A disjoint frame topology-independent TDMA MAC policy for safety applications in vehicular networks

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ABSTRACT

Medium access control (MAC) is a challenging problem in vehicular environments due to a constantly changing topology due to vehicle’s mobility and stringent delay requirements, especially for safety-related applications (e.g., for vehicular-to-vehicular communication). Consequently, topology-independent TDMA MAC policies that guarantee a number of successful transmissions per frame independently of the underlying topology, can be regarded as a suitable choice for the particular vehicular environment. One such policy (TiMAC) is revisited and considered in this paper for a vehicular environment and is also extended to one that considers disjoint frames depending on the vehicle’s direction of movement (d-TiMAC). Both TiMAC and d-TiMAC are evaluated against VeMAC – a well-established TDMA MAC protocol in the area of vehicular networks – based on simulations. It is observed that throughput under the considered TiMAC policy is close to that induced by VeMAC, whereas the number of retransmissions is reduced leading to a smaller time delay. Furthermore, the proposed d-TiMAC appears to achieve a higher throughput than VeMAC, and an even lower number of retransmissions (when compared to TiMAC), suggesting that d-TiMAC yields an even smaller time delay. Eventually, this observation is also supported when d-TiMAC is compared against TiMAC showing a further reduced number of retransmissions.

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1. Introduction

Vehicular networks have seen a significant growth over the last decade, improving the quality – and most importantly – the safety of a journey. The timely access of the medium is a core factor when safety is considered [1,2], even at the expense of some throughput compromise [3].

Although contention-based MAC protocols are mainly proposed for vehicular networks [4,5], scalability issues arise, particularly when traffic load is increased. It has been shown [3] that the most prominent standard, IEEE 802.11p [6], suffers from time unbounded transmission delays and thus, it is not suitable for improving road safety. Currently, the research trend tends to consider TDMA-based approaches for medium access control to capitalize on the inherent time-coordinated transmissions [3]. The traditional problem of synchronization in TDMA-based approaches has been shown to be overcome by using GPS technologies that are present in vehicular networks [7–10].

Depending on the underlying communication configuration, vehicular networks can be categorized into three...
types: inter-vehicle communication or vehicle-to-vehicle, vehicle-to-roadside, and vehicle-to-infrastructure communication. Note that these types may co-exist in order to provide various services [11]. The focus of this paper is on vehicle-to-vehicle communication. Still, the results presented in this paper can be applied for the vehicle-to-infrastructure case, as well [12].

Several vehicle-to-vehicle protocols have been proposed in the past like VeSOMAC [13], ATSA [14], CFR [15], STDMA [16], VeMAC [17] etc. More can be found in Section 2. Under the well-established VeMAC [17], every node initially listens to the channel for one frame time and gathers information about neighboring nodes, subsequently reserving a time slot that neither its one-hop nor its two-hop neighbors use. VeMAC will be considered in the sequel for comparison purposes against the topology-independent MAC policies that is the focus of this paper.

Motivated by existing topology-independent MAC policies that guarantee packet delivery on a per frame basis [18,19], these established frameworks are revisited here and further enhanced. 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 [20]. 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 guaranteeing nature despite the topology unawareness, motivates its introduction in vehicular networks for safety applications.

The topology independent MAC policy presented in [18] (to be referred to hereafter as TiMAC), is revisited to show its effectiveness in vehicular environments and a novel policy (based on TiMAC) that considers disjoint subframes for each vehicles’ direction called d-frames, is also proposed and evaluated. This MAC policy is referred to hereafter as d-TiMAC. The main contribution here is to show that by revisiting the existing topology-independent approaches, this can be beneficial for medium access control in vehicular networks. Furthermore, when the existing policies are enhanced by certain features (e.g., disjoint frames for different vehicle directions), the overall performance – in terms of throughput and time delay – can be further improved.

Both policies (the existing TiMAC [18] and proposed d-TiMAC) are evaluated here against the well-established VeMAC [17] policy. As it will be shown later, VeMAC has specific features suitable for vehicular environments, like time slots assignment depending on the direction of the vehicle and knowledge of two-hop neighbors. However, both TiMAC and d-TiMAC are also suitable for the particular environment, mostly due to their inherent topology-independent nature that guarantees a minimum throughput immune to mobility. In addition, d-TiMAC employs disjoint subframes for allocating time slots to vehicles depending on the direction of their movement.

Simulation results demonstrate the effectiveness of TiMAC for vehicular network environments, and reveal a further enhancement when d-TiMAC is employed. TiMAC’s throughput is close to that of VeMAC and depending on the case, it may be slightly higher (which is a noteworthy result considering the lack of any information) as shown in a preliminary version of this work [21]. In addition, the number of retransmissions is smaller under TiMAC when compared against VeMAC. However, as it is shown here the proposed d-TiMAC achieves better results both in terms of throughput and time delay when compared to VeMAC. Finally, TiMAC is compared against d-TiMAC showing a further reduction of retransmissions, thus demonstrating the effectiveness of the proposed d-TiMAC for safety applications in vehicular networks.

Section 2 contains the discussion of previous related works, where similarities and differences with other approaches are presented. Section 3 briefly describes the most important characteristics of the considered vehicular network. VeMAC is discussed in Section 4, whereas Section 5 is devoted in TiMAC and d-TiMAC. The evaluation of their performance using simulation results is included in Section 6 and, finally, Section 7 concludes this study by summarizing its results and discussing future directions.

2. Past related work

Several works address the problem of multiple access in vehicular networks. In this section the emphasis is on approaches that are closely related to TiMAC and the proposed d-TiMAC policy.

TDMA-based approaches have recently gained a lot of attention [17,22]. In particular, a novel time division MAC protocol is proposed in [22], called VAT-MAC, where the number of vehicles within a range is predicted in order to properly allocate the time slots, avoiding collisions. Another TDMA variant of a MAC protocol that is proposed regarding VANETs applies game-theoretic techniques in order to settle the problem of slot allocation among the nodes.

ATSA [14] is an adaptive TDMA protocol focusing on vehicular networks where sets of timeslots are formed depending on vehicles’ directions. In this protocol, the frame length is dynamically adapted (shortened or doubled) in order to facilitate the optimal number of vehicles, aiming to reduce the probability of collisions. CFR in [15] tackles the problem of collisions and that of the hidden terminal by taking advantage of the driving status and traffic flow of each vehicle in the network in order to appropriately allocate time slots. Another TDMA-based protocol is the self-organizing TDMA or STDMA [16]. Although limited to the highway case, it achieves some good results for various network densities by (re)allocating timeslots depending on the traffic load of the network. VeSOMAC is one of the first medium access protocols for inter-vehicular networks [13,23]. It exploits the knowledge of vehicles’ location and direction in order to minimize the delivery delay. VeSOMAC promises low-bounded time delay using an in-band control mechanism for exchanging TDMA frame information during the distributed MAC process.

One of the most eminent and widely used algorithms for vehicular networks is that of VeMAC [17,24]. VeMAC, which is considered in this paper for evaluation of both TiMAC and d-TiMAC, is shown to outperform other known protocols, such as ADHOC MAC [25]. A more detailed description of VeMAC is presented in Section 4. A similar concept with d-TiMAC is seen in [26] where frames are...
separated into two disjoint sets, each dedicated to a different vehicular direction. This solution is implemented in the control channel (CCH) of IEEE 802.11p [6]. Under this policy, nodes exploit their location in order to pick a slot, besides the appropriate subframe, thus improving their performance in terms of time delay (they do not consider results on throughput).

Several other TDMA-based policies have appeared in literature that are not as closely related to this work, although they are focusing on vehicular networks. For example, one can see the algorithms in [27–30] (based on VeMAC), [31–33] etc. Whereas TiMAC and d-TiMAC use polynomials from a Galois field (GF), other works include the use of Latin squares combined or not with GF polynomials [34]. Another popular choice is the use of Hamming distance and coding theory (initiated by [19], see also the work in [35]) and the cooperation of nodes through information exchange with one another [36,37]. Furthermore, various papers consider the problem of slot scheduling in the prism of finding appropriate clustering techniques [38], or provide one collision-free transmission only with a certain probability [39].

Further detailed survey papers for in-depth analysis of particular MAC protocols, especially for problems related to vehicular networks and related MAC policies, can be found in [3–5,40] (dedicated to vehicle-to-vehicle communication), [41], and [11].

GPS-based systems (or in general Global Navigation Satellite Systems - GNSS) is a well-established method to achieve time synchronization [42–44]. Meanwhile, they constitute a standard feature in modern vehicles, therefore their use in VANET infrastructures seems straightforward, e.g., for Basic Safety Messages (BSM) [45]. GPS as a source of time reference is discussed in [9], where the advantages of using GNSS for synchronization in VANETs are analyzed using the one-pulse-per-second (1PPS) signal method [46]. As discussed in [8], each 1PPS signal is considered as the reference instance of the start of a frame. Consequently, knowing the number of time slots per frame, the number of frames per second, and the actual duration of a time slot, each vehicle is able to detect the start time of a frame [47,48]. Synchronization using GPS in TDMA application is also met in Automatic Identification Systems (AIS) [10] (see also in [49] for technical details regarding the actual implementation).

3. Vehicular network characteristics

A vehicular network can be seen as a special case of a mobile ad hoc network in which the nodes (vehicles) typically move along predefined routes, i.e., roads. It is important to note that, 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. As already mentioned, this work focuses on improving safety through vehicle-to-vehicle communication, therefore messages are exchanged among vehicles.

Due to vehicular networks' mobility, a MAC protocol should be able to adapt to frequent topology changes and the various patterns of these changes (e.g., vehicle move along roads and not randomly). Two 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); and (ii) urban (lower speeds and higher density than the highway scenario).

The typical speed in vehicular network is e.g., between 35 km/h and 110 km/h in an urban environment, and e.g., between 70 km/h and 150 km/h in a highway environment. Such mobility characteristics – not typical in mobile ad hoc networks – may significantly affect the overall performance of the system (e.g., [50–52]). The fact that vehicles have, to some extent, a predictable behavior in terms of 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. This remark is important and justifies the assumption made by TiMAC and d-TiMAC regarding a predefined maximum number of neighbors.

Another special characteristic of vehicular networks refers to the inherent capability of vehicles to include a GPS (Global Positioning System) [7] device that can give accurate measurements 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, 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 and d-TiMAC is significantly smaller than under VeMAC. TiMAC's throughput is comparable with that under VeMAC, whereas d-TiMAC marginally outperforms the latter. A detailed description of VeMAC, TiMAC and the proposed d-TiMAC is given in the following sections.

4. VeMAC description

VeMAC [17] 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 into frames of fixed number of time slots. As mentioned, node synchronization is achieved using GPS. GPS is also employed to determine the moving direction of each vehicle. Each frame is divided into 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 (in this case 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 of its direction \((L \text{ or } R)\) 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 so as other nodes are not able to reserve it.

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 of 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 unoccupied, again.

**Fig. 1** graphically illustrates an example of time slot assignment under VeMAC. Nodes in this example are depicted moving to different directions, thus 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 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 (arbitrary) select 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 collisions. 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 occurs (irrespective 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 be included in the list sent by its neighbor nodes during the following frame.

## 5. TiMAC and d-TiMAC description

The proposed d-TiMAC (disjoint TiMAC) is presented just after its predecessor’s TiMAC description.

### 5.1. TiMAC description

Let a network of \(N\) nodes. Under TiMAC \([18]\) 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, as stated in Section 3). 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 [18]. It is satisfied that \(k \geq 1\) and \(q > kD\) or \(q > kD + 1\) \((k\text{ and } D\text{ are integers})\), to allow at least one transmission in one frame to be successful, and \(q^{k+1} > N\) to satisfy that there exist enough unique polynomials for all nodes in the network [18].

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 \(f_u(s) \mod q\), [18]. Consequently, one time slot is assigned for each node in each subframe. Let \(\Omega_u\) 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, it holds that \(|\Omega_u| = q\).

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 are 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 \( q > kD + 1 \) (\( k \) 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 [18]. The assignment of the unique polynomials, or equivalently the assignment of the time slot sets \( \Omega_{\chi} \) to any node \( \chi \), is random in the sense that neither node \( \chi \) nor its neighbor nodes are taken into account in order to assign any polynomial.

5.2. The proposed d-TiMAC description

The proposed d-TiMAC (disjoint TiMAC) policy considers two disjoint frame sets, called d-frames, for the assignment of time slots based on the particular vehicle’s direction. Each frame consists of two d-frames (e.g., first d-frame for north and west and second d-frame for south and east directions of vehicle movement). Similarly to other TDMA MAC protocols, time is divided into frames of fixed number of time slots. GPS is used for synchronization among nodes as well as for determining the moving direction of each vehicle.

As before, 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\( (q) \)). The assumptions on the maximum number of neighbor nodes denoted as \( D \) still holds. The properties of the assigned polynomials are the same as in the case of TiMAC.

Each d-frame is fixed and consists of \( q^2 \) time slots divided into \( q \) subframes \( s \) of size \( q \). When a node changes its direction (information obtained using GPS), it then changes the d-frame that is allowed to transmit. Note that as before, each node \( u \) transmits in a slot \( i \) within its d-frame only if \( i \in \Omega_u \), provided that it has data to transmit. Each node is assigned a unique polynomial and any direction change affects only the d-frame for the transmission and not any change of the assigned polynomial. Consequently, under d-TiMAC, vehicles transmit in disjoint time slots when moving to opposite directions on a road. All subframes are positioned alternately inside the frame, based on which d-frame they belong to.

6. Performance evaluation

A program in the OMNeT++ simulation platform [53] has been developed for the evaluation of TiMAC and d-TiMAC in a vehicular environment, compared against VeMAC. In order to have a fair comparison, and given that the frame length value for TiMAC and d-TiMAC is derived following the algorithm presented in [18], the same frame length is considered for VeMAC for each comparison case separately.

The network size is set to \( N = 1000 \) 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 \( D = 19 \) for all simulation scenarios. Given these values, the algorithm in [18] outputs the values \( k = 1 \) and \( q = 37 \). Therefore, under TiMAC the frame size is set to \( q^2 \) in every scenario and under d-TiMAC the size of each d-frame is set to \( q^2 \) (thus, frame size of \( 2q^2 \)). All considered scenarios correspond to averaged values for ten independent runs. The corresponding 95% confidence intervals are not depicted since their range is calculated to be less than 1% for the case of throughput and less than 8% for the case of the average number of retransmissions.

6.1. 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. The 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. For simulation purposes, when a node reaches the end of the road, it reappears at the corresponding edge at the other side of the 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 randomly set. Speed is also randomly chosen among the aforementioned ones. Finally, each node is able to determine its moving direction and to consequently allocate itself with the proper subframe where it is allowed to transmit (in case the underlying protocol utilizes this information, like in the case of VeMAC and d-TiMAC).

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, regardless of the chosen protocol. This probability (i.e., traffic load) is the same for all vehicles. If a transmission fails, the collided packets are retransmitted at the next available slot. If the transmission succeeds (or there is no transmission at all), a new package is created according to the previously mentioned probability at the next available slot. The number of successful transmissions per node per time slot is referred to hereafter as throughput. Note that the channel is assumed to be ideal, thus no retransmissions are expected due to channel errors.

The maximum number of retransmissions is used to compare the evaluated MAC policies as an indicative factor of time delay, since small numbers of retransmissions indicates small time delays. Therefore, the number of re-
transmissions will be used in the sequel as the delay metric. Each retransmission corresponds on average to a delay of 100ms (depending on the exact slot position in the frame which varies between frames on TiMAC and d-TiMAC) which is an acceptable time delay value even if there is a need for retransmissions.

6.2. Simulation results for TiMAC vs. VeMAC

Fig. 2 depicts throughput as a function of traffic load for both the highway and the urban vehicular environment. For the highway case (Fig. 2.a), as the traffic load increases, throughput under both VeMAC and TiMAC increases. This is expected since both protocols are TDMA-based and not contention-based ones. It is observed that for traffic load less than 0.6, the obtained throughput under TiMAC is about 3% larger than that under VeMAC, whereas as traffic load further increases the observed picture changes in favor of VeMAC (5% for the case of heavy load). This change is attributed (i) to the disjoint set of time slots assigned to different directions under VeMAC (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). Nevertheless, it is observed, that the obtained throughput under both policies remains close.

Throughput remains close for the case of the urban environment too (Fig. 2.b), where it is interesting to see that in this case TiMAC outperforms VeMAC under all traffic load conditions by about 5% most of the time (falling down to a minimum of 0.4% increase for the case of full load). This is attributed to the fact that in an urban environment, traffic is not that predictable as it is the case for highways and therefore, the assigned time slots under VeMAC that correspond to a certain direction should be reallocated to avoid 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. 3, respectively. It is clear that the (average) number of retransmissions under TiMAC is less than that under VeMAC (depending on the traffic load it is observed to be decreased more than 50%). 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 with smaller delay than VeMAC.

Fig. 4 depicts the obtained distribution of retransmissions over nodes for both highway and urban vehicular environments and traffic load probability 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 more than the corresponding average value (the averaged values are depicted in Fig. 3). Therefore, a random...
node under VeMAC is expected (on average) to retransmit more frequently than under TiMAC, under the same conditions.

6.3. Simulation results for d-TiMAC vs. VeMAC

The proposed d-TiMAC policy is evaluated against VeMAC in the sequel. In particular, Fig. 5 shows simulation results regarding throughput for both MAC policies. For the highway scenario, as depicted in Fig. 5.a, it is evident that d-TiMAC is always (even though marginally) better than VeMAC about 4%. This is an improvement with respect to the performance of TiMAC as depicted in Fig. 2.a.

For the case of the urban environment (Fig. 5.b), d-TiMAC’s performance in terms of throughput is even more improved compared to VeMAC (around 5.8% and dropping to 4.1% for heavy load; the corresponding values regarding the TiMAC versus VeMAC comparison are 5% and 0.4%, as observed from Fig. 2.b). Note again that in an urban environment, traffic is constantly changing and therefore, the assigned time slots under VeMAC that correspond to a certain direction need be reassigned to avoid collisions.

The average number of retransmissions per node for the highway and the urban vehicular environments are depicted in Fig. 6. It is clearly observed that under d-TiMAC this number is in most cases more than 50% smaller than that under VeMAC. Furthermore, if d-TiMAC is to be compared with TiMAC (Figs. 3 and 6), it is observed that the average number of retransmissions further decreases in d-TiMAC. This comparison can take place since the number of slots attributed to each node within a frame are the same for both TiMAC and d-TiMAC, despite the fact that the frame size is different.

Finally, the obtained distribution of retransmissions over nodes for both highway and urban vehicular environments and medium traffic load probability values (i.e., 0.5), is illustrated in Fig. 7. Once again, it is obvious that d-TiMAC inherits the positive properties of TiMAC since the majority of the nodes under d-TiMAC are concentrated around the average value, whereas under VeMAC there is a large number of nodes whose retransmissions are much more than the corresponding average value. Similarly to the case of the average number of retransmissions, a small improvement in favor of d-TiMAC is noticeable, when compared to TiMAC (Figs. 4 and 7).

6.4. Simulation results for TiMAC vs. d-TiMAC

As it is already shown, in terms of throughput all three considered protocols are close (see Figs. 2 and 5), even though a small improvement under d-TiMAC and TiMAC against VeMAC can be traced. This throughput improve-
ment is almost negligible especially when compared to the improvement with respect to the average number of retransmissions as depicted in Figs. 3 and 6. Note that the focus in this paper – and the motivation behind the introduction of d-TiMAC – is to reduce time delays and consequently, as it has already been mentioned, to reduce the average number of retransmissions.

Fig. 8 depicts simulation results for both TiMAC and d-TiMAC. As it is observed the average number of retransmissions under d-TiMAC is smaller than that under TiMAC. An interesting observation is that the depicted difference increases as the traffic load increases. Note that one of the differences of TiMAC and d-TiMAC is that the frame size for the latter is twice the frame size of the former. However, for heavy traffic load (i.e., probability of packet generation approaches one) where collisions are expected to occur, it is observed that d-TiMAC is less affected than TiMAC. This observation supports the claim that d-TiMAC successfully utilizes the disjoint set concept behind the considered d-frames and eventually reduces time delays that is an important factor for supporting safety applications in vehicular environments.

7. Conclusions

Vehicular networks possess certain idiosyncrasies, like the constantly changing topology due to vehicle mobility, that challenge the research community. Especially when it comes to safety applications, the need for fast and guaranteed packet delivery is critical and increasingly, TDMA-based techniques are considered in such environments. In this direction, this work presents particular policies that try to tackle the aforementioned challenges.

This paper’s contribution is twofold. At first, TiMAC, a policy described in [18], is revisited and applied to vehicular networks (as also done in the preliminary work in [21]), to assess its potential. Then, d-TiMAC, a novel extension of TiMAC that assumes disjoint subframes for each vehicles’ direction called d-frames, is introduced here. Both TiMAC and d-TiMAC are compared against VeMAC [17], a well-established TDMA-based MAC suitable for vehicular networks. Different scenarios are considered for evaluation purposes, such as highway and urban network environments.

Simulation results demonstrate the effectiveness of TiMAC and reveal a further improvement when d-TiMAC is employed. TiMAC’s throughput remains close to that of VeMAC and depending on the case, it is higher. Moreover, the number of retransmissions turns out to be smaller under TiMAC when compared against VeMAC. When comparing d-TiMAC and VeMAC, simulation results demonstrate that d-TiMAC can achieve better results both in terms of throughput and time delay. Last but not least, TiMAC is compared against d-TiMAC showing a further reduction of retransmissions, thus further demonstrating the effectiveness of the proposed d-TiMAC for safety applications in vehicular networks.

Based on this study, it may be proposed that TiMAC and its novel extension d-TiMAC can be considered as suitable candidates for applications related to safety in vehicular networks, where the combination of both guaranteed time delay and good throughput are critical factors. Future work in this area include further enhancements on d-TiMAC in order to adapt further to the idiosyncrasies of vehicular environments, considering for example smart clustering processes or selective initial allocation of the assigned polynomials to reduce collisions. Furthermore, simulation scenarios including specific vehicle movement patterns will also be considered.

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References

and VANETs, J. pp.


S. Han, D. Miyamoto, Y. Wakahara, Rtb: a TDMA-based MAC protocol to achieve high reliability of one-hop broadcast in VANET, in: Proceedings of the 2015 IEEE International Conference on Pervasive Computing and Communication Workshops (PerCom Workshops), IEEE, 2015, pp. 67–72.

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