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An active signaling mechanism to reduce access collisions in a distributed TDMA based MAC protocol for vehicular networks

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Summary. A Vehicular Ad-Hoc NETwork (VANET) is an emerging technology consisting in a set of vehicles, mobile devices and an infrastructure, which uses wireless transmission technologies to enable real-time communication between them. VANETs help to improve traffic safety and efficiency by enabling each vehicle to exchange information about vehicle positions, speeds and the state of the road. Due to its promising applications, this type of network has attracted a lot of attention in the research community, including those in the domain of Medium Access Control (MAC). In fact, an efficient MAC protocol design in VANETs is crucial to guarantee safety-critical message broadcasting with high reliability and minimum delay. A Time Division Multiple Access (TDMA)-based MAC protocol is advantageous in VANETs thanks to its ability to prevent the hidden node problem, and to guarantee high quality of service for real-time applications. However, time slot assignments to vehicles could suffer from the access collision problem which can frequently occur between vehicles trying to access the same time slots. This problem is mainly due to the lack of infrastructure and potentially high density of vehicles in VANETs. In this paper, we focus on the problem of access collision in the time slot assignments of the DTMAC protocol, and present an enhanced version based on active signaling (AS-DTMAC, i.e. Active Signaling-DTMAC). Extensive simulations are conducted considering various traffic densities to demonstrate the performance of AS-DTMAC.

Keywords - VANETs, MAC, TDMA, Active signaling, Low latency, 5G, Network simulation.

1 Introduction and motivation

The automotive field is currently undergoing a massive transformation with the car becoming a connected device and efforts being made for autonomated driving vehicles. In this context, connectivity will become a key issue for the future of the automotive industry, allowing new usages and new services to be offered. To ensure this new functionality, the future services need to benefit from the best connectivity with high transmission rates for huge data exchange and low latency which will enable real time services with immediate reaction, high levels of scalability, quality of service (QoS) and greater reliability. All of these features will be included in the future 5G standard [1]. This new network is very important for the automotive sector because it enables direct communication between vehicles (V2V), this leads to a better reaction time which means that collisions between vehicles can be avoided and hence passenger safety will be increased. V2V will complete the information obtained from sensors (radar, camera, etc.) with more real time information such as location, heading speed and intention.

This promising evolution cannot come about without a new medium access control (MAC) design that can support all these requirements. The difficulty being that VANETs are very different from traditional networks due to their special features like a dynamic topology, a high mobility of the connected device [2]. Many studies have been proposed to address these issues [3][4]. The main goal of MAC is to provide an efficient way to share the channel between nodes and cover the largest possible number of users without decreasing the QoS. MAC protocols are classified into two categories: contention-based and contention-free. The former allows multiple access to the channel based on channel sensing, however the collision can be high due to the high probability that neighbors detect the channel being idle at the same time. Contention-based approaches use CSMA/CA scheme which is used in the current standard for vehicular communication (IEEE 802.11p)[5]. Recently, many scientific studies proposed contention-free protocols that try to reduce the collision probability, essentially by remoring the sensing phase and enhancing robustness, the number of collisions even in high density scenarios. Contention-free protocols enable multiple access by dividing the channel in various ways: code sequence, frequency band or time slot which correspond respectively to these three protocols: Code Division Multiple Access (CDMA), Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA)[6].

TDMA-based MAC are one of the most appreciated protocols that can enable a multiple access to the channel by dividing it efficiently. The use of this kind of access protocols in vehicular networks will allow the vehicles to access to the channel by using the same channel frequency. Consequently, each time slot will be assigned to a vehicle depending on the priority of its message. However, these protocols suffer from the access collision problem which can frequently occur between vehicles trying to access the same time slots. Motivated by this observation, we propose in this paper an enhanced technique to reduce access collisions for a fully distributed and location-based TDMA scheduling scheme for VANETs named DTMAC [7], with the aim to meet the requirements of the emerging applications. DTMAC takes into consideration the linear topology of VANETs and provides an improved broadcast coverage due to the spatial reuse of the slots, which gives a lower rate of collision compared to other protocols.

The remainder of the paper is organized as follows. In the next section, we present related work. Section 3 contains a brief recall of the DTMAC protocol and its specification. Section 4 introduces the active signaling technique and the proposed protocol. Section 5 presents our simulation studies that evaluate and campare the proposed AS-DTMAC protocol, which is an enhanced version of DTMAC with the active siganling. Finally, section 6 concludes this paper.

2 Related work

MAC protocols generally fall into one of two broad categories: contention-based and contention-free. In contention-based protocols, each node can try to access the channel when it has data to transmit using the carrier sensing mechanism [11]. The IEEE 802.11p [12], which is the emerging standard deployed to enable vehicular communication, is a contention-based MAC protocol which uses a priority-based access scheme that employs both Enhanced Distributed Channel Access (EDCA) and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanisms [13]. Since the IEEE 802.11p standard is a contention-based MAC, it cannot provide a reliable broadcast mechanism with bounded communication delay. This disadvantage is particularly important in VANETs which are specifically designed to improve road safety.

In Contention-free MAC protocols, only one vehicle can access the channel at any given time within a given neighborhood. Therefore, these protocols provide collision-free transmission with bounded access delay for real-time applications. In recent years, many distributed TDMA-based MAC protocols have been proposed to guarantee real-time and reliable communications in VANETs while avoiding the access collision and the merging collision problems [10]. Each protocol has been proposed for a particular problem in a specific mobility scenario. For instance, the authors in [14] have proposed an ADHOC Medium Access Control (ADHOC MAC) to provide an efficient broadcast service for inter-vehicle communications and solve the issues such as the hidden-exposed terminal problem and QoS provision. ADHOC MAC is a contention-free medium access protocol which implements a dynamic TDMA mechanism that is able to provide prompt access based on a distributed access technique, R-ALOHA (Reliable R-ALOHA [15]). Each vehicle can access the channel at least once in each frame by randomly selecting a time slot as its Basic CHannel (BCH). In [18] Omar et al. developed and evaluated a contention-free multi-channel MAC protocol proposed for VANETs, called VeMAC. This protocol supports efficient one-hop and multi-hop broadcast services on the control channel without the hidden terminal problem caused by node mobility. VeMAC reduces the collision rate by assigning disjoint sets of time slots to vehicles moving in opposite directions (Left;Right) and to Roadside Units (RSUs). Since ADHOC MAC and VeMAC are fully distributed protocols, an access collision problem can occur between vehicles trying to access the same time slots. A completely distributed TDMA scheduling scheme, named DTMAC which exploits the linear topology of VANETs is proposed and presented in [10]. The scheme is based on the assumption that the road is divided into small fixed areas and the time slots in each TDMA frame are partitioned into three sets associated with vehicles in three contiguous areas. The ways that slots are allocated and reused between vehicles in DTMAC are designed to avoid collisions caused by the hidden node problem.

Although the distributed-TDMA-based MAC protocols show improvements compared to the IEEE 802.11p standard and can support QoS requirements of safety applications, as the size of the VANET grows, the access collision problem frequently occurs between vehicles trying to access the same time slots. Motivated by this observation, we mainly focus in this paper on the problem of access collision in the DTMAC protocol, and we propose an enhanced version based on active signaling (AS-DTMAC) to effectively alleviate the access collision problem in the slot assignment process.

3 System model and DTMAC protocol

In this section, we present the system model and we briefly describe the DTMAC protocol [16]. DTMAC is the scheme on which, we present an enhancement in Section 4 operates.

A VANET in a highway scenario consists of sets of vehicles moving in directio same or different ns and under varying traffic conditions (speed, density). In this paper, we suppose that each vehicle in a VANET is equipped with a GPS (Global Positioning System) or a GALLILEO receiver so that it can obtain an accurate real-time three-dimensional geographic position (latitude, longitude and altitude), speed and exact time. Moreover, synchronization between vehicles may be performed by using GPS timing information. As shown in Figure 1, the road is divided into N small fixed areas, denoted by $x_i, i = 1, \dots, N$ of length equal to

R, where R is the communication range of the vehicles. Area IDs can be easily derived using maps and GPS devices. In the following, we will briefly describe the TDMA scheduling principle of the DTMAC protocol.

DTMAC is a distributed TDMA-based MAC protocol for VANETs which exploits the linear topology of VANETs. The time slots in each TDMA frame are partitioned into three sets, S_0, S_1 and S_2, associated with vehicles in three contiguous areas: x_i, x_{i+1} and x_{i+2}, respectively, see Figure 1. Each frame consists of a constant number of time slots, denoted by τ and each time slot is of a fixed time duration, denoted by s. Each vehicle can detect the start time of each frame as well as the start time of a time slot. In the VANET studied here, all the vehicles are equipped with a GPS and thus the one-Pulse Per-Second (1PPS) signal that a GPS receiver gets from GPS satellites can be used for slot synchronization. In DTMAC, each vehicle moving in area x_i knows only the slot scheduling information of its neighboring vehicles moving in areas x_{i+1} and x_{i+2}.

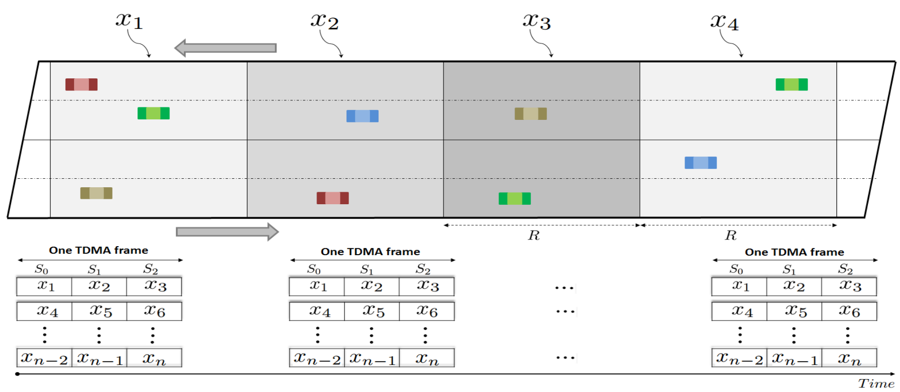

Fig. 1. TDMA slots scheduling principle.

The TDMA scheduling mechanism of the DTMAC protocol uses the vehicle location and slot reuse concept to ensure that vehicles in adjacent areas have collision-free schedules in which the three subsets of time slots will be reused between neighboring areas in such a way that no vehicles in different adjacent areas can access the channel at the same time, and thus no interference can occur. To acquire this information, messages are exchanged between neighboring vehicles. Furthermore, specific information, called frame information (FI) is added to each transmitted packet to notify the neighboring vehicles of a time slot assignment. Each time slot is dynamically reserved by an active vehicle (a vehicle whose communication device is transmitting) for collision-free delivery of safety messages or other control messages. The FI consists of a set of ID Fields (IDFs) of size equal to the number of time slots per frame, τ. Each IDF consists of three fields: VEC_ID, SLOT_STATUS and PKT_TYPE. The VEC_ID field contains the ID of the vehicle that is accessing the corresponding slot. The SLOT_STATUS field contains the status of the slot which indicates whether the slot is *idle*, *busy* or in *collision*. Finally, the PKT_TYPE field indicates the type of packet transmitted by the vehicle, i.e. periodic information or event-driven safety messages. When an active vehicle v moving within the area x_i needs to acquire a time slot on the transmission channel, it starts

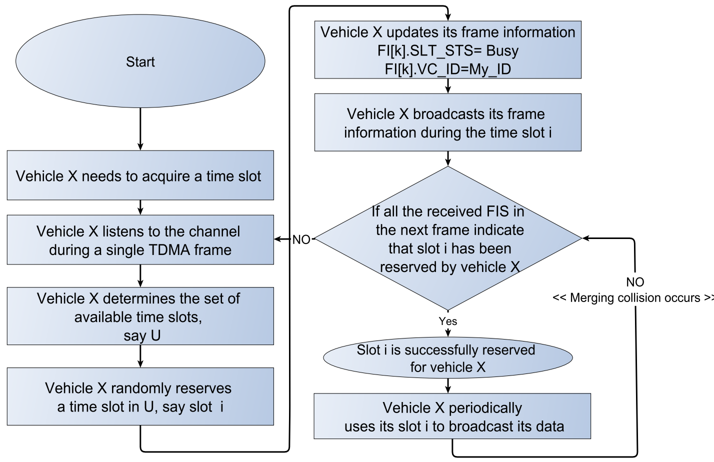

Fig. 2. DTMAC protocol principle

listening to the channel during the set of time slots reserved for the area in which it is traveling, this set is $S_j(v)$, where $j = (i+2)$ *mod* 3. At the end of the frame the vehicle v can determine the set of its neighbors $N(v)$, the set of busy slots in $S_j(v)$, denoted by $B(v)$ and the set of available time slots denoted $F(v)$. Vehicle v selects one slot in $F(v)$ at random. Figure 2 shows a flowchart summarizing the slot reservation mechanism of the DTMAC protocol which is executed by each vehicle x that needs to acquire a time slot.

4 Active Signaling based DTMAC protocol (AS-DTMAC)

4.1 General scheme

Although the concept of active signaling is not very well-known in the research community, it has been shown to improve the IEEE 802.11 access scheme. However, to our best knowledge, we are the first to combine this technique with a fully distributed and location-based TDMA scheduling protocol. Active signaling is used to improve the slot selection process, mostly by avoiding access collisions, but it can also increase the probability of successful transmission when these slots have been acquired. The main idea is to introduce a scheme which, with a high probability, ensures that a slot will be successfully acquired by a single vehicle to send its packet.

To integrate the active signaling scheme with DTMAC, the slot is divided into two time intervals as shown in Figure 3. The first interval is reserved for the selection process based on our active signaling scheme. During this time interval, the nodes compete in order to access the channel and hopefully at this end of time interval only one node remains as a winner. The second interval is used by the winning node to transmit its payload packet.

The selection interval contains a set of mini-slots where a competing node can be either in transmission mode or in listening mode. In transmission mode, the node sends a signaling

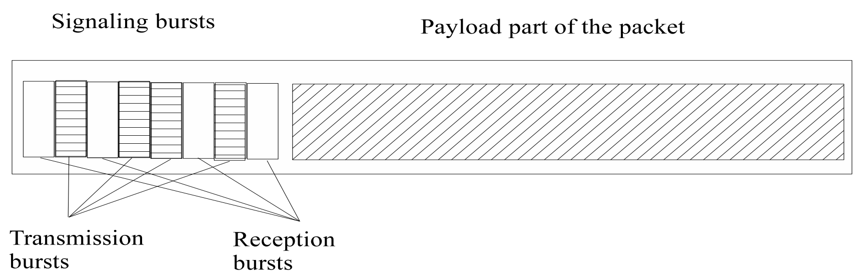

Fig. 3. Structure of the AS-DTMAC slot

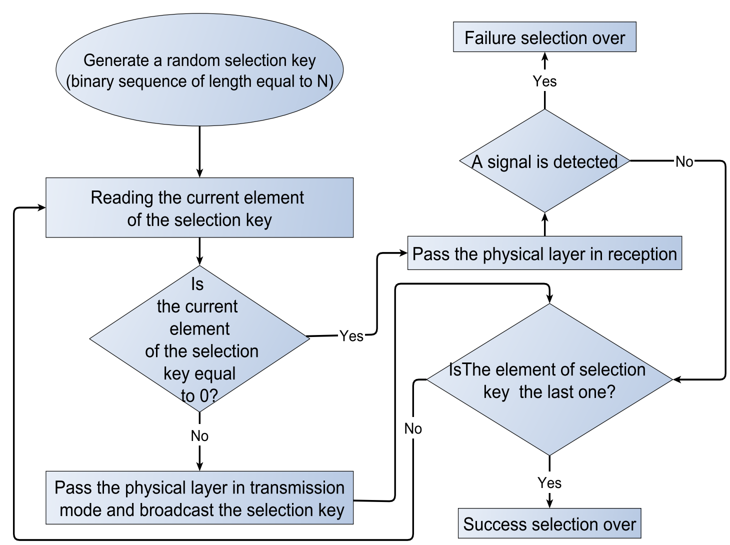

Fig. 4. Active signaling mechanism

burst whereas in listening mode the node listens for possible concurrent transmissions. We summarize the transmission and reception activity of a competing node by a binary transmission key e.g. '1010101100...10'. By convention '1' corresponds to a mini-slot in transmission and '0' to mini-slot in reception mode. When nodes compete for a given slot, they use their binary transmission key. The key is consumed from left to right and we assume that the binary transmission key has n digits.

To compete for a slot, each node with a message to send shows its presence by sending a burst signal, which is generated by drawing a random key. If we suppose that the first value is '0' the vehicle will sense the channel during this mini-slot. If during this listening period the node senses a transmission it withdraws from the competition. If no competing transmission is sensed, the process can continue and the next digit of the key is used. Let us assume that is the case, then the vehicle reads the next bit of its transmission key. If this value is 1, then the vehicle will transmit his signaling burst during this next mini slot. The process will continue following this algorithm until the last bit of the key is reached. In this way, there are fewer and fewer vehicles in competition from one mini-slot to the next. The description of this technique is summarized in the flowchart in Figure 4.

The vehicle that successfully gets a slot will keep it for the next frames, and free the slot only if a collision occurs or when the vehicle changes the zone. In these two cases the active signaling technique is needed to reserve again. Thus, the competition is limited to the node that are trying to get a slot for the reasons described above.

A very important property of this selection process is that at least one node reads all the bits of its selection key and successfully completes the selection process. It can be shown that with a high probability there is one and only selected node in the selection process and thus we have no collision.

4.2 Using Active signaling with priority and for emergency traffic

4.2.1. Priority

The default functioning of the active signaling scheme is with a random key. However it is possible to divide the transmission key into a priority part and a random part. In contrast to the random part, the priority part is the deterministic part of the transmission key. If we allocate n_1 bits to the priority part ($n_2 = n - n_1$ bits being left to the random part), we can handle 2^{n_1} different priority levels. The n_2 bits of the transmission key are left to the random part and are used as in the default functioning.

4.2.2. Emergency traffic

The idea is to build a special access scheme for emergency packets. We assume that these packets are sporadic packets and produce a small additional channel load. Examples of such packets can be DENMs(Decentralized Environmental Notification Messages).

In the default functioning of the AS-DTMAC protocol, the vehicles use the active signaling to decrease the access collision probability and, after the initial access, to overcome the merging collision probability. However, the first attempt to reserve a slot is performed on a free slot according to the DTMAC procedure, see Section 3. In some cases, one may wish almost immediate access to a very next slot without doing the DTMAC listening procedure. In that case, the priority scheme can be used. To illustrate, let us suppose that we have $n_1 = 1$ priority bit, the default traffic will set its priority bit to 0 whereas the emergency packet will set its priority bit to 1. By doing so the emergency packet will eliminate any other usual packet on the coming slot. However, in order to save the reservation granted in the slot to a node, we use the following technique. The last bit of the n_2 of the random part will be deterministic. For default packets this bit will be set to 0 and this bit will be set to 1 by an emergency packet. Using this coding for the transmission key, a node with a usual packet and with a slot already reserved can determine if it has been eliminated by an emergency packet. In that case, this node will continue to use this slot in the next frame and will hopefully be able to successfully transmit since the vehicle with emergency packets will use another slot.

5 Performance evaluation

In this section, we evaluate and compare the performance of DTMAC and AS-DTMAC. The methodology and the scenarios are taken from [16].

5.1 Simulation scenarios and parameters

We use MOVE and SUMO [21] to generate vehicular traffic scenarios and to perform real vehicular mobility simulations, respectively.

In our simulations we consider a digital map to build a VANET environment close to real highway configurations taking into account lane with different directions. In Figure 5, we can see a metropolitan area taken from a Map of San Jose (California) of size $3000m \times 100m$. This map was exported from OpenStreetMap (OSM) and adapted with the help of OpenStreetMap Editor (JOSM). The resulting roads are then populated with vehicles traveling in both directions. Each flow of vehicles is characterized by a set of parameters which consist of the starting and ending time of the flow, the initial point and the destination of the flow and the maximum number of vehicles. In this environment, each vehicle is assigned a random speed between $120km/h$ and $150km/h$. The resulting traffic traces generated by MOVE were injected into the Network Simulator $ns2.34$. Table I summarizes the simulation parameters used in our scenarios.

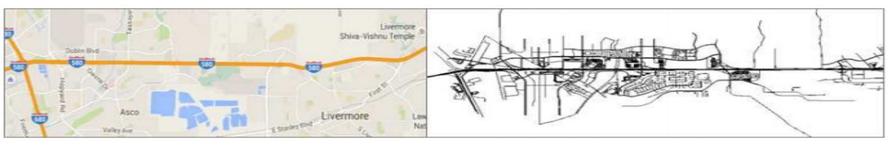

Fig. 5. VANET network topology captured from Google MAP.

Table 1. *Simulation parameters*

Parameter	Value
Simulation duration	120 (s)
Speed	120 (km/h)
Speed standard deviation	30 (km/h)
Number of slots per frame (τ)	100
Slot duration	0.001 (s)
Mini slot duration	0.000025 (s)
Highway length	2.5 (km)
The number of lanes per direction	2
The radio range (R)	250 (m)

5.2 Simulation results

We will keep the same parameters as those used in the previous study [16] and we vary the density of vehicles in the network. This parameter is called area occupancy (AO); the definition of this metric is given in [18]. We also introduce the following metrics:

- Overhead: is the total number (in bytes) of packets transmitted from one vehicle to another in order to maintain a collision-free schedule. It consists of the overhead of the basic protocol plus the additional bytes created in the burst of the signaling process. In our case, only the latter is computed.
- Number of slots acquired : this is the number of vehicles that have successfully acquired a time slot per frame.
- Average Access Time : this is the average time for a vehicle to access a slot in a given frame.
- Access collision rate : is defined as the average number of access collisions per slot and per area.

5.2.1. Best length of the signaling interval

To tune the performance of our AS-DTMAC protocol, a preliminary study is necessary to determine the adequate number of mini-slots that will be used during the selection phase described in Section 4. In order to find that optimal number which guarantees a good compromise between the metrics, we plot the curves of the access collision rate, the overhead and the average access time versus the number of the mini-slots for different network loads. In fact, on the one hand, a high number provides a small access collision rate but, on the other hand, it significantly increases the number of control messages needed to establish and maintain a collision-free schedule.

The results of our study are given in Figures 6, 7 and 8. For example if we take the value 4 as a number of mini slots, we have a lower access time and overhead, while the access collision is high. Also if we take a large $n = 14$, the access collision rate is very low but the overhead is significantly high. It is clear from these observations that the best compromise is located approximatively for the number of bits in the transmission key: $n \in [6, 10]$, as there is an acceptable access latency, low access collision rate and it generates of a reasonable overhead. For the rest of this paper, using 9 mini-slots seems appropriate, as it requires less computing and presents good performance. In Figures 6, 7 and 8, we can also see that the network load significantly affects the above metrics, the more we increase it, the larger are the access time, the overhead, and the access collision rate.

5.2.2. Comparison of DTMAC and AS-DTMAC

The aim of this sub-section is to compare the performance of DTMAC and AS-DTMAC in terms of the number of vehicles acquiring a time slot, access collision rate and, finally, the average access delay.

Figure 9 shows the slot allocation for the 10 first frames of DTMAC and AS-DTMAC with AO is equal to 0.9. From this graph, we could conclude that DTMAC requires approximatively twice as many frames as AS-DTMAC to obtain a reservation for each vehicle in the network. In fact, when the number of frames is equal to 2 in AS-DTMAC, 93 % of vehicules have

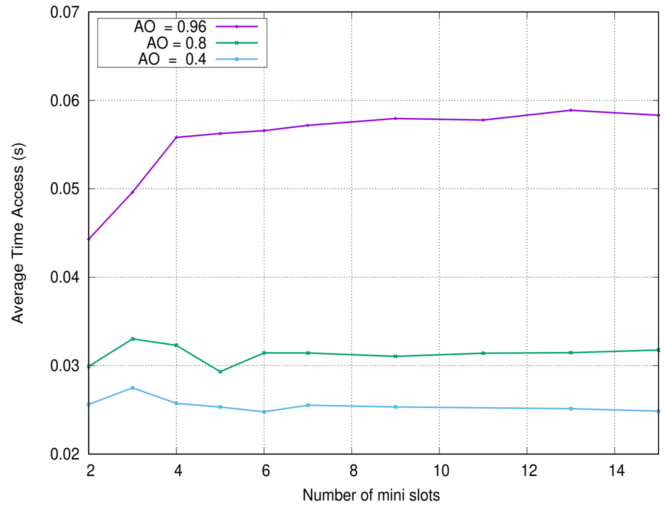

Fig. 6. Average access time

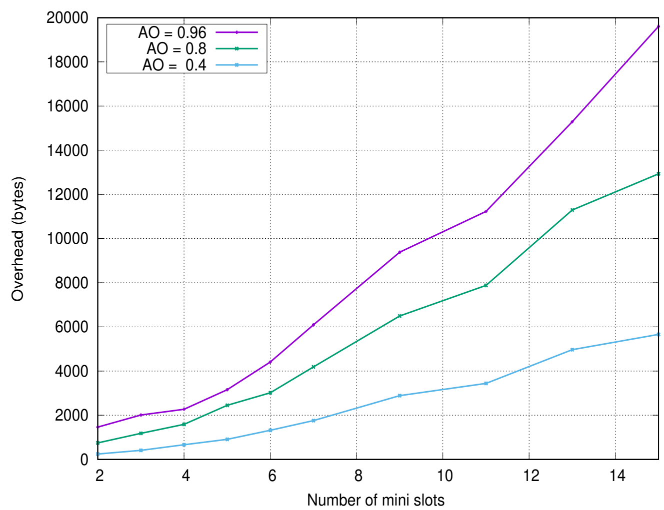

Fig. 7. Total overhead versus the number of bits of the transmission key

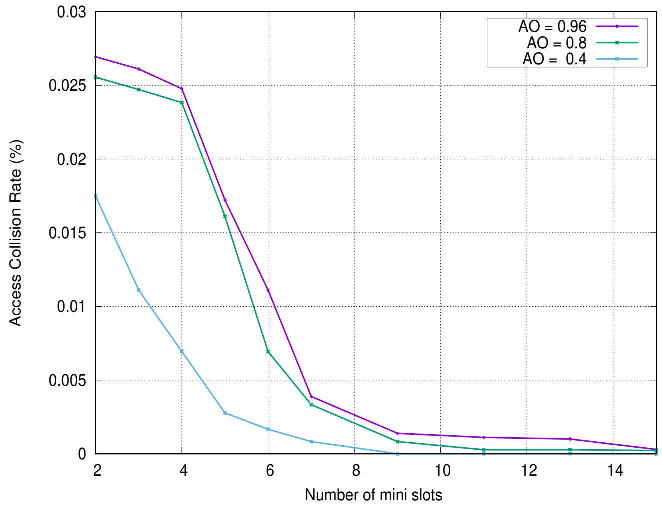

Fig. 8. Access collision versus the number of bits of the transmission key

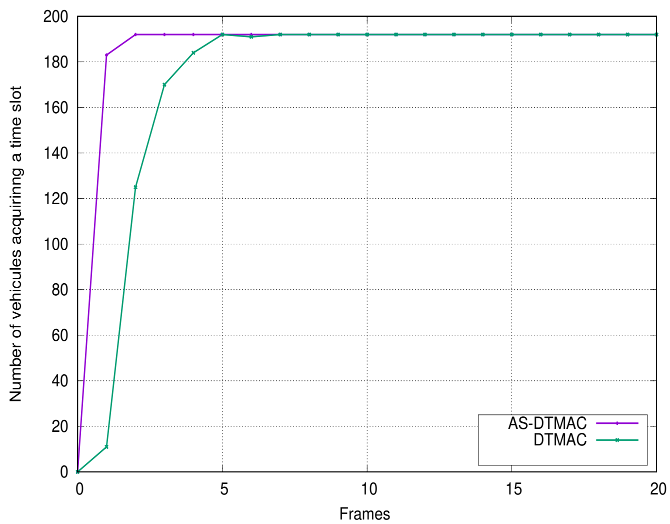

Fig. 9. Number of vehicles acquiring a time slot within *N* frames.

successfully reserved a slot, whereas only 5% of vehicles were able to reserve a slot using the DTMAC protocol.

Figure 10 (plotted in logscale) presents the percentage of access collisions for DTMAC and AS-DTMAC. It's clear that the difference between the two curves is roughly of three orders of magnitude, which is evidently a very significant result. For instance, if we take the [0.4, 0.7] interval of AO, we observe that the difference in the access collision rate using DTMAC and AS-DTMAC is very large and almost the same for all the values (i.e. at the value 0.4, the access collision rate is 0.00015 for AS-DTMAC whereas it's nearly 0.03 when the DTMAC protocol is used).

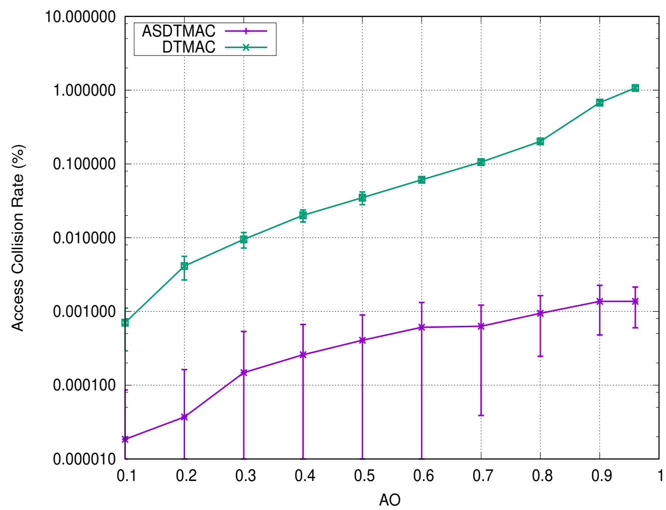

Fig. 10. Access collision versus channel occupancy for DTMAC and AS-DTMAC with error bar (95% confidence interval).

Figure 11 illustrates that AS-DTMAC provides a significantly smaller access delay than DTMAC. As we can see, the difference in time between the two protocols stays relatively the same except for the two last values where the load of the network AO is very high (0.9 and 0.96).
In [16] it is shown that DTMAC significantly outperforms VeMAC [18] which is very well-known TDMA protocol for VANETs in the literature. As we have used the same simulation tools and the same scenarios used in [16], we can ensure by transitivity that AS-DTMAC outperforms VeMAC and similar TDMA schemes.

6 Conclusion

In this paper, we have proposed to enhance DTMAC protocol by integrating active signaling. The simulation results show that AS-DTMAC drastically reduces the access collision rate and

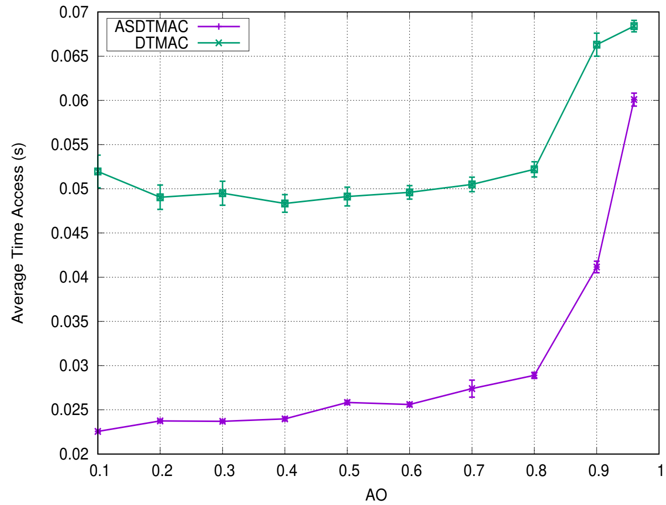

Fig. 11. Average access time versus channel occupancy for DTMAC and AS-DTMAC with error bar (95% confidence interval).

allocates slots to all the vehicles in the network in half the time it takes DTMAC to do so. We also presented a use case in the V2V for urgent and high priority traffic message like DENM, that can help to avoid an accident, all these new features are very important for the future technology described in the beginning of this paper. As future work, we will do additional simulations to compare with the standard used in V2V (IEEE 802.11p) and we plan to develop an analytical model for AS-DTMAC as well as to investigate further advanced access features that could be provided using the active signaling scheme.

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