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Delay and Interference Comparison of CSMA and Self-Organizing TDMA When Used in VANETs

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Abstract – **IEEE 802.11p is the proposed wireless technology for communication between vehicles in a vehicular *ad hoc* network (VANET) aiming to increase road traffic safety. In a VANET, the network topology is constantly changing, which requires distributed self-organizing medium access control (MAC) algorithms, but more importantly the number of participating nodes cannot be restricted. This means that MAC algorithms with good scalability are needed, which can fulfill the concurrent requirements on delay and reliability from road traffic safety applications. The MAC method of IEEE 802.11p is a carrier sense multiple access (CSMA) scheme, which scales badly in terms of providing timely channel access for a high number of participating nodes. We therefore propose using another MAC method: self-organizing time division multiple access (STDMA) with which all nodes achieve timely channel access regardless of the number of participating nodes. We evaluate the performance of the two MAC methods in terms of the MAC-to-MAC delay, a measure which captures both the reliability and the delay of the delivered data traffic for a varying number of vehicles. The numerical results reveal that STDMA can support almost error-free transmission with a 100 ms deadline to all receivers within 100 m, while CSMA suffers from packet errors. Moreover, for all considered cases, STDMA offers better reliability than CSMA.**

Keywords – STDMA, CSMA, VANET, IEEE 802.11p, self-organizing TDMA, vehicle-to-vehicle communication, V2V

I. INTRODUCTION

Intelligent transport systems and services (ITS) using wireless inter-vehicle communications currently receive much attention worldwide, [1, 2]. One of the, both strong and many, motivations is to reduce traffic accidents and human injuries by introducing road traffic safety applications based on vehicular communications. The basic idea of such applications is to enhance the situation awareness of the driver such that the time to react to dangerous events is increased. Many road traffic safety applications will rely on messages broadcasted regularly from every vehicle, containing information about position, speed, direction etc. [2], a.k.a. beacons. From these messages a local dynamic map (LDM) can be constructed [3]. Apart from the broadcasted messages, the LDM concept will also contain static map information and temporary information about, e.g., road construction sites communicated from road-side units. In addition, the map is to be complemented with warning messages, broadcasted by vehicles or road-side units in the event of a hazard. This LDM can be used as a facility for several types of applications, e.g., within traffic safety to predict dangerous situations before they actually occur. The position messages need to be time stamped with a global clock, which could be provided through a global navigation satellite system (GNSS), such as GPS or Galileo. If there are time discrepancies between the vehicles' position messages due to different local clocks, this could lead to erroneous behavior of road traffic safety applications using the LDM facility. This is described in more detail in Ch. 2 of [4].

From ongoing standardization activities, it is clear that most traffic safety applications relying on vehicular communications will be based on vehicular *ad hoc* networks (VANETs). The *ad hoc* structure is advantageous for traffic safety applications, since it eliminates the problem of guaranteeing coverage by base stations or access points. However, since an *ad hoc* network has no central mechanism for controlling the network resources and the number of nodes in a VANET cannot be restricted, problems with scalability may arise in certain situations. The current suggestion within standardization is to use different frequency channels at the 5.9 GHz band for VANETs, divided into one control channel and several service channels. This channel multiplexing is proposed world-wide, however, different parts of the world have access to a different number of service channels (i.e., two to six). In Europe, all vehicles must listen to the common control channel which will carry both position messages as well as hazard warnings.

The first generation of VANETs will use the IEEE 802.11p standard [5], which is based on the medium access control (MAC) method carrier sense multiple access (CSMA). In earlier work [6] we have shown that CSMA has scalability problems, such that when the number of nodes and/or the data traffic injected in the network increases, it can cause unbounded channel access delays and many simultaneous transmissions with increased interference as a result. As the network load increases (overloaded situations), CSMA transmitters start dropping packets before they are even transmitted due to deadlines expiring (the delay exceeds the beacon interval). We have also pointed out that CSMA causes unfairness between users as the network load increases [7]. The CSMA algorithm has been in [6, 7] compared to another MAC method namely

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self-organizing time division multiple access (STDMA), where STDMA was found to perform better than CSMA. STDMA is already in commercial use in a collision avoidance system, i.e., Automatic Identification System (AIS)[8], for the shipping industry. In earlier work [6, 7] there was no channel model present and performance in terms of predictability and fairness was evaluated on the transmitter side. In this paper we have added a Nakagami channel model to our simulator and evaluate the performance of CSMA and STDMA from the receiver side in terms of the MAC-to-MAC delay, i.e., the end-to-end delay for one hop. This measure captures both the reliability and the delay of the messages since it considers the MAC induced interference. CSMA and STDMA are two different approaches to channel access and the motivation for comparing them is that STDMA is already in commercial use in a similar system as the one currently being proposed for road traffic safety applications within the vehicular environment. CSMA has been chosen as the standard for the first generation of VANETs despite its very well-known drawbacks, due to its simplicity.

II. MEDIUM ACCESS CONTROL

Providing access to the shared medium while at the same time providing the Quality of Service (QoS) in terms of, e.g., delay and reliability, requested by the application, is an important and challenging task of the MAC layer. Although, the reliability is mostly addressed in the physical layer, the MAC protocol can minimize simultaneous channel access attempts in an effort to decrease the interference in the system and thereby increase reliability. The broadcast nature of messages excludes traditional automatic repeat request (ARQ) strategies at the link layer found in unicast communication, which implies that important messages have to rely on forward error correction methods, e.g., repeated broadcasts of the same message in an effort to increase the reception probability.

STDMA is a guaranteed medium access protocol [9], where nodes access the channel in an orderly manner and all nodes know when to transmit. The protocol is, in this respect, predictable as the channel access delay is upper bounded. Time-slotted MAC approaches such as STDMA requires synchronization and one transmission fits into one slot, i.e., fixed packet length. Time-triggered data traffic, such as the LDM beacons, is suitable for TDMA schemes. CSMA, on the other hand, works best for event-driven data traffic where high utilization periods are followed by low utilization periods, which allows collisions to be resolved, i.e., the network can recover. CSMA belongs to the group of random access schemes [9], where nodes contend for gaining channel access. Hence, nothing can be said about when the channel access will actually take place. CSMA does not require synchronization and variable packet lengths are supported. Below is a brief description of the channel access procedure of CSMA (as used in 802.11p) and STDMA. For further protocol details see [5, 10] for CSMA and [6, 8] for STDMA.

A. CSMA

In CSMA of 802.11p, each node initiates a transmission by listening to the channel, i.e., performs a carrier sense operation, during a predetermined listening/sensing period called the arbitration interframe space (AIFS), T_{AIFS}. If the sensing is successful, i.e., no channel activity is detected, the node transmits directly. If the channel is occupied or becomes occupied during the T_{AIFS}, the node must perform a backoff procedure, i.e., it has to defer its access for a randomized time period. The backoff procedure works as follows: (*i*) draw an integer from a uniform distribution [0, *CW*], where *CW* refers to the current contention window, (*ii*) multiply this integer with the *slot time,* T_{slot}, derived from the physical (PHY) layer in use (i.e., in 802.11p $T_{slot}=13$ μs), and set this as the backoff value, (*iii*) decrease the backoff value by one T_{slot} whenever the channel has been free for one T_{slot}, (*iv*) upon reaching a backoff value of 0, send immediately. Further, nodes must defer their backoff decrementation whenever the channel becomes busy and they must listen a T_{AIFS}, after a busy channel becomes clear, before decrementation of the backoff value can resume. CSMA of 802.11p has support for QoS, where each node maintains 4 different queues. The different queues have different T_{AIFS} and size of the *CW*, see [10] for further details.

B. STDMA

In STDMA the time is divided into time slots constituting a frame. The major difference between STDMA and other self-organizing TDMA schemes is the lack of a random access channel for slot assignment. Instead the nodes in STDMA listen to the channel during one frame and then select a number of free slots for transmission. If no slots are free, a node chooses to send in an occupied slot, used by the node situated furthest away. Therefore, the position messages used by the LDM are also needed by the MAC layer for STDMA. The frame is seen as a ring buffer and all nodes have their own frame start. Hence, the nodes are slot synchronized, but not frame synchronized. In AIS the synchronization is done through GPS. When a node is turned on, it follows four different phases; (*i*) initialization*,* (*ii*) network entry, (*iii*) first frame, and (*iv*) continuous operation. During phase (*i*) the node will monitor the channel during one frame to determine the existing slot assignments, i.e., listen to the position messages sent in each slot, which contains the sending node's position and future slot assignments. In phase (*ii*), the node determines its first transmission slot based on the information gathered during phase (*i*) and introduces itself to the network by using this slot. After the first slot has been used for transmission the node enters phase (*iii*), where it continues to reserve a predetermined number of slots in the current frame and using them. If all slots are occupied, the node will select an occupied slot based on its knowledge of positions, namely the slot used by the node located furthest away from itself. This way channel access is always granted and the distance between two concurrently transmitting nodes is maximized. In the last phase (*iv*) all the slots determined in the first frame are used for transmission in future frames. To cater for network topology changes, the same slot assignment is not kept for long. During phase (*iii*) the node will also draw a random integer, $n = \{3,...,8\}$, for each allocated slot which determines for how many consecutive frames this slot will be used. This random number is different for each slot in the frame. When the specific slot has been used for its number of frames, the node must find a new slot and attach a new random number to it. In the AIS standard [8], when nodes have packets to transmit that are longer than the allowed slot size, they can allocate up to five consecutive slots to accommodate the longer packet. A node is also allowed to transmit event-triggered messages in one or more free slots. STDMA needs synchronization and a GNSS will be present in the vehicle due to the global time stamp required for, e.g., position messages. As long as the GNSS system is connected to a sufficient number of satellites, the quality of GNSS-derived global clock will be sufficient for synchronizing STDMA. However, whether this is true also when satellite coverage is limited or nonexisting is out of scope for this article.

III. RELATED WORK

Slotted Aloha (S-Aloha), proposed in 1975 in [11], has served as the foundation for many of time-slotted approaches adapted to the VANET environment [12-18]. The major difference between these time-slotted approaches and the herein proposed STDMA is that the former ones cannot handle scalability in overloaded situations, i.e., when all slots are occupied – no more nodes can be added to the network. STDMA does not have this limitation since a node that wants to join the network when all slots are occupied will pinch a slot from another node situated furthest away from itself. Another difference is that in STDMA, the slot allocation as perceived by a particular node is not distributed to its neighbors. Instead the slot allocation performed by each STDMA node is based only on the position information broadcasted by all participating nodes.

One way to handle the problems with scalability in MAC algorithms, such as CSMA and slotted Aloha, is the addition of transmit power control (TPC) or/and data congestion control algorithms. The most prominent proposals for handling scalability through TPC are found in [19]. Of course, also scalable MAC algorithms such as STDMA will benefit from the use of TPC and data congestion control. However, the methods must be carefully designed since the restriction of the transmit power and data communicated can deteriorate the performance of certain road traffic safety applications, e.g., LDM.

IV. PERFORMANCE METRIC

Periodic position messages can be regarded as real-time messages because they have deadlines, τ_{dl}, i.e., they must be delivered to the recipients in a timely fashion. Therefore, we define a performance measure called MAC-to-MAC delay, τ_{MM}, which must satisfy $\tau_{MM} < \tau_{dl}$ to meet the deadline. In Figure 1 the delays encountered at the transmitter, TX, the receiver, RX, together with the channel are depicted. At t_0 a channel access request at TX is done, and the time elapsing from t_0 to t_{T_x} is denoted the channel access delay, τ_{ca}, i.e., the time from channel access request to actual transmission. For periodic position messages, there is no use to transmit the packet if $\tau_{ca} > \tau_{dl}$, because a new message with updated position information has then already been generated. The packet is therefore dropped already at the transmitter, and we say that $\tau_{ca} = \infty$. The propagation delay is denoted τ_p and the decoding delay is τ_{dec}. If decoding fails, due to noise, fading or/and interference, we set $\tau_{dec} = \infty$. At t_d the decoded packet is delivered to higher layers at the receiver. Hence, τ_{MM} is the sum of τ_{ca}, τ_p, and τ_{dec} and it is finite if and only if the packet is actually delivered to the higher layers at the receiver. The cumulative distribution function (CDF) of τ_{MM} captures both the delay and the reliability of the system, and this metric will be used for performance evaluation in Section V. It should be noted that τ_{ca} is not upper bounded in some random access schemes, e.g. CSMA.

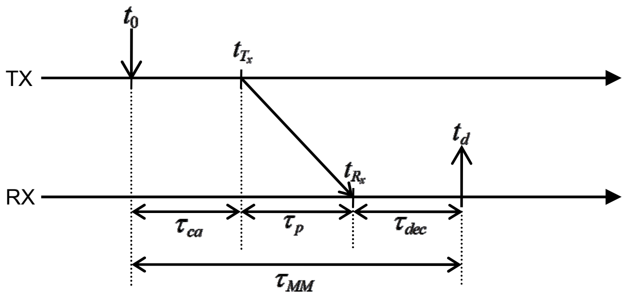

Fig 1. Delays found in the MAC layer.

V. PERFORMANCE EVALUATION

We study the performance of the MAC methods CSMA of 802.11p and STDMA when used on a control channel that carries both time-triggered position messages and event-driven hazard warnings. We consider single-hop communications since messages of multi-hop character are restricted to the service channels in the current European standardization proposal. A highway scenario with 10 lanes (five in each direction) is used for evaluating the two MAC methods through computer simulations in Matlab. The vehicles arrive at the highway entrance according to a Poisson distribution with an inter-vehicle arrival rate of 1/3 Hz. The resulting vehicle density is then approximately 10 vehicles/lane/km. The data traffic generated by each vehicle is periodic, i.e., time-triggered position messages, where each vehicle's initial transmission time is independent and random. Hence, no event-driven hazard warnings are present. The position messages are transmitted using the highest priority in CSMA, implying a T_{AIFS} of 58 μs and the *CW* set to 3. The vehicle speeds are drawn independently from Gaussian distributions with a common standard deviation of 1 m/s, but with different mean values (23 m/s, 30 m/s and 37 m/s) depending on lane. The vehicles maintain the same speed as long as they are on the highway. All vehicles broadcast position messages with a fixed data rate, R = 6

Mbps, and two different packet lengths in bytes, B, and update frequencies, f_p, are used, Table 1.

Table 1. Data traffic models.

	B [byte]	f_p [Hz]	Band-width req. [kbps]	No of slots/ frame
Data traffic model Europe	800	2	12.8	904
Data traffic model USA	300	10	24	2283

These two data traffic models are selected based on discussions in Europe within ETSI and in the US within IEEE, respectively. The bandwidth requirements for each node based on the data traffic models and the number of slots in the STDMA frame for each model are also found in Table 1. The frame size in STDMA is 1 second.

The channel model used in the simulator is based on outdoor channel sounding measurements performed at 5.9 GHz between moving vehicles [20]. The collected data has served as a foundation to find a suitable statistical model and its parameter setting. The small scale and the large-scale fading is both represented by the Nakagami *m* model [21], which has earlier been pointed out to be a suitable candidate for channel modeling of the vehicular environment [22]. The probability density function for the Nakagami *m* distribution is:

$$f\left(x;m,P_r(d)\right)=\frac{2m^m x^{2m-1}}{\left[P_r(d)\right]^m\Gamma(m)}e^{\frac{mx^2}{P_r(d)}}, \tag{1}$$

where m represents the fading intensity, $P_r(d)$ the average received power at a distance d, and $\Gamma(m)$ is the gamma function. Rayleigh fading conditions, i.e., no line-of-sight exists, can be obtained through Nakagami by setting $m=1$. Higher values of m can be used for approximating Rician distributed channel conditions where a line of sight exists, while $m<$ 1, the channel conditions are worse than the Rayleigh distribution. The estimated values of m from the channel measurements are distance-dependent [20], Table 3. The average received power, P_r, is assumed to follow the dual-slope model suggested in [19], i.e.,

$$P_{r,dB}(d)=\begin{cases}P_{r,dB}(d_0)-10\gamma_1\log_{10}\dfrac{d}{d_0}, & d_0\le d\le d_c\\[2ex] P_{r,dB}(d_c)-10\gamma_2\log_{10}\dfrac{d}{d_c}, & d>d_c\end{cases} \tag{2}$$

where numerical values for the parameters are found in Table 2. Hence, the instantaneous received power is found by drawing a random number from the distribution in (1), in which $P_r(d)=10^{P_{r,dB}(d)/10}$ is computed from (2).

Table 2. The path gain model's parameter values.

Parameter	Value
Dual slope γ_1	2.1
Dual slope γ_2	3.8
Critical distance d_c [m]	100
Reference distance d_0 [m]	10

Table 3. The different m values in the Nakagami distribution.

Distance bin (in meters)	m
0-6	4.07
6-14	2.44
14-36	3.08
36-91	1.52
91-231	0.74
231-588	0.84

All vehicles use the same output power, $P_{t,dB}$, of 20 dBm (100 mW) and the reference power, $\mathrm{P}_{r,dB}\left(d_o\right)$, is calculated using the following free space path gain formula[23]:

$$P_{r,dB}\left(d_0\right)=P_{t,dB}-10\log\left(\frac{\lambda^2}{\left(4\pi\right)^2 d_0{}^2}\right), \tag{3}$$

where $d_0=10$ m and the wavelength, λ, is based on a carrier frequency of f = 5.9 GHz. The carrier sense threshold for CSMA is -96 dBm and by employing (2), the carrier sense range for each vehicle is approximately 500 meter. The resulting signal-to-interference-plus-noise (SINR) ratio at the receiver is calculated using the following formula:

$$SINR=\frac{P_r}{P_n+\sum_k P_{i,k}}, \tag{4}$$

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.

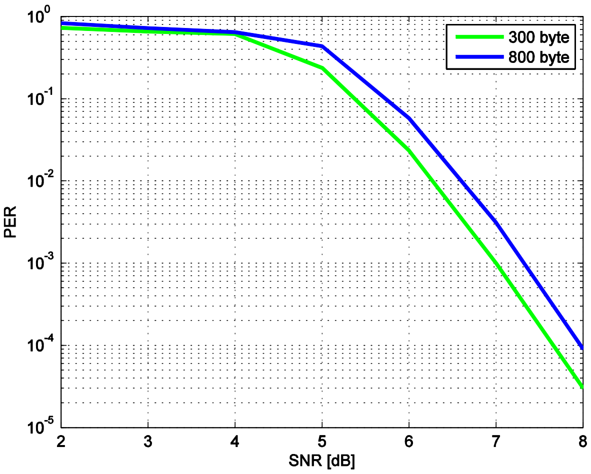

Fig. 2 Packet error rate versus signal-to-noise ratio for 300 byte and 800 byte long packets, respectively.

Both MAC methods are using the same PHY layer of 802.11p, i.e., orthogonal frequency multiplexing (OFDM). The packet error probability (PER) for the two different packet lengths using the PHY layer of 802.11p is derived from PHY layer simulations over an additive white Gaussian noise channel (AWGN), Figure 2. These PHY layer simulations lack interferers and therefore this result in signal-to-noise ratio

(SNR) curves. However, if we approximate the interference as extra AWGN, we can read off the PER from plots in Figure 2 by using the SNIR instead of the SNR.

In Figure 3 the CDF of the MAC-to-MAC delay is depicted for receivers located within different distances from the transmitter, i.e., 100 m, 300 m, and 500 m, when a packet length of 800 byte and 2 Hz has been used. The deadline, τ_{dl}, is then 500 ms. In Figure 4 the MAC-to-MAC delay for 300 byte packets at a rate of 10 Hz is shown, implying τ_{dl}=100 ms. Recall that while $\tau_{ca} < \infty$ is always fulfilled for STDMA, packet drops may occur at the receiver side for CSMA. However, by inspecting the results it was found that no packet drops occurred for CSMA for any of the data traffic settings evaluated, i.e., $\tau_{ca} < \infty$. At the receiver, packets may also be dropped due to decoder failure caused by noise and/or interference. This leads to $\tau_{dec} = \infty$ and missed deadlines (the position message was never successfully received). The decoder failures being defined as $\tau_{dec} = \infty$ explains why the CDF curves do not reach 1 for finite delays.

For STDMA nearly 100% of all nodes within 100 meter from the transmitter receive the packet correctly for 800 bytes and 2 Hz in Figure 3, i.e., nearly 100% packet reception probability. The deadline miss ratio, i.e., $\Pr\{\tau_{MM} > \tau_{dl}\}$ is easily found in Figure 3 and Figure 4. For nodes situated 100 meter from the transmitter in Figure 4, roughly 2% of the deadlines are missed for STDMA and 8% for CSMA. Since, in Figure 3 and 4, missed deadlines are only caused by decoding failures, the packet reception probability is simply $1-\Pr\{\tau_{MM} > \tau_{dl}\}$.

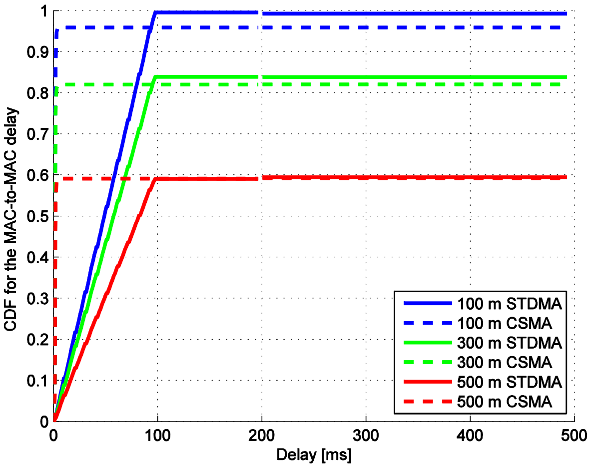

Fig. 3 CDF for MAC-to-MAC delay, 2 Hz, 800 byte, for different maximum distances from the transmitter.

STDMA has on average a longer channel access delay due to the slotted scheme but have a higher reliability since the transmissions are scheduled further apart in space. The channel access delay τ_{ca} in STDMA is uniformly distributed in the interval $[0,(\tau_{dl}/5)]$. The scheduling results in less interference for the closest neighbors of the transmitter. For CSMA, on the other hand, concurrent transmissions are unplanned and occur mainly when multiple nodes reach the backoff value zero at the same time. This phenomenon occurs despite carrier sensing due to the randomness in the CSMA protocol. Therefore, the reliability of CSMA is decreased compared to STDMA for all settings in this study. It should be noted that neither the *CW* setting of CSMA nor the channel access delay of STDMA have been optimized. In Figure 4, the overall reliability has decreased compared to Figure 3, because there is more data traffic injected into the network. Still the nodes employing STDMA have a higher probability of receiving packets. At a distance of 500 meter from the transmitter, it is the noise rather than the interference that limits the reception of transmissions and the performance of CSMA and STDMA are therefore similar for both settings.

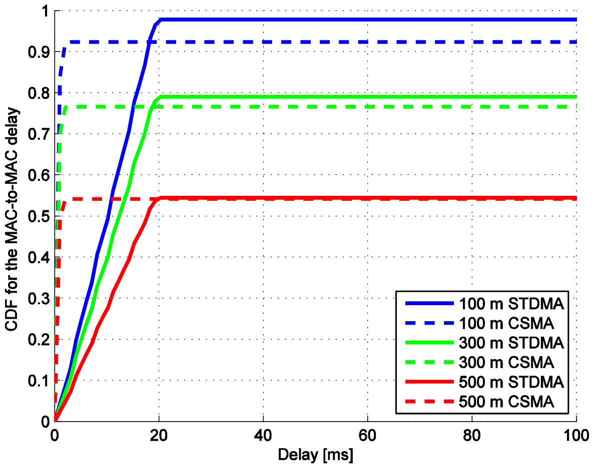

Fig. 4. CDF for MAC-to-MAC delay, 10 Hz, 300 byte, for different maximum distances from the transmitter.

VI. CONCLUSIONS

A key component to successful deployment of road traffic safety applications using an LDM is the ability to transmit position messages periodically and reliably on the control channel. The delay and interference experienced with two different MAC methods CSMA and STDMA have been investigated through computer simulations of a highway scenario in this paper. In contrast to CSMA where nodes may be hindered from transmitting, nodes using STDMA will always get timely channel access regardless of the number of participating nodes in the VANET. The delay is, however, on average higher for STDMA than CSMA. Of course a low delay is beneficial but for messages that have requirements on a finite delay it is more important that the deadlines are kept, i.e., $\tau_{MM} < \tau_{dl}$. A major difference between STDMA and CSMA is that the former schedules transmission in space. The scheduling of transmissions results in lower interference and higher packet reception probability for the closest located receivers. The CSMA scheme is less reliable, i.e., has lower packet reception probability, due to simultaneous channel access by potentially closely located nodes despite the carrier sensing, either in the initial channel access attempt or due to reaching a backoff value of zero at the same time. To increase the reliability and to keep the maximum delay bounded we therefore propose using the STDMA algorithm on the control channel of VANETs.

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