. CONCLUSION

In this paper, we compare the performance two of our TDMA slot scheduling schemes namely CTMAC and DTMAC, with other well-known protocols called ADHOCMAC and VeMAC. The simulation results presented in this paper reveal that CTMAC outperforms other protocols in terms of merging collision ratio, especially for a high vehicle density. Moreover, compared to a centralized solution, the distributed protocols suffer from a higher overhead because it must be aware of the slot allocation of neighboring vehicles. Therefore, we can conclude through these results that CTMAC provides the best performance among the four protocols analyzed for the case of highway scenario, while DTMAC generates a lower merging collision rate and it incurs the least amount of overhead among the three distributed protocols.

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