ON THE ABILITY OF IEEE 802.11P AND STDMA TO PROVIDE PREDICTABLE CHANNEL ACCESS

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

[†]Centre for Research on Embedded Systems, Halmstad University, Sweden
[§] Department of Signals and Systems, Chalmers University of Technology, Sweden
[‡]Volvo Technology Corporation, Transport, Information and Communication, Sweden

{katrin.bilstrup, elisabeth.uhlemann, urban.bilstrup}@hh.se, erik.strom@chalmers.se

ABSTRACT
Emerging traffic safety applications requiring low delay communications will need vehicle ad-hoc networks. The only communication standard currently supporting this is IEEE 802.11p. However, 802.11p uses the medium access method CSMA/CA, which has a major drawback: *unbounded worst case channel access delay*. We therefore propose an algorithm already in commercial use in the shipping industry: STDMA. With STDMA, nodes always get predictable channel access regardless of the number of competing nodes and the maximum delay is deterministic. In this paper we elaborated with different parameter settings for the two protocols with the aim of improving performance without altering the standards.

KEYWORDS: IEEE 802.11p, MAC, V2V, vehicular communications, STDMA

INTRODUCTION
One of many emerging applications intended for enhancing traffic safety is the cooperative awareness system, where vehicles periodically broadcast position messages containing information about their own speed, heading, etc. The EU project SAFESPOT [1] are developing a facility called Local Dynamic Map (LDM) that will rely upon the reception of position messages called Cooperative Awareness Messages (CAM). This facility will dynamically build up an advanced map of its local surroundings containing information about moving objects, traffic signs etc. The IEEE 802.11p will be the first standard supporting broadcast in vehicular ad hoc networks (VANET), i.e. direct communication between vehicles without relying on any kind of communications infrastructure. ISO and ETSI are also using 802.11p as the basis for their work on producing vehicular communication standards. However, a major drawback with 802.11p is its medium access control (MAC) procedure, which determines how the common wireless radio channel is shared among the users. 802.11p inherits the MAC procedure found in 802.11, namely carrier sense multiple access with collision avoidance (CSMA/CA) where nodes start by sensing the channel and if it becomes busy (i.e. a transmission starts within the node's reception range) during the sensing period, the node must await a random time before attempting to send again. This MAC method is not predictable and nodes can experience unbounded channel access delay when the network load increases due to increased data traffic or when many nodes are within radio range of each other.

Automatic Identification System (AIS) is a surveillance system similar to the LDM that is already in commercial use within the shipping industry [2]. Every ship larger then 300 gross ton must carry a transponder that periodically broadcasts messages containing the ship's size, direction, speed etc., and the captain on the bridge can easily follow other ships in the vicinity

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and their intentions. The system was developed to overcome the shortcomings of radar in bad weather situations and to enable communication where no line of sight is possible. Like IEEE 802.11p, the AIS system supports direct ad hoc communication between ships but it has a completely different MAC method, where the available time is divided into slots and the nodes choose their slots according to an algorithm called self-organizing time division multiple access (STDMA). One transmission fits into one slot. The algorithm relies upon the existence of CAMs in the system. When the network load increases due to increased data traffic or many participating members, the nodes will start to pinch slots from each other based on the available position information, i.e. slots are pinched from nodes currently situated furthest away from the pinching node. This algorithm is predictable implying that all nodes always get a timely channel access regardless of the number of competing nodes.

Since the CAMs will be of utmost importance in emerging traffic safety systems, the probability that these messages are properly received by especially the nodes closest to the transmitting node should be made as high as possible. The MAC must therefore be deterministic such that the time between channel access request to actual channel access is upper bounded. In [4] it was shown that the MAC method used in 802.11p does not fulfill this criterion and is therefore unsuitable for CAMs. STDMA, on the other hand, is deterministic and performs remarkably well for the LDM facility, thus providing a really interesting alternative to 802.11p. *In this paper our aim is to enhance the performance of both MAC protocols as much as possible, without altering the original standards. We do this by elaborating with different parameter settings used in the standards.* For example, the 802.11p provides the possibility to assign different priorities to the data packets, which implies different listening/sensing periods and different backoff times (the time before a new channel access is possible). In the evaluation made in [4], all data traffic had the highest priority resulting in short initial listening periods, but also few discrete backoff values to choose from. This implies that the probability of collisions occurring due to the fact that several nodes choose the same discrete random backoff value, is fairly high. In this work, we use our simulator to determine whether the performance of CSMA/CA, when used for broadcasting CAM messages, can increase by using the other available priority classes. The question is whether the potential drawback of increasing the initial listening periods is compensated by increasing the number of discrete random backoff value and thereby reducing the number of collisions. In addition, for CSMA/CA we try to mitigate the problem with several consecutive packet drops found in [4] by introducing an algorithm that changes the priority class on a packet per packet basis depending on if the previous channel access attempt was successful or not. Since channel access with STDMA is always granted regardless of the number of competing nodes, we instead focus on how the nodes are pinching slots from each other, when the wireless channel becomes crowded. In order to improve STDMA we therefore improve how the pinched slot is selected and for how long it is kept. We also make a numerical evaluation on the probability of two nodes using STDMA, interfering with each other by selecting the same time slot. This loosely corresponds to collisions due to the same random backoff value with CSMA/CA, even if the distance between the two concurrently transmitting nodes is likely to be longer in STDMA since the pinching of time slots is carefully orchestrated. Finally, we elaborate on the synchronization issues implied by STDMA.

CSMA/CA OF IEEE 802.11p

The MAC method CSMA/CA that is used by 802.11p [5] is derived from 802.11 [6] where it is referred to as distributed coordination function (DCF). In a scenario where the nodes employ CSMA/CA, they first listen to the wireless channel for a predetermined listening period and if the channel is or becomes busy during this period, the node must perform a backoff procedure. If, however, the channel is sensed free for the entire listening period, the node can transmit directly. In a unicast transmission each transmitting node awaits an acknowledgment (ACK) in return from its destination node. If this is not received successfully for some reason, the sending node must also perform a backoff procedure, retransmit and again await an ACK. In contrast, a broadcast situation implies that a node will perform at most one backoff procedure since no ACKs are employed nor expected.

The backoff procedure in 802.11 works as follows: (*i*) draw an integer from a uniform distribution [0, *CW*], where *CW* refers to current contention window, (*ii*) multiply this integer with the *slot time* derived from the physical layer in use, and set this as the backoff value, (*iii*) decrement the backoff value only when the channel is sensed free and (*iv*) upon reaching a value of 0, send immediately. Note that a node is only allowed to decrement its backoff value while the channel is free and that after the channel has been sensed busy, a listening period must elapse before the countdown can be resumed. Every unsuccessful channel access attempt for a specific packet will result in a doubling of the *CW* size up to a maximum number, determined by the physical layer in use. *In a broadcast situation when the nodes perform only one backoff procedure, the mechanism with increasing the backoff window during high utilization periods and thereby spreading the transmissions in time to reduce collisions will never occur.* By spreading the backoff times, nodes will experience a longer average delay but the probability that two transmitters within radio range transmit at the same time decreases.

802.11p will also use the physical layer supplement 802.11a and the Quality of Service (QoS) amendment 802.11e [7] to prioritize the data traffic within each node. In 802.11e there are four different priority levels called access categories (AC), i.e., queues. The different ACs have different listening periods and *CW* settings. In Table 1 the different priorities with their corresponding listening periods and backoff settings are found. P1 is the highest priority and P4 is the lowest. The values are taken from the default settings found within 802.11e together with the physical layer attributes in 802.11a. The highest priority results in shortest listening period and the fewest, but lowest backoff values. When a node with a data packet with high priority, *P1*, starts to listen to the channel at exactly the same time as a node with a data packet with priority *P3*, the first node with *P1* will win the race and access the channel. This is due to the fact that the *P3* node will experience that the medium becomes busy during its listening period (43 μs) and must then perform the above described backoff procedure.

Table 1. The different listening periods and backoff values within 802.11p.

Priority	Listening period [μs]	Backoff values [μs]
P1	34	{0, 9, 18, 27}
P2	34	{0, 9, 18, 27, 36, 45, 54, 63}
P3	43	{0, 9, 18, 27, 36, 45, 54, 63, 72, 81, 90, 99, 108, 117, 126, 135}
P4	79	{0, 9, 18, 27, 36, 45, 54, 63, 72, 81, 90, 99, 108, 117, 126, 135}

With this type of QoS mechanism, nodes can prioritize the traffic internally within the node but still there can be priority inversion between competing nodes. Therefore there are no guarantees of first-in-first-out (FIFO) services for messages that arrive at different nodes with the same priority. Similarly, since the backoff times are random, there is a possibility that a lower priority message is sent before a high priority message within a node even if the lower priority message arrives earlier since the backoff intervals all contain the lower values.

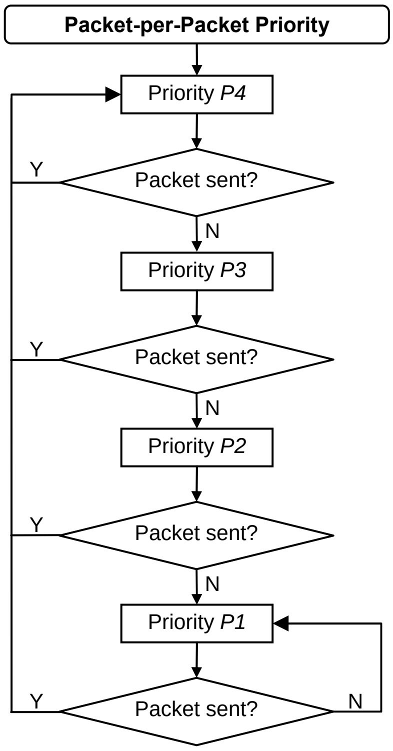

Figure 1. New algorithm for changing the priority on a packet-per-packet basis.

In this work, we investigate if the lower priority classes are better suited for broadcasted CAM, since a higher number of backoff values to choose from lowers the probability of collisions even if the initial listening period is increased.

Proposal of a new packet-per-packet change of priorities in CSMA/CA

When CSMA/CA is used to broadcast periodic CAM, in order to save bandwidth, it is better to discard packets that have not yet been sent if a newer version of the same CAM becomes available. Thus, a packet that has not been granted channel access when the next periodic message arrives should be dropped. In [4] it was shown that using CSMA/CA for high network loads, the number of consecutive packets that were dropped could be as a high as 100. This implies that a sending node did not get channel access for over 10 seconds and thus no position messages was transmitted by this node, resulting in invisibility to the surroundings for more than 10 seconds. In this work we therefore propose an algorithm that increases the priority of the current message if the previous message was dropped. All nodes start with the lowest priority, *P4* as shown in Table 1, i.e. listening period of 79 µs and 16 different backoff values. If a packet was sent successfully with these values the node will maintain its priority. Otherwise the next packet will get a higher priority, i.e. *P3* in this case. Once the node experience a successful transmission, the next packet will again get the lowest priority, *P4*. In Figure 1 the procedure of this packet-per-packet change of priority is depicted.

STDMA

STDMA [2] is a deterministic MAC method where all messages always will be granted channel access despite the number of competing nodes. STDMA is also decentralized and 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 thus relies on the nodes being equipped with GPS receivers.

Time is divided into frames as in a TDMA system. These frames are further divided into slots, which typically corresponds to one packet duration. All nodes will randomly select among free slots, a number of slots within each frame to transmit in. However, when there are more nodes within radio range than available slots, the nodes will start to pinch slots from each other. However, the pinching is done in a controlled manner where the node pinching will select a slot occupied by someone that is situated furthest away from it. Since positioning messages are sent periodically, this is easily determined and hence unlike other TDMA algorithms, STDMA contains no random slot assignment or contention-based periods to self-organize.

All network members start by determining a report rate, i.e., how many CAMs that will be sent during one frame (corresponding to how many slots that needs to be reserved in each 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 (i.e., which slots are occupied and what the position is of the node using it). 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* (this slot will be the start of the frame for the node and therefore each node has its own NSS), (*iii*) determine a selection interval (SI) of slots as 20% of *NI* and put this interval around the NSS according to Figure 2, (*iv)* now the first actual slot to be used for transmission is determined by picking a slot randomly within the interval SI around NSS and this slot is denoted nominal transmission slot (NTS), Figure 2. If the randomly 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.

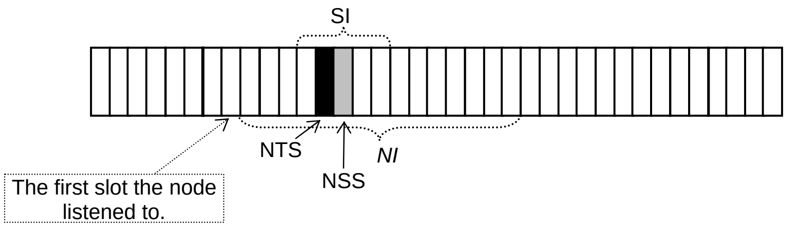

Figure 2. The STDMA algorithm in the network entry phase.

When the first NTS is selected, the node will enter the third phase called the *first frame*. Here the next slot transmission is decided by first assigning a nominal slot (NS) by adding *NI* to NSS. Thereafter the interval SI is placed around NS 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), Figure 3. For each NTS that is selected during the *first frame* phase, the node draws a random integer $n \in \{3,...,8\}$ which determines how long this particular NTS should be maintained. When one of the node's NTS has been used during its assigned *n* frames, a new NTS will be selected within the same SI as the original NTS. This procedure of changing slots after a certain number of frames is adopted 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. Note that since each NTS has its own *n*, not all slots in the frame are reassigned at the same time, and this further enhances the algorithm since the assignment will then depend on instantaneous channel conditions.

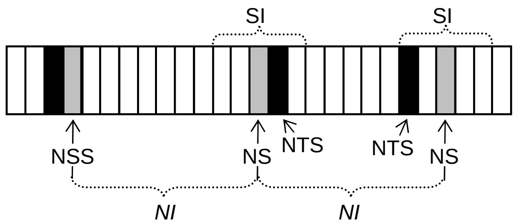

Figure 3. The STDMA algorithm in the first frame phase.

After the first frame phase when all NTS have been selected (which lasts for one frame), the station will enter the *continuous operation* phase. This phase, starting with the NSS, is when the node first starts using the selected NTSs for transmission.

Fine tuning of the slot assignment procedure in STDMA

The chosen NTS, i.e. the actual transmission slot, is kept for a number of consecutive frames. When a node uses a transmission slot, it also sends information about how many times it will continue to use this particular slot. In the original AIS standard [2] the number of times, *n*, a NTS is kept is decided by a uniform distribution, $n \in \{3,...,8\}$. A particular slot is hence kept at least three consecutive frames and at maximum eight frames. In our vehicular simulation scenario the frame is chosen to be one second, implying that a slot could be kept for eight seconds. Since the vehicular network scenario rapidly changes, this window of randomized numbers could become too large to cater for network topology changes with the result that two nodes could come really close to each other and still use the same slot. Therefore, choosing a different size of the window could be advisable for vehicular environments. We have run simulations using $n \in \{2,3,4\}$ which implies that an NTS kept for two up to four times.

SIMULATION STUDY OF THE TWO PROPOSED MAC METHODS

Our simulator is based on a highway scenario with 10 lanes, 5 lanes in each direction, where vehicles appear Poisson distributed with a mean inter-arrival time of 3 seconds. Vehicle speeds are modelled as Gaussian random variables with mean values for each lane, 23 m/s, 23 m/s, 30 m/s, 30 m/s and 37 m/s, the standard deviation being 1 m/s. All vehicles start sending periodic positioning messages of 500 byte every 100 ms with a transfer rate of 3 Mbps when they enter the highway. Since we evaluate the performance on the transmitter side, the channel model is circular and all nodes within a given sensing range of 1000 meters sense and receive the message perfectly. More details about the simulator can be found in [2]. The highway scenario appears to be the most challenging scenario for the MAC procedure since it should be able to cope with high relative speeds, rapidly changing network topology and dense vehicle traffic.

SIMULATION RESULTS

We evaluate the performance of CSMA/CA and STDMA from the sending nodes' perspective in terms of Channel Access Delay or, for periodic messages, Percent Packet Drops, Number of Consecutive Packet Drops, and Distance between Two Concurrently Transmitting Nodes.

We have run several simulations to evaluate the different priority classes in 802.11p. The priorities *P1* and *P2* have the shortest listening period, but randomize between two different sets of backoff values, see Table 1. For a simulation with a particular priority, all nodes in our system are using the same priority during the entire simulation, i.e., there are no nodes with higher/lower priority than the others. The packet-per-packet priority changing algorithm as described above has also been simulated and in Figure 4 the cumulative distribution function (CDF) for the channel access delay is shown for the five different schemes. The channel access delay is defined as the time it takes before a node is allowed to send its packet after a channel request. However, if a channel access request was never resolved into an actual channel access before a new periodic packet arrived, the old packet will be thrown away, i.e., the packet is dropped at the sending node. This explains why the CDFs found in Figure 4 never reach 1. Figure 4(a) shows the best case for an individual node, Figure 4(b) the average case for all nodes and 4(c) the worst case for a single node in the network. With a sensing range of 1000 meter as in Figure 4, there are approximately 230 nodes within sensing and interfering range. Since every node has a bandwidth requirement of 40 kbps (500 byte packets sent every 100 ms at a transfer rate of 3 Mbps) the network is overloaded. No node in the network is able to resolve all channel access requests into actual channel access.

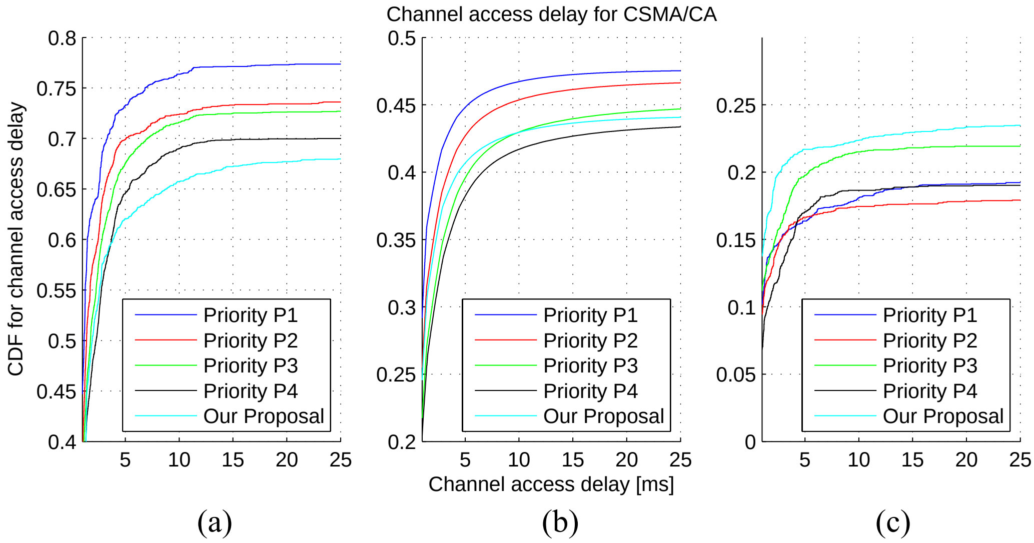

Figure 4. CDF for the channel access delay in CSMA/CA for the different priorities and our proposed packet-per-packet priority change. (a) Best case for an individual node, (b) average case for all nodes and (c) worst case for an individual node.

As can be seen in Figure 4, the different priorities do not significantly impact the channel access delay. In the average case, Figure 4b, only 50% of the generated CAMs will actually be sent. However, our proposed packet-per-packet priority changing algorithm decreases the difference between the best and the worse case nodes in the system, i.e., it is able to improve the network fairness since the priority of the next CAM is increased whenever a node was previously mistreated. When it comes to the performance measure “distance between two concurrently transmitting nodes”, the priorities have a bigger impact since the size of the different backoff windows now comes into play. Nodes that have more discrete random backoff values to choose from will have transmissions that are more spread in time. Consequently, the probability of two closely located nodes having chosen the same backoff value decreases, and thereby the collision effects are mitigated.

In the STDMA scenario simulations have been run to see what impact the factor n has, i.e., the number of times a specific slot is kept. In the original AIS standard, a specific NTS is kept for three to eight times. In Figure 5, the NTS is instead kept for two to four times. Figure 5 illustrates the CDF for the distance between two concurrently transmitting nodes using STDMA. Three different packet lengths; 100, 300 and 500 byte, and the transfer rate 3 Mbps have been used. The sensing range is 1000 m and there are approximately 230 nodes within this range. The frame size is one second and the number of available slots within the frame is altered depending on the packet size; 100 byte = 3076 slots, 300 byte = 1168 slots, and 500 byte = 718 slots. Every node is using 10 transmission slots, as decided by the report rate of the STDMA algorithm. In the case with 500 byte packets, the system has a requirement of approximately 2300 slots within every frame with the sensing range of 1000 m and there are 718 available slots implying an overload situation of 300%. The dotted lines in Figure 5 represent simulations run with the reduced window size (i.e., our suggested procedure) and it can be seen that the performance is indeed increased.

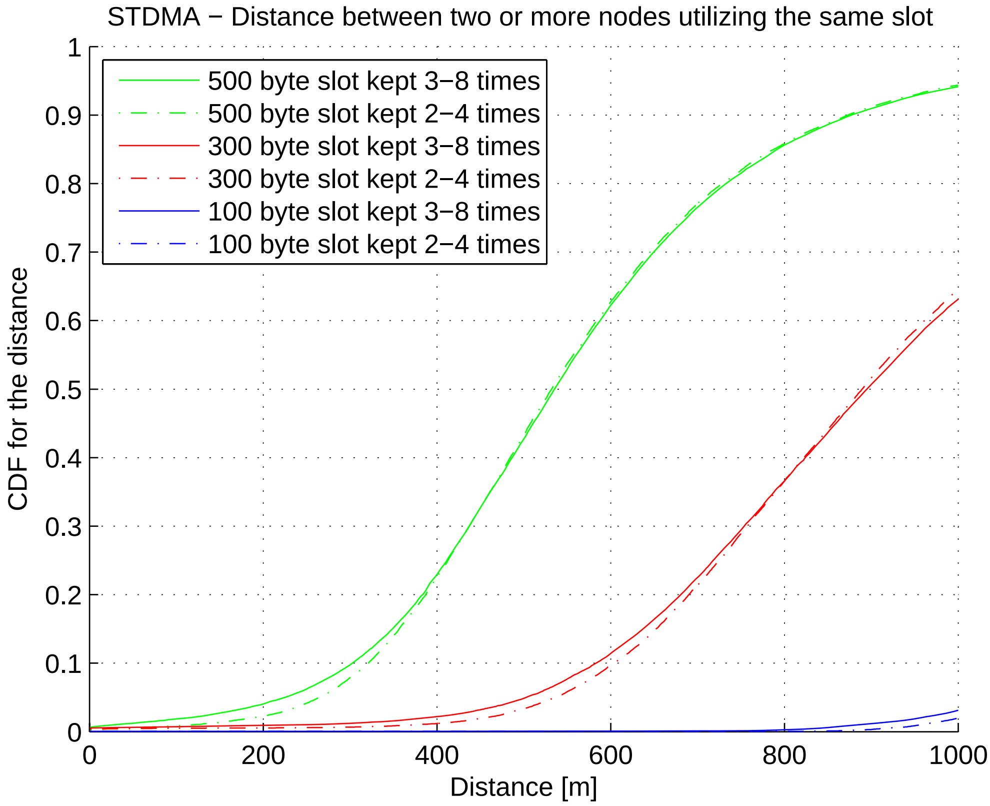

Figure 5. STDMA: CDF for distance between two or more nodes using the same slot.

DISCUSSION

The CSMA/CA approach has many advantages. It has support for arbitrary packet sizes and does not need synchronization among the nodes. The CSMA/CA is suitable for event-driven data traffic, especially when there is data traffic with variable packet sizes. In STDMA the packet size is fixed and should fit into one slot. If a packet is longer than one time slot, it must be fragmented and more slots allocated.

STDMA is very suitable for time-triggered positioning messages such as the CAMs that constitute the LDM since then the overhead messages required for self-organization is included naturally in the payload. Synchronization in STDMA is a requirement and this is done through a Global Navigation Satellite System (GNSS). In today's GPS system, the time resolution is on a nanosecond level, which fortunately is enough for synchronizing STDMA nodes in a vehicular environment. If no GNSS signal is available, the STDMA system can fall back to become a CSMA/CA system. Note however, that if there is no GNSS signal available, there will no longer be any position information available in the vehicle, and thus applications relying on CAMs may breakdown anyway. It is important to note that STDMA, unlike many other self-organizing TDMA schemes does not need any random access channel to allocate time slots. Instead it uses available positioning information at the MAC layer and the overhead introduced by the self-organizing mechanism is negligible in an STDMA system using

CAM, since the CAM messages themselves constitute the required positioning messages. In STDMA the worst case in terms of concurrently transmitting nodes is the probability that two or more nodes have totally overlapping selection intervals, *SI*, and therefore have the opportunity of choosing among the same set of transmission slots. If the two nodes with overlapping *SI* are really close to each other, they will also have the same information about allocated slots by neighbouring nodes in their respective frames. However, the probability that they have chosen exactly the same transmission slot in all of their *SI* in the superframe is low and can be calculated according to [8]. The probability of *l* consecutive transmission conflicts is

$$P(l) = \frac{1}{(N_{frame} - N_{SI})(N_{SI})^l}, \quad \text{Eq. 1}$$

where N_{frame} is the total number of slots in the frame and N_{SI} is the number of slots in the *SI*. If there are 718 slots in the frame, the *SI* will be fourteen slots and every node would want to send ten times in each frame. The probability that two nodes within radio range of each other has chosen the same slots for ten consecutive transmissions within the same superframe is tabulated in Table 2. The probability of two approaching nodes not being aware of each other is consequently very low.

Table 2. The probability of *l* consecutive transmission conflicts between two nodes with totally overlapping *SI* having a frame size of 718 slots and a *SI* of 14 slots.

l	P(*l*)
1	1×10^{-4}
2	7×10^{-6}
3	5×10^{-7}
4	1×10^{-8}
5	3×10^{-9}
6	1×10^{-10}
7	1×10^{-11}
8	1×10^{-12}
9	1×10^{-14}
10	1×10^{-15}

The STDMA algorithm is very suitable for vehicular ad hoc networks with periodic heartbeat messages such as CAMs. Up to now the algorithm has been evaluated using the parameter settings of the AIS specification. However, STDMA could be further tuned and adopted to the conditions in a vehicular ad hoc network. The procedure for pinching slots can be made more sophisticated, e.g., it could be advantageous to pinch a slot from a vehicle moving away, in the opposite direction even if this node is not currently the one situated furthest away. Our initial simulations show that being able to choose freely the node situated furthest away among all nodes within range is better than to only be allowed to chose among the nodes in the opposite direction. This result will of course be influenced by relative vehicle speeds and report rate, as well as how many more times a particular slot will be occupied. Thus there are still several opportunities to enhance the performance of STDMA.

CONCLUSION

Since there cannot be any restrictions on the number of participating stations in a VANET, the MAC method must be able to handle overloaded situations. CSMA/CA becomes unfair when the network load increases and thus unbounded access delays and thereby packet drops become more frequent. Given our CAM based data traffic model, some nodes in the CSMA/CA system were forced to drop several consecutive packets, resulting in invisibility to the environment for very long periods of time. The results in this paper show that using the priorities available in 802.11p (through 802.11e) will not significantly enhance the probability of channel access for CAMs in overloaded situations. Our proposed packet-per-packet priority change algorithm, where the priority is changed depending on previous successful/unsuccessful channel access attempts, did enhance the overall performance of CSMA/CA, i.e., it decreases the difference between the worst affected node and the most favoured node in the system (the variance was decreased). Power control and restrictions on amount of data traffic seem to be the only efficient tools for proper system function with CSMA/CA.

STDMA, on the other hand, is predictable in the sense that a node always will get channel access within a bounded time upon request. By decreasing the number of times a specific slot is kept, an increase in system performance was noted. The pinching of slots in STDMA could also be combined with efficient power control to increase the overall capacity in the network. There are further possibilities to develop and adapt STDMA in order to enhance the performance when used in vehicular ad hoc networks.

To conclude, both CSMA/CA and STDMA have benefits and drawbacks which all must be considered carefully when developing traffic safety applications.

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