A Flexible TDMA Overlay Protocol for Vehicles Platooning

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CISTER-TR-181103

2018/05/17

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Abstract

Vehicular Ad-hoc Networks (VANETs) can enable a wide range of vehicle coordination applications such as platooning. A good use of the communication channel is paramount for an adequate quality of service. Currently, IEEE 802.11p is the standard used in VANETs and relies on CSMA/CA, which is prone to collisions that degrade the channel quality. This has led to recent proposals for TDMA-based overlay protocols that synchronize vehicles beacons to prevent or reduce collisions. In this paper, we propose RA-TDMAp that puts together properties of two previous works. On one hand, it allows the nodes in one platoon to remain synchronized even in the presence of interfering traffic, e.g. from other vehicles, by adapting the phase of the TDMA round to escape periodic interference. On the other hand, it reduces channel occupation by having just the leader transmitting with high power, to reach all the platoon at once, while the followers transmit with low power. The order of transmission is such that the leader gathers information from the whole platoon in just one round. We simulated RA-TDMAp in realistic conditions using the PLEXE simulation framework. We show the phase adaptation of the TDMA round and we compare RA-TDMAp to state of the art protocols tailored for platooning, with three networking metrics: channel busy ratio, collisions and safe time ratio, all of which confirm the superiority of RA-TDMAp.

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Abstract. Vehicular Ad-hoc Networks (VANETs) can enable a wide range of vehicle coordination applications such as platooning. A good use of the communication channel is paramount for an adequate quality of service. Currently, IEEE 802.11p is the standard used in VANETs and relies on CSMA/CA, which is prone to collisions that degrade the channel quality. This has led to recent proposals for TDMA-based overlay protocols that synchronize vehicles beacons to prevent or reduce collisions. In this paper, we propose RA-TDMAp that puts together properties of two previous works. On one hand, it allows the nodes in one platoon to remain synchronized even in the presence of interfering traffic, e.g. from other vehicles, by adapting the phase of the TDMA round to escape periodic interference. On the other hand, it reduces channel occupation by having just the leader transmitting with high power, to reach all the platoon at once, while the followers transmit with low power. The order of transmission is such that the leader gathers information from the whole platoon in just one round. We simulated RA-TDMAp in realistic conditions using the PLEXE simulation framework. We show the phase adaptation of the TDMA round and we compare RA-TDMAp to state of the art protocols tailored for platooning, with three networking metrics: channel busy ratio, collisions and safe time ratio, all of which confirm the superiority of RA-TDMAp.

Keywords: VANETs; MAC protocol; TDMA; CSMA/CA

1 Introduction

Vehicular Ad-hoc Networks (VANETs) are an important component of an Intelligent Transportation System (ITS) enabling communication among vehicles for collaborative applications, both safety-oriented, e.g., platooning, and non-safety ones, e.g., infotainment.

Safety applications are particularly demanding concerning the communication channel reliability, requiring less packet drops, e.g., caused by access collisions, and lower latency. Existing standards, namely WAVE in the US and

ITS-G5 in Europe, use the IEEE 802.11p DSRC (Dedicated Short-Range Communication) protocol [1] that relies on CSMA/CA distributed access arbitration with different enhancements. For example, ITS-G5 adds Distributed Congestion Control (DCC) which acts on certain MAC parameters (e.g., transmission frequencies, data rate and power levels) to reduce channel occupation. However, CSMA/CA does not preclude collisions and the channel quality can degradeeignificantly under intense traffic [1] [2].

In this paper, we focus on the specific case of vehicles platooning applications. We investigate the use of the RA-TDMA framework [3] on top of IEEE 802.11p to combine the benefits of both TDMA and CSMA/CA paradigms, namely collisions reduction through synchronization of beacons and efficient bandwidth usage with asynchronous access. This framework is particularly effective in this scope in which most communications are periodic and with similar period. It allows synchronizing the beacons of the vehicles engaged in each platoon independently, thus avoiding global TDMA schemes that synchronize all vehicles in range. Then, the adaptive feature of the framework detects the delays caused by interference from other vehicles outside the platoon and shifts correspondingly the TDMA round, escaping that periodic interference.

However, the original RA-TDMA protocol was developed for teams of robots operating in a WiFi infrastructured area. This is not compatible with vehicle platooning where minimizing the channel occupation requires a judicious use of transmission power. Thus, we take inspiration from the technique used in [4] in which the leader of each platoon, only, transmits its beacons at high power while the other platoon members use lower power beacons and forward information of each other in a multi-hop scheme. We combine this technique with the adaptive feature of RA-TDMA and we propose the new RA-TDMAp protocol, which is tailored for platooning applications. We use the PLEXE/ Veins/ OMNeT++ simulation framework [5] to compare both approaches under similar platooning operational conditions, as well as with the native CSMA/CA mechanism of IEEE 802.11p. We can see that our adaptative approach brings a clear improvement of the channel quality with a near one order of magnitude reduction in collisions and busy time ratio, and a visible increase in the safe time ratio.

The remainder of the paper starts by presenting state of the art TDMA based protocols for Vehicle-to-vehicle communications, highlighting the fact that avoiding collisions at the MAC layer in an efficient way is still open. Then section 3 presents the PLEXE simulation framework while our approach using RA-TDMAp is presented in section 4. Section 5 presents simulation results under different traffic conditions and section 6 concludes the paper.

2 Related work

The literature on MAC protocols for VANETs is vast. These protocols need to deal with highly dynamic topologies, aiming, at the same time, at providing equal access to the channel for all vehicles, improving the reliability of the communication channel and increasing the efficiency of channel utilization [6] [7].

ITS-G5 proposes Cooperative Awareness Messages (CAMs) broadcast at fixed intervals in the range of 0.1 s to 1 s for cooperative applications, e.g., platooning [8]. These messages contain vehicle state information such as speed, position, and heading, enabling neighbor vehicles to share their states. CAMs are also typically known as *beacons* in the vehicular networks domain, i.e., periodic messages broadcast to all one-hop neighbors [9].

One of the problems of the CSMA/CA native arbitration of IEEE 802.11p that supports ITS-G5 and WAVE is a potential excess of collisions ans channel degradation in dense traffic scenarios. To alleviate this problem several TDMA-based MAC protocols and general information dissemination protocols [9] have been proposed for VANETs that synchronize beacons to reduce collisions and channel congestion. Here we present just the main features of some representative protocols in that class that address certain issues in specific scenarios. A longer discussion and a possible taxonomy can be found in [10].

VeMAC [11] is a contention-free multi-channel protocol for VANETs aiming at structured highway scenarios and using the Control Channel (CCH) of IEEE 802.11p. It targets reducing access and merging collisions caused by vehicle mobility, assigning disjoint sets of time slots to vehicles moving in opposite directions and to the roadside unit (RSU). VeSOMAC [12] also aims at highways but does not rely on infrastructure (RSUs) or leader vehicles in platoons. It uses an in-band signalling scheme that carries information about allocated slots supporting fast slot reconfiguration following topology changes, e.g., when platoons merge. DMMAC [13] is an alternative to IEEE 802.11p that provides an adaptive broadcasting mechanism designed to provide collision-free and delay-bounded transmissions. STDMA [14] provides a decentralized dynamic slot assignment mechanism aiming at real-time communication. DTMAC [15] is based on VeMAC (and IEEE 802.11p) but it is infrastructure-free (no RSUs) and uses vehicular location information to improve channel reuse and increase scalability. Another distributed and infrastructure-free approach for platoons is proposed in [4], built on top of IEEE 802.11p, in which the beacons of vehicles are synchronized within each platoon, only, with potential collisions with external vehicles, including from different platoons, being sorted out by the native CSMA/CA arbitration of IEEE 802.11p.

Among the previous approaches we can find two groups, those that add an overlay TDMA layer on top of IEEE 802.11p, and those that propose alternatives to that MAC layer. The second ones are typically collision-free but also intolerant to collisions, being more sensitive to synchronization precision thus requiring tight synchronization. Moreover, they consider the communication channel as a global entity that is partitioned in time slots in different ways, potentially allowing slots reuse. Such a global approach raises a scalability issue depending on the range of the communications, limiting the number of vehicles that can engage the VANET or increasing the number of slots complicating synchronization and efficient bandwidth usage.

With respect to the first group (TDMA overlay over IEEE 802.11p), the approach of Segata etal [4] deserves a special reference for bearing similarities with

RA-TDMAp and being directly comparable. It is tailored for platooning, considering the requirements of the formation control and the reliability of communications under different traffic conditions. It does not require tight synchronization and tolerates collisions with external traffic using the underlying CSMA/CA of IEEE 802.11p. The beacons of all vehicles in the platoon are equally spaced along the beacon interval, creating a cycle. The leader vehicle transmits first with higher power, reaching the whole platoon in one-hop and setting the start of a cycle. All follower vehicles compute their offset with respect to the leader beacon, starting from the one closest to the leader down to the last vehicle in the platoon, and transmit at their assigned time with lower power. Each follower retransmits relevant control information received from its followers in the direction of the leader. Since it is implemented in the PLEXE simulation framework, which we describe next, we will refer to it as "PLEXE-Slotted" approach.

3 Simulation Framework

To analyse the RA-TDMAp protocol under different network and road traffic conditions we decided to use PLEXE[1] [5], which is an Open Source extension to the well known and widely used Veins[2] [16] simulation framework that builds on SUMO[3] for road traffic simulation and on the discrete event simulator OMNeT++[4]. The Veins simulation framework provides a simulation environment able to test real-world scenarios, considering high mobility, high-level application protocols, together with communication and networking protocols with the full stack of IEEE 802.11p/ IEEE 1609.4 standards. In turn, OMNeT++ sets the environment to define the applications and protocols logic, allowing to collect operational data for performance analysis.

PLEXE is the current state-of-the art system level platooning simulator, incorporating mobility tightly-coupled with automatic control and communications. It allows defining highway scenarios, effective application, and protocols as well as analyzing network metrics such as collisions and packet delivery ratio etc. Figure 1 shows a snapshot of the PLEXE graphical front-end with a platoon (red cars) together with other external traffic (blue cars).

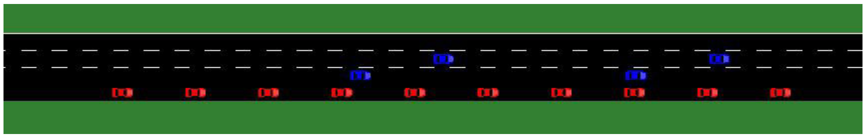

Fig. 1. Screenshot of the PLEXE

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[1] `http://plexe.car2x.org/`

[2] `http://veins.car2x.org/`

[3] `http://sumo.sourceforge.net/`

[4] `https://www.omnetpp.org/`

4 RA-TDMAp for vehicle platoons

RA-TDMAp is an instantiation of RA-TDMA [3] to vehicle platoons that use transmission power control. It is a thin layer inserted just above the IEEE 802.11p MAC protocol that controls the transmission instants, being transparent for the applications that run on top (Fig. 2).

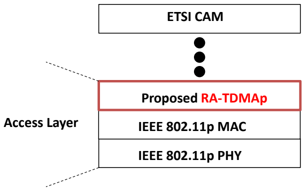

Fig. 2. Modified ITS-G5 architecture

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The power management approach is that of [4] (PLEXE-Slotted) in which the leader transmits with high power so that it reaches all platoon members and serves as a synchronization mark setting the start of a round (Fig. 3). The follower vehicles transmit with low power equally spaced in the beacon interval (round period). Low power transmissions allow reducing significantly the channel occupation increasing scalability of the protocol. However, RA-TDMAp differs from [4] in two main aspects, the leader adjusts its transmission instants according to the delays suffered by the platoon members in the previous round and the order of transmissions of the followers is inverted, starting from the last vehicle, which transmits after the leader, up to the first follower that transmits at the end of the cycle, before the next leader beacon.

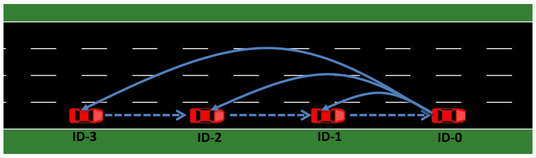

Fig. 3. Synchronization in a platoon, with up-stream multi-hop communication

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In the presence of interfering traffic from other vehicles, the native IEEE 802.11p arbitration serializes contending transmitters generating delays that can affect the beacons of platoon members. These delays can be observed by the neighboring platoon members that log them in a *Delay vector*. This vector is piggybacked in the beacons and forwarded up the line topology, reaching the leader in a single

TDMA round. The leader uses the maximum of these delays to delay its next transmission, thus delaying the following TDMA round (Fig. 4). This allows, in the following rounds, escaping the periodic interference that caused the delays, effectively reducing the chance of recurrent collisions that would otherwise occur. Figure 4 also shows the assignment of logical IDs to vehicles according to their position in the platoon, starting with the leader that is node 0, followed by the last vehicle, 3 in this case, then 2 and then 1, the closest to the leader. This position-based rule can rely on GPS, on a topology tracking method or on both.

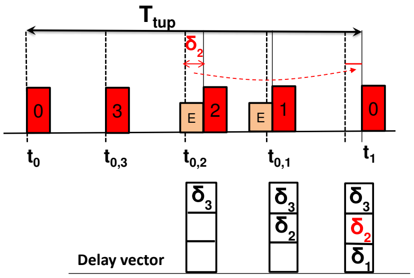

Fig. 4. Adaptive synchronization in RA-TDMAp, with interference and delays measurement and propagation.

The beacon interval in RA-TDMAp, interchangeably called TDMA round period, is represented by T_{tup}. It is divided by N vehicles currently engaged in the platoon creating a target separation between consecutive platoon beacons equal to $T_{xwin} = T_{tup}/N$. If in the n^{th} round the leader transmits at time $t_{n,0}$, the follower $i > 0$ in that round is expected to transmit at time $t_{n,i}$ (Eq. 1).

$$t_{n,i} = t_{n,0} + T_{xwin} \times (N - i) \tag{1}$$

Once vehicle 1 transmits, the leader becomes aware of all delays that may have affected the platoon beacons in that round (δ_i, i=1..N-1) and uses the maximum value, if within a tolerable limit (Δ), to delay its next beacon transmission. Using Δ allows bounding the maximum delay that can affect the leader beacon, which is normally a fraction of the beacons separation T_{xwin}.

This is formalized in Eq. 2. Note that δ_i is the delay between the effective and expected reception instants of the preceding vehicle(s).

$$t_{n+1} = t_n + T_{tup} + \min(\Delta, \max_{i=1..N-1}(\delta_i)) \tag{2}$$

In the presence of packet losses, if the leader does not receive information from the delays that affected the followers, it considers them as null and transmits one beacon interval after the previous transmission. Similarly, if a follower misses the leader beacon it transmits its own beacon one beacon interval after its previous transmission. This makes the protocol very robust to varying channel conditions.

5 Evaluation of the protocol

In this section we analyse the performance of the proposed RA-TDMAp protocol in demanding traffic conditions resorting to the PLEXE simulation framework (Section 3). We first show the simulation setup including the used models and scenarios, after we validate the adaptive feature of RA-TDMAp in platooning, and then we compare RA-TDMAp with two other state of the art protocols, namely PLEXE-Slotted and IEEE 802.11p (CSMA/CA). For the comparison we use two typical network metrics, similarly to [4], which are the *channel busy ratio* and the *collisions rate*. Finally, we include another comparison using the so-called *safe time ratio*, which represents how well the protocols meet specified application timing requirements.

5.1 Simulation setup

We used the PHY and MAC models of IEEE 802.11p proposed in [17], using a bitrate of 6 Mbit/s, which is suited for demanding safety related applications [18]. We configured the transmission power of the leader to 100mW (high power) as it needs to reach all the cars in the platoon. For the followers we used three different power values (low power), namely 0.05mW, 0.5mW and 1mW, since they only need to communicate with the car in front. Furthermore, we did not enable the switching between Control Channel (CCH) and Service Channel (SCH), using only the CCH, and all beacons use the same Access Category (*AC*). Table 1 summarizes all communication related parameters.

Table 1. PHY and MAC parameters

Parameter	Values
PHY/MAC model	IEEE 802.11p/1609.4 only (CCH)
Channel	5.89 GHz
Bitrate	6 Mbit/s
MSDU size	200B
Leader’s Tx power	100mW
Follwer’s Tx power	0.05mW, 0.5mW and 1mW

To investigate the proposed protocol performance, we carried out a set of simulations in a moderately dense traffic environment. We specifically simulated a realistic case with a stretch of a 4-lane highway filled with 160 cars organized in platoons of 10 vehicles, plus 10 external cars that create extra communication interference. Other relevant parameters are the distance between vehicles inside the platoon (gap), set to 5m, and the speed of all the platoons, set to 100 km/h. The summary of the simulation parameters is shown in Table 2.

Table 2. Scenario configurations

Parameter	Values
Number of cars	160
Platoon size	10 cars
External cars	10
Inter-vehicle gap	5m
Controller	ACC

5.2 Validating RA-TDMAp adaptation to interference delays

The distinctive feature of RA-TDMAp is its capacity to shift the TDMA round made of the beacons in the platoon to avoid other transmissions that were causing interference delays. If the interference is periodic and with similar period, shifting the round removes the interference. If further delays subsist, the protocol continues shifting the round. Thus, given its relevance, we show here a validation of this adaptive feature of the protocol before moving to the comparisons. For the sake of simplicity of representation, we use a platoon with just 4 vehicles in the same simulation scenario and we log the respective transmission instants.

Figure 5 shows the evolution of the offsets of the transmissions of the platoon members with respect to the leader transmission in each cycle. Each trace corresponds to the offset of one member (1 to 3 starting from below), except for the upper trace that represents the next leader transmission with respect to its previous one, thus it shows how much the leader has delayed the next TDMA round (or cycle). Without interference from external vehicles the offsets would be constant as given by Eq. 1. However, the figure shows there are in fact interferences, which are then accommodated by the leader in the following cycle (upper trace) according to Eq. 2. This behavior is clear in the figure with the upper trace containing the variations of the lower traces. However, it has more variations than these, since the leader transmissions also suffer direct interference. Finally, the tall spikes that sporadically affect the upper trace represent leader beacon losses, doubling the difference between consecutive leader beacons.

5.3 Comparison of protocols

We ran the simulation for 30s of simulated time and gathered traces in the scenario referred in Table 2 using the three protocols, namely RA-TDMAp, PLEXE-Slotted and CSMA/CA. The first metric we use for comparison is the *channel busy time ratio* or *busy time ratio*. This is a physical layer metric that indicates the percentage of times each node tried to access the channel and the channel was busy. This metric is described with more detail in [9].

Figure 6 shows the results for the three followers transmission power levels. We can see that while PLEXE-Slotted and CSMA/CA perform approximately similarly, RA-TDMAp shows a 4 to 5 times reduction for all the three cases. This is a direct consequence of the adaptation feature of the protocol that quickly moves the platoon transmissions away from the interferences. Concerning the

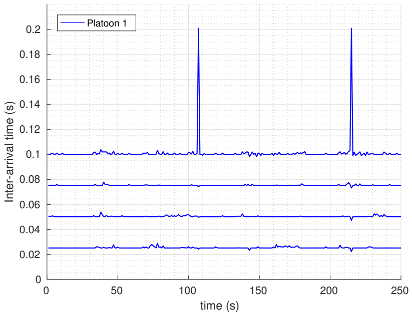

Fig. 5. Adaptation mechanism of RA-TDMAp

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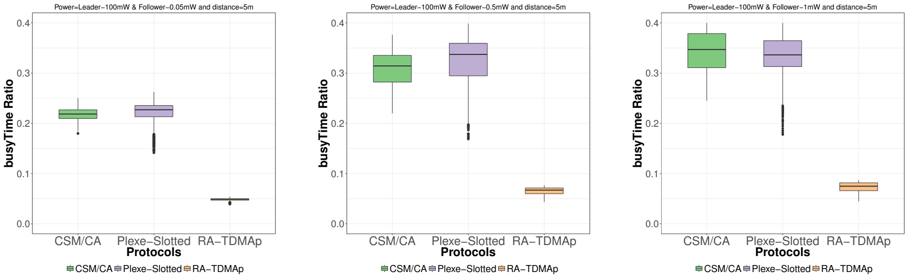
followers' transmission power, we can see that as it increases it causes the busy time ratio to increase approximately similarly for all approaches. This is expected as higher power reduces channel spatial reuse and increases interference.



(a) TX power 0.05mW

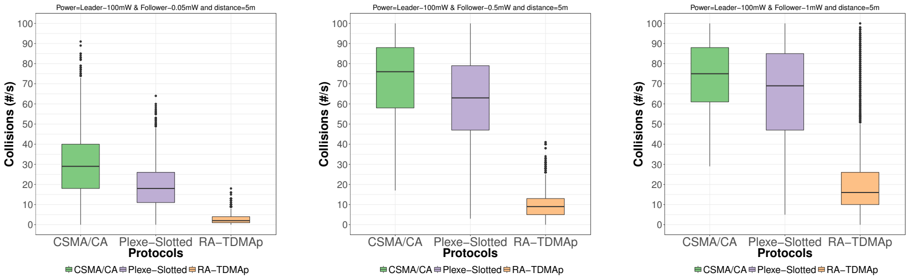
(b) TX power 0.5mW

(c) TX power 1mW

Fig. 6. Busy time ratio for given scenario under 5m and three follower's TX powers

The second metric is the collisions rate, i.e., the average number of collisions per second. The simulator determines collisions as the frames that were not correctly decoded due to interference. More details can also be found in [9].

The results are shown in Fig. 7. PLEXE-Slotted exhibits some benefit when compared to CSMA/CA because of synchronizing the beacons inside each platoon. However, the benefit is small. A much larger benefit is achieved by RA-TDMAp, from near one order of magnitude for very low power to around 7 times for intermediate and 5 times for high followers' transmission power. Again, this is due to the adaptive feature of the protocol that, upon interference, pulls the platoon away from it from one cycle to the next. Thus, periodic interferences will not persist interfering as opposed to the other cases. Similarly to the previous metric, the relative performance of the three protocols is kept as the followers' transmission power increases, since the corresponding larger range leads to increasing collisions.



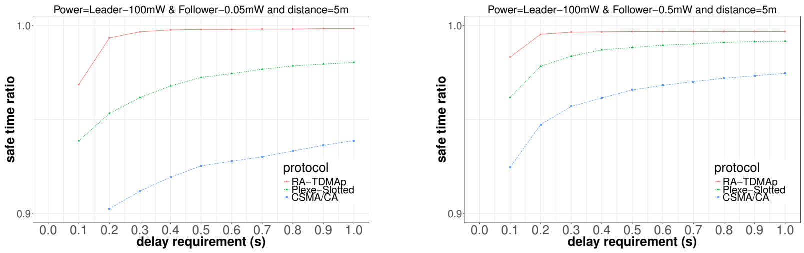
(a) TX power 0.05mW (b) TX power 0.5mW (c) TX power 1mW

Fig. 7. Collisions rate for given scenario with 5m gap and three follower's TX powers

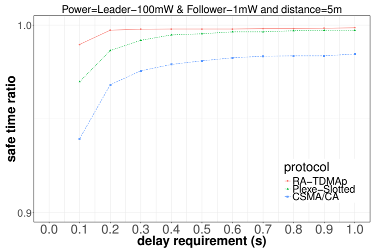
Beyond properties of the communication channel, it is also relevant to assess how well the channel meets application requirements. Thus, we use the metric proposed in [4] called *safe time ratio* that aims at distributed feedback control in the context of vehicle platooning. This metric captures how much time a platoon is in safe state during the simulation time. A safe state occurs when the communication delay affecting the platoon controller is below a given requirement for which the controller was tuned. Longer delays are considered unsafe. The results show, again, a superiority of RA-TDMAp, being the only protocol, among PLEXE-Slotted and CSMA/CA, that keeps the platoons in safe state above 99% of the time for delay requirements down to 0.2s and for all tested power levels of the platoons' followers. The advantage is specially noticeable for very low transmission power and tighter delay requirements, e.g., 99% for 0.2s with RA-TDMAp against 95% for PLEXE-Slotted and 90% for CSMA/CA.

6 Conclusion

Vehicular networks are growingly important as the level of vehicles driving automation is increasing. In particular, collaborative applications such as platooning can improve vehicle and users safety as well as fuel efficiency. However, the effectiveness of these applications relies on the quality of the channel. In this paper we proposed the RA-TDMAp protocol that is deployed on top of IEEE 802.11p, which is the state-of-the-art standard for vehicular networks and which relies on CSMA/CA arbitration. RA-TDMAp organizes the vehicle beacons in each platoon in a TDMA round, separately, and shifts this round to escape from periodic interference from other vehicles. We carried out simulations in realistic scenarios using the PLEXE-Veins-SUMO-OMNeT++ framework and we assessed RA-TDMAp against two state-of-the-art alternatives, CSMA/CA from native IEEE 802.11p and PLEXE-Slotted, which was proposed



(a) TX power 0.05mW (b) TX power 0.5mW



(c) TX power 1mW

Fig. 8. *Safe time ratio* for all approaches under three follower's transmit power levels

within PLEXE and works similarly to RA-TDMAp but without the capacity to shift the TDMA round. The results show a clear benefit of using RA-TDMAp, with nearly one order of magnitude reduction in collisions rate, a factor of 4 to 5 reduction in channel occupation and a significant improvement in safe time ratio, a communications-related control metric. Future work will extend the RA-TDMAp assessment to more scenarios and more protocols.

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