Using RA-TDMA to Support Concurrent Collaborative Applications in VANETs

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***Abstract*—Vehicular Ad-hoc Networks (VANETs) have a significant potential to enable new applications among multiple types of vehicles. In these networks, the Medium Access Control (MAC) plays an important role in providing an efficient communication channel. Currently, existing standards use the PHY and MAC of IEEE 802.11p, which is fully distributed and based on Carrier Sense Multiple Access with collision Avoidance (CSMA/CA), thus still prone to collisions. This has led to recent proposals for TDMA-based overlay protocols to prevent collisions, including one based on Reconfigurable and Adaptive TDMA (RA-TDMA). This protocol sets a TDMA round allocating slots to the nodes engaged in a given collaborative application, only, e.g., a platoon or a multimedia group. Then, other traffic, including from other TDMA rounds of concurrent applications can co-exist in space and time using the native CSMA/CA mechanism of IEEE 802.11p and the synchronization mechanism of RA-TDMA. In this paper, we do a qualitative comparison among TDMA protocols in VANETs showing the advantages of RA-TDMA. Early experimental results validate the capacity of RA-TDMA to support multiple concurrent rounds in a scalable manner.**

I. Introduction

A Vehicle Ad-hoc Network (VANET) is an important component of an Intelligent Transportation System (ITS) that enables communication among vehicles, in which all vehicles are equipped with wireless devices that support collaborative applications. The paradigm of sharing information among vehicles and infrastructure enables a wide range of applications for safety purposes, such as driver assistance, collision avoidance, hazardous situation warning, and non-safety purposes, such as infotainment and urban sensing.

However, the wireless medium is known to suffer from issues that can affect the Quality of Service (QoS) that VANETs provide to ITS applications, particularly safety related. For instance, the topology of the network changes rapidly because vehicles in VANETs have a high degree of mobility; passing vehicles can produce interfering traffic, not only making bandwidth limited but also variable; and, the communication medium is shared, potentially suffering from transmission collisions.

Therefore, much effort has been devoted to improving the QoS of the communication channel acting on the Medium Access Control (MAC) towards reducing access collisions and network delay as well as increasing throughput.

Existing standards, namely WAVE in the US and ITS-G5 in Europe, use the IEEE 802.11p protocol at the physical and MAC layer. This protocol relies on the well-known CSMA/CA distributed access arbitration method that still suffers from chained collisions and poor performance under dense traffic situations [1][2].

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 into consecutive and cyclic 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 the number of engaged nodes. Thus, the TDMA mechanism must also provide dynamic slot assignment [3].

A particular proposal consists of using the Reconfigurable and Adaptive TDMA (RA-TDMA) protocol initially developed for teams of robots [4][5]. This protocol automatically synchronizes the nodes engaged in a collaborative application so that they transmit approximately periodically in a round, each one in a different slot, virtually eliminating collisions among such nodes. However, it is an overlay protocol installed over IEEE 802.11p and thus, the native CSMA/CA mechanism is still in place and it is used to tolerate other traffic that is not related to the referred application, i.e., external traffic. This feature can equally be used to tolerate other concurrent collaborative applications that have their own TDMA rounds and co-exist in space and time.

In this paper, we carry out a qualitative comparison of RA-TDMA against several other TDMA-based proposals for VANETs and we show preliminary experimental results that confirm the capacity of the protocol to support multiple concurrent TDMA rounds in a mutual agnostic way, potentially boosting scalability with high bandwidth efficiency. On the other hand, the problem of admitting new vehicles in an ongoing collaborative application requires an adequate admission control per application that needs to consider vehicles localization. This problem is left for future work and we will consider TDMA rounds with fixed number of slots.

The remainder of the paper is organized as follows. The next section presents related work and ends with the qualitative

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comparison among TDMA-based protocols. Then section 3 presents the basic concepts behind RA-TDMA while section 4 shows the respective timing model. Section 5 presents preliminary experimental results and section 6 concludes the paper.

II. Related work

Several recent works have proposed using TDMA-based MAC techniques for VANETs that either fully eliminates or at least significantly reduce access collisions [6][7]. The benefits of these techniques include a fair (equal) access to the channel for all vehicles, improved reliability of vehicles communications and more efficient channel utilization due to fewer collisions. Among these techniques, some use centralized traffic scheduling in the Road-Side Units (RSU), such as V-FTT [8] to achieve superior traffic management capabilities while meeting strict real-time guarantees. Conversely, distributed TDMA-based MAC protocols coordinate channel access in a distributed manner and agree on a cyclic structure of consecutive time slots that are allocated exclusively to one vehicle each. The design of these protocols for VANETs must consider:

- **mobility** - the slot scheduling mechanism should be compatible with the dynamic topology created by nodes movement and their limited range;
- **scalability** - it should handle large number of vehicles and potentially high load;
- **fairness** - equal opportunity to access the communication medium;
- **packet losses** - tolerance to occasional losses and minimization of their occurrence whenever possible, e.g., collisions when accessing the medium.

When a distributed mechanism is used to allocate a time slot, two types of collision may occur, access collision and merge collision [7].

- **Access collision:** Occurs when two or more vehicles within communication range, or up to two hops away, attempt to access the same available time slot. This problem is likely to happen when a distributed mechanism is used.
- **Merging collisions:** Occur when two vehicles initially more than two hops away try accessing the same time slot while getting within a two hops neighborhood due to mobility. Generally, in vehicular networks, merging collisions are expected to happen in the following cases: when vehicles move at different speeds, vehicles move in opposite directions and with RSUs installed along the road.

When the traffic density grows, the rate of access and merging collisions will increase rapidly leading to inefficient channel utilization and high access delay, which is particularly penalizing for safety applications. In the literature, several distributed TDMA-based MAC protocols have been proposed for VANETs that try to resolve or reduce both type of collisions. Each of the protocols is focused on certain issues in specific scenarios:

VeMAC [9], is a contention-free multi-channel protocol for VANETs that supports efficient one-hop and multi-hop broadcast services on the control channel (CCH), which gives smaller rates of access and merging collisions caused by vehicle mobility. In this protocol, merging collision rate is reduced by assigning disjoint sets of time slots to vehicles moving in opposite directions (Left and Right) and to the roadside unit (RSU), being targeted to highway scenarios. In VeMAC, each vehicle has two transceivers, the first one is always tuned to the CCH while the other can be tuned to any service channel (SCH). The synchronization among vehicles is performed using the 1PPS signal provided by the GPS in each vehicle. Each frame transmitted on the CCH is divided into four essential fields: header, the announcement of services (AnS), acceptance of services (AcS) and high priority short applications. Although communications over the SCHs are overhead-free, the overhead of the VeMAC protocol on the CCH is reasonable due to the size of the control frame transmitted on the CCH. Moreover, merging collisions can still occur with high vehicle density. Indeed, if a moving vehicle detects that it cannot access a time slot from the set of slots reserved for vehicles moving in its direction, then it will attempt to access any available time slot reserved for vehicles moving in the opposite direction.

DMMAC [10], standing for Dedicated Multi-channel MAC protocol is an alternative to the IEEE 802.11p standard. The aim of the protocol is to support an adaptive broadcasting mechanism designed to provide collision-free and delay-bounded transmissions for safety applications under different traffic conditions. The DMMAC structure is identical to IEEE 802.11p with the difference that the CCH has a cyclic window divided into an adaptive broadcast frame (ABF) and contention-based reservation period (CRP). The ABF further consists of time slots that are reserved by each vehicle as the basic channel for collision-free delivery of safety messages. The CRP uses CSMA/CA mechanism as its channel access scheme. During the CRP, vehicles negotiate and reserve bandwidth on the SCHs for non-safety applications. DMMAC implements a dynamic TDMA mechanism for basic channel (BCH) reservation based on the distributed access technique R-ALOHA. The length of the ABF frame is not uniform over the entire network. Each vehicle dynamically adjusts its ABF length according to its neighbors.

VeSOMAC [11], stands for Vehicles Self-Organizing MAC protocol and uses an in-band signaling scheme that carries information about allocated slots and allows fast slot reconfiguration following topology changes such as when platoons merge. It aims at achieving fast TDMA slot reconfiguration without relying on roadside infrastructure or leader vehicles, thus enhancing throughput for applications in highway scenarios. The VeSOMAC protocol operates in both synchronous and asynchronous manner. In the synchronous case, all the vehicles are assumed to be time-synchronized by using GPS where they

TABLE I
QUALITATIVE COMPARISON BETWEEN DISTRIBUTED TDMA BASED MAC PROTOCOLS

	VeMAC	DMMAC	VeSMOC	STDMA	DTMAC	RA-TDMA
Channel scheme	TDMA	TDMA	TDMA	TDMA	CSMA / TDMA	CSMA / TDMA
Resilience to external traffic	No	No	No	No	No	Yes
Real-Time applications	Yes	Yes	Yes	Yes	Yes	Yes
Clock Synchronization	Yes	No	Yes	Yes	Yes	No
Vehicular traffic	bidirectional	bidirectional	bidirectional	bidirectional	bidirectional	bidirectional
Mobility model	Highway	Highway	Highway	Highway	Highway	Highway
Mobility support	High	High	Low	High	High	High

share the same frame and slot boundaries. In the asynchronous mode, each vehicle maintains its own frame boundaries.

STDMA [12], presents a decentralized TDMA scheme aiming at real-time communication. It uses periodic frames further divided into 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 to provide exclusive access to the channel for the following transmissions. In the *initialization* phase, the vehicle listens for the channel activity within one frame called super frame to determine the frame structure. In *network entry* the joining vehicle introduces itself to the VANET by determining the first transmission slot. If all slots are occupied the vehicle will use the slot of the farthest away vehicle. In the *first frame* phase, slot start transmitting in the slot that it chose before and finally the vehicle falls into *continuous phase* transmitting periodically messages in that slot.

DTMAC [13], standing for fully Distributed and infrastructure free TDMA-based MAC protocol, is based on VeMAC protocol such that channel time is partitioned into frames and each frame is further partitioned into two sets Left and Right as discussed before. In DTMAC protocol the road is dissected into small fixed areas in which the time slots can be reused between them in a way any vehicles in different nearby areas access the channel at the same time and thus no interference will occur. DTMAC uses the vehicular location information to help the vehicles access the channel in an efficient way, in order to solve the collision problem caused by the high mobility of vehicles and to reduce the channel access delay. Thus, it contributes to alleviating the scalability limitations of VeMAC by allowing parallel transmission in different areas.

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 a 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, except for DTMAC, they do not use the underlying CSMA/CA native MAC in IEEE 802.11p, thus not tolerating possible asynchronous transmissions. The qualitative comparison between distributed TDMA-based MAC protocols is shown in Table I.

III. BASICS OF RA-TDMA IN VANETS

The Reconfigurable and Adaptive TDMA protocol (RA-TDMA) was previously developed for dynamic teams of autonomous mobile robots [4] and recently proposed for VANETs [5]. The resulting protocol directly addresses several limitations of the solutions surveyed in the previous section.

On one hand, the protocol 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 the transmissions separated in time as much as possible. Simultaneously, RA-TDMA tolerates asynchronous (called external) traffic using the CSMA/CA native MAC. The synchronization is based on detecting delays affecting the packets coming from the other nodes engaged in the same application caused by interfering external traffic and shifting the phase of the TDMA round correspondingly (Fig. 1). This features allows multiple independent (asynchronous) rounds, associated with different collaborative applications, to coexist intermingled but out of phase and unaware of each other (Fig. 2).

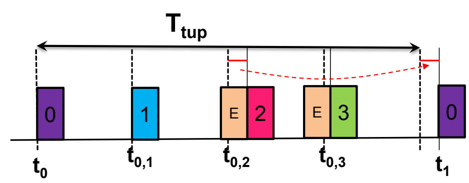


Fig. 1. Synchronization in RA-TDMA round, with external traffic

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 of the round of the other application. As the vehicles of an application move away from those of another one, their interference ceases and parallel transmissions can occur without any adjustment, leading to a full channel reuse and thus, high scalability.

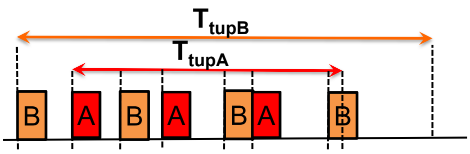


Fig. 2. Synchronization in RA-TDMA round, with 2 concurrent RA-TDMA rounds

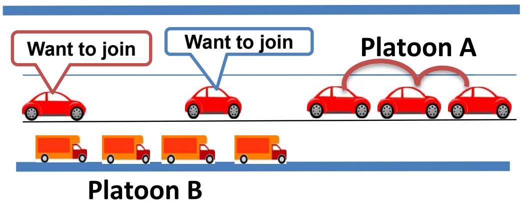


Fig. 3. Two platoons with their own RA-TDMA rounds

Moreover, the synchronization mechanism of RA-TDMA does not use clock synchronization, as opposed to common TDMA protocols (Sec. II). Note that clock synchronization in VANETs is typically achieved from GPS, which signals are not always available, particularly inside cities and at vehicles start up. This makes common TDMA protocols brittle due to their strong dependence on GPS, which does not occur in RA-TDMA.

In particular, the adaptive synchronization mechanism of RA-TDMA allows avoiding a detrimental scenario in which one or more non-synchronized vehicles transmit periodically with a period that is similar to the TDMA round period of an on-going collaborative application, or similar to a multiple or sub-multiple of it. In this case, a rigid clock synchronization based approach could lead to intervals of time (critical intervals) with recurrent simultaneous transmissions during which the probability of transmission collisions would be very high.

Finally, the reconfigurable part of RA-TDMA allows creating and destroying slots at run-time, tracking the actual number of vehicles currently engaged in a collaborative application. In fact, each application sets its specific TDMA round period according to its own requirements, and this period is divided at run-time by the current number of vehicles engaged in the respective application to create the needed slots.

One aspect that needs to be referred is admission control, which is invoked every time a vehicle gets within communication range of an on-going collaborative application and issues a joining request (Fig. 3). The admission control module verifies i) whether the application capacity in number of vehicles is not exhausted and ii) whether the position of the joining vehicle is compatible with the application. The admission control and dynamic reconfiguration of the slot structure will be addressed in detail in future work. The main properties of RA-TDMA are also shown in Table I.

IV. RA-TDMA TIMING MODEL

The TDMA round has a predefined period called team update period (T_{tup}), which is set according to the requirements of typical applications, e.g., $100ms$ is a common value in VANETs. The round is then divided equally among the N vehicles currently engaged in the collaborative application (team). Each vehicle gets one slot with duration $T_{xwin} = T_{tup}/N$ and broadcasts its state right in the beginning of its own slot. Thus, the transmissions in the team are separated as much as possible.

Each collaborative application uses a specific rule, e.g., ascending physical IDs or relative positions, to allocate nodes to slots. The first node, which gets slot 0, is called the reference node and it is the one that marks the start of each new round. It is also the only node in charge of adapting the phase of the round according to the delays suffered by the transmissions of the other team members (Fig. 1).

The transmission instants of the reference node (node 0) are determined by Equation 1. Note that δ_j is the delay between the effective and expected reception instants of node j in slot j, with $j = 1..N-1$. Moreover, the protocol limits the maximum delay that can be applied in a round to Δ, which is normally a fraction of the slot width T_{xwin}.

$$t_{0,next} = t_{0,now} + T_{tup} + min(\Delta, max(\delta_j)) \ \forall_{j=1..N-1} \quad (1)$$

The transmission instants for the remaining nodes are set after receiving the reference packet in the beginning of the round. These nodes estimate the instant at which the reference packet was transmitted, i.e. t_0, and they adjust their next transmission instants $t_{j,next}$ using appropriate offsets to the respective slots as shown in Equation 2.

$$t_{j,next} = t_0 + j \times T_{xwin} \ \forall_{j=1..N-1} \quad (2)$$

V. PRELIMINARY RESULTS

In this section, we present early experimental results that were obtained using IEEE 802.11 standard, essentially aiming at verifying the coexistence of multiple concurrent applications, each with its own TDMA round and each considering the other as external traffic. For convenience, we used IEEE 802.11b in ad-hoc mode with broadcast frames, which uses a similar MAC than IEEE 802.11p. Thus we believe these results are relevant for our purpose.

This experiment shows the phase adaptation and synchronization mechanism embedded in RA-TDMA that automatically sets multiple rounds when multiple teams co-exist in space. Each TDMA round simply senses the delays in its own traffic caused by the interference of the other rounds, as well as other external traffic, and adapts its phase, thus being out of phase without being explicitly aware of each other.

We organized an experimental setup in the laboratory with two teams, A and B. Team A comprised three laptops and team B comprised four laptops, all configured in ad-hoc mode, i.e., without using an access point. We also used one more laptop

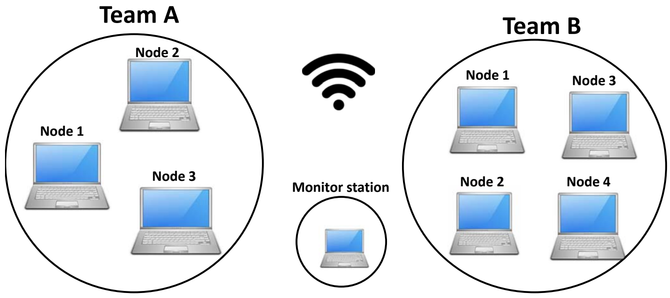


Fig. 4. Laboratory setup with two teams, A and B

for monitoring purposes that time-stamped and logged frame receptions, without performing any transmission (Figure 4). We configured the wireless card of this laptop in monitor mode so that it could capture all types of packets from all the networks operating on the selected channel.

We started by setting the round length T_{tup} with approximately coherent periods in both teams. Note that T_{tup} is an application dependent parameter typically configured offline. The round length for team A was set to T_{tup_A} = 100ms corresponding to a slot duration $T_{xwin_A} \approx$ 33ms. Similarly, the round length for team B was set to T_{tup_B} = 101ms corresponding to a slot duration $T_{xwinB} \approx$ 25ms. The small variation in round periods aims at creating a slowly sliding relative phase among both teams.

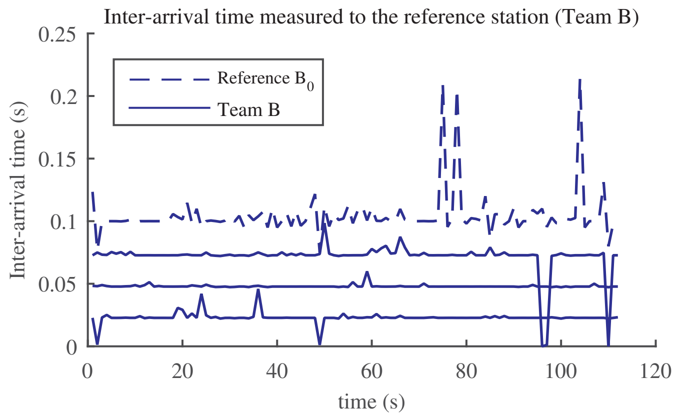
All members of both teams are active and run the RA-TDMA protocol. Note that the protocol allows each member to synchronize internally in each team, independently of each other. Finally, we ran the set up for 280 seconds with the two teams coexisting in close proximity, to observe the impact of using RA-TDMA.

The operation of RA-TDMA is better illustrated by the time offsets of the receptions of each team member transmissions with respect to its team reference node. These offsets should be constant and equal to the slot interval T_{xwin} but suffer deviations caused by interfering traffic and packet losses. Figure 5a shows the time offsets for Team B where the horizontal full lines represent the receptions from nodes 1, 2 and 3 after the reception of the respective reference (node 4) represented by the x-axis. Negative spikes in these curves indicate lost packets while positive spikes indicate delays caused by interference.

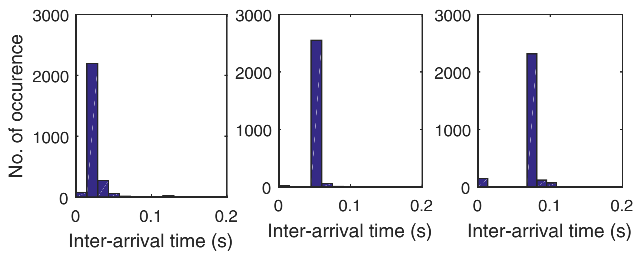
The upper dotted line represents the time offset of the reception of the next reference transmission, representing, thus, the actual round period including its continuous adaptation. The strong positive spikes around seconds 80 and 100 represent lost packets from the reference node.

The same information is represented in Figure 5b in the form of histograms, showing the precision of the slots structure in the round, with nodes 1, 2 and 3 transmitting at 25, 50 and 75ms after the reference, respectively.

Figure 6 shows the same information for Team A, which has just two nodes beyond the reference.

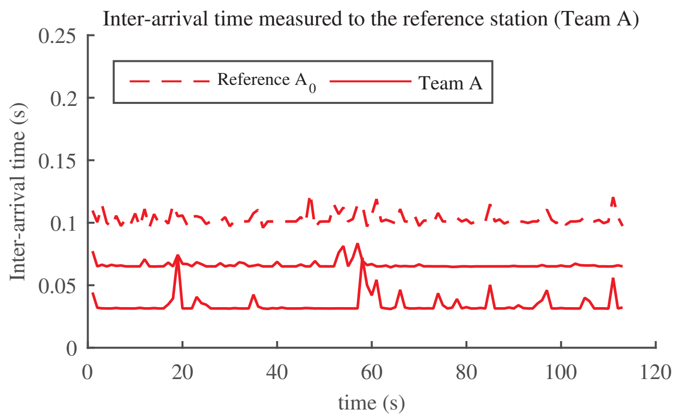


a) Transmission offsets of Team B

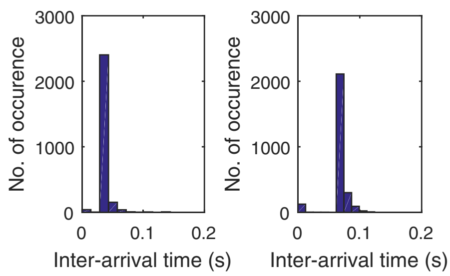


b) Histogram of the offsets in Team B

Fig. 5. Time offsets of team B receptions measured by its reference node



a) Transmission offsets of Team A



b) Histogram of the offsets in Team A

Fig. 6. Time offsets of team A receptions measured by its reference node

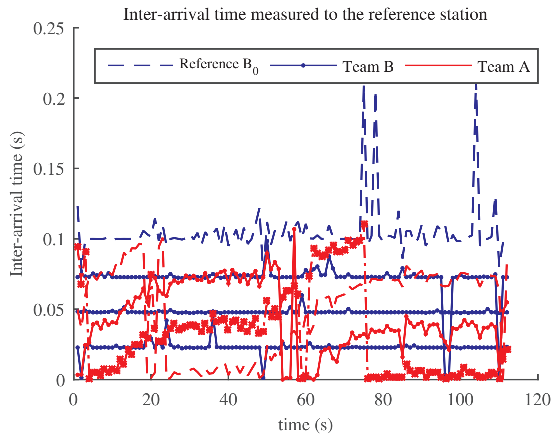


Fig. 7. Time offsets of both teams receptions (A and B) measured by the reference node of Team B

Finally, Figure 7 shows the same data but with both teams superimposed, using the reference of Team B for both. Naturally, the data of Team B matches that in Figure 5a. Conversely, Team A is now clearly unsynchronized, exhibiting the desired sliding phase with respect to Team B. This figure shows that both teams synchronize internally but co-exist in a mutually agnostic way, imposing occasional interference to each other.

VI. Conclusion

In VANETs, the design of efficient MAC protocols is an important issue due to the impact this layer has on the quality of the channel and thus on the performance of collaborative traffic applications. This is still an open issue and several ways of improving the MAC layer are possible.

One way is to remove or reduce access collisions by using a TDMA-based approach. Therefore, we surveyed this kind of protocols but we realized they were generally incompatible with the IEEE 802.11p standard and required a tight synchronization of all nodes. Conversely, we followed a different approach using RA-TDMA which sets an overlay TDMA protocol on top of IEEE 802.11p. This protocol is fully distributed and uses a relaxed synchronization simply to separate transmissions in time while tolerating asynchronous transmissions using the native CSMA/CA arbitration of the standard. We then showed that RA-TDMA can be used to separate the transmissions of nodes engaged in one collaborative application. Then, multiple RA-TDMA rounds corresponding to multiple concurrent applications can co-exist in space and time in an efficient manner, also granting a high level of scalability to the protocol. This feature was validated experimentally with two concurrent asynchronous TDMA rounds.

In future work, we will address the reconfiguration of the RA-TDMA round structure as vehicles dynamically join and leave the collaborative applications, thus creating and destroying slots online. Moreover, we are also building upon the current experience with plain IEEE 802.11 technology to assess the applicability of these techniques to a broader concept of vehicles, particularly bicycles, to allow multimedia communication among groups of users in an urban mobility concept.

VII. Acknowledgements

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