A Proposal for an Improved Distributed MAC Protocol for Vehicular Networks

Aqsa Aslam[1(✉)], Luis Almeida[1], and Joaquim Ferreira[2]

[1] Instituto de Telecomunicações/FEUP, Universidade Do Porto, Porto, Portugal
engr.aqsa.tl@gmail.com, lda@fe.up.pt
[2] Instituto de Telecomunicações/ESTGA, Universidade de Aveiro, Aveiro, Portugal
jjcf@ua.pt

Abstract. Vehicular Ad-hoc Networks (VANETs) have a significant potential to enable new applications in the vehicular domain, some of which addressing traffic safety. In these networks, the Medium Access Control (MAC) plays an important role in providing an efficient communication channel. Currently, there are two protocols for ITS, proposed in the USA (IEEE WAVE) and in Europe (ETSI ITS-G5). Both cases use the PHY and MAC of IEEE 802.11p, the latter being fully distributed and based on CSMA/CA, thus still prone to collisions. This has led to recent proposals for TDMA-based overlay protocols to prevent collisions but leading to complex synchronization and scalability limitations. In this paper we propose enhancing IEEE 802.11p with an overlay protocol based on Reconfigurable and Adaptive TDMA. We specifically target multiple concurrent applications such as multiple platoons. Our proposal separates between the application level, with its own TDMA round and slots allocated to engaged nodes, e.g., a platoon, and the global level that manages multiple TDMA rounds in a mutually agnostic manner, thus, dynamic and scalable. We believe this is the first applications-oriented MAC protocol proposed for VANETS and we discuss its deployment and potential advantages in two typical uses cases, namely platooning and smart intersections.

Keywords: VANET · IEEE 802.11p · TDMA · Admission control

1 Introduction

The impact of increasing road accidents and traffic congestion has motivated the appearance of Intelligent Transportation Systems (ITS) and associated applications that aim at improving road efficiency and safety [1]. Vehicular Ad-hoc Networks (VANETs) are important components of an ITS in which all vehicles are equipped with wireless devices that support collaborative applications, be it for safety purposes (such as accident alerts) or non-safety (such as Internet access), through direct Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I) communication.

J. Ferreira and M. Alam (Eds.): Future 5V 2016, LNICST 185, pp. 24–33, 2017.
DOI: 10.1007/978-3-319-51207-5_3

These collaborative applications generally benefit from a more reliable communication channel with less access collisions, lower latency and higher throughput, properties that call upon an adequate Medium Access Control (MAC) protocol. Currently, there are two similar but non-interoperable ITS communication standards, operating in the 5.9 GHz band, namely the IEEE Standard for Wireless Access in Vehicular Environments (WAVE) and the ETSI Standard for Intelligent Transport Systems (ITS-G5). At the physical and MAC layer, both use the IEEE 802.11p protocol to arbitrate access within each of the channels provided by the standards, both control and service channels. This protocol relies on the well known CSMA/CA distributed access arbitration method, with different enhancements on both cases. Nevertheless, IEEE 802.11p still suffers from chained collisions and poor performance under dense traffic situations [2,3].

Recently, several MAC protocols that are based on the Time Division Multiple Access (TDMA) technique were proposed to allow vehicles to use the same frequency channel without, or with less, transmission collisions. This technique divides time in consecutive non-overlapping slots and allocates each slot to one vehicle for exclusive channel access. In the specific case of VANETs, vehicle mobility must be considered since it causes the network topology to change, particularly regarding number of engaged nodes. Thus, the TDMA mechanism must also provide dynamic slot assignment [4].

As we will show in the following section, the issue of avoiding collisions at the MAC layer in an efficient way is still open. Thus, in this paper, we propose a new MAC overlay protocol for use over IEEE 802.11p. In particular, we aim at improving the channel quality provided to each well defined set of interacting vehicles, i.e., those engaged in a specific collaborative application, using TDMA to reduce access collisions. Moreover, we propose a mechanism that allows multiple TDMA rounds to co-exist in time and space, corresponding to concurrent groups of interacting vehicles, i.e., concurrent collaborative applications. Thus, we aim at providing per application slots coordination (slots in one TDMA round), together with coordination of multiple applications (multiple TDMA rounds).

For this purpose, motivated by the work done in [5] we will make use of the dynamic mechanisms of the Reconfigurable and Adaptive TDMA (RA-TDMA) protocol, which was developed to provide communications for dynamic teams of cooperating mobile autonomous robots. With RA-TDMA we can offer a dynamic fully distributed TDMA framework on top of IEEE 802.11p to combine the benefits of both TDMA and CSMA/CA paradigms, namely collision reductions with efficient bandwidth usage. Moreover, the reconfiguration feature of RA-TDMA can handle the slots coordination per application while the adaptation feature can handle the co-existence of multiple applications by adjusting the phases of the respective TDMA rounds.

To the best of our knowledge, this paper puts forward the first proposal towards an application-oriented TDMA overlay MAC protocol and is organized as follows. The next section discusses related work. Section 3 introduces the basics of RA-TDMA. Our proposal is presented and discussed in Sect. 4 while

Sect. 5 presents two illustrative use cases. A concluding Sect. 6 wraps up the paper and discusses the next steps in our work.

2 Related Work

Several methods are available in the literature for the MAC protocol in VANETs, particularly in the context of road safety. Generally, MAC protocols are classified in two broad categories such as contention-based and schedule-based. In contention-based MAC protocols, each node tries accessing the channel when it has data to transmit using the CSMA mechanism. IEEE 802.11p, used by both ITS standards, is a contention-based MAC protocol. In WAVE, it is further enhanced with the priority based access scheme of Enhanced Distributed Channel Access (EDCA). Conversely, in ITS-G5 it is enhanced with Distributed Congestion Control (DCC) which acts on certain MAC parameters (e.g., transmission frequencies, data rate and power levels). However, both enhancements do not preclude access collisions and the quality of the channel can be significantly degraded in the presence of intense localized traffic, particularly of the same priority class [3,6,7].

Thus, several recent works have proposed using TDMA-based MAC techniques that either fully eliminate or at least significantly reduce access collisions [1,8]. At the VANET level, the benefits of these techniques include a fair (equal) access to the channel for all vehicles, improved reliability of vehicles communications, more efficient channel utilization due to less collisions, deterministic network access time under dense traffic and QoS suitable for real-time applications. Among these techniques, some use centralized traffic scheduling in the Road-Side Units (RSU), such as V-FTT [9] to achieve superior traffic management capabilities and meeting strict real-time guarantees. Conversely, in this work we follow a fully distributed approach that does not necessarily require RSUs, even if providing weaker real-time guarantees, thus leading to lower infrastructure requirements and easier deployment. Several protocols were proposed in this direction that are particularly related to our work and which we discuss next.

VeMAC [10] is a contention-free protocol that supports efficient broadcast in the control channel. This protocol reduces collisions by assigning disjoint sets of time slots to vehicles moving in opposite directions (Left and Right) and to the road side unit (RSU).

DMMAC [11], standing for Dedicated Multi-channel MAC protocol, has an adaptive broadcasting mechanism designed to provide collision-free and delay-bounded transmissions for safety applications under different traffic conditions. It divides the control channel into an adaptive broadcast frame that further consists of time slots and each time slot is reserved by one vehicle for collision free transmission of safety messages.

DTMAC [12], standing for fully Distributed TDMA-based MAC protocol, extends VeMAC with a traffic scheduling approach that considers the road dissected into small fixed areas in which the time slots can be reused. Thus, it contributes to alleviate the scalability limitations of VeMAC by allowing parallel transmission in different areas.

VeSOMAC [13] aims at achieving fast TDMA slot reconfiguration without relying on roadside infrastructure for coping with vehicular topology changes. The allocation scheme is based on a bitmap in-band signaling scheme that carries information about allocated slots and allows fast slot reconfiguration following topology changes such as when platoons merge.

STDMA [14] presents a decentralized TDMA scheme aiming at real-time communication. It uses periodic frames further divided in time slots. When a vehicle joins the VANET, it first listens to the channel to get information from other vehicles positions and then performs four different phases, namely initialization, network entry, first frame, and continuous operation. This approach reserves slots for the following transmissions to provide exclusive access to the channel.

All previous approaches consider the communication channel as a global entity that is partitioned in time slots in different ways. This raises a scalability issue, limiting the number of vehicles that can engage the VANET. However, some of the approaches already include mechanism to overcome this limitation, such as DTMAC and STDMA, but both with limited efficiency given their specific slot reuse techniques. Moreover, all those approaches use complex synchronization mechanisms to virtually avoid slots overlapping and transmissions collisions. In particular, they do not generally use the underlying CSMA/CA native MAC in IEEE 802.11p to handle possible asynchronous transmissions.

Conversely, our proposal follows a significantly different approach based on RA-TDMA [5]. It synchronizes small sets of vehicles, only, i.e., those engaged in each collaborative application, making them transmit in a round with an adequate period and transmissions separated in time as much as possible. Simultaneously, our proposal tolerates asynchronous traffic using the CSMA/CA native MAC. Moreover, our approach uses a fully distributed adaptive mechanism that allows multiple synchronized rounds, associated to different collaborative applications, to coexist intermingled. Such mechanism keeps the rounds out of phase using a feedback approach based on the detection of mutual interference that they can occasionally cause to each other. As a result, there is no concept of slot reuse and the whole channel can be reused up to its capacity. When one application is within the range of another one, the phase of its round will be adjusted as needed to avoid the interference. As an application moves away from another one, its interference ceases and parallel transmission can occur without any adjustment, leading to a full channel reuse.

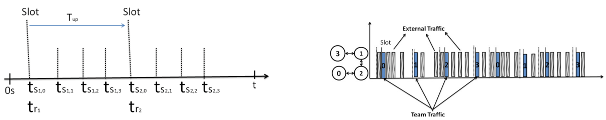
To the best of our knowledge, this is a novel approach to the joint management of a shared channel by multiple concurrent applications that set up a synchronous set each. Given the full channel reuse and absence of global management structures, we claim that our approach provides full scalability.

3 RA-TDMA Basics

We will build upon our previous experience with dynamic teams of autonomous mobile robots making use of the RA-TDMA protocol that was explicitly developed for that context [5]. Thus, in this section we review its main features.

RA-TDMA is an overlay protocol that works on top of a native distributed arbitration mechanism, typically CSMA/CA, such as in IEEE 802.11. The nodes engaged in the protocol form a team and transmit periodically in a round, with a predetermined period that meets the application requirements (t_{up}). The round is divided into a dynamic number of slots according to the current number of nodes in the team. Figure 1a depicts the structure of two consecutive RA-TDMA rounds where t_{r_1} represents the beginning of round 1 and $t_{s_{1,0}}$ represents the beginning of slot 0 of round 1. The nodes transmit as soon as possible in their slots, thus separating the transmissions of team nodes in time as much as possible. The synchronization of all team nodes in a common round is achieved trying to enforce a slot separation between consecutive transmissions, thus without using clock synchronization (Fig. 1b).

If other nodes are not engaged in the team, or when new nodes try to join the team, the underlying CSMA/CA arbitration is used to control access to the channel. This can cause delays in the regular team transmissions. However, by trying to keep a slot separation between consecutive team transmissions the protocol incorporates such delays resulting in a phase adjustment of the TDMA round. This mechanism effectively avoids periodic interference as that caused by other nodes transmitting periodically with similar periods. Figure 1b shows the synchronization mechanism where the initial slots are marked with dashed lines. A delay in node 0 is noticed by node 2 that delays its next slot setting a new time-frame, marked with full lines. Nodes 1 and 3 are still unaware of this delay and keep their initial slots. Once node 2 transmits in the adjusted slot, node 1 is made aware of this adjustment and will synchronize. Finally, node 3 will also synchronize after receiving a packet from node 1.



(a) Structure of TDMA rounds

(b) slots synchronisation mechanism

Fig. 1. RA-TDMA round with synchronization mechanism

4 Towards an Application-Oriented VANET MAC

In this paper, we propose using RA-TDMA within the vehicular context to manage state sharing in the scope of collaborative applications.

In this case, each group of vehicles engaged in one collaborative application, e.g., a platoon or smart intersection, form a team. RA-TDMA is then used to manage the periodic transmissions of each vehicle in the team for state sharing, allocating them to different slots in a TDMA round with an application dependent fixed period.

As typical in RA-TDMA, the slots will be larger than the nodes communication requirements, leading to substantial available time between transmissions of consecutive nodes in the round. These periods of availability are used to tolerate external traffic, i.e., traffic not engaged in the application, using the underlying CSMA/CA native MAC.

We propose using these *availability periods* to support the coexistence of multiple applications, each with its own TDMA round and considering all other as external traffic. The phase adaptation embedded in RA-TDMA allows setting the multiple rounds out of phase without being explicitly aware of each other. Each application (round) simply feels the delays in its own traffic caused by the interference of the other rounds.

We conjecture that such coordination of transmissions enhances channel Quality-of-Service (QoS) in an inherently scalable manner.

4.1 Application-Based Admission Control

One aspect that needs to be addressed when applying RA-TDMA in the scope of VANETs is Admission Control. In the original RA-TDMA, any robots within communication reach of the team would automatically be incorporated. However, with vehicular coordination applications, it is not enough to consider the vehicles that are within communication range but also other application dependent aspects, such as vehicles position and application capacity. For example, a platooning application may be limited to control a maximum of 5 vehicles, or a smart intersection may be set to coordinate a maximum of 20 vehicles. In such cases, there may be more vehicles within the communication range, thus, those that must be integrated in the team are those that are in more adequate physical positions, such as consecutive aligned positions in platoons or those that are closer to the intersection core in smart intersections.

Therefore, our proposal also includes adding an admission control module for RA-TDMA that verifies (i) whether the application vehicles capacity is exhausted and (ii) whether the position of the joining vehicle is compatible with the application. Moreover, it is likely that vehicles will engage one application at a time, e.g., only one platoon, or one intersection.

Figure 2 shows a simplified diagram with the Admission Control (AC) deciding whether a given vehicle can be incorporated in the respective application RA-TDMA round or whether it will be rejected and its transmissions considered as external traffic and applied directly to the underlying protocol.

Note that this admission control approach does not prevent nodes from transmitting. In fact, when a join request is rejected, the requesting application should back off and retry later on, if convenient. The vehicle can continue issuing other joining requests, potentially joining another application. It is also common that the frequency with which a vehicle shares its state is lower before engaging in an application (asynchronous scanning phase) and faster once accepted (synchronous collaboration phase).

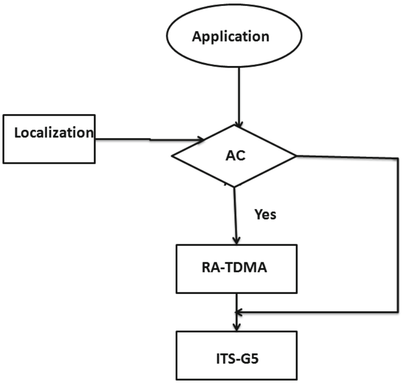


Fig. 2. Adding Admission Control (AC) on top of RA-TDMA

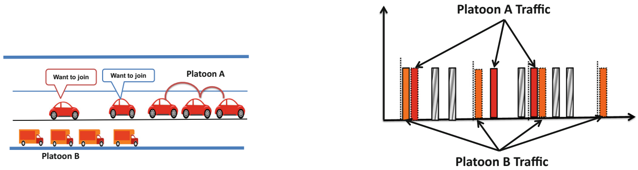
5 Illustrative Use Cases

In this section we present two use cases that show how our proposal works in practice. One is a platooning scenario and another one is a smart intersection.

5.1 Platooning Scenario

In long distance roads, particularly highways, groups of vehicles can coordinate to travel closely together in a straight line thus improving safety, fuel economy, driver comfort while reducing traffic congestion. These groups of vehicles traveling together at approximately constant speed and relatively short inter-vehicle distance are called platoons. These formations have one leader and a number of followers that is typically bounded. For control purposes, their speeds and positions are exchanged at a relatively high frequency. A vehicle can only be a member of one platoon at a time.

Consider that we have a scenario like the one shown in Fig. 3a. Platoon A consists of three cars in the middle lane that are already engaged in such collaboration. Meanwhile another vehicle approaches from the tail of the platoon, with a platoon application enabled. At a certain moment it starts hearing the platoon messages. At that moment it checks if it is compatible with that platoon and issues a join request. When this request is received by at least one platoon member, such member shares the request with the whole platoon and invokes the admission control that will take a consistent decision. If the on-going platooning application can accept a fourth vehicle and it is in a compatible position, i.e., inline with the platoon and at the tail, at less than a maximum distance, then the application will reconfigure its round to create a new slot and the new vehicle will integrate the platoon. If the maximum number of vehicles was four, a fifth vehicle requesting to join would be rejected from this platoon but it still continuous transmitting as external traffic.



(a) Two concurrent platoons

(b) Two concurrent RA-TDMA rounds

Fig. 3. Platooning use case with multiple RA-TDMA rounds

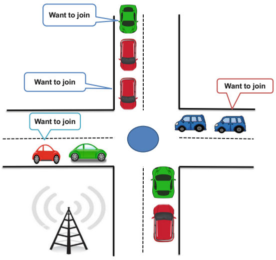
To highlight the position-based feature of our proposed admission control, consider now the situation in which two vehicles approach platoon A at approximately the same time (Fig. 3a) and request joining. If both requests are considered together, the admission control should favor the vehicle closer to the platoon and reject the farther one. If for some reason, e.g., a better antenna, the last vehicle issues a join request before, the admission control should detect the large distance to the current platoon tail and reject it, later accepting the joining request from the closer vehicle.

Finally, when two different platoons meet each other, such as platoons A and B in Fig. 3a, they check whether they are compatible, i.e., same type of vehicles on the same lane. If so, if the total number of vehicles is within the capacity of at least one of the platooning applications and the platoons are sufficiently closer to each other, both platoons are merged. However, if any of these conditions fails, the platoons continue separately and their RA-TDMA rounds are interpreted as external traffic to each other. This is the major feature of our proposal that grants it full scalability.

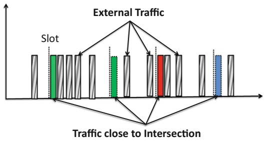
5.2 Intersection Scenario

Another useful traffic coordination scenario is that of smart intersections where the vehicles automatically coordinate to arbitrate access to the shared area, possibly using an intersection controller as shown in Fig. 4a. The intersection controller then issues announcing messages that will be detected by the vehicles within range. These will check whether they are approaching or leaving the intersection and, if approaching, issue joining requests to the intersection application. Again, the admission control feature will check the capacity of the application and the position of the joining nodes, accepting those that are sufficiently close to the center of the intersection, only. Moreover, if the capacity limit is reached and a joining request comes from a vehicle closer to the intersection than another one already engaged in the application in the same lane, the latter is disengaged and the request accepted. Similarly, when a vehicle crosses the intersection, it is disengaged, too, giving room for approaching vehicles.

Finally, when a platoon reaches a smart intersection, the latter gains priority and the platoon application disengages all its vehicles that will then compete for



(a) Smart intersection with controller



(b) Intersection traffic RA-TDMA round

Fig. 4. Smart intersection use case with an RA-TDMA round

the access to the intersection application. New platoons can then be automatically formed at the exit of an intersection.

6 Conclusion

In VANETs, the design of efficient MAC protocols is an important issue due to the impact this layer has on the performance of collaborative traffic applications. In this paper we proposed adding an overlay transmissions coordination protocol to the MAC layer of current ITS standards, essentially based on IEEE802.11p. This overlay protocol is based on RA-TDMA, previously developed for dynamic teams of robots. We use RA-TDMA, enhanced with a position-based admission control, to coordinate the traffic issued by vehicles engaged in a particular collaborative application. We use the reconfigurable part of RA-TDMA to automatically create a round with as many slots as active vehicles, keeping their transmissions as separated in time as possible, thus reducing collisions. However, RA-TDMA also tolerates external traffic, handled with the CSMA/CA arbitration of IEEE802.11p.

Particularly, multiple concurrent collaborative applications can now coexist, each with its own RA-TDMA round, seeing the others as external traffic. The adaptive feature of RA-TDMA allows dephasing the multiple rounds to minimize interference among each other. This feature simplifies the protocol management, which is fully distributed, reduces collisions without any global information and uses minimal configuration thus granting full scalability. To the best of our knowledge, this is the first proposal for such an application-level overlay MAC protocol.

In the next steps we will formalize, model and implement the proposed approach, to quantify its benefits.

References

1. Hadded, M., Muhlethaler, P., Laouiti, A., Zagrouba, R., Saidane, L.A.: TDMA-based MAC protocols for vehicular ad hoc networks: a survey, qualitative analysis, and open research issues. IEEE Commun. Surv. Tutorials **17**(4), 2461–2492 (2015)
2. E. ETSI, 302 663 (v1. 2.1) (11-2012): Intelligent Transport Systems (ITS), Access layer specification for Intelligent Transport Systems operating in the 5 GHz range (2012)
3. Eckhoff, D., Sofra, N., German, R.: A performance study of cooperative awareness in ETSI ITS G5 and IEEE WAVE. In: 2013 10th Annual Conference on Wireless On-demand Network Systems and Services (WONS), pp. 196–200, March 2013
4. Chen, Q., Jiang, D., Delgrossi, L.: IEEE 1609.4 DSRC multi-channel operations and its implications on vehicle safety communications. In: 2009 IEEE Vehicular Networking Conference (VNC), pp. 1–8. IEEE (2009)
5. Santos, F., Almeida, L., Lopes, L.S.: Self-configuration of an adaptive TDMA wireless communication protocol for teams of mobile robots. In: IEEE International Conference on Emerging Technologies and Factory Automation, ETFA 2008, pp. 1197–1204. IEEE (2008)
6. Uzcategui, R., Acosta-Marum, G.: Wave: a tutorial. IEEE Commun. Mag. **47**(5), 126–133 (2009)
7. Subramanian, S., Werner, M., Liu, S., Jose, J., Lupoaie, R., Wu, X.: Congestion control for vehicular safety: synchronous and asynchronous MAC algorithms. In: Proceedings of the Ninth ACM International Workshop on Vehicular Internetworking, Systems, and Applications, ser. VANET 2012, pp. 63–72. ACM, New York (2012)
8. Autolitano, A., Campolo, C., Molinaro, A., Scopigno, R., Vesco, A.: An insight into decentralized congestion control techniques for VANETs from ETSI TS 102 687 V1.1.1. In: 2013 IFIP Wireless Days (WD), pp. 1–6, November 2013
9. Meireles, T., Fonseca, J., Ferreira, J.: Deterministic vehicular communications supported by the roadside infrastructure: a case study. In: Alam, M., Ferreira, J., Fonseca, J. (eds.) Intelligent Transportation Systems. SSDC, vol. 52, pp. 49–80. Springer, Cham (2016)
10. Omar, H., Zhuang, W., Li, L.: VEMAC: a TDMA-based MAC protocol for reliable broadcast in VANETs. IEEE Trans Mob. Comput. **12**(9), 1724–1736 (2013)
11. Lu, N., Ji, Y., Liu, F., Wang, X.: A dedicated multi-channel MAC protocol design for VANET with adaptive broadcasting. In: IEEE Wireless Communication and Networking Conference, pp. 1–6. IEEE (2010)
12. Hadded, M., Laouiti, A., Zagrouba, R., Muhlethaler, P., Saidane, L.A.: A fully distributed TDMA based MAC protocol for vehicular ad hoc networks. In: International Conference on Performance Evalutaion and Modeling in Wired and Wireless networks, PEMWN 2015 (2015)
13. Yu, F., Biswas, S.: A self-organizing MAC protocol for DSRC based vehicular ad hoc networks. In: 27th International Conference on Distributed Computing Systems Workshops, ICDCSW 2007, pp. 88–88. IEEE (2007)
14. Alonso, A., Sjöberg, K., Uhlemann, E., Ström, E., Mecklenbräuker, C.: Challenging vehicular scenarios for self-organizing time division multiple access. European Cooperation in the Field of Scientific and Technical Research (2011)