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Katrin Bilstrup, Elisabeth Uhlemann, Erik G. Ström and Urban Bilstrup

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Evaluation of the IEEE 802.11p MAC method for Vehicle-to-Vehicle Communication

Katrin Bilstrup[†,§], Elisabeth Uhlemann[†,‡], Erik G. Ström[†,§] and Urban Bilstrup[†]

[†]Centre for Research on Embedded Systems
Halmstad University
Box 823, SE-301 18 Halmstad, Sweden

[‡]Volvo Technology Corporation
Transport, Information and Communication
M1:6, SE-405 08 Göteborg, Sweden

[§]Department of Signals and Systems
Chalmers University of Technology
SE-412 96 Göteborg, Sweden

Email: Katrin.Bilstrup@hh.se, Elisabeth.Uhlemann@hh.se, Erik.Strom@chalmers.se and Urban.Bilstrup@hh.se

Abstract – **In this paper the medium access control (MAC) method of the upcoming vehicular communication standard IEEE 802.11p has been simulated in a highway scenario with periodic broadcast of time-critical packets (so-called heartbeat messages) in a vehicle-to-vehicle situation. The 802.11p MAC method is based on carrier sense multiple access (CSMA) where nodes listen to the wireless channel before sending. If the channel is busy, the node must defer its access and during high utilization periods this could lead to unbounded delays. This well-known property of CSMA is undesirable for time-critical communications. The simulation results reveal that a specific node/vehicle is forced to drop over 80% of its heartbeat messages because no channel access was possible before the next message was generated. To overcome this problem, we propose to use self-organizing time division multiple access (STDMA) for real-time data traffic between vehicles. This MAC method is already successfully applied in commercial surveillance applications for ships (AIS) and airplanes (VDL mode 4). Our initial results indicate that STDMA outperforms CSMA for time-critical traffic safety applications in *ad hoc* vehicular networks.**

I. Introduction

The area of intelligent transportation systems (ITS) has attracted a lot of attention during the last years due to the range of new applications enabled by emerging wireless communication technologies. Existing in-vehicle safety systems together with new cooperative systems using wireless data communication between vehicles can potentially decrease the number of accidents on the roads. Due to this, a tremendous interest in cooperating safety systems for vehicles can be noticed through the extensive range of project activities around the world. Lane departure warning, merge assistance and emergency vehicle routing are all examples of applications which can be found in for example the American VII [1], the European Safespot [2], and the Japanese DSSS [3] projects.

These new traffic safety systems implies increased requirements on the wireless communication and the challenge is not only to overcome the behavior of the unpredictable wireless channel but also to cope with rapid network topology changes together with strict timing and reliability requirements. The timing requirements can be deduced from the fact that it is only relevant to communicate about an upcoming dangerous situation before the situation is a fact and perhaps can be avoided (e.g., communicate a probable collision *before* the vehicles are colliding). Therefore traffic safety systems could be classified as real-time systems [4]. Real-time communication implies that there needs to be an upper bound on the communication delay that is smaller than the deadline. If the correct data does not reach its intended recipient before a certain deadline in a real-time system, the data is more or less useless and the missed deadline will have more or less severe consequences for the system performance. Communicating real-time messages does not necessarily require a high transmission rate, or a low delay, but it does require a predictable system that is able to deliver the message before the deadline. Thus, the ability to predict worst case system behavior is the most important feature in a real-time system.

One crucial thing in this respect is how the shared communication channel should be divided in a fair and predictable way among the participating users. This is done through the medium access control (MAC) method. Much attention within the standardization of vehicle communication systems has been devoted to enhancing the MAC method by introducing different quality of service (QoS) classes for data traffic with different priorities [5]. However, in the context of safety applications applied in a high speed vehicular environment, there has been limited discussion about the type of real-time requirements actually imposed by the new traffic safety systems and if the MAC method is able to meet these requirements.

The MAC layer in a traffic safety application is unlikely to need many different service classes or transfer rates. Instead, to guarantee that time-critical communication tasks meet their deadlines, the MAC method must first of all provide a finite *worst case access time to the channel.* Once channel access is a fact, different coding strategies, diversity techniques and retransmission schemes can be used to achieve the required correctness and robustness against the impairments of the unpredictable wireless channel. However, if the MAC scheme does not provide an upper bound on the maximum delay before channel access, it is not possible to give any guarantees about meeting deadlines. Information that is delivered after the deadline in a critical real-time communication system is not only useless, but implies severe consequences for the traffic safety system. This problem has also been pointed out in [6].

The IEEE 802.11p, also known as dedicated short-range communication (DSRC), is an upcoming WLAN standard

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intended for future traffic safety systems. This is currently the only standard with support for direct vehicle-to-vehicle (V2V) communication [7]. Unfortunately, the term DSRC is ambiguous. The original DSRC standards, which are found in Europe, Japan and Korea, are more application-specific standards containing the whole protocol stack with a physical (PHY), a MAC and an application layer. They are intended for hot spot communication such as electronic toll collection systems.

The PHY in 802.11p and its capabilities have been treated in several articles [8-10]. The PHY mainly affects the reliability (error probability) of the system; however, if we do not get channel access the benefits of the PHY cannot be exploited. The 802.11p MAC method is based on carrier sense multiple access (CSMA), where nodes listen to the wireless channel before sending. If the channel is busy, the node must defer its access and during high utilization periods this could lead to unbounded delays. Evaluations and enhancements of CSMA have been proposed in [11-15]. In [11] an investigation of 802.11p is made using real-world application data traffic, collected from three vehicles communicating with each other on a highway in the US. However, this scenario does not show the scalability problem of the MAC protocol. All MAC methods will function well as long as they are not loaded in terms of nodes and data traffic. Hence, a worst case analysis of a vehicular communication system is needed. The performance of 802.11p is evaluated analytically and through simulation in [12]. It is concluded that 802.11p cannot ensure time-critical message dissemination due to the amount of data that needs to be sent. The solution proposed in [12] is to decrease the amount of data traffic. The suggested enhancements of 802.11p include trying to avoid packet collisions by using a polling scheme [13] or by decreasing the amount of data traffic, e.g., through better prioritization [14-15]. However, none of these papers clearly point out that the MAC layer lacks the real-time properties required by traffic safety systems.

This paper evaluates the real-time requirements on the MAC protocol when used in *ad hoc* vehicle communication systems for low-delay traffic safety applications. Next two different MAC methods are evaluated by means of computer simulations: the MAC method in 802.11p, CSMA, and a solution potentially better suited for decentralized real-time systems, namely self-organizing time division multiple access (STDMA). First, an introduction to the concept of MAC is given together with functionality descriptions of CSMA and STDMA. Next, the system model is detailed and results from the simulator are presented. The paper is concluded with a discussion and conclusions regarding the two examined MAC methods in the context of traffic safety applications.

II. Medium Access Control

A vehicular *ad hoc* network (VANET) is a spontaneous, unstructured network based on direct V2V communication and its topology is changing constantly due to the high mobility of the nodes. In a VANET it is harder to deploy a MAC scheme that is relying on a centralized controller, e.g., time division multiple access (TDMA), frequency division multiple access (FDMA), or code division multiple access (CDMA). In a centralized, infrastructure-based network, a base station or an access point is responsible for sharing the resources among the users, thereby enabling guaranteed QoS for time-sensitive data traffic. The idea of having a node that could act as a central control unit in a distributed VANET is not appealing because of the high mobility nodes. The central unit would not remain central for long and constantly changing the central unit would require much information exchange and negotiation among the nodes. The negotiation can be expected to incur excessive delay and once a decision is made it is likely to already be outdated. A MAC scheme that does not require a central control unit is CSMA, where each node starts by listening to the wireless channel and transmits only if the channel is free. This scheme is easily deployed in a distributed network, but has one big disadvantage; the nodes could experience unbounded delays due to constantly sensing a busy channel during high utilization periods. This is not acceptable in real-time systems.

Real-time systems such as traffic safety applications, call for a deterministic MAC method. We define a *deterministic MAC method to be a scheme for which the time from channel access request to channel access has a finite upper bound*. In the following we will evaluate CSMA and STDMA in this respect.

A. IEEE 802.11p

An upcoming amendment to the WLAN standard IEEE 802.11 is the DSRC standard of North America. This standard, 802.11p [16] intended for V2V communication, is still in its draft stage. It will make use of the PHY supplement 802.11a and the MAC layer QoS amendment from 802.11e. The IEEE 802.11p is one part in the protocol stack called Wireless Access in Vehicular Environments (WAVE) developed by IEEE. 802.11p will use the enhanced distributed channel access (EDCA) as MAC method, which is an enhanced version of the basic distributed coordination function (DCF) from 802.11. EDCA uses CSMA with collision avoidance (CSMA/CA), meaning that the node starts by listening to the channel, and if it is free for an AIFS (arbitration interframe space), the node starts transmitting directly. If the channel is busy or becomes busy during the AIFS, the node must perform a backoff. The backoff procedure in 802.11 works as follows: (*i*) draw an integer from a uniform distribution [0, *CW*], (*ii*) multiply this integer with the *slot time* derived from the PHY in use to get a backoff value, (*iii*) decrement the backoff value only when the channel is free, (*iv*) when reaching a backoff value of 0, send immediately.

The MAC protocol of 802.11 is a stop-and-wait protocol and therefore the sender awaits an acknowledgment (ACK). If no ACK is received due to e.g., the transmitted packet never reaching the recipient, the packet being incorrect at reception, or the ACK being lost or corrupted, a backoff procedure is invoked before a retransmission is allowed. For every attempt to send a specific packet, the size of the contention window (CW) will be doubled from its initial value (CW_{start}) until a maximum value (CW_{end}) is reached. This is due to the fact that during high utilization periods, it is convenient to spread the nodes that want to send in time. After a successful transmission or when the packet had to be thrown away because the maximum number of channel access attempts was reached, the contention window will be set to its initial value again. In 802.11p different QoS classes are obtained by prioritizing the data traffic within each node. There are four different priority levels implying that each station maintains four queues. These queues have different AIFS and different backoff parameters, e.g., the higher priority, the shorter AIFS. In a broadcast situation, i.e., when packets destined for all nodes are transmitted, none of the receiving nodes will send ACKs in response. Therefore, a sender never knows if anyone has received the transmitted packet correctly, and it will perform at most one backoff (which occurs when a busy channel is sensed at the initial channel access attempt). Hence, at most one backoff decrement will take place for broadcasted packets.

B. Self-Organizing Time Division Multiple Access

The STDMA algorithm, invented by Håkan Lans [17, 18], is already used in commercial applications for surveillance, i.e., the Automatic Identification System (AIS) used by ships and the VHF data link (VDL) mode 4 system used by the avionics industry. Traditional surveillance applications for airplanes and ships are based on ground infrastructure with radar support. Radar has shortcomings such as the inability to see behind large obstacles or incorrect radar images due to bad weather conditions. By adding data communication based on STDMA, more reliable information can be obtained about other ships and airplanes in the vicinity and thereby accidents can be avoided. Since STDMA is so successful in these systems, it is interesting to investigate if it can manage a more dynamic setting such as a vehicular network.

STDMA is a decentralized MAC scheme where the network members themselves are responsible for sharing the communication channel. Nodes utilizing this algorithm, will broadcast periodic data messages containing information about their position. The algorithm relies on the nodes being equipped with GPS receivers. Time is divided into frames as in a TDMA system and all stations are striving for a common frame start. These frames are further divided into slots, which typically corresponds to one packet duration. The frame of AIS and VDL mode 4 is one minute long and is divided into 2250 slots of approximately 26 ms each. All network members start by determining a report rate, i.e., how many position messages that will be sent during one frame. Then follows four different phases; *initialization, network entry, first frame,* and *continuous operation*. During the *initialization,* a node will listen to the channel activity during one frame length to determine the slot assignments. In the *network entry* phase, the node determines its own transmission slots within each frame according to the following rules: (*i*) calculate a nominal increment (*NI*) by dividing the number of slots with the report rate, (*ii*) randomly select a nominal start slot (NSS) drawn from the current slot up to *NI*, (*iii*) determine a selection interval (SI) of slots as 20% of *NI* and put this around the NSS according to Fig. 1, (*iv)* now the first actual transmission slot is determined by picking a slot randomly within SI and this will be the nominal transmission slot (NTS). If the chosen NTS is occupied, then the closest free slot within SI is chosen. If all slots within the SI are occupied, the slot used by a node furthest away from oneself will be chosen. When the first NTS is reached in the superframe, the node will enter the third phase called the *first frame*. Here a nominal slot (NS) is decided for the next slot transmission within a frame and the procedure of determining the next NTS will start over again. This procedure will be repeated as many times as decided by the report rate (i.e., the number of slots each node uses within each frame), Fig. 1.

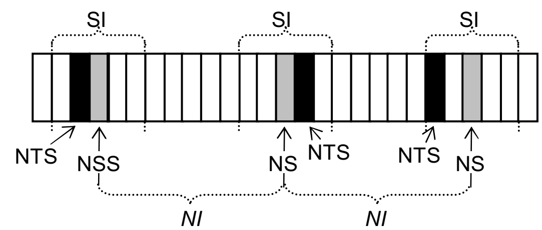

Figure 1. The STDMA algorithm in the first frame phase.

After the first frame phase (which lasts for one frame) when all NTS were decided, the station will enter the *continuous operation* phase, using the NTSs decided during the *first frame* phase for transmission. During the *first frame* phase, the node draws a random integer $n \in \{3,\ldots,8\}$ for each NTS. After the NTS has been used for *n* frames, a new NTS will be allocated in the same SI as the original NTS. This procedure of changing slot after a certain number of frames is to cater for network changes, e.g., two nodes using the same NTS which were not in radio range of each other when the NTS was chosen could have come closer and will then interfere. The STDMA relies on the position information sent by other network members and it will not work without this.

III. Simulations

Many future traffic safety systems will rely on vehicles periodically broadcasting messages containing their current state (e.g., position, speed, etc). We have developed a simulator in Matlab where each vehicle sends a position message according to a predetermined heartbeat of 5 or 10 Hz. Simulations have been conducted both for the CSMA of 802.11p as well as for the proposed STDMA algorithm. The vehicle traffic scenario is a highway of 10 000 meter with 5 lanes in each direction. The highway scenario is chosen because here the highest relative speeds in vehicular environments are found and hence it should constitute the biggest challenge for the MAC layer. The vehicles are entering each lane of the highway according to a Poisson process with a mean inter-arrival time of 3 seconds (consistent with the 3-second-rule used in Sweden, which recommends drivers to maintain a 3 second spacing between vehicles). The speed of each vehicle is modeled as a Gaussian random variable with different mean values for each lane; 23 m/s (~83 km/h), 30 m/s (~108 km/h) and 37 m/s (~133 km/h), and a standard deviation of 1 m/s. For simplicity we assume that no overtaking is possible and vehicles always remain in the same lane. There is no other data traffic in addition to the heartbeat broadcast messages. The channel model is a simple circular transmission model where all vehicles within a certain sensing range will sense and receive packets perfectly. The simulated sensing ranges are 500 m and 1000 m. We focus on how the two MAC methods perform in terms of time between channel access request until actual channel access within each node. Three different packet lengths have been considered: 100, 300 and 500 byte. The shortest packet length is just long enough to distribute the position, direction and speed, but due to security overhead, the packets are likely longer. The transfer rate is chosen to be the lowest rate supported by 802.11p, namely 3 Mbps. Since all vehicles in the simulation are broadcasting, no ACKs are used. Table 1 contains a summary of the simulation parameter settings.

Table 1. Simulation parameter setting for highway scenario simulation

Parameter	**Value**
Length of highway	10 000 m
Number of lanes	10 (5 in each direction)
Speed of vehicles	70-140 km/h
Packet sending frequency	5, 10 Hz
Packet length	100, 300, 500 byte
Transfer rate	3 Mbps
Sensing range	500, 1000 meter
AIFS (listening time before sending) CSMA parameter	34 μs (highest priority)
STDMA frame size	1 s
No of slots in the STDMA frame	3076 slots (100 byte packets), 1165 slots (300 byte) 718 slots (500 byte)

IV. Results

We evaluate CSMA and STDMA in terms of channel access delay, i.e., the time between channel access request and the actual channel access. Simulations have been carried out with the parameter settings in Table 1, yielding 12 different scenarios. Data from the simulations have been collected only when the highway was filled with vehicles, i.e., not in the beginning of the simulation and not close to the edges of the highway.

The results from all 12 simulated scenarios using CSMA are shown in Table 2 where the numbers represent the packet drops in percent. A packet is dropped (discarded) by the node when the next heartbeat packet is generated. The old packet is dropped because a newer packet with more accurate position data has arrived from the application within the node. We consider the channel access delay to be infinite for dropped packets.

Table 2. Packet drops on average for different data traffic scenarios.

CSMA		**Sensing range:**			
		500 meter		**1000 meter**	
Heartbeat rate:		**5 Hz**	**10 Hz**	**5 Hz**	**10 Hz**
Packet length:	**100 byte**	0%	0%	0%	0%
	300 byte	0%	0%	0%	35%
	500 byte	0%	22%	33%	53%

From Table 2 it can be seen that, if 500 byte long packets are sent every 100 ms and the sensing range is 1000 meters, only 47% of the channel access requests will result in actual channel access for 802.11p. However, this value is averaged over all transmissions made by all vehicles in the system which means that certain nodes experience an even worse situation. In Figure 2, the best and worse performance experienced by a single user is depicted together with the average for all users in the system. In the worst case, a node achieves successful channel access only 16% of the time, i.e., over 80% of all generated packets in this node are dropped. When the sensing range is 1000 meters, a node will compete for the channel with approximately 230 other nodes.

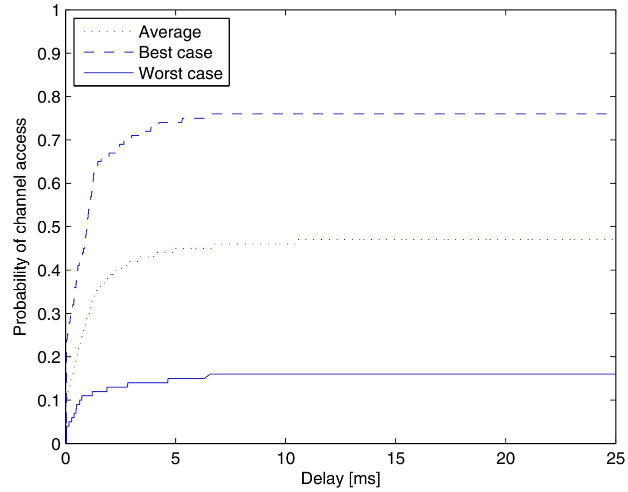

Figure 2. Cumulative density functions for the channel access delay in CSMA with a sensing range of 1000 m, report rate 10 Hz and packet length 500 byte.

In Figure 3, the results from a sensing range of 500 m are depicted, and the worst-case nodes are experiencing packet drops of 55%. In this scenario, approximately 115 nodes are competing for channel access.

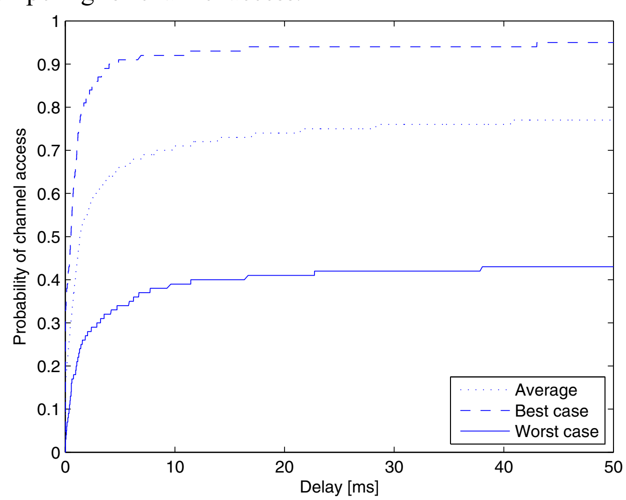

Figure 3. Cumulative density functions for the channel access delay in CSMA with a sensing range of 500 m., report rate 10 Hz and packet length 500 byte.

The STDMA algorithm will always ensure that a node requesting channel access will be granted channel access and thus no packets are dropped. If all slots within an SI are occupied, the node searching for a new NTS will select a slot belonging to another node (located furthest away from itself). Since a node using STDMA always achieves channel access albeit by sharing a slot with a node located further away, it is instead interesting to see how many slots that are reused in this way and how far away nodes sharing a slot are. Simulations have been carried out with the same parameter settings found in Table 1. The STDMA frame size of 1 s was kept constant while the number of slots changed for different packet sizes. The results from the STDMA simulations are found in Table 3, where the percentage of slots being reused within sensing range is tabulated. In the case with a sensing range of 1000 meter and a heartbeat of 10 Hz, 30% of all slots are reused within sensing range, i.e., around 200 slots in a frame consisting of 718 slots. The average distance between two nodes utilizing the same slot is approx. 825 meters. The number of nodes within sensing range is the same as in the CSMA case; ~230 nodes for 1000 m and ~115 nodes for 500 m.

Table 3. STDMA results in terms of slot reuse.

STDMA		Sensing range:			
		500 meter		1000 meter	
Heartbeat rate:		5 Hz	10 Hz	5 Hz	10 Hz
Packet length:	100 byte	0%	0%	0%	0%
	300 byte	0%	0%	0%	0.1%
	500 byte	0%	1%	0%	30%

V. CONCLUSIONS

Future traffic safety system can be classified as real-time systems which mean that the data traffic sent on the wireless channel has a deadline. The most important component of a real-time communication system is the MAC protocol. In this paper, two MAC methods have been evaluated according to their ability to meet real-time deadlines, i.e., having a bound on the time from channel access request to channel access.

The MAC of the upcoming vehicular communication standard IEEE 802.11p CSMA was examined through simulation, and the results indicate severe performance degradation for a heavily loaded system, both for individual nodes and for the system as a whole. The simulations show that 802.11p is not suitable for periodic position messages in a highway scenario, if the network load is high (range, packet size and report rate) since some nodes will drop over 80% of their data packets. Heartbeat position messages will be a central part of vehicle communication systems and many traffic safety applications will depend on vehicle locations. The simulation results indicate how 802.11p should be configured in order to avoid severe performance loss: short packet lengths together with a low heartbeat repetition frequency or shorter range. It should be noted though that if retransmissions are used to increase reliabilty, the system will be heavily loaded already at low heartbeat frequencies. The main drawback with CSMA is its unpredictable behavior, meaning that no finite upper bound on channel access delay exists since nodes could experience unbounded delays due to collisions. This implies that CSMA is unsuitable for real-time data traffic.

The second evaluated algorithm STDMA scheme will always grant channel access regardless of the number of competing nodes. If all slots are occupied, a node will use the same slot as another node which is situated furthest away from it. The worst case access time in STDMA is thus bounded and equal to the listening period plus a nominal increment. From a sending perspective STDMA outperforms CSMA during high utilization periods. The reuse of slots in STDMA is not noticeable until 500 byte long packets and an inter-arrival time of 100 ms with a sensing range of 1000 m are used. Then 30% of all slots are reused within sensing range implying a potential increase in interference – but no packet drops. This is much better than the CSMA algorithm using the same data traffic model since increased interference can be combated with coding and diversity, but the 53% packet drops in the corresponding CSMA scenario are lost.

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