Stabilization Time Comparison of CSMA and Self-Organizing TDMA for different channel loads in VANETS

A. Alonso*† and C.F. Mecklenbräuker*†
*Institute of Telecommunications, Technische Universität Wien, Vienna, Austria
†Christian Doppler Laboratory for Wireless Technologies for Sustainable Mobility, Technische Universität Wien, Vienna, Austria
Contact: arrate.alonso@nt.tuwien.ac.at

***Abstract*—Traffic safety-related messages have to meet low and predictable delay constraints. For vehicles using IEEE802.11p medium access control (MAC) algorithm the channel access delay increases unpredictably (using random backoff time) every time the channel is sensed busy. In contrast, Self-Organizing Time Division Multiple Access (STDMA) provides an upper bound on channel access delay defined by the selection interval (SI) length. Our contribution studies the performance of both protocols during the start-up phase of the vehicular ad-hoc network (VANET). Results show MAC-to-MAC delay of each correctly decoded packet for lightly-loaded and heavily-loaded scenarios. The cumulative distribution function (CDF) of these measurements for a maximum observable MAC-to-MAC delay value of 100ms for different vehicle densities show that both MAC algorithms perform reliably (above 90%) within 60s simulation. We define stabilization time as the time instant from which on the MAC protocol reaches a reliable performance. For lightly-loaded scenarios with 25 vehicles within range, STDMA and the IEEE802.11p MAC algorithm have a stabilization time of 1s and 20ms, respectively. For heavily-loaded scenarios with 400 vehicles within range, STDMA and the IEEE802.11p MAC algorithm have a stabilization time of 1s and 3.2s. In conclusion, STDMA shows a reliable performance and better predictability, regardless of the number of vehicles accessing the channel, and it also provides lower stabilization time in comparison to IEEE802.11p MAC algorithm for vehicle densities higher than 350 vehicles sending periodic messages every 500ms.**

I. Introduction

Cooperative vehicular systems enable new applications to be developed where data is exchanged wirelessly. In a cooperative system nodes share information, such as safety warnings and traffic information. This can be used for avoiding accidents and traffic congestions. The cooperation between vehicles for enhancing road traffic safety and efficiency will in many cases use vehicular *ad hoc* networks (VANETs), where all nodes are peers, vehicles as well as roadside units (RSUs). The *ad-hoc* topology implies that there is no central coordination in the system.

There has been extensive work on standardization to define a communication standard for Intelligent Transport Systems (ITS) operating in the 5.9 GHz frequency band. In June 2010, the IEEE 802.11p [1] was ratified, which is an amendment to the IEEE 802.11 wireless local area network (WLAN) standard. The major difference between the legacy 802.11 and 802.11p is the removal of the access point functionality in the latter. 802.11p uses enhanced distributed channel access (EDCA) functionality enabling prioritization similar to IEEE 802.11e. The access function used by EDCA is carrier sense multiple access with collision avoidance (CSMA/CA). The enhancements that EDCA brings to 802.11 distributed coordination function (DCF) is introducing traffic priorities instead of unique traffic queue supporting quality of service (QoS) through 802.11e [2] . The physical (PHY) layer of 802.11p, orthogonal frequency division modulation (OFDM), is inherited from 802.11a with the major difference that the channel bandwidth is narrowed to 10 MHz in 802.11p. In Europe a profile standard of IEEE 802.11p has been approved by the European Telecommunication Standards Institute (ETSI), called ITS-G5 [3].

New kind of applications such as e-safety, traffic management, enhanced driver comfort and vehicle maintenance applications, lead to new communication scenarios in vehicular environments. Road traffic safety applications are the ones with the strongest requirements on the communication. For example sending *emergency notifications* requires a low channel access delay, in order to notify relevant receivers in time to avoid for example collisions; for *risk anticipation* the key feature is predictable channel access delay. Vehicles are monitored so abnormal behaviours are detected and any change on the cadence of the data traffic must be tracked. ETSI has defined two types of messages for safety-related applications, namely cooperative awareness messages (CAM) [4] and decentralized environmental notification messages (DENM) [5]. CAMs are broadcasted periodically and contain position, speed, heading of the vehicle, they are time-triggered and always present. DENMs, on the other hand, are event-driven and will be triggered when a dangerous situation is about to happen. The MAC layer protocol for scheduling safety-related data traffic must be predictable, self-organizing and support both event-driven and time-triggered data traffic. Both, the periodic beacon message or the active safety messages (such as Emergency braking Message, Slow/Stop Message or Cooperative Collision Warning) are transmitted through control channel.

CSMA/CA of 802.11p provides low channel access delay given that the channel is sensed idle. If the channel is busy, a node waits a random time until it attempts to access the channel again. This random amount of time is calculated via the exponential backoff algorithm. The main drawbacks of CSMA/CA when scheduling safety-related data are: the stochastic nature of the exponential backoff which makes CSMA/CA (*i*) *unpredictable* as the maximum delay is unbounded and (*ii*) causes *simultaneous channel access* when two nodes select the same backoff value which leads to collisions and a degradation of the reception performance and finally (*iii*) *blocking*, which means that as long as the node senses the channel busy, it keeps waiting and never gets to transmit.

A potential remedy to the problems of CSMA/CA is the use of self-organizing time division multiple access (STDMA) [6], where access to the channel always is provided, regardless of the channel occupancy. STDMA has a periodic structure, where the channel is divided in timeslots, and further grouped into frames. These features are translated into *predictable channel access delay*, *low probability of simultaneous co-located transmissions*, *non-blocking* and better ability for scheduling periodic traffic. For these reasons, STDMA is a suitable alternative for managing safety-related data traffic. However, it requires CAMs to be present in the system since the scheduling of transmission slots is based on position information. STDMA has earlier been compared to CSMA/CA ([7] [8]) through simulation of a highway scenario where only the time-triggered CAMs have been present. The data evaluated was retrieved from a loaded and stable scenario where all the vehicles where active and transmitting periodically. The results show that STDMA is very suitable for VANETs and that in such highway scenarios it outperforms CSMA/CA. Previous work carried out by our team shows the throughput of STDMA MAC layer for vehicular networks based on measured SNR time-series [9].

The communication requirements of traffic-safety applications differ slightly from most applications relying on wireless communications. A key feature of traffic-safety systems is the concurrent requirements on reliable and timely communications, which is due to the distributed control system. Timely and accurate data is needed to monitor and regulate the system. As the time-triggered position messages are generated periodically, typically between 2-10 Hz, it is useless to transmit a delayed position message if a new updated message has been generated. We say that the packet has a deadline to meet.

In this article we analyze the effects of different channel loads on the MAC-to-MAC delay suffered by each packet. We analyze which percetange out of all received packets meets a deadline defined by a maximum observable MAC-to-MAC delay of 100 ms. The reason for us to study this feature is to test the ability of the IEEE802.11p MAC algorithm to meet such restrictive deadlines, which are demanded for deploying active safety applications, such as Cooperative Collision Warning. One of our goals is to see the effects of different channel loads in the MAC-to-MAC delay for the IEEE802.11p MAC algorithm. We will analyze lightly-loaded and heavily-loaded scenarios. We will also show the results measured in the same scenarios obtained for STDMA, which provides an upper bounded channel access delay defined by the Selection Interval (SI) length.

II. Stabilization Time

Safety related periodic messages have to be delivered within a maximum observable delay (τ_{dl}), i.e. they must be delivered to the recipients periodically and on time. The parameter we have used in this contribution for evaluating the performance of the MAC algorithms is the MAC-to-MAC delay [10]. In order to meet the deadline, it must satisfy $\tau_{MM} < \tau_{dl}$.

MAC-to-MAC delay is defined as the sum of the following delays:

- *Channel Access Delay (τ_{ca})*: it is defined as the length of time it takes a transmitter node from the channel access request until the actual tranmission takes place. For periodic messages if $\tau_{ca} > \tau_{dl}$ the packet is dropped at the transmitter $\tau_{ca} = \infty$, as a new message with updated position has already been generated.
- *Propagation Delay (τ_p)*: it is defined as the length of time it takes for the signal to travel from the transmitter node to the receiver node.
- *Decoding Delay (τ_d)*: it is defined as the length of time it takes the decoded packet to be delivered to higher layers at the receiver. If decoding fails, due to noise, fading or interference, we set $\tau_d = \infty$.

The results will be analyzed by means of the cummulative distribution function (CDF) of the MAC-to-MAC delay. CDF describes the probability that a random variable (e.g. MAC-to-MAC delay) is less than or equal to x (e.g. deadline is defined as 100 ms)

$$F_{\tau_{MM}}(\tau_{dl}) = P(\tau_{MM} \leq \tau_{dl}) \tag{1}$$

Safety-related data needs to meet a hard deadline (i.e. there are penalties or costs associated with missing the deadline). Here, we define two states: *State (0)*:= *poor* MAC performance and *State (1)*:= *good* MAC performance. Specifically, we say that MAC performance is *good* if at least 90% of all received packets have a MAC-to-MAC delay ≤ 100 ms otherwise we say that MAC performance is *poor*. For the purposes of this paper, we further define the *stabilization time* t_{stab} as the duration required for reaching a reliable performance, i.e. the duration required to achieve *good* MAC performance and keep it consistently until the end of the simulation time ((t_{stab}:end)).

$$t_{stab} \Rightarrow F'_{\tau_{MM}}(\tau_{dl}) = P(\tau_{MM}(t_{stab} : end) \leq \tau_{dl}) \geq 90\% \tag{2}$$

III. Effects of channel load in the MAC algorithm performance

Depending on channel access approach of each MAC algorithm, the channel load has different effects on the delay.

A. On IEEE802.11p MAC Algorithm

We assume that safety-related data traffic uses high priority queues as provided by the EDCA mechanism, implying short sensing periods but also few back-off values to select from when the channel is sensed busy. The IEEE802.11p MAC algorithm implements an exponential back-off scheduler. For low channel loads it provides low channel access delay after the sensing period. But as the channel load increases, the channel access delay increases exponentially and becomes unpredictable. In fact, the only way for the IEEE802.11p MAC algorithm channel access time to exceed the deadline is when the transmitter senses the channel as busy (and, for this reason, cannot decrease the back-off counter) sufficiently many times for the deadline to expire. As we are leading only with safety-related data traffic nature, there is just one queue applying maximum priority traffic scheduling constrains which are recorded in Table I.

B. On STDMA

STDMA presents a structured channel access and provides a predictable delay even in worst case scenario where the channel is full. The nodes are time slot synchronized. Everytime a new vehicle enters the channel, it listens to the channel activity during one frame period, then divides the frame into so many groups as many messages it wants to transmit per frame, and selects one nominal transmision slot (NTS) from each group to transmit in; finally it begins to send continuously. In order to adapt to the changes taking place in the channel, to each NTS a reuse fator is assigned, which defines a certain number of subsequent frames in which this transmission slot is used by the vehicle. When this counter expires another NTS is selected out of the availables within its selection interval (SI). Even though all the timeslots of the selection interval may be occupied, STDMA always provides channel access, by selecting as nominal transmission slot the one of its furhest node. Channel access delay is predictable, meaning with this term that, in contrast to IEEE802.11p MAC algorithm, it is upper-bounded by the SI length. The parameter settings for STDMA used in our simulations are presented in Table II.

IV. Results

The scenario presented in this paper is used for evaluating IEEE802.11p and STDMA MAC methods, through computer simulations in Matlab. The data traffic generated by each vehicle is periodic and has a hard-dealine to meet, where each vehicle's initial transmission time is independent and random. In order to study worst case scenario, it is static so the time persistency of the effects in this of the start-up phase can be analyzed from a lightly-loaded scenario (25 and 50 vehicles) to heavily-loaded scenario (200, 300, 350 and 400 vehicles).

All the vehicles broadcast messages with a fixed data rate of 6 Mbps. The data traffic model is defined following the ETSI recommendations for safety-related messages (broadcasted messages are 800 bytes long and are generated every 500 ms). The bandwidth requirements for each node is $12,8$ kbps.

The used physical model, the same as in [10], is based on outdoor vehicle-to-vehicle channel sounding measurements performed at 5.9 GHz [11]. The statistical model concluded from that measurement campaign shows how small scale and large scale fading are represented by the Nakagami *m* model [12], also for vehicular channel modeling. Rayleigh fading conditions are obtained by setting *m* = 1, whereas higher *m* values are used for approximating Rician distributed channel conditions. As shown in [11], the estimated values of *m* from the channel measurements are distance-dependent. The average received power, P_r, is assumed to follow the dual slope model suggested in [12]. All vehicles use the same output power, $P_{t,dB}$, of 20 dBm (100 mW) and the resulting signal-to-interference-plus-noise (SINR) ratio at the receiver is calculated using the following formula:

$$SINR = \frac{P_r}{P_n + \sum_{k=0}^{K} P_{i,k}} \tag{3}$$

where P_r is the power of the desired signal, $P_{i,k}$ is the power of the k-th interferer, and P_n the noise power. The noise power is set to -99 dBm and the SINR threshold is set to $6\ dB$.

Regarding the parameter setting for the IEEE802.11p MAC algorithm, Table I shows that the Arbitration Interframe Space (AIFS) is set to 58 μs, the back-off value is randomly selected depending on the priority. Safety-related data traffic has highest priority so the contention window (CW) size is selected out of [0..3] values and clear channel assessment (CCA) threshold is set to -96 dB. On the other side, the parameter setting for the STDMA MAC algorithm are shown in Table II.

TABLE I
Parameter Settings for IEEE802.11p MAC Simulations

	Parameter Settings
AIFS (μs)	58
CW size	[0...3]
CCA Threshold (dB)	- 96

TABLE II
Parameter Settings for STDMA Simulations

	Parameter Settings
Superframe Size (s)	1
Number of slots	904

We are going to simulate two kinds of start-up scenarios: lightly-loaded and heavily-loaded scenarios. Start-up scenarios are those in which a group of vehicles attempts to access an stable channel simultaneously. The vehicles are started randomly and independently from each other. The vehicle interarrival time defines the frequency in which vehicles are activated in the scenario. In our simulator it describes the interarrival time amongst vehicles already active and newly activated vehicles, and it is a tunable parameter. For our scenarios it is set to 0 s, as the effect to be studied is the impact of the amount of vehicles joining the channel within the same frame.

In the case of lightly-loaded scenarios, a urban road is simulated along which 25 or 50 vehicles in parking position are activated, and begin to transmit CAM messages periodically. In Fig. 1 and Fig. 2 we see the MAC-to-MAC delay for all correctly decoded packets within 60 s simulation for CSMA/CA and STDMA respectively. In blue we see the packets that have arrived on-time, e.g. they have met 100 ms deadline, and in red the amount of packets that have arrived later than 100 ms. From the reception trend, we see that it is very constant throughout the whole simulation time.

In such lightly-loaded scenarios, as it is highly probable to sense the channel idle to transmit, CSMA/CA results show that all correctly decoded packets meet 100 ms.

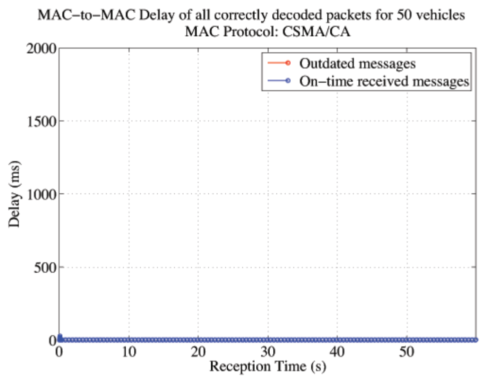

Fig. 1. CSMA/CA MAC-to-MAC delay of all correctly decoded packets vs. reception time for lightly-loaded scenarios (50 vehicles)

Comparing Fig. 1 and Fig. 2, we see that in these scenarios CSMA/CA shows a higher amount of correctly decoded packets than STDMA.

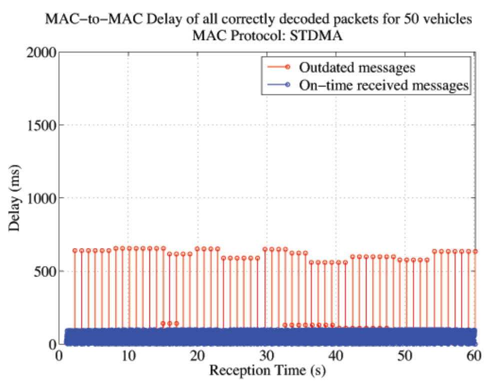

Fig. 2. STDMA MAC-to-MAC delay of all correctly decoded packets vs. reception time for lightly-loaded scenarios (50 vehicles)

In Fig. 3 the cummulative density function of the MAC-to-MAC delay is shown for both MAC algorithms.
The curves show the probability of received messages to meet a deadline below the x axis normalized values to a maximum observable MAC-to-MAC delay value of 100 ms. We define as *realiable performance* when the CDF function achieves the 90%. For the 100 ms deadline both curves reach a reliable performance within 60 s simulation.

In the case of heavily-loaded scenarios, they are either a parking lot situations, where more than 200 vehicles are

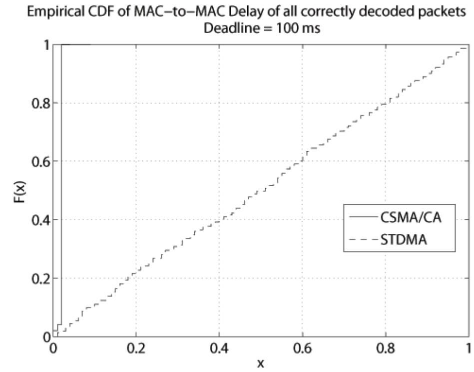

Fig. 3. Empirical CDF of MAC-to-MAC delay of all correctly decoded packets for 100 ms deadline in lightly-loaded scenarios (50 vehicles)

activated, and begin to transmit CAM messages periodically; or a highway scenario where 300 to 400 vehicles are activated as an emergency occurs and begin to transmit DENM messages periodically. In these kind of scenarios, CSMA/CA is less likely to sense the channel idle to transmit, so vehicles are backing-off within the first seconds until they transmit. Fig. 4 shows this trend where higher MAC-to-MAC delays are recorded in the initial seconds of the simulation.

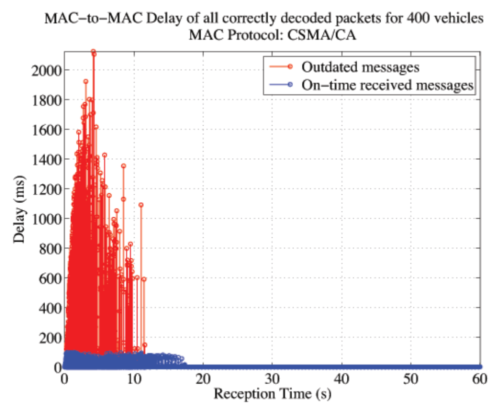

Fig. 4. CSMA/CA MAC-to-MAC delay of each correctly decoded packet vs. reception time for heavily-loaded scenarios (400 vehicles)

The MAC-to-MAC delay vs. reception time of STDMA in Fig. 5 for these scenarios looks similar to the results from Fig. 2, proving its stable and reliable performance.

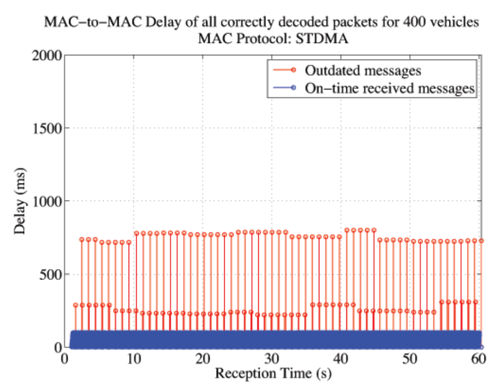

Fig. 5. STDMA MAC-to-MAC delay of each correctly decoded packet vs. reception time for heavily-loaded scenarios (400 vehicles)

In Fig. 6 the results for CSMA/CA show that the performance has dropped in comparison to Fig. 3, as the vehicular traffic load has increased. It also shows the performance achieved throughout the whole simulation time. Analyzing the temporal evolution of this parameter we accurately describe the performance at different instants of the simulation.

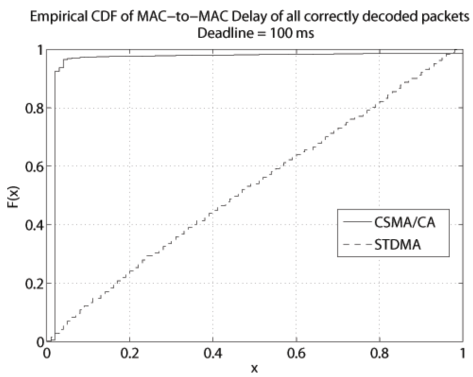

Fig. 6. Empirical CDF of MAC-to-MAC delay of all correctly decoded packets for 100 ms deadline in heavily-loaded scenarios (400 vehicles)

Fig. 7 shows the performance achieved at 1.05 s simulation time, where we see a poor performance of CSMA/CA as the CDF of the MAC-to-MAC delay falls below 90%. On the other hand, STDMA shows a good performance as its CDF of the MAC-to-MAC delay raises above 90%.

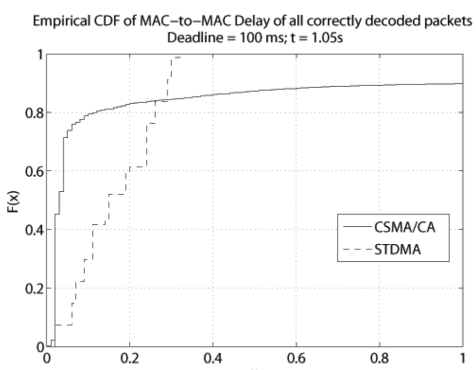

Fig. 7. Empirical CDF of MAC-to-MAC delay of all correctly decoded packets for 100 ms deadline in heavily-loaded scenarios (400 vehicles) for t=1.05 s

For evaluating the time CSMA/CA needs to reach a reliable performance, we define the two states mentioned in Section II: *State (0)*:= where the CDF performance falls below 90% and *State (1)*:= where the CDF performance raises up to 90% or above. This temporal evolution is shown in Fig. 8.

The stabilization time for 400 vehicles for CSMA/CA is 3.2 s and STDMA is 1 s. Further simulations have shown that from 350 vehicles on, sending periodic messages every 500 ms, CSMA/CA performs worse than STDMA in heavily-loaded scenarios, as it requires a longer time to achieve a reliable performance.

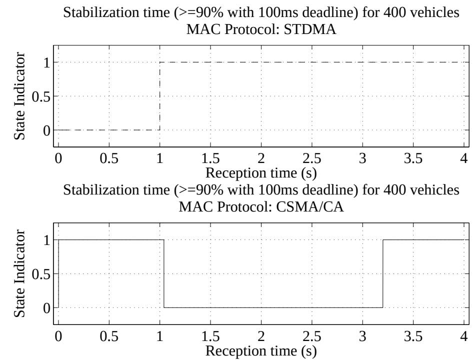

Fig. 8. Stabilization time for heavily-loaded scenarios (400 vehicles).

V. CONCLUSIONS

Safe operation of ITS applications relies on the traffic safety related messages (CAMs and DENMs). Both have periodic nature and each packet has a deadline to meet. Therefore MAC-to-MAC delay (which consists of channel access delay, propagation delay and decoding delay) has to be low and predictable.

Our contribution presents performance results of IEEE802.11p MAC algorithm in terms of MAC-to-MAC delay and reliability for VANETs in start-up phase. We have analyzed delay-related performance for lightly-loaded scenarios (25 vehicles or 50 vehicles accessing within the same frame) and heavily-loaded scenarios (300 vehicles, 350 vehicles or 400 vehicles accessing within the same frame). We have studied the ability of received packets to meet a certain deadline, τ_d, in our simulations set to 100 ms. We have also shown that the CDF performance varies with the simulation time. In order to evaluate the temporal evolution, we´ve measured the stabilization times for each scenario.

Our results indicate a decrease in MAC performance of the IEEE802.11p MAC algorithm due to the busy state of the channel in response to an increasing channel load in terms of CDF of the MAC-to-MAC delay. This is translated in higher stabilization times; e.g. for 50 vehicles attempting to access the channel simultaneously, it takes CSMA/CA 20 ms and for 400 vehicles it takes CSMA/CA 3.2 s to reach a reliable performance. On the other hand, our results indicate robust performance of STDMA regardless of the channel population (stabilization time is always 1 s and the CDF never fluctuates).

Further simulations have shown that from 350 vehicles on, sending periodic messages every 500 ms, CSMA/CA performs worse than STDMA in heavily-loaded scenarios, as it requires a longer time to achieve a reliable performance. If the periodic message generating rate is increased, a lower amount of vehicles will load the channel this much, so the same performance decrease occurs. This could be the case for emergency warning messages, which are meant to be sent every 100 ms.

Overall this leads to higher delays for IEEE802.11p MAC and higher number of outdated messages which makes IEEE802.11p MAC algorithm less robust for scheduling safety application data traffic than STDMA.

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