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(Article begins on next page)

Scalability Issues of the MAC Methods STDMA and CSMA of IEEE 802.11p When Used in VANETs

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Abstract – Position messages will be the foundation for many emerging traffic safety applications based on wireless communications. These messages contain information about the vehicle’s position, speed, direction, etc. and are broadcasted periodically by each vehicle. The upcoming IEEE 802.11p standard, intended for vehicle *ad hoc* networks (VANETs) has flaws caused by the unpredictable behavior of its medium access control (MAC) scheme, which imply that traffic safety applications cannot be supported satisfactorily when the network load increases. We study the MAC mechanism within IEEE 802.11p being a carrier sense multiple access (CSMA) algorithm and compare it with a self-organizing time division multiple access (STDMA) scheme when used for broadcasting periodic position messages in a realistic highway scenario. We investigate their scalability in terms of the number of vehicles that the VANET can support using metrics such as channel access delay, probability of concurrent transmissions and interference distance. The results show that STDMA outperforms CSMA of 802.11p even when the network is not saturated.

I. INTRODUCTION

The main motivation for using vehicular communications to form cooperative systems is to decrease the number of traffic accidents by introducing traffic safety applications, but also to reduce congestion, travel-time and pollution through traffic efficiency applications. In addition, other types of services may be offered to facilitate system introduction and provide sustainable business and operation models. Mainly three types of applications are considered: *traffic safety*, *traffic efficiency* and *value-added services*. These applications will use different wireless access technologies to meet the diverse set of communication requirements. The main focus of this article is traffic safety applications since the communication requirements of these applications are particularly complex and demands on *reliability* and *predictable delay* are needed concurrently. Traditionally, applications have had demands on reliability *or* delay but not simultaneously. Existing wireless technologies such as 2G/3G and IEEE 802.11 have been designed with specific applications in mind. 2G/3G was originally intended only for voice, indicating a delay sensitive application that can tolerate lower data reliability, whereas IEEE 802.11 is designed for data communication where reliability is more important than delay.

Many traffic safety applications will rely on position messages, broadcasted periodically by every vehicle containing information about speed, position, heading, etc. These messages are generated periodically, typically between 2-10 Hz and have timing requirements, i.e., a deadline. This implies that there is no use to transmit a delayed position message after its deadline, i.e., when a new one has been generated. In addition, to prevent mute, invisible vehicles, all nodes need access to the channel in a fair way to transmit their position message.

Many of the traffic safety applications being proposed both in the US and in Europe will rely on *ad hoc* communications, i.e., direct vehicle-to-vehicle communications, using the upcoming IEEE 802.11p standard [1]. A typical vehicular *ad hoc* network (VANET) is a spontaneous network with no central mechanism controlling the network resources [2]. This is advantageous for traffic safety applications, since it eliminates the need for coverage by access points or base stations. The VANET, as specified in 802.11p, must self-organize, provide distributed channel access, and have support for all nodes within radio range. Therefore, the medium access control (MAC) procedure in a VANET must be decentralized to fit the *ad hoc* structure. The MAC method also needs to cope with rapid topology changes, i.e., nodes entering and leaving the network, as well as overloaded situations in terms of increased number of nodes and/or increased amount of data traffic injected without collapsing.

IEEE 802.11p uses the MAC method carrier sense multiple access (CSMA), which is decentralized, has support for variable packet sizes and requires no strict synchronization between nodes, resulting in an algorithm with fairly low complexity. The IEEE 802.11p has been evaluated for VANETs previously, but from an average performance viewpoint [3, 4]. However, when considering traffic safety applications worst case aspects are required. The authors have previously shown that CSMA has problems with unbounded channel access delay and multiple consecutive packet drops [5]. This shows that the CSMA has problems with predictability and fairness, especially when periodic positioning messages are used. Due to these problems the authors proposed to use a self-organizing time division multiple access (STDMA) scheme, where nodes, regardless of how many, always are granted access to the channel, i.e., the channel access delay is upper

This work was funded in part by the Knowledge Foundation, www.kks.se. E. Uhlemann is partly funded by the Swedish Governmental Agency for Innovation Systems, Vinnova, through the VINNMER program, www.vinnova.se.

bounded. STDMA is fair and has a predictable delay, properties that remain even during heavily loaded periods [5]. However, strict synchronization is needed, through a global navigation satellite system (GNSS) and the self-organizing mechanism requires periodic position messages to be present in the system.

Apart from predictable delay and fair channel access, the MAC method used in a VANET also needs to scale well, since the number of participating vehicles cannot be limited. In this paper we therefore evaluate the scalability of the two MAC methods; STDMA and CSMA of IEEE 802.11p for periodic position messages. Rather than focusing on average behavior, we consider performance metrics such as interference distance, the probability that two or more nodes within radio range transmit concurrently and the channel access delay.

The remainder of this paper is organized as follows. In Section II, the performance measures are derived. The evaluated MAC schemes are described in Section III and evaluated in Section IV. Finally, Section V contains our conclusions.

II. PERFORMANCE MEASURES

Since the data traffic model is periodic time-triggered position messages having a deadline the traditional performance measure throughput is of less importance. Therefore, this section derives the measures used for performance evaluation in this paper. The *period*, T_p , is defined as

$$T_p = \frac{1}{f_p}, \quad (1)$$

where f_p is the *update rate* of the position messages. Hence, the MAC layer of the transmitting node will receive a channel access request every T_p seconds.

The *channel access delay*, T_{acc} , is defined as the time from channel access request to actual channel access, Fig 1. The *transmission time*, denoted T_{TX} , is defined as the time it takes to complete a transmission counted from having gained channel access until the packet has been decoded at the receiver. Hence, T_{TX} is the sum of the processing time of the transmitting physical (PHY) layer, the propagation delay, and the processing time of the receiver's PHY and MAC layers. Note that the packet is not necessarily correctly decoded at the receiver. This yields:

$$T_{MAC} = T_{acc} + T_{TX}, \quad (2)$$

where T_{MAC} is the total time spent on a transmission from a MAC to MAC layer perspective. We assume that a packet awaiting channel access is dropped if a new periodic packet is generated. By convention, we let $T_{acc} = \infty$ for dropped packets. We note that, in general, T_{acc} is a random variable.

The deadline miss ratio is a central performance measure in traffic safety applications [5]. For simplicity, we will assume that the relevant deadline for transmitting the position messages at the MAC layer is T_p . A missed deadline in a wireless broadcast communication system, as seen from the MAC layer perspective, is therefore caused by one of two mutually exclu-

sive events;

- (i) if $T_{acc} \geq T_p$, i.e., the packet was never transmitted
- (ii) if $T_{acc} < T_p$ and the packet was not decoded correctly due to noise, fading, and interference.

Case (i) is studied further in Section IV by characterizing the distribution of T_{acc} .

To characterize the interference, we study the geographical distribution of nodes that are involved in simultaneous transmissions. Nodes that are within sensing range, d_s , of each other when transmitting are considered to interfere. Given that a node i initiates a transmission at time instance t_i , let n be the number of nodes within d_s of node i , that also initiate transmissions at time t_i . Let

$$p_k = \Pr[n = k], \quad (3)$$

where p_k is the probability of k concurrently transmitting nodes. Since $p_1 \gg p_2$, which will be demonstrated by our performance evaluation later on, we concentrate on p_1 . We define the *interference distance*, d_i , as the distance between concurrently transmitting nodes, conditioned on $n = 1$. Clearly, the smaller d_i is, the worse interference situation occurs for the receiving neighboring nodes. For this reason, we will study the distribution of the d_i and p_k in Section IV.

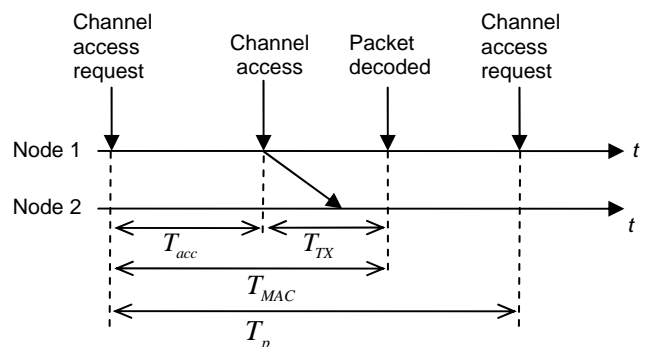


Fig. 1. Time line for channel access request to channel access.

III. CSMA AND STDMA

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 sensing period, the node must perform a backoff procedure, i.e., the node has to defer its access 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 PHY layer in use (i.e., in 802.11p $T_{slot} = 13 \mu s$), and set this as the backoff value, (iii) decrease the backoff value by one *slot time* when a carrier sense operation declares the channel as free, (iv) upon reaching a backoff value of 0, send immediately. Hence, after a busy channel becomes clear, all nodes must perform a carrier

sense operation, i.e., listen T_{AIFS} , before decrementation of the backoff value can resume.

STDMA [6] is already in commercial use in a system called automatic identification system (AIS), with focus on collision avoidance between ships [7]. In STDMA the time is divided into time slots constituting a frame and one packet fits into one time slot. 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 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, position messages are used also by the MAC layer. 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. When a node is turned on, it follows four different phases; (i) initialization, (ii) network entry, (iii) first frame, and (iv) continuous operation. During (i) the node will listen for the channel activity 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 the (ii), the node determines its own slot assignment based on the information gathered during (i). 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 (iii) the node starts transmitting in the slots decided during (ii), implying that the node now introduces itself to the network for the first time. In the last phase (iv) the slots determined earlier are used for transmission. However, to cater for network topology changes, the same slot assignment is not kept for long. During the (iii) the node will also draw a random integer for each assigned slot which determines for how many consecutive frames this particular slot will be used. Note that the random number is different for each assigned slot in the frame. When the specific slot has been used for its number of consecutive frames, the node must assign a new slot and attach a new random number to it.

IV. PERFORMANCE EVALUATION

We have evaluated the scalability of CSMA and STDMA by means of computer simulation using periodic position messages as data traffic model. Depending on the transfer rate, the packet size and the frequency of the position messages, a VANET can support a certain number of vehicles within radio range without being overloaded. The maximum number of packets that theoretically can be sent without collisions during one second in a broadcast scenario using CSMA of IEEE 802.11 is given by:

$$N_{CSMA} = \left\lfloor \frac{1}{B \times 8 / R + T_{AIFS}} \right\rfloor \quad (4)$$

where $\lfloor x \rfloor$ is the largest integer smaller or equal to x , B is the packet size in bytes, R is the transfer rate in bits/second and T_{AIFS} is in seconds. For STDMA the maximum number of packets per second is:

$$N_{STDMA} = \left\lfloor \frac{1}{B \times 8 / R} \right\rfloor \quad (5)$$

since no carrier sense is needed. By knowledge of the periodicity and the maximum number of packets per second, we can calculate the maximum number of vehicles within radio range that the two MAC protocols theoretically can support without collisions. Note, however, that this number is an upper bound and is achievable only if the arrival of the packets (i.e., the start of the periods in the different nodes) is uniformly spaced in time. The channel would then be fully loaded and completely filled with packets, i.e., a network load of 100%. In Table 1, the theoretical numbers of packets and vehicles supported during one second are tabulated for $R = 6$ Mbit/s, $f_p = 2$ Hz, and $B = 800$ byte, together with the shortest AIFS possible in 802.11p, $T_{AIFS} = 58 \mu s$. In Table 2, the corresponding calculations are shown for $f_p = 10$ Hz and $B = 300$ byte. The two different packet lengths and update frequencies are selected based on discussions in Europe within ETSI and in the US within IEEE, respectively. In Europe $f_p = 2$ Hz and $B = 800$ byte is proposed whereas the US proposal is for $f_p = 10$ Hz and much shorter packet lengths, in the order of 100-300 bytes.

Table 1. Theoretical number of vehicles supported within transmission range with an update rate of 2 Hz and 800 byte packets.

	CSMA	STDMA
Number of packets/s	889	937
Number of vehicles	444	468

Table 2. Theoretical number of vehicles supported within transmission range with an update rate of 10 Hz and 300 byte packets.

	CSMA	STDMA
Number of packets/s	2183	2500
Number of vehicles	218	250

The difference between STDMA and CSMA lie in how far away from the ideal case (as tabulated above) the two schemes are when used in practice. When we increase the number of vehicles within communication range beyond the maximum number that can be supported (e.g., 120% network load), it has different effects in CSMA and STDMA. When the network becomes overloaded in CSMA, the transmitters will start to drop packets before they are even sent, since a new packet with updated position information will be generated, i.e., the deadline of the previous packet was missed. When the network becomes overloaded in STDMA, all packets are sent in time, but the distance between nodes that use the same slot is reduced, thereby increasing the interference. In CSMA the *message arrival distribution* or the offset between the start of the periods in different nodes plays an important role when considering the number of supported vehicles. In the best case, the message arrival distribution is uniform and all nodes have a

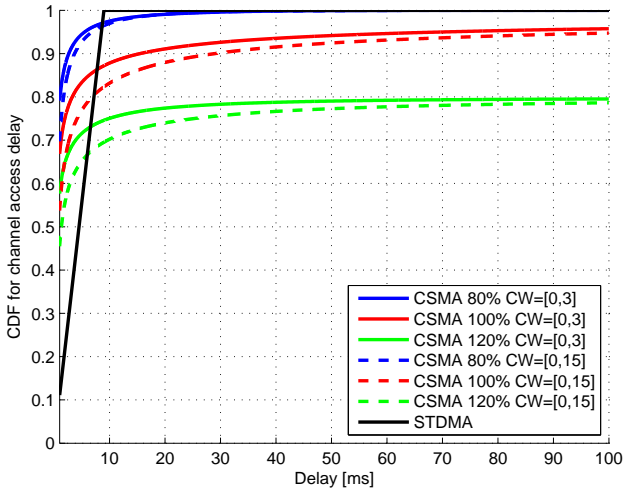


Figure 2. The CDF for channel access delay for CSMA and STDMA for 10 Hz and 300 byte at different traffic loads – 80%, 100% and 120%. The CSMA has also two different CW setting.

unique start of their period and evenly distributed. In the worst case, all vehicles want to transmit their periodic position messages at the same time and the start periods are completely synchronized. This would result in all vehicles sensing the channel, determining that it is free and then all vehicles would transmit at the same time, implying that the distance between simultaneously transmitting nodes is minimized. Another bad situation for CSMA is that one vehicle have started to transmit its message while all remaining vehicles want to send, sense the channel, determine that it is busy, randomize a backoff value and then collisions occur for all nodes that have chosen the same backoff value (this occurs with a nonzero probability since the backoff values are chosen from a finite set $\{0, T_{slot}, 2 \times T_{slot}, \dots, CW \times T_{slot}\}$). For STDMA these two situations entail no problems since all vehicles have to wait for their timeslot regardless of when a message arrive and when two nodes do send at the same time the distance between them is maximized. To show these findings we have used the fol-

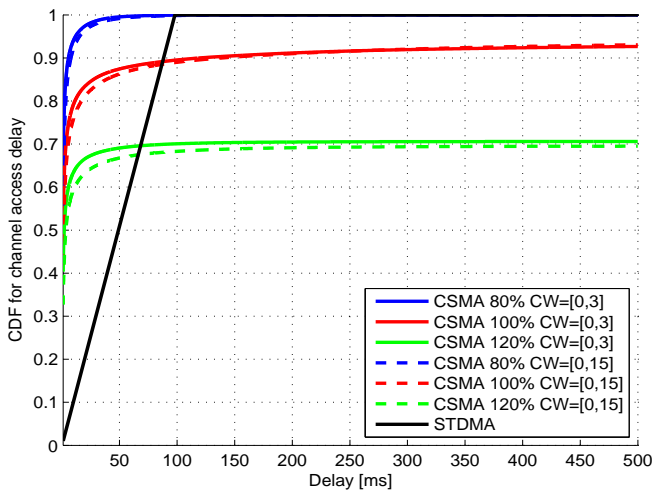


Figure 3. The CDF for channel access delay for CSMA and STDMA for 2 Hz and 800 byte at different traffic loads – 80%, 100% and 120%.

lowing simulation.

We consider a highway scenario with five lanes in each direction. The vehicles arrive at the highway entrance according to a Poisson distribution. The inter-vehicle arrival rate is 1/3 Hz, which reflects dense traffic. The data traffic is periodic with independent and random starting times. A speed is randomized for each vehicle, which they maintain as long as they are on the highway. In [5] more details about the simulator are found. All vehicles broadcast position messages at a predetermined periodicity with two different packet lengths and update frequencies – 800 byte, 2 Hz and 300 byte, 10 Hz. Simulations have been conducted with three different network loads; 80%, 100% and 120% (note that each MAC scheme is loaded with the respective number of vehicles that constitutes its 100%, load, as seen in Table 1 and 2). The network loads have been achieved by altering the communication range for the nodes and thereby different numbers of nodes come within range. Since the vehicles are moving, the number of vehicles within communication range differs slightly from vehicle to vehicle, but on average the loads have been obtained. CSMA simulations have been run with two different sizes of the contention window, $CW=3$ and $CW=15$. The former CW is from the highest priority queue found in 802.11p and the latter is from the lowest priority queue. A longer listening period, AIFS, when all packets have the same priority results in lower channel usage. A larger backoff window will spread the nodes in time. The transmitting side has been evaluated using the performance measures distribution of channel access delay, the probability that two or more nodes transmit concurrently together with the distribution of the interference distance.

In Fig. 2, the *cumulative distribution function (CDF) for channel access delay* for CSMA and STDMA is depicted for a packet size of 800 byte and an update frequency of 2 Hz. For this setting, each STDMA frame of duration 1 second contains 937 slots. For 2 Hz, each STDMA node selects two slots in each frame separated approx. T_p apart to transmit in. Each slot can only be selected from a subset of available slots. The subset is 20% of the number of slots that fits into T_p . This explains why the CDF for STDMA reaches one already after 20% of the T_p , because all channel access request have then resulted in channel access. However, in CSMA at a load of 100%, the nodes do not transmit all generated packets since some deadlines are missed and the corresponding packet is then dropped. By convention, $T_{acc} = \infty$ in this case. The results show that no packet drops occur with CSMA for a network load of 80%, but for 120% almost 30% of all generated packets averaged over all nodes are dropped. The CW setting for CSMA shows that a few more packets are dropped when the CW is increased due to the backoff values on average being longer, resulting in more deadlines expiring.

In Fig. 3, the channel access delay for CSMA and STDMA is depicted for a packet size of 300 byte and an update frequency of 10 Hz. On average there are fewer packet drops for this CSMA setting since the packet size is shorter and therefore every node keeps the channel occupied a shorter time,

favoring some packet arrival distributions.

In Table 3 the *probability that multiple nodes transmit at the same time* is depicted for the setting of 2 Hz and 800 byte packets at a network load of 80%. The probability that two nodes initiate transmissions at the same time, $k=1$, is almost the same for STDMA as for CSMA with $CW=15$, but significantly higher for $CW=3$. The larger CW results in nodes being spread more in time, thereby reducing the probability of multiple concurrent transmissions and at the same time increasing the probability of dropped packets, as seen in Fig. 2.

Table 3. Probability that one, $k=0$, two, $k=1$, or more nodes initiate transmission at the same time at a network load of 80%, update frequency of 2 Hz, and 800 byte packets.

	$p_k = \Pr[n = k]$			
	$k = 0$	$k = 1$	$k = 2$	$k = 3$
CSMA , $CW=3$	0.9156	0.0769	0.007	4.8×10^{-4}
CSMA , $CW=15$	0.9717	0.0275	8.2×10^{-4}	8.6×10^{-6}
STDMA	0.9795	0.0204	2.6×10^{-5}	0.000

In Fig. 4 the *CDF for the interference distance*, d_i , is shown for 2 Hz and 800 byte packets. The probability of at least two CSMA nodes sending at the same time is almost the same regardless of the CW setting and the load. However, there is a huge difference between CSMA and STDMA. In STDMA, nodes use available position information to schedule the transmissions with the aim to maximize the distance between two concurrently transmitting nodes. In CSMA (not using this side information) the randomness of the protocol plays a major role. A second reason is that the discrete random backoff values are too few, even with $CW = 15$, i.e., multiple transmissions start at the same time instant.

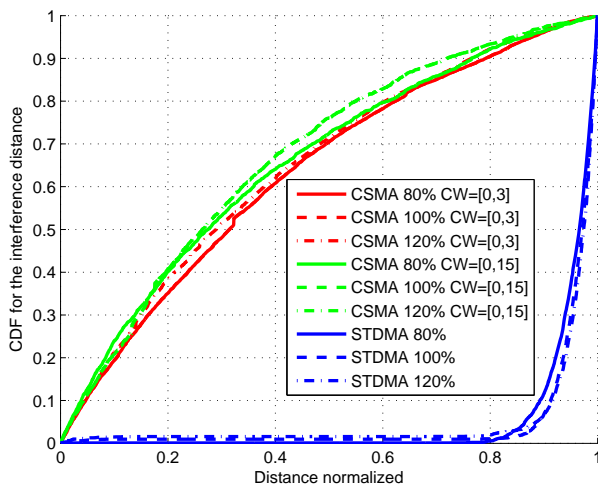


Figure 4. The CDF for interference distance for CSMA and STDMA for 2 Hz and 800 byte at different traffic loads – 80%, 100% and 120%.

V. CONCLUSIONS

The first generation of traffic safety systems based on VANET will use IEEE 802.11p. However, the randomness of the CSMA protocol causes randomness of concurrent transmis-

sions in space. This means that the probability that two concurrently transmitting nodes are situated close to each other is much higher than for STDMA. When using STDMA, the nodes located closest to a transmitter are better protected since concurrent transmissions are scheduled to be as far apart as possible. The main difference between the MAC methods CSMA and STDMA is *where in space concurrent transmissions take place* – in CSMA it is randomly distributed and in STDMA it is scheduled using the side information from the position messages. Therefore, when the network load in a VANET increases, STDMA becomes more and more attractive compared to CSMA. STDMA may also provide increased *reliability* due to reduced interference for nodes situated closest to the current transmitters. Intuitively, these nodes are most interested in receiving information from the transmitters. Consequently, when considering the performance measure *interference distance* we found that STDMA outperforms CSMA even for non-saturated networks. In an attempt to reduce the amount of concurrently transmitting nodes in CSMA, simulations were conducted with an increased backoff window. This resulted in a slightly higher number of packet drops at the sending side, i.e., more missed deadlines, but indeed fewer concurrent transmissions. However, the distance between concurrently transmitting nodes in CSMA is independent of the CW setting. STDMA provides *fairness*, *predictable channel access delay*, and good *scalability* since all channel requests turn into channel access that are scheduled far apart in space. However, STDMA does require slot synchronization and position information to function. The latter is already present but the synchronization issue must be studied further. CSMA will work well when the network load is moderate; it does not require synchronization and supports arbitrary packet lengths. However, the question is what happens when there is an accident on a highway with highly congested vehicle traffic. Will CSMA handle that situation?

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