A Topology-Independent TDMA MAC Policy for Safety Applications in Vehicular Networks

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***Abstract*—The problem of accessing the medium to support safety applications in vehicular networks is challenging, when vehicles' mobility increases and time constraints become tight. In such environments, and particularly for vehicular-to-vehicular communication where safety is the main concern, time delay bounded data packet delivery is a prerequisite. Consequently, topology-independent MAC policies that guarantee a number of successful transmissions independently of the underlying topology, can be employed as a suitable choice for the particular vehicular environment. One such policy is revisited in this paper and its performance is demonstrated against VeMAC – a well-established MAC protocol in the area of vehicular networks – using simulation results. As it is shown in this paper, throughput under the considered topology-independent policy remains comparable to that of VeMAC whereas the number of retransmissions are significantly reduced leading to a reduced time delay.**

***Index Terms*—Vehicular networks, TDMA, MAC, Topology-independent.**

I. Introduction

Vehicular networks have seen a significant growth over the last decade and they are closely related to human everyday life either for improving the quality of a journey or – and most importantly – for safety reasons. Improving safety [1], [2] is closely related to efficiently accessing the medium in terms of time delay even though throughput may be severely compromised [3].

Even though contention-based *medium access control* (MAC) protocols are mainly proposed for vehicular networks, it appears that there are scalability problems, especially when traffic load is increased. In particular, regarding the most prominent standard, IEEE 802.11p [4], it has been shown [3] that it suffers from time unbounded transmissions and therefore, it is not suitable for improving road safety. The current research trend is to employ TDMA-based approaches for medium access control to capitalize on the inherent time-coordinated transmissions [3].

For the purposes of vehicular-to-vehicular communication, that is the focus of this paper, a distributed TDMA-based MAC protocol of common and synchronized frame is considered. Several such protocols have been proposed in the past like ATSA [5], CFR [6], STDMA [7], VeSOMAC [8] and VeMAC [9]. An extensive survey of the various TDMA-based MAC protocols can found in [3]. Under VeMAC [9], every node initially listens to the channel for one frame time so as to obtain information about neighboring nodes and subsequently reserves a slot that neither its one-hop nor its two-hop neighbors use. In addition, it splits the frame in two disjoint sets associated with the moving direction whose length is adjusted according to the traffic conditions. ATSA [5] suggests a slot management mechanism based on a binary tree and employs a variable frame length according to the traffic density. CFR's [6] medium access control mechanism further divides these two disjoint sets of time slots according to the speed of vehicles thus, dealing with the problem of nodes selecting the same slot when they move in the same lane but at different speeds. Other protocols, especially for non-safety application have been proposed, e.g., STDMA [7] and VeSOMAC [8].

The main idea of this paper is to revisit *topology-independent* MAC policies proposed in the past that guarantee data packet delivery on a per frame basis [10], [11]. This is achieved by allowing users (in this case vehicles) to transmit, within a frame, during a specific set of time slots carefully selected according to polynomials of Galois fields [12]. Since this approach is fully distributed and makes no assumptions regarding the topology – apart from an upper bound on the network size and the number of neighbor nodes – it can be effectively employed in vehicular networks. Its guaranteed nature despite the topology unawareness, motivates its introduction in vehicular networks.

The comparison between the aforementioned topology-independent MAC policies and VeMAC is carried out in this paper using simulation results for different topologies and for various velocity levels. Even though VeMAC has specific features for vehicular environments (e.g., time slots assigned depending on the direction of the vehicle, knowledge of two-hop neighbors), the particular topology-independent MAC considered in this paper (to be referred to hereafter as TiMAC) corresponds to the one originally described in [10], without any enhancements due to the vehicular environment. The obtained results demonstrate the effectiveness of TiMAC for vehicular network environments. It is shown here that throughput is close to that of VeMAC and depending on the case it may be slightly higher. In addition, the number of retransmissions is significantly smaller under TiMAC than under VeMAC, thus motivating the revisiting of the particular topology-independent MAC policies.

Section II briefly presents the most important characteristics of the considered vehicular network. In Section III and Section IV, VeMAC and TiMAC are presented, respectively. The evaluation of their performance using simulation results is included in Section V and the conclusions are drawn in Section VI.

II. Vehicular Network Characteristics

A vehicular network can be seen as a special case of a mobile ad hoc network where the nodes are the vehicles. As it is the case in ad hoc networks, nodes are self-organized, may have access to infrastructure (even in a multi-hop manner) and are expected to move. Clearly, vehicles move on predefined routes, i.e., roads. Furthermore, even though energy consumption may be an issue in mobile ad hoc networks, this is not the case in their vehicle counterparts due to the latters' inherent battery recharging capabilities.

Vehicular communication may be distinguished as communication among vehicles (i.e., vehicle-to-vehicle communication) and communication between a vehicle and an existing infrastructure at the roadside (i.e., vehicle-to-infrastructure communication). The latter communication type is usually realized as an ad hoc communication between the vehicle and the roadside unit that is usually connected to the Internet [13]. This work focuses on improving safety through vehicle-to-vehicle communication.

A distinctive characteristic of vehicular networks is high node mobility and therefore, a MAC protocol should be able to adapt to the frequent changes of topology and the various patterns of these changes (e.g., vehicle move along roads and not randomly). Three different environments may typically be considered: (i) Highway (high speed environment with variable density of traffic and number of vehicles depending on time and day); (ii) City (lower speed than in highways and a high density of cars depending on time); and (iii) Urban (speed in between that in highways and city environments and car density lower than in the other two environments). The typical speed in vehicular network is between 30 km/h and 50 km/h in a city environment, between 50 km/h and 80 km/h in an urban environment, and between 90 km/h and 150 km/h in a highway environment. Such mobility characteristics – not typical in mobile ad hoc networks – may have significant effects on the overall performance (e.g., [14], [15], [16]). The fact that vehicles have to some extent a predictable behavior with respect to their movement, also limits the upper bound on the number of neighbor vehicles. For example, the worst case with respect to the number of neighbors is during a traffic jam in cross-roads.

Another special characteristic of vehicular networks refers to the inherent capabilities of vehicles like including a GPS (Global Positioning System) [17] device that can give accurate measures with respect to position, velocity, direction and time. In addition, vehicles have ample energy for operating their electronic devices that can be of adequate processing power and storage capacity.

Finally, when the focus is on vehicular-to-infrastructure communication, there are different constraints with respect to performance (e.g., throughput may be more important compared to time delay) than for the case of vehicular-to-vehicular communication. For the latter case, and particularly for safety applications, as it is the case in this paper, time delay plays a critical role. As it will be shown later, the number of retransmissions under TiMAC are significantly smaller than under VeMAC for comparable values of throughput. Both VeMAC's and TiMAC's main characteristics are briefly described in the following two sections.

III. VeMAC Description

VeMAC [9] is a TDMA protocol operating in a multichannel manner, thus suitable for both safety and non-safety applications. One channel is used for safety applications and the rest for non-safety ones. In this paper, the focus is one safety applications, thus, on VeMAC's single channel operation.

Time is divided in frames of fixed number of time slots. Synchronization among nodes is achieved using GPS. GPS is also employed to determine the moving direction of each vehicle. Each frame is divided in three separate sets of time slots: L and R for those nodes moving on the left and right direction (or downwards/upwards) and S for those communicating with roadside units. Since the focus here is on vehicular-to-vehicular communication, the latter set will be omitted, focusing on the L and R time slots only.

The medium access control policy of a node (i.e., a vehicle) realized by VeMAC is based on continuous transmissions (even in the absence of data) during time slots that are marked as free within a frame by the one-hop and two-hop neighbors (i.e., the potential interference nodes due to the hidden terminal problem). Note that each node is aware about its direction (L or R) and competes for the corresponding set of time slots within the frame. In particular, when a node enters the network, first is synchronized and then keeps track of the transmissions of its neighbor nodes for one frame. When a node transmits during a particular time slot, this time slot is marked as being *occupied* by this particular node. Those time slots occupied by the transmitting node's one-hop neighbors are also enlisted within the header of each transmission. Eventually, each node is aware about the set of time slots occupied by its two-hop neighbors after the first frame. The next step is to select one of the unoccupied time slots and keep transmitting during this slot even if data are not available for transmission, since it is important to announce to its neighbor nodes the occupation of the particular time slot and the piece of information regarding its neighbor nodes. Clearly, if no message is sent in a previously occupied slot, the corresponding node is either powered off or went out of range so this time slot is now free again.

Fig. 1 graphically illustrates an example of time slot assignment under VeMAC. Nodes in this example are depicted moving to different directions so each one competes for a time slot that corresponds to its direction. Take for example, node 3 moving downwards and is now entering the network. Time

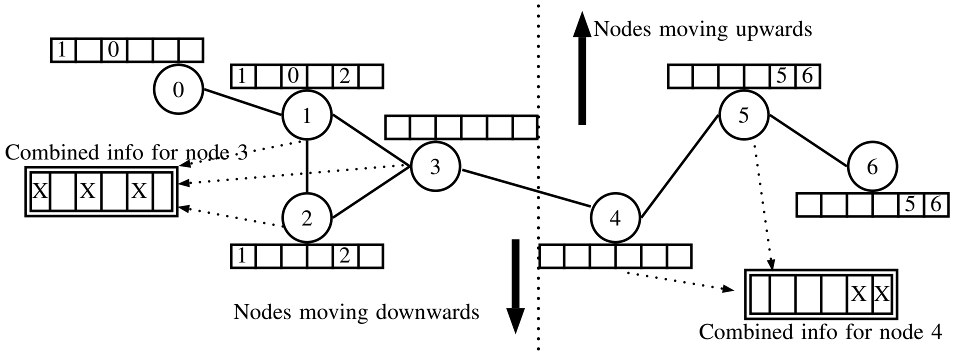

Fig. 1. Nodes 3 and 4, moving towards opposite directions, become aware of occupied under VeMAC time slots by their two-hop neighbors and they randomly choose one of the non-occupied to transmit (and declare as occupied). The depicted time slots sets are different for each direction.

slots occupied by its neighbor nodes (i.e., nodes 1 and 2) are also depicted. The double lined box contains the information that node 3 has received (including the information about the two hop neighbors). Mark "X" corresponds to the occupied time slots and therefore, node 3 may select (randomly) any other time slot (e.g., the second one). The same applies for node 4. Both time slot are different (disjoint sets) since node 4 and node 3 are moving to opposite directions.

However, collisions do happen and there are mainly two types: access and merging. Access collisions occur when two or more nodes in the process of randomly selecting their time slot, select the same one. Merging collisions occur when nodes initially positioned out of each others two-hop neighborhood and occupying the same slot, suddenly come close enough so their transmissions collide. When a collision takes place (irrespectively of the type), the particular nodes occupying this time slot release it and choose a new one (randomly) based on the information gathered during the last frame.The collision detection mechanism is based on listening the frame following a transmission. If a collision occurs, then the transmitting node will become aware of it since it will not included in the list sent by its neighbor nodes during the following frame.

IV. TiMAC Description

Under TiMAC [10], for a network of N nodes, each node u is randomly assigned a unique polynomial f_u of degree k with coefficients from a finite Galois field of order q ($GF(q)$). It is assumed that the maximum number of neighbor nodes in this network will be D (a realistic assumption to have an upper limit for vehicular environments). Polynomial f_u is represented as $f_u(x) = \sum_{i=0}^{k} a_i x^i$, where $a_i \in \{0, 1, 2, \ldots, q-1\}$; parameters q and k are calculated based on N and D, according to the algorithm presented in [10]. It is satisfied that $k \geq 1$ and $q > kD$ or $q \geq kD + 1$ (k and D are integers), to allow at least one transmission in one frame to be successful, and $q^{k+1} \geq N$ to satisfy that there exist enough unique polynomials for all nodes in the network [10].

The frame is fixed and consists of q^2 time slots divided into q subframes s of size q. The particular time slot assigned to node u in subframe s, ($s = 0, 1, \ldots, q-1$) is given by $f_u(s)$ mod q, [10]. Consequently, one time slot is assigned for each node in each subframe. Let Ω_u be the set of time slots assigned to node u. Given that the number of subframes is q and a node is allowed to transmit only during one time slot in a subframe, $|\Omega_u| = q$. Each node u transmits in a slot i only if $i \in \Omega_u$, provided that it has data to transmit.

Suppose that two neighbor nodes u and v have been assigned two (unique) polynomials f_u and f_v of degree k, respectively. Given that the roots of each node's polynomial correspond to the assigned time slots to each node, k common time slots is possible to be assigned among two neighbor nodes. Given that D is the maximum number of neighbor nodes of any node, kD is the maximum number of time slots over which a transmission of any node is possible to become corrupted. Since the number of time slots that a node is allowed to transmit in a frame is q, if $q > kD$ or $q \geq kD+1$ (k and D are integers) is satisfied, there will be at least one time slot in a frame in which a specific transmission will remain uncorrupted for any node in the network [10]. The assignment of the unique polynomials, or equivalently the assignment of the time slot sets Ω_χ to any node χ, is random in the sense that neither node χ nor its neighbor nodes are taken into account in order to assign any polynomial.

Even though TiMAC could be further improved given the particular characteristics of the vehicular environment, the purpose here is to compare it against VeMAC and leave any possible enhancements for future work.

V. Performance Evaluation

A simulator program in the omnet++ simulation platform [18] has been developed for the evaluation of TiMAC [10] in a vehicular environment and to be compared against VeMac [9]. In order to have a fair comparison, time slot duration was fixed and equal (3 ms) for both protocols and the comparison is made in a per time slot basis. Under TiMAC the frame size is set to q^2. Given that for any given subframe of length q a node may transmit only once under TiMAC [10], and since this is also the case under VeMAC, the latter's frame is also set to q. The network size $N = 1000$ vehicles. It is assumed that all nodes are perfectly synchronized for both protocols. Transmission range is the same for all vehicles and the maximum number of neighbor nodes $D = 17$ for all simulation scenarios. According to the algorithm in [10] these particular values of N and D correspond to $k = 1$ and $q = 37$.

A. Network Topology, Traffic Characteristics and Evaluation Parameters

Two different network topologies are considered for the evaluation. First, a highway, 12 km long, containing two lanes of opposite directions. Node transmission range is set to 28 m. The distance between the two lanes is 10 m, so each vehicle may be in range with vehicles of the opposite lane too. Each vehicle may move with medium, high or very high speed which corresponds to 72 km/h, 108 km/h and 144 km/h, respectively. When a node reaches the end of the road, reappears at the corresponding edge at the other side of the to topology. The second topology corresponds to an urban road network, 1200 m long and 1200 m wide, consisting of 4 (parallel) horizontal and 4 (parallel) vertical roads. Parallel roads are positioned 400 m from each other and crossroads are formed at the intersection of horizontal and vertical roads. Each vehicle may move with low, medium, or high speed which corresponds to 36 km/h, 72 km/h and 108 km/h, respectively. When a node reaches a crossroad, it randomly chooses one of the available directions excluding the opposite of its current one. For both topologies, nodes' initial positioning and direction is random. Speed is also randomly chosen among the aforementioned ones.

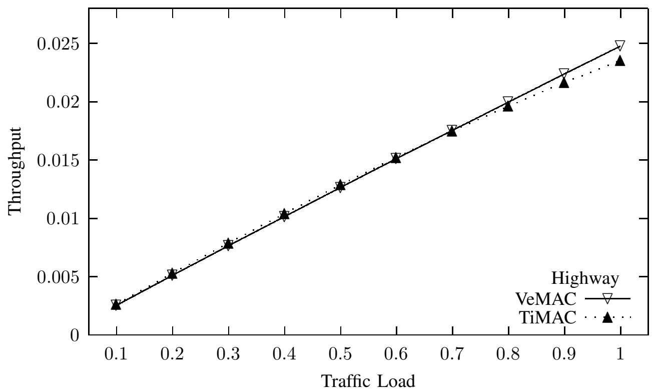

Fig. 2. Throughput as a function of traffic load for a highway vehicular environment.

Traffic load hereafter corresponds to the probability that there is a data packet available for transmission for a randomly chosen neighbor destination at a particular time slot, provided that the transmitting node is allowed to transmit during this slot under either VeMAC or TiMAC. This probability (i.e., traffic load) is the same for all vehicles. The number of successful transmissions per node per time slot is referred to hereafter as *throughput*. The number of retransmissions is used to compare both MAC policies as indicative of time delays. Note that a small number of retransmissions result indicates small overall time delay (e.g., no need for retransmissions).

B. Simulation Results

Fig. 2 depicts throughput as a function of traffic load for a highway vehicular environment. As expected, as traffic load increases, throughput for both under VeMAC and TiMAC increases. It is observed that for traffic load less than 0.6, the obtained throughput under TiMAC is slightly larger than that under VeMAC, whereas as traffic load further increases the observed picture changes. This change is attributed (i) to the disjoint set of time slots under VeMAC assigned to different directions (and thus, as traffic load conditions increase, VeMAC behaves better than TiMAC in terms of throughput); and (ii) to the fact that as traffic load increases the collision probability under TiMAC also increases (note that under TiMAC nodes transmit only if there are data for transmission and not during every frame as it is the case under VeMAC). Still, as it is observed, the obtained throughput under both policies remains close.

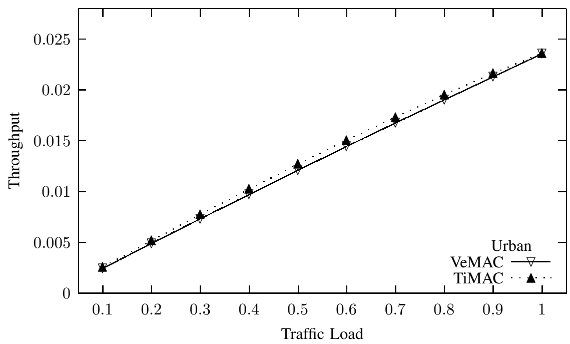

Fig. 3. Throughput as a function of traffic load for an urban vehicular environment.

The throughput remains close under both policies in an urban environment as well, as depicted in Fig. 3. It is interesting to see that TiMAC slightly outperforms VeMAC under all traffic load conditions. This is attributed to the fact that in an urban environment, traffic is not that predictable as it is the case for highways (e.g., nodes may turn in crossroads) and therefore, the assigned time slots under VeMAC that correspond to a certain direction should be reassigned in the face of collisions.

The average number of retransmissions per node for the highway and the urban vehicular environments are depicted on the left and the right side of Fig. 4, respectively. It is clearly observed that the (average) number or retransmissions under TiMAC is significantly less than that under VeMAC and specifically, more than 50% reduced depending on the traffic load. Given that throughput is close for both VeMAC and TiMAC, the smaller number of retransmissions indicates that TiMAC can deliver (almost) the same amount of data in lesser time than VeMAC.

Fig. 5 depicts the obtained distribution of retransmissions over nodes for both highway and urban vehicular environments

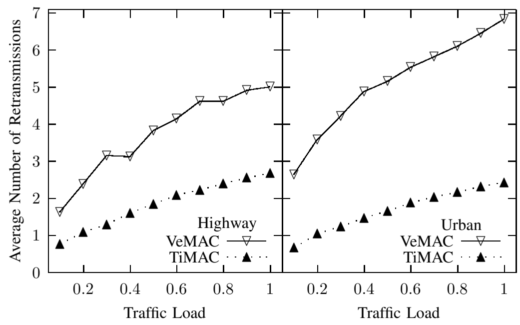

Fig. 4. Average number of retransmissions per node as a function of traffic load for both the highway and urban vehicular environments.

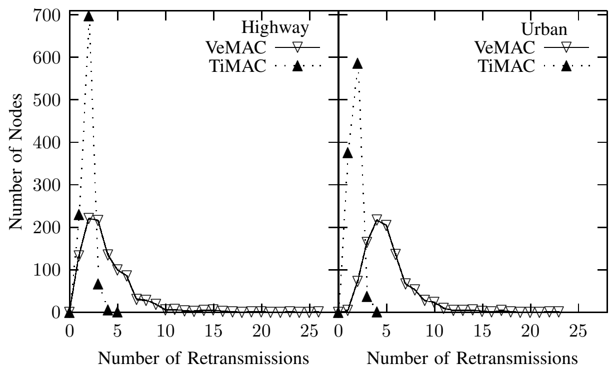

Fig. 5. Distribution of retransmissions over nodes for both the highway and urban vehicular environments and traffic load 0.5.

and traffic load 0.5. It is interesting to see that the majority of the nodes under TiMAC are concentrated around the average value, whereas under VeMAC there is a large number of nodes whose retransmissions are larger than the corresponding average value (the averaged values are depicted in Fig. 4). Consequently, a given node under TiMAC is expected (on average) to retransmit fewer times than under VeMAC for the same conditions.

VI. Conclusions

The topology-independent (TDMA-baased) MAC policy (refered to as TiMAC in this paper) [10], is considered for a vehicular environment where the underlying network topology is expected to change constantly and, thus, be practically impossible to account for. TiMAC is compared against VeMAc [9], a TDMA-based MAC suitable for vehicular environments, considering the vehicle-to-vehicle communication case and highway/urban network environment. It was demonstrated using simulation results that the throughput under TiMAC is close to that under VeMAC ($\pm 2\%$). However, the mean number of retransmissions under TiMAC is shown to be significantly reduced, thus permitting this policy to be used for safety applications as the access delay would be lower than that under VeMAC. Future work in the area will include enhancements on TiMAC in oder to adapt further to the idiosyncrasies of vehicular environments.

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