Performance Evaluation of a Platooning Application Using the IEEE 802.11p MAC on a Control Channel Vs. a Centralized Real-Time MAC on a Service Channel

Annette Böhm, Magnus Jonsson and Elisabeth Uhlemann
CERES (Centre for Research on Embedded Systems)
Halmstad University, Halmstad, Sweden
{Annette.Bohm, Magnus.Jonsson, Elisabeth.Uhlemann}@hh.se

Abstract – **Recent advances in cooperative driving hold the potential to significantly improve safety, comfort and efficiency on our roads. An application of particular interest is platooning of trucks, where it has been shown that keeping a minimum inter-vehicle distance results in considerably reduced fuel consumptions. This, however, puts high requirements on timeliness and reliability of the underlying exchange of control messages between platoon members. The European profile of IEEE 802.11p, recently adopted by ETSI, defines two message types to this end, periodic beacons for basic cooperative awareness (CAM) and event-triggered decentralized environmental notification messages (DENM), both using the common control channel. The IEEE 802.11p employs a random medium access protocol, with excessive delays that may prevent proper functionality of a platooning application. To mitigate the effects of this, ETSI standardizes a decentralized congestion control algorithm to, e.g., lower the CAM frequency when needed. Some service channels with less strict requirements on send rates, data traffic types or medium access methods are available. In this paper we compare the performance of decentralized, standard-compliant inter-platoon communication using IEEE 802.11p on the control channel with a solution based on a service channel, which combines a random access phase for DENM with a centralized, scheduled access phase for CAM. A dedicated service channel for platooning applications enables us to always guarantee timely channel access of CAM packets before a specified deadline and our simulations show that this is achieved at very small sacrifices in DENM dissemination delay.**

I. Introduction

A multitude of emerging cooperative traffic safety applications are based on the exchange of status updates. These are typically broadcasted periodically and contain basic information like vehicle position, direction and speed. Consider a platoon of trucks driving on a highway at relatively high speed, keeping a fuel-efficient inter-vehicle gap of 5 m or less. Periodic status updates must in this case be considered highly safety-critical as the control loop needed to keep the platoon at a safe distance at any time and quickly adapt to changes, requires a frequent, timely and reliable exchange of status updates within the platoon. Very high requirements on timing and reliability are also put on the dissemination of event-driven messages within the platoon in case of an incident. The delay between event detection (e.g., the leading vehicle in the platoon detecting the end of a traffic jam or a vehicle suddenly breaking) and the point in time when the entire platoon successfully received the warning must be minimized. In Europe, ETSI has standardized two messages types Cooperative Awareness Messages (CAM) [1] and Decentralized Environmental Notification Messages (DENM) [2], corresponding to status updates and hazard warnings, respectively. However, recent decisions within ETSI move away from the strictly periodic nature of CAMs towards an on-demand approach where CAMs are sent only when the change in vehicle status (i.e., position, heading or speed) is above a certain threshold.

The strict timing requirements of platooning applications are not easily met, especially if we consider the premises dictated by the recently adopted IEEE 802.11p standard [3] for short-range vehicular ad-hoc networks (VANETs), coupled with the European requirement to use one common 10 MHz control channel (CC) shared by both CAMs and DENMs. Further, IEEE 802.11p employs a random access protocol for medium access control (MAC), which may cause excessive delays preventing proper functionality of a platooning application [4]. Alternatively, the required safety distance between members in a platoon may have to be extended such that the desired gains in fuel efficiency may no longer be achievable.

In previous work [5], we evaluated the co-existence of CAMs and DENMs over the shared CC in a network consisting of both a platoon and surrounding non-platoon vehicles. The goal of this paper is to compare such a fully standard-compliant implementation of a platooning scenario based on CAMs and DENM transmitted on the CC with a solution implementing the platooning application using one of the available service channels. Using a service channel (SC) allows us to deviate from the specifications of ETSI and IEEE 802.11p in terms of message types, send rates and also MAC protocol. However, according to European standard, all vehicles must listen to the CC at all times. This implies that an extra transceiver is needed and the question is if the additional hardware cost implied by a transceiver tuned to a service channel is justified. Using a SC has several advantages. Firstly, a SC can be used by platoon members only and does not have to be shared by other vehicles. As both time-triggered control data and event-driven warnings are more critical within a platoon due to the highly reduced inter-vehicle distance, it is desirable not to share the channel with less safety-critical data traffic from a potentially high number of surrounding vehicles. Secondly, the use of a SC enables us to tune the send rates of CAMs and DENMs to the specific timing requirements of the platooning application without limitations from the standard. Thirdly, we are able to select a centralized MAC method coordinated by the platoon leader that has been shown to better match the demands from safety-critical real-time applications than the IEEE 802.11p random access protocol [6]. The performance of the two solutions is evaluated both in terms of the CAM up-to-dateness (UTD) as well as the DENM dissemination delay (DD).

The rest of the paper is organized as follows: Section II introduces the prerequisites from standardization and provides an overview of related research. The real-time MAC protocol is presented in Section III, while the results from the comparison are discussed in Section IV. Section V concludes the paper.

II. Background and Related Works

In this section we introduce relevant details of the IEEE 802.11p standard and the European profile defined by ETSI. Furthermore, we survey some related works.

A. Prerequisites from Standardization

The amendment IEEE 802.11p [3] defines physical and MAC layer details for short to medium range communication in a VANET. ETSI has standardized a profile of IEEE 802.11p adapted to the 30 MHz frequency spectrum at the 5.9 GHz band allocated in Europe [7] and considers two types of messages, periodic status updates, CAMs [1] and event-triggered warning messages, DENMs [2]. One dedicated control channel is reserved for data exchange in traffic-safety applications and shared between CAMs and DENMs. Recent decisions within ETSI move away from the strictly periodic nature of CAMs towards an on-demand approach where CAMs are sent only when the changes in vehicle status (i.e., position, heading or speed) are above a certain threshold.

The MAC layer of IEEE 802.11p uses CSMA/CA, where a node attempts to transmit only if the channel is sensed free during a certain time period (Arbitration Inter Frame Spacing, AIFS). If the channel is busy or if it becomes busy during the AIFS, the node randomizes a backoff time, which is counted down only during time periods when the channel is sensed free. When the backoff value reaches zero, the node transmits directly without any further delay. Since messages are broadcasted, no acknowledgements are used and thereby no collision detection is possible. Therefore, the contention window is never extended as in traditional IEEE 802.11 and maximum one backoff procedure is invoked. IEEE 802.11p defines four priority levels characterized by the length of the AIFS and the parameters of the backoff window. This way, DENMs can e.g. be given prioritized channel access over CAMs. Due to the random nature of the 802.11p MAC protocol, a control channel utilization level (Channel Busy Time, CBT) of 25% or less is recommended by ongoing ETSI standardization [4]. This implies that as soon as a node discovers that the CBT exceeds 25%, it will use a predefined decentralized congestion control algorithm to e.g. lower the CAM frequency.

B. Related Works

The performance of the IEEE 802.11p MAC method has been subject to several recent studies [4][5][8] where its limitations to support delay-sensitive data traffic have been pointed out. One way to deal with this issue is to improve the chance of successful channel access through congestion control mechanisms, e.g., adapting the send rate to the current channel conditions [9] or adjusting the output power [10-12]. While congestion control increases the probability of timely channel access, strict timing guarantees can still not be provided.

The concept of dividing the bandwidth into two parts: a collision-free and a contention-based part to support safety and non-safety data traffic respectively in vehicular networks is evaluated in [6],[13],[14]. Both [13] and [14] present a centralized, infrastructure-based multi-channel protocol with a centrally controlled collision-free phase for safety data exchange and an ad-hoc mode where nodes may switch to a service channel for non-safety services. The approach in [6] uses a single channel, and adopts a combined decentralized/centralized MAC approach consisting of a contention-based phase (CBP) using CSMA/CA and a collision-free phase (CFP) based on centralized scheduling. Next, real-time schedulability analysis is used to adapt the CFP/CBP ratio to the current data traffic requirements. The solution targets a system with infrastructure support and the timely delivery of safety-critical data in the presence of best-effort services on the same channel. The idea is extended in this paper to the case where the platoon leader takes on the role as central coordinator in place of the road-side infrastructure. The idea of using multiple channels for differentiated services in a vehicular network has been discussed by several authors [13],[14], [15]. These multi-channel proposals, however, aim at providing non-safety critical data over service channels, while the control channel is used for safety data exchange. Our approach is rather to make use of the design freedom a service channel offers in terms of packet send rates and MAC design to support data traffic with particularly high timing and reliability requirements that are not fully supported by the control channel. For example, we argue that, for the high sampling rates required by the platooning control algorithm, periodic CAM updates with a high frequency are more suitable than the on-demand updates currently considered by ETSI. Similarly, the feature of reducing the CAM report rate during channel congestion is not desirable for a platooning application.

Kaul *et al.* [9] identified the age of periodic status updates in vehicular networks as an important performance metric and propose a rate control algorithm to improve its properties. The effects of channel load (a combination of the number of communicating nodes and their CAM and DENM send rates) on both CAM UTD and DENM DD performance has been studied in previous work [5] for a decentralized, IEEE 802.11p compliant model. To the best of our knowledge this is the first study of the use of two MAC phases: decentralized random access and centralized real-time collision free access to match the requirements of highly safety-critical cooperative driving applications as platooning based on CAM and DENM.

III. Real-Time MAC: Protocol Details

We propose a combination of a contention-based MAC phase (CBP) utilizing CSMA/CA, a random access scheme where packet collisions are possible and timing guarantees cannot be provided and a collision free phase (CFP) where channel access is centrally governed and pre-scheduled by the platoon leader such that guarantees can be given that a packet will be granted channel access before its specified deadline. Time is divided into superframes (SF) and one SF consists of a CFP and a CBP. The CFP is initiated by a beacon sent out by a dedicated platoon member (typically the platoon leader), stating the channel access schedule for the upcoming CFP, the start of the CBP and the end of the entire SF.

The CFP is suitable for periodic data with relatively stable and predictable data traffic patterns. The number of platoon members changes rarely compared to the length of a SF. At the same time, the exchange rate of periodic beacons can be considered fixed and even if the CAM send rate is be adapted to e.g. what role within the platoon a certain vehicle maintains at the moment or the overall channel conditions, these context-aware changes still do not happen frequently. This makes CAMs the perfect candidate for the scheduled MAC protocol used in the CFP. The CBP, on the other hand, suits event-based DENM traffic. Channel access during the CBP is decentralized and based on the CSMA/CA MAC protocol defined by the IEEE 802.11p standard. This is most suitable for non-periodic data with an unpredictable traffic pattern. When an event is detected (by e.g. the leading vehicle in the platoon), DENMs are typically flooded backwards in the platoon according to some dissemination model until all platoon members can be expected to have received a warning. All DENMs compete for channel access and despite the collision avoidance mechanism defined for CSMA/CA, packet collisions are still possible and, just as in the CC case, timing guarantees cannot be provided. However, as the CBP on the SC is used by DENMs only, the probability of packet collisions is lower than in the CC case where the channel is shared by CAMs both from platoon members and from other vehicles.

A. Dynamic Superframe Adaptation

The sizes of both CFP and CBP, and thereby the duration of a SF, is adapted to the number of vehicles in the platoon and current application requirements (e.g. worst-case CAM UTD required by the control application). This is done in two steps, together determining the size of the SF suitable for the current platoon length, as well as the proper CFP/CBP ratio supporting timely delivery of CAMs and a low DENM DD:

Step 1: Choice of CBP size

A safety-critical event requires a fast dissemination of warning messages. The size of the CBP must be chosen with this requirement in mind and can be based on simulation results or intelligent algorithms learning from input from real platoons on the road or a combination of both.

a) Choice of dissemination method - To determine a suitable CBP size, the typical DENM DD should be known. To do this, we first select a suitable DENM dissemination model from [5], based on the number of platoon members, the radio conditions (i.e. current transmission range), inter-vehicle spacing etc. Next, we use this model in a simulator to get the DD.

b) Choice of CBP size – Note that an event may be detected at the end of a CBP. If then the CBP size is selected based on the length of the DENM DD, we know that the DD would be at most two SF. Alternatively, if the SF is very long, the DD can be reduced if the CBP size is selected as half the DENM DD.

Step 2: Choice of CFP size

Having selected the CBP size, we can now apply real-time schedulability analysis to the platoon size at hand to determine the minimum CFP size required to support the specified CAM settings. Note that the smallest CFP allowed by the schedulability analysis is able to guarantee that all generated CAM packets get channel access before their specified deadlines, and is also the best from a DENM DD perspective. Details on the real-time schedulability analysis are provided below.

B. Real-time Schedulability Analysis

The kind of real-time schedulability analysis that our analysis is based upon was first introduced in [17] for processor scheduling. Two conditions have to be fulfilled to ensure that enough bandwidth is reserved for the CFP so that no real-time deadlines are missed. Firstly, the *utilization* of the wireless channel must not exceed one, and secondly, the *workload function*, i.e., the sum of the transmission times for all packets with an absolute deadline less than or equal t, must be less than or equal to t, [18]. For our platooning scenario, assume Q different, logical real-time channels (RTC), one per platoon member, representing its CAM packet flow. A RTC is defined by its source, destination, period, P_i, packet length, L_i, and deadline, D_i, where $i = 1, 2,\ldots, Q$. To be implementable on top of IEEE 802.11p, we assume that any transmission is preceded by an AIFS included in the total packet transmission time, T_i:

$$T_i = \frac{L_i}{R} + T_{AIFS}, \tag{1}$$

where R is the data rate. A superframe of length T_{SF}, consists of a CBP of predetermined length, T_{CBP}, and a CFP of a duration, T_{CFP}, still to be determined by the RT analysis. The very beginning of a CFP is occupied by the beacon of duration T_{max}, used to distribute the schedule and it is assumed to have the longest available packet length. Further, towards the end of the T_{CFP}, there might not be enough time for a full packet to be scheduled. This is accounted for in the real-time analysis by reducing T_{CFP} by a blocking time, i.e., again corresponding to the transmission time of the longest possible packet, T_{max}. The fraction of CFP actually usable for CAM packets is thus:

$$CFP_{usable} = T_{CFP} - 2T_{\max}. \tag{1}$$

Expressed as the usable fraction of the entire SF this is:

$$F_{CFP} = \frac{CFP_{usable}}{T_{SF}}. \tag{1}$$

The original transmission time of a packet, T_i, is thereby adapted into an experienced transmission time T_i':

$$T_i' = \frac{T_i}{F_{CFP}}. \tag{1}$$

To extract the pure scheduling deadline, D_i is reduced to D_i' by subtracting the worst-case delay until the CBP starts:

$$D_i' = D_i - T_{CBP} - 2T_{\max} \tag{1}$$

The actual analysis is done in two steps. A necessary but not sufficient condition is that the utilization U of the wireless link must never exceed one. According to EDF scheduling theory [19], the utilization of periodic traffic is calculated as:

$$U = \sum_{i=1}^{Q} \frac{T_i'}{P_i}, \tag{1}$$

where Q is the number of vehicles, i.e. the number of RTCs.

For the second step, the workload function, $h(t)$ is the sum of the transmission times of all packets of all RTCs with an absolute deadline less than or equal to *t*, where *t* signifies the number of time units elapsed since the beginning of the hyperperiod [17, 18]. A hyperperiod is defined as the least common multiple of all periods of all RTCs:

$$h(t) = \sum_{i=1}^{Q} \left(1 + \left\lfloor \frac{t - D_i'}{P_i} \right\rfloor T_i' \right). \qquad (1)$$

For a known CBP duration, the "minimal" CFP size that supports all the required RTCs can be found by choosing a CFP of $2T_{max}$ and increasing it gradually until schedulable.

IV. SIMULATION EVALUATION

A comparison between the standard-compliant CC case (co-existing CAM and DENM as well as potential non-platoon traffic using IEEE 802.11p MAC) and the proposed centralized approach using the real-time MAC approach over a SC was conducted in Matlab and performance in terms of CAM UTD and DENM DD was evaluated.

We assume that the leading vehicle has a coordinating role in the platoon, such that DENMs often originate from the leading vehicle for dissemination backwards in the platoon. As it cannot be presumed that all platoon members are within radio range of each other, DENMs need to be relayed or re-broadcasted either periodically or upon reception. We consider a platoon of 4-20 vehicles with a vehicle spacing of 30 m (antenna to antenna) and a radio range of approximately 500 m. This implies that, in the case of 15 platoon members or more, DENMs have to be relayed/re-broadcasted by intermediate vehicles to reach those in the back of the platoon. The choice of both radio range and line-of-sight (LOS) channel model stems from results from field trials conducted in [16]. Further, we model shadowing by other vehicles (obstructed LOS) by multiplicative Rayleigh fading and reduce the probability of LOS for each vehicle that is located in-between the sender and the receiver (for the first vehicle, we reduce the probability of LOS to 20% and for each additional vehicle that is located in-between the sender and the receiver, we reduce the probability another 5%). To model a busy highway situation with data traffic from additional co-existing applications, we add non-platoon vehicles to some of the simulated use cases using the CC. In these cases, all vehicles continuously send CAMs while DENMs are only transmitted by and in-between platoon members. Following ETSI standard, we use 400 byte packet sizes (for CAMs, DENMs and the beacon sent out by the MAC coordinator to start a SF and distribute the access schedule) and a data rate of 6 Mbit/s. The AIFS and backoff window sizes are based on a slot time of 13 µs, and we employ the highest defined priority class for DENMs and the second highest for CAMs to give warning messages priority over status updates. Each test case is run 500 times.

In accordance with the steps described in section III, the construction of a schedule for the centralized SC approach is divided into two steps: a step that determines an appropriate CBP length and a second step using real-time schedulability analysis to produce the proper CFP length and complete SF settings. The comparison between the standard-compliant CC setup and the centralized SC version considers a set of different schedules for the SC. Two different types of metric: CAM UTD and DENM DD are used to evaluate performance.

DENM dissemination delay - The DENM DD denotes the time that passes from the generation of the first DENM (as a reaction to some safety-critical event) by the leading vehicle of the platoon until every platoon member has received a warning. Each of the 500 simulated runs results in a DENM DD value. Note that, given the same settings, the same simulated values for DENM DD are used for evaluating both the CC-based approach as well as the SC-based approach. However, for the latter, the start of the DENM (the time when the platoon leader sends its first DENM) is randomized 1000 times, uniformly distributed over the entire SF, to cater for the probability of the DENM dissemination starting during a CFP or a CBP.

CAM up-to-dateness - We measure this metric in terms of the worst-case CAM UTD, i.e. the worst-case inter-arrival time between CAMs a vehicle received from a specific neighbor. For simplicity, we only monitor the CAMs generated by platoon members and received from the neighbor in-front. In the SC case, a CAM is always guaranteed channel access before a predefined deadline. We assume the CAM deadline to be equal to the point in time when the next CAM is generated, both in the CC and in the SC case. Due to the provided timing guarantees, the worst-case CAM UTD with the SC approach will never exceed one period (assuming an error free channel). When CAMs coexist with other traffic classes using CSMA/CA as MAC scheme, as is the case on the shared CC, packet collisions and long backoff times while the channel is busy can lead to CAM UTD values of several periods, jeopardizing the platooning application and the safety of platoon members as a vehicle remains invisible to its neighbors. For the CC case, the CAM UTD is determined by simulation where each simulated run produces one worst-case CAM UTD value for each vehicle that has an in-front neighbor (i.e., not the leading vehicle). This is then used to determine the average worst-case CAM UTD for the entire run. Note that in the SC-based solution, the CAM UTD is based on strict calculations (no simulation is needed as access is guaranteed), and thus to make the comparison fair, we assume that no packet errors occur for CAMs in either of the compared cases.

Determining the CBP size

The first step is to determine a suitable CBP size by running the simulator for different platoon sizes with DENM traffic only. The DENM dissemination model and send rate is chosen based on what was successfully applied to a similar platooning scenario in [5]. Consequently, a DENM send rate of 100 Hz is adopted, which is higher than the maximum allowed on the CC. As DENM dissemination from the platoon leader backwards throughout the platoon is assumed, the selected dissemination strategy allows vehicles to repeat a DENM periodically only until a warning about the same event is received from a vehicle situated further back in the platoon. In this case it is assumed that the information has successfully spread past the vehicle in question and that its DENMs are not needed anymore to ensure a full platoon warning. Details about the suitability of this strategy for platooning are found in [5].

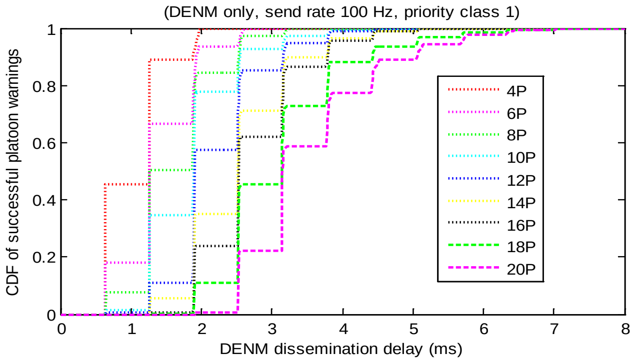

Figure. 1: DENM DD to find CBP size for diff. platoon sizes

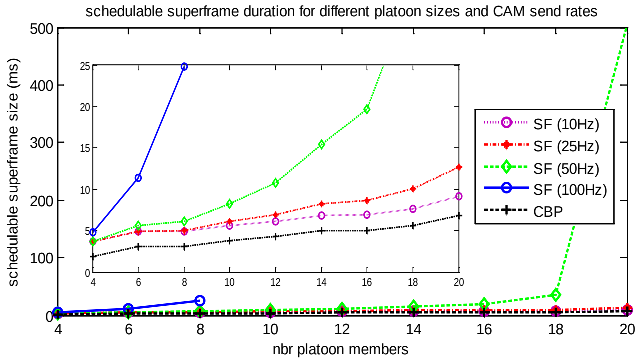

Figure. 2: SF and CFP sizes determined through RT analysis with full CBP size (full view and zoomed in view)

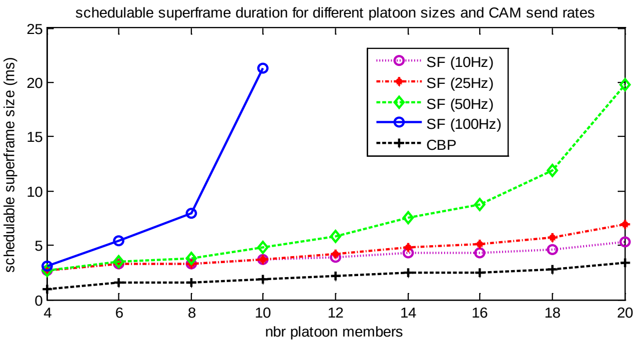

Figure. 3: SF and CFP sizes determined through RT analysis with half the CBP size

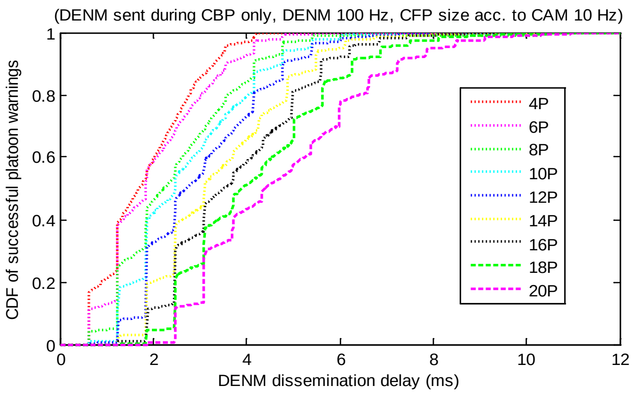

Figure. 4: SC - DENM DD, based on full CBP size and CFP size for CAM send rate 10 Hz

Figure 1 shows the resulting cumulative distribution function (CDF) for the DENM DD. The DD for a platoon of 20 vehicles shows that the entire platoon was warned after 4 ms in 75% of our 500 test runs, whereas it took almost 7 ms to reach a CDF of 0.99, i.e. a successful platoon warning in 99% of the rest runs. These simulation results give a good indication on the suitable CBP size to apply to the SC case. For each platoon size we therefore choose the DENM DD that showed a 99% success rate as input to step 2, the determination of the CFP size by the help of real-time schedulability analysis.

Determining the CFP size

Given the CBP size, number of platoon members (and thereby RT channels) and their corresponding communication requirements (packet length, period, deadline), we can use real-time schedulability analysis to determine how long the CFP (and thereby the entire SF) needs to be. Figures 2 and 3 show the resulting SF sizes for platoons of 4-20 vehicles and different CAM send rates (10, 25, 50 and 100 Hz). Figure 2 uses the CBP sizes determined by the DENM DD in the previous step whereas in Figure 3 the CBP sizes are set to half of the DENM DD. The drawback is that in this case, the dissemination process is spread over at least two SFs adding the duration of intermediate CFPs to the total DD. However, shorter, more frequently occurring CBPs also reduce the time until the DENM dissemination can be started. Figure 2 shows that, for send rates of 10 and 25 Hz, all CAMs are schedulable within SF sizes of 13 ms or below. More specifically, consider a platoon of 10 vehicles. With a predefined CBP size of 3.8 ms, the RT analysis arrives at a CFP size of roughly 1.8 ms as the smallest possible still to guarantee timely channel access for all CAM packets. Given a transmission time of approx. 0.6 ms per packet, three out of the ten CAMs can be scheduled in each CFP. In the worst case when all 10 vehicles generate their CAMs at the same time, all ten packets are granted channel access within four SFs, i.e. 5.6 ms. Figure 2 further shows that a CAM send rate of 50 Hz is still feasible but, in the case of long platoons of 20 vehicles, only schedulable within an extremely long SF of around 500 ms. This is not desirable from a DENM dissemination point of view where a 500 ms SF and a 6.8 ms CBP for 20 vehicles translates into a worst case delay of >490 ms in case the dissemination process is interrupted by a CFP. Cutting the CBP in half improves the situation considerably, as can be seen in Figure 3. Here CAMs from 20 vehicles with a send rate of 50 Hz can be scheduled within a SF of 20 ms. With a CAM send rate of 100 Hz, on the other hand, it is only possible to produce schedules for short platoons. No schedule could be found for long platoons due to the large amount of data traffic. We therefore consider CAM send rates of 10, 25 and 50 Hz as the most interesting cases for our further investigations.

Performance comparison: control channel vs. service channel

For the performance comparison of the CC-based and SC-based approaches, we consider a DENM send rate of 100 Hz and varying CAM send rates. In the CC case, we also assume the presence of non-platoon vehicles sending CAMs on the CC. Figures 4-10 shows the DENM DD for different settings. For the SC case, DENM dissemination takes place in the CBP part of the SF only. If an event happens during the CBP and

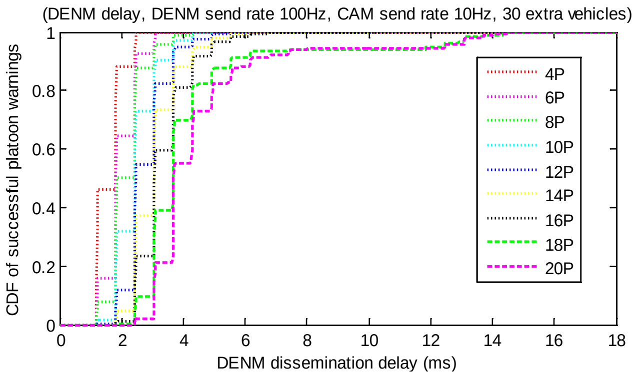

Figure. 5: CC - DENM DD with 30 extra vehicles and for CAM send rate 10 Hz

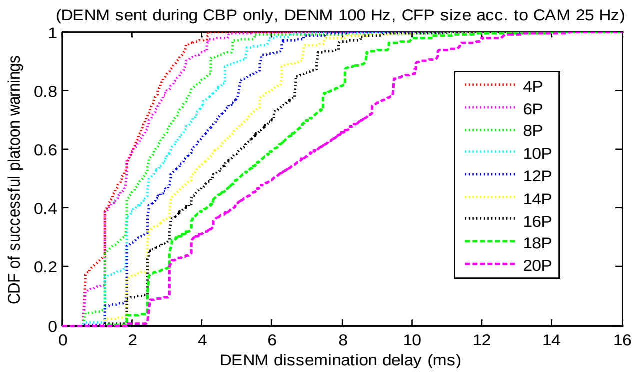

Figure. 6: SC - DENM DD, based on full CBT size and CFP for CAM send rate 25 Hz

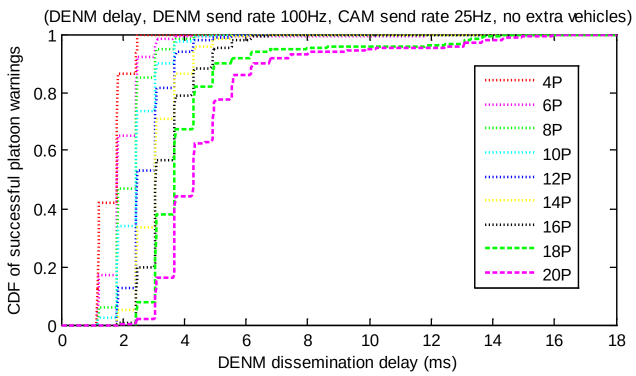

Figure. 7: CC - DENM DD with no extra vehicles and for CAM send rate 25 Hz

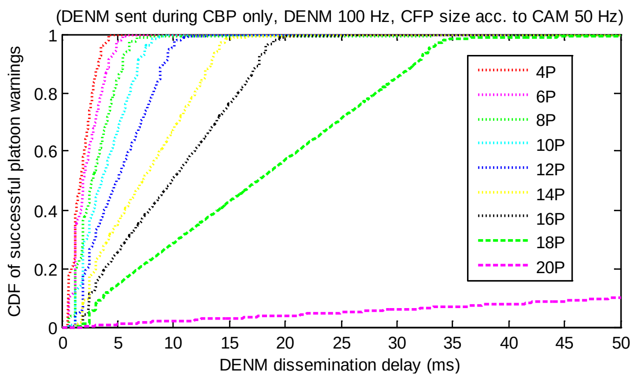

Figure. 8: SC- DENM DD, based on full CBT size and CFP for CAM send rate 50 Hz

there is enough time left for the entire dissemination process to finish before the next CFP starts, no further delays have to be added. If, on the other hand, an event is detected outside the CBP, the idle time until the start of the next CBP has to be added as additional delay to the DENM dissemination. Alternatively, if the dissemination process continues over more than one CBP, the delay due to intermediate CFPs has to be considered.

The results for the DENM DD in the presence of different CFP sizes can be found in Figures 4-10. Figures 4 and 5 employ the relatively low CAM send rate of 10 Hz. The DENM DD for the centralized SC-based approach shown in Figure 4 can be compared to the decentralized CC approach in Figure 5. No other traffic is interfering with the DENM transmissions during the CBP (Figure 4), leading to an overall quicker channel access. For platoons of short to medium length, this advantage is canceled out by an overall increase in DENM DD due to the presence of CFPs. Compare to the delay over the continuously shared CC (Figure 5), we can conclude that the worst case DEMN DD only increases slightly for shorter platoons (e.g. from 6 ms to 8 ms for 10 vehicles), while we even see a reduced dissemination delay for long platoons of 18 and 20 vehicles. The competition for channel access from an increasing number of CAMs over the shared CC clearly impacts the DENM dissemination for that MAC approach, leading to worst case delays of 14 ms while the corresponding delay for the centralized PC-based approach remains below 10 ms. Similar results were found for a CAM send rate of 25 Hz. Figure 6 shows the DENM DD for the SC approach that can be compared to the CC case in Figure 7. While the DENM DD is increased on average in Figure 6, it reaches a CDF of 1 faster, which means that a shorter worst-case dissemination delay could be achieved compared to the results in Figure 7.

Figure 8 shows the DENM DD for the SC approach with a CAM send rate of 50 Hz. As could be seen in Figure 2, the amount of CAMs that had to be scheduled during a CAM period for long platoons in the case of CAM rates of 50 Hz lead to considerably increased CFP sizes. For 18 vehicles a CFP of 30 ms was needed, whereas for 20 vehicles the required CFP duration was close to 500 ms. This, of course, does not translate well for the DENM DD. In Figure 9, we therefore test the more favorable CFP lengths the RT analysis produced for a shortened CBP size (as could be seen in Figure 3) and see a clear reduction in the DENM delay for long platoons. (Simulations for half the regular CBP size were also run for CFP settings corresponding to lower CAM send rates but no significant effect on the DENM DD could be reported there.) Compared to the CC case in Figure 10, however, the increase in DENM DD stemming from the DENM-free CFPs in the SC approach is still obvious. We conclude that the ratio of DENM and CAM traffic in the network is a key factor for the SC approach. As long as the amount of CAM traffic that has to be scheduled in the CFPs is small enough to produce a CFP and CBP of about the same size, the DENM DD is affected positively by centralized SC approach compared to competing for shared access on the CC. High CAM send rates, and thereby considerably longer CFPs, on the other hand, lead to a starvation of DENM traffic with unreasonable delays as a consequence.

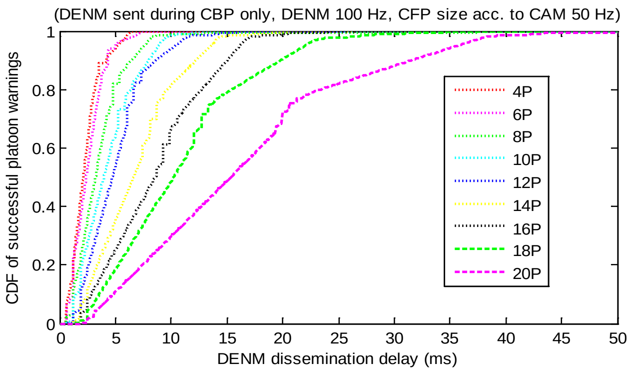

Figure.9: SC - DENM DD, based on half CBT size and CFP for CAM send rate 50 Hz

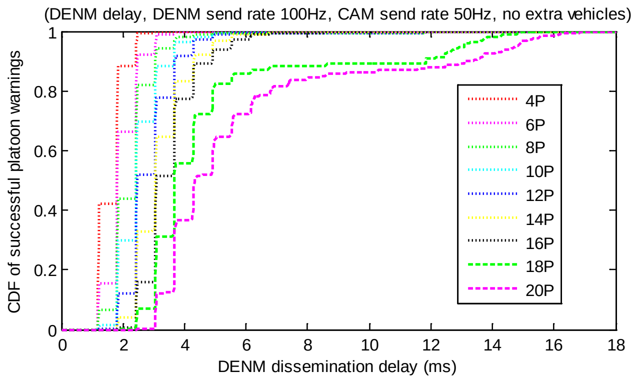

Figure. 10: CC - DENM DD with no extra vehicles and for CAM send rate 50 Hz

The CAM performance is evaluated in terms of CAM UTD in Figures 11-13. CAM traffic scheduled during the CFP in the SC approach is guaranteed channel access before a new CAM is generated, i.e. a worst-case CAM UTD of one period will never be exceeded. In case of the shared CC employing the CSMA/CA random access MAC protocol, the simulator is run with CAM rates of 10, 25 and 50 Hz for different platoon lengths. The channel is always shared with DENMs assigned the highest priority settings provided by the standard while CAMs operate at the second highest priority settings. As in the DENM DD evaluation, CAM traffic from 30 surrounding non-platoon vehicles is added at send rates of 10 Hz to simulate a situation where the CC is shared with other road users. An increased CAM UTD can be observed for long platoons for all CAM send rates. Figure 11 shows that in approx. 75% of the test runs with a platoon of 20 vehicles and a CAM send rate of 10 Hz, the worst-case CAM UTD is one period, while the remaining 25% have a worst-case CAM inter-arrival time of two periods, indicating that a CAM packet was delayed beyond its deadline and discarded. At a higher CAM send rate of 50 Hz, the SC case still guarantees a CAM UTD of one period, i.e. 20 ms, while the shared CC with its random access scheme shows worst-case CAM UTDs of ten times that number or more for long platoons. It becomes obvious that the CSMA/CA MAC scheme is not able to handle the large amount of channel access attempts while the SC approach is able to successfully adapt the CFP size to the required traffic requirements. While the RT analysis always finds SF settings that suit the periodic CAM traffic and leads to considerably

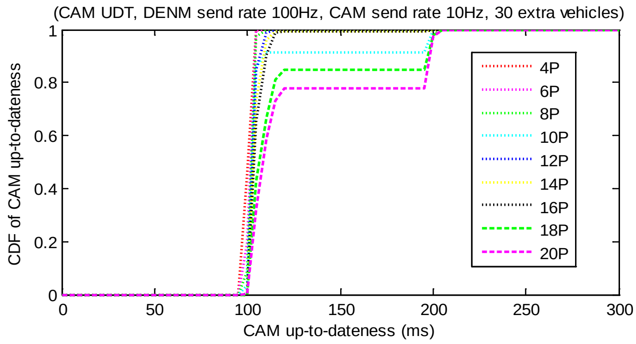

Figure. 11: CAM UTD with coexisting DENM traffic on the control channel (platoon and non-platoon vehicles)

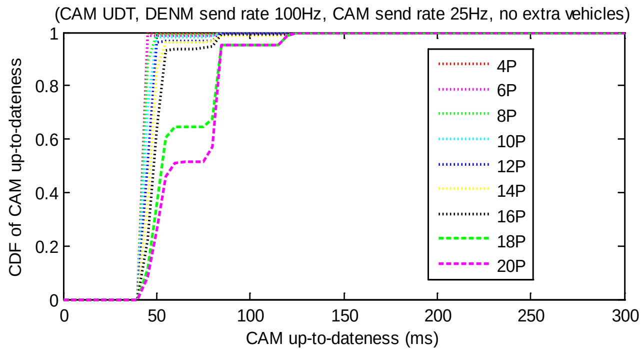

Figure. 12: CAM UTD with coexisting DENM traffic on the control channel (platoon vehicles only)

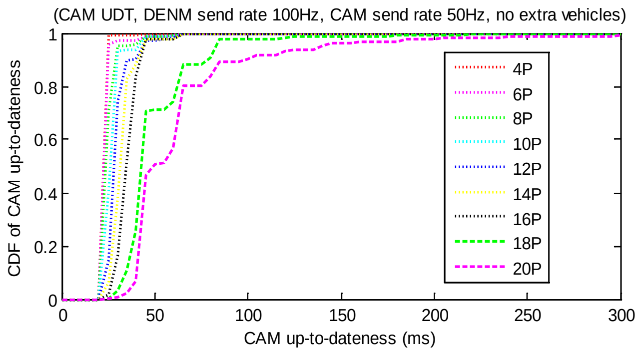

Figure. 13: CAM UTD with coexisting DENM traffic on the control channel (platoon vehicles only)

improved CAM UTD values as seen in Figures 11, 12 and 13, increased CFP durations have a negative effect on the DENM DD. There is a clear tradeoff between supporting a high frequency of CAMs and leaving enough bandwidth for DENM dissemination with reasonable delays.

V. Conclusion

The random access MAC method defined by the IEEE 802.11p standard for inter-vehicle communication coupled with the shared resources of the 10 MHz control channel for traffic-safety messages provides insufficient support for highly delay-sensitive applications as platooning. In order to maintain an inter-vehicle gap of 5 m or less for increased fuel efficiency, it is vital that both periodic status updates and event-driven warning messages can access the channel with low delay and high probability. In this paper, we presented a service channel based alternative to the standard-compliant approach using the control channel. On a dedicated service channel, we can use part of the bandwidth to employ a centralized, collision-free MAC scheme for periodic data traffic, scheduling resources and thereby guaranteeing channel access before a certain deadline. Those collision-free phases are interleaved with contention-based phases based on the decentralized random access MAC method used in IEEE 802.11p. During the contention-based phase unpredictable event-triggered traffic gets a chance to access the channel. We present a way to determine the proper duration of both phases to support both traffic types and compare our service channel based approach with the standard-compliant use of 802.11p over the shared control channel. Simulation studies of the inter-arrival time of status updates show that the control channel approach is unable to support the amount of periodic updates produced by long platoons using high update rates, while our service channel solution is able to successfully adapt the size of the collision free phase to the required traffic requirements. A comparison of the dissemination delay of event-triggered hazard warnings shows that, for CAM send rates of 10 and 25Hz, this is accomplished without increasing the worst case warning dissemination delay. For long platoons, the worst case dissemination delay was even decreased by several milliseconds.

References

[1] ETSI *EN 637-2: ITS; Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service*, June 2012.

[2] ETSI *EN 637-3: ITS; Vehicular Communications; Basic Set of Applications; Part 2: Specification of Decentralized Environmental Notification Basic Service*, June 2012.

[3] IEEE Std. 802.11-2012 *Part11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications.* March 2012.

[4] K. Bilstrup, E. Uhlemann, E. G. Ström and U. Bilstrup, ”Evaluation of the IEEE 802.11p MAC method for vehicle-to-vehicle communication,” *Proc. IEEE Vehicular Technology Conference*, Calgary, Canada, Sept. 2008, pp. 1-5.

[5] A. Böhm, M. Jonsson and E. Uhlemann, “Co-existing periodic beaconing and hazard warnings in IEEE 802.11p-based platooning applications”, to appear in *Proc. ACM International Workshop on VehiculAr Inter-NETworking, Systems and Applications (VANET)*, Taipei, Taiwan, June 2013.

[6] A. Böhm and M. Jonsson, “Real-time communication support for cooperative, infrastructure-based traffic safety applications”, *International Journal of Vehicular Technology*, vol. 2011, Article ID 541903, 17 pages, 2011.

[7] ETSI *EN 302 663: Draft V1.3.2, ITS; Access Layer Specification for Intelligent Transport Systems operating in the 5 GHz frequency band*, Tech. Rep., 2010.

[8] S. Eichler, “Performance evaluation of the IEEE 802.11p WAVE communication standard,” *Proc. IEEE Vehicular Technology Conference (VTC)*, Baltimore, MD, Sept. 2007, pp. 2199-2203.

[9] S. Kaul, M. Gruteser, V. Rai and J. Kenney, “Minimizing age of information in vehicular networks”, *Proc. 8th IEEE Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, Salt Lake City, UT, USA, June 2011.

[10] D. B. Rawat, D. C. Popescu, G. Yan and S. Olariu, “Enhancing VANET performance by joint adaptation of transmission power and contention window size”, *IEEE Transactions on Parallel and Distributed Systems*, vol. 22, no. 9, pp. 1528-1535, September 2011.

[11] M. Sepulcre, J. Gozalvez, J. Härri and H. Hartenstein, “Contextual communications congestion control for cooperative vehicular networks”, *IEEE Transactions on Wireless Communications*, vol. 10, no. 2, pp. 385-389. February 2011.

[12] M. Sepulcre and J. Gozálvez, "Optimizing adaptive transmission policies for wireless vehicular communications," *Proc. IEEE Vehicular Technology Conference (VTC)*, Calgary, Canada, Sep. 2008.

[13] T. K. Mak, K. P. Laberteaux and R. Sengupta, “A multi-channel VANET providing concurrent safety and commercial services,” *Proc. ACM International Workshop on VehiculAr Inter-NETworking, Systems and Applications (VANET)*, New York, NY, Sept. 2005.

[14] N. Cheng, N. Lu, P. Wang, X. Wang and F. Liu, “A QoS-provision multi-channel MAC in RSU-assisted vehicular networks”, *Proc. IEEE Vehicular Networking Conference (VNC)*, Amsterdam, Netherlands, November 2011.

[15] K. Hong, J. B. Kenney, V. Rai and K. P. Laberteaux, “Evaluation of multi-channel schemes for vehicular safety communications”, *Proc. 71st IEEE Vehicular Technology Conference (VTC)*, Taipei, Taiwan, May 2010.

[16] A. Böhm, K. Lidström, M. Jonsson and T. Larsson, ”Evaluating CALM M5-based vehicle-to-vehicle communication in various road settings through field trials,” *Proc. IEEE LCN Workshop on User Mobility and Vehicular Networks*, Denver, CO, Oct. 2010.

[17] M. Spuri, “Analysis of Deadline Scheduled Real-Time Systems”, *Technical Report RR No. 2772*, Institute National de Recherche en Informatique et en Automatique (INRIA), France, 1996.

[18] J. A. Stankovic, M. Spuri, K. Ramamritham, and G. C. Buttazzo, *Deadline Scheduling for Real-Time Systems - EDF and Related Algorithms*, Kluwer Academic Publishers, Boston, MA, USA, 1998.

[19] C. L. Liu and J. W. Layland, “Scheduling algorithms for multiprogramming in a hard-real-time environment,” *Journal of the ACM*, vol. 20, no. 1, pp. 46-61, Jan. 1973.