Data age based MAC scheme for fast and reliable communication within and between platoons of vehicles

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Abstract— **Heavy vehicles driving as platoon with highly reduced inter-vehicle gaps has shown considerable fuel saving potential, but put high timing and reliability requirements on the underlying control data exchange. The recently standardized IEEE 802.11p protocol suite for Vehicular Ad-Hoc Networks (VANETs) and its message types do neither support the demands of a platooning application nor take advantage of its properties. We therefore propose a framework for centralized channel access with retransmission capabilities for safety critical control data exchange based on the data age of earlier received messages, DA-RE (Data Age based REtransmission scheme). A simulation comparison to the 802.11p random access Medium Access Control (MAC) protocol shows that the intelligent assignment of retransmission opportunities considerably improves the reliability of platooning control data. We also propose a power control based scheme for early platoon detection allowing several platoons to temporarily share a channel and show that the safe and reliable operation of their vehicles is not compromised.**

I. INTRODUCTION

The latest advances in sensing, communication and computation have considerably improved safety and comfort on our roads today. Introducing wireless communication between vehicles enables vehicles to share current status information (e.g. position, speed or other in-car sensor data) with surrounding traffic participants. One application of such Cooperative Intelligent Transport Systems (C-ITS) that gained interest from researchers, vehicle manufacturers and government organizations alike is platooning. Consider a platoon of tightly spaced trucks driving on a highway. The leading vehicle is operated by a driver while all following vehicles act autonomously once they joined the platoon and activated platooning mode. Several studies have shown considerable reductions in fuel consumption by driving vehicles in close proximity in a single lane. In [1], Bonnet and Fritz could show a 21% fuel reduction for trailing trucks travelling at 80 km/h and an inter-vehicle gap of 10 m. Even the lead truck showed a fuel reduction of 6%. As heavy vehicles account for 5% of the total global carbon emissions, the environmental and economic benefits of platooning are indisputable and make platooning an interesting showcase of the introduction of semi-automated driving on our highways.

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Platooning, like many emerging cooperative traffic safety applications, relies on the periodic exchange of basic status messages. These sensor readings must be both fresh and received within a tight time frame to ensure the safe operation of the platoon. This puts demands on the timing and reliability properties of the underlying communication protocols that the recently standardized IEEE 802.11p protocol suit for inter-vehicle communication [2] - in particular its decentralized, random access Medium Access Control (MAC) protocol - has difficulties to match. The standard was developed with the high mobility and flexible network topology of a Vehicular Ad-hoc NETwork (VANET) in mind. A platoon, however, with its relatively stable topology, well-defined group leader and strict timing requirements, lends itself much better to a centralized, pre-scheduled MAC solution.

In this paper, we present DA-RE (Data Age based REtransmission scheme), a framework for reliable and timely communication both within a platoon (intra-platoon) and between platoons (inter-platoon). We assume a dedicated Service Channel (SCH) for platoon-related communication. Data exchange with or between non-platoon members happens on a separate Control Channel (CCH) without interference. Platoon Announcements (PA) on the CCH enable the platoon to make its presence known to its surrounding. A separate SCH not only provides extra bandwidth, it even enables us to deviate from the MAC method of the IEEE 802.11p protocol suit [2] that is mandatory on the CCH and design a MAC scheme that supports the specific requirements platooning, as well as take advantage of its properties.

There are two distinct parts to our proposal: a) a centralized, time-slotted MAC protocol for intra-platoon communication offering retransmission opportunities based on the data age of previously received data. This allows the prioritization of packets from vehicles that are in most need to communicate. And b) a mechanism to safely and efficiently integrate several platoons into a common MAC scheme while sharing the SCH. The early detection of and negotiation between platoons is done at the maximum output power of 23 dBm [3]. Power control of all intra-platoon data exchange ensures that the approaching platoons interfere as little as possible with each other before a schedule for collision-free bandwidth sharing has been agreed upon.

We compare DA-RE to the standard's Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol as well as other retransmission mechanisms in terms of Packet Delivery Ratio (PDR) and Data Age (DA) and show that

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granting retransmission opportunities to the vehicle with the highest need to communicate significantly improves timing and reliability of intra-platoon control data exchange. Furthermore, we show that the proposed early detection scheme enables platoons to temporarily share available resources with no or minor impact on the exchange of safety-critical data.

The rest of the paper is organized as follows: Section II discusses relevant work from standardization and related research, while Section III presents the details of the proposed data age based retransmission model. The mechanisms for early platoon detection and bandwidth sharing are explained in Section IV. The simulation details and results are presented in Sections V and VI, before Section VII concludes the paper.

II. Background and Related Works

A platoon differs from regular VANETs in several aspects. This is reflected in our choices of e.g. MAC method, message update rate and message content. Here, we provide the background for our assumptions by discussing current standardization and related research.

A. Prerequisites from Standardization

Recently, IEEE 802.11p, a protocol suit based on the IEEE 802.11 Wireless Local Area Network (WLAN) standards adapted to vehicular networking, was incorporated into the IEEE 802.11 standard [2]. IEEE 802.11p defines the physical and MAC layer protocols of the Wireless Access to Vehicular Environments (WAVE) protocol suit. A typical C-ITS application often assumes an ad-hoc type of network where topology changes are frequent due to very high node mobility. Therefore WAVE communication protocols are based on a decentralized approach avoiding the overhead of choosing and maintaining a candidate for centralized control. IEEE 802.11p employs the CSMA/CA random access MAC method 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 or becomes busy during the AIFS, the node randomizes a backoff time (limited by a maximum backoff window value), which is counted down only while the channel is sensed free. When the backoff value reaches zero, the node transmits directly without any further delay. Despite its listen-before-talk approach packets might still collide, rendering their content useless to the intended receiver. For the strict timing and reliability needs of a platoon, this is not a feasible solution. Due to its stable topology, platooning lends itself to a centralized, time-slotted channel access scheme where slots are assigned to individual nodes without contention, thereby providing deterministic channel access delay.

The European Telecommunications Standards Institute (ETSI) standardized a profile of IEEE 802.11p adapted to the 30 MHz frequency spectrum in the 5.9 GHz band comprising one CCH and two SCHs. Typical C-ITS safety applications rely on the exchange of two basic message types, periodic status updates and event-triggered hazard warnings. ETSI therefore defines two types of messages, periodic Cooperative Awareness Messages (CAM) [4] and event-triggered Decentralized Environmental Notification Messages (DENM) [5]. Recently, European Standardization moved away from a strictly periodic generation of status updates. According to ETSI's specification of CAMs, a CAM is triggered based on a number of triggering states. This was done to lessen the load on the common CCH from "unnecessary" status updates when no status change had to be reported. The current triggering rules state that a CAM will be triggered at least once per 1000 ms and never more frequent than every 100 ms. Further triggering parameters are connected to changes in the vehicle's position, speed and direction. As a consequence status updates can no longer be expected at periodic intervals. For a highly deadline dependent application as platooning, where a control loop has to periodically and reliably be fed with data, this is an unfortunate choice that makes CAMs in their standard-compliant form difficult to use.

In order to support the needs of intra-platoon control data exchange, we argue that the use of a dedicated SCH for platooning is a requirement. A platoon-specific SCH enables us to deviate from the CSMA/CA MAC method the standard requires on the CCH, define our own message types and send control data at the required periodicity (20 ms is often mentioned as the desired update frequency by the truck manufacturing industry as it corresponds to the highest sensor reading interval achievable today). Furthermore, the CCH will not be flooded with the potentially very high data load associated with platoon control, especially when two or more platoons occupy the same transmission area. A platoon-specific SCH requires a platoon vehicle to either periodically switch between the CCH and the SCH or to carry two sets of transceivers to simultaneously listen to both. For commercial vehicles the benefits from platooning in terms of reduced fuel consumption would by far outweigh the cost of dual transceivers. We therefore deem the presence of a second transceiver dedicated to the platooning SCH to be very realistic.

B. Related Works

Several recent studies are concerned with strategies to improve timing and reliability in platooning scenarios [6-9], pointing out the inadequacy of CSMA/CA to provide reliable data delivery in time-critical C-ITS safety applications. Lei et. al. [6] concluded that CAMs' update rate and PDR have significant influence on platoon stability. In [7], Fernandes et al. suggest the use of a time-slotted MAC approach, priority levels and anticipatory information to improve the reactivity to e.g. velocity changes. The authors of [8] successfully employ a slotted, prescheduled approach for periodic control data exchange making use of the predictability of the bandwidth needs of periodic status updates in a platooning scenario. Predictability and estimation is even a key issue in [9], proposing the use of link reliability estimations to form Quality of Service (QoS) classes.

While most work (in the area of VANETs in general or platooning in particular) is concerned with enhanced reliability by making the first transmission more likely to succeed, the number of proposed retransmission schemes is very limited. An efficient scheme for acknowledging video packets in a highly mobile VANET environment was proposed by [10], rather fo-

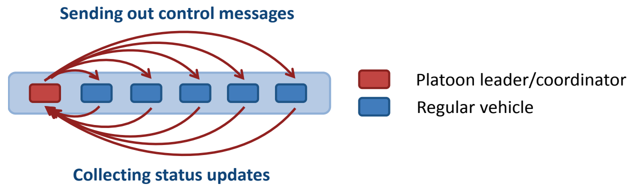

Figure 1: Intra-Platoon Message Exchange

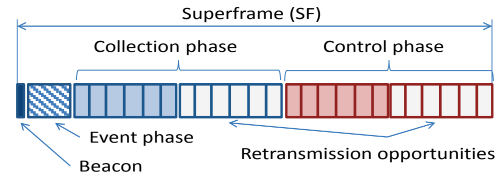

Figure 2: Superframe Structure

cusing on the low-jitter requirements of the target application than the tight timing and reliability needs of platoon control. Broadcasted acknowledgement (ACK) as the basis for the choice of a suitable relay node is discussed in [11]. As we are assuming that all platoon members are in each other's transmission range, relaying, however, is not an issue at this point. We therefore introduced the idea of using the DA of received messages to assign retransmission capabilities within a platoon in [12], our previous work that constitutes the basis of this paper. As it directly reflects the application requirements, DA is a very useful parameter to assess intra-platoon control data exchange. The concept of DA is well-studied and described in e.g. the field of data base systems or data aggregation [13], but rarely used as performance metric in networking and communications. Furthermore, to the best of our knowledge is has not been used as input to a scheduling or retransmission scheme within the VANET research community before.

The use of power control to limit the load on the CCH in densely trafficked VANET scenarios has been studied in [14-15]. To assign power levels based on the vehicle's role in a platoon has been proposed by Segata et al. [16]. Here, the power levels are, however, only used to more efficiently use the CCH by limiting the output power of non-leading platoon vehicles to only reach their closest neighbors, while the leading vehicle's more generous power level enables it to reach the entire platoon. The use of power control for early detection of and between platoons is a concept that, to our knowledge, has not been proposed so far.

III. Intra-Platoon Communication

A platoon is made up of a leading vehicle and one or more followers keeping a speed and inter-vehicle gap that ensures the safe operation of the platoon at the current road, weather and radio conditions. In order to provide the platoon control loop with sufficiently fresh status data from all platoon members, they must be able to access the channel and successfully transmit their updates periodically. If this is not ensured, decisions are based on increasingly outdated information. The DA is therefore a valuable parameter to measure the success of timely intra-platoon communication. We measure the DA of the information a vehicle holds from a specific fellow platoon member as the time that has passed since the arrival of the latest status update from this particular member.

Making use of the relatively stable topology of a platoon, we employ a centralized, slot based MAC method, where a dedicated vehicle per platoon (the coordinator) is responsible for assigning retransmission slots to platoon members based on DA. The coordinator can be the leading vehicle or a vehicle situated in the middle of the platoon. The leading vehicle is usually the first to detect situations that require an adaptation of the platoon's behavior. We therefore choose the leading vehicle as coordinator with two responsibilities (see Fig. 1): From the platooning application's point of view, the coordinator collects Status Updates (SU) from all platoon members and sends out Control Packets (CP) concerning the overall organization of the platoon (e.g. announcing a general speed reduction due to changes in weather conditions or an increased gap between individual vehicles based on collected sensor data). From the communication's point of view, the coordinating node acts as the packet scheduler.

A. Superframe Structure

All intra-platoon communication takes place on a dedicated SCH that is divided into superframes (SF). The length of a SF depends on the requirements from the platooning control application. The smaller the inter-vehicle gap, the higher the update rate of periodic status and control data needed to safely maintain that gap.

We define four message types on the platoon-specific SCH (see Fig. 2): Beacons are sent out by the coordinator to start off the SF. The beacon is followed by an event phase for event based messages. As these messages are non-periodic, they are not schedulable in advance. A vehicle that has an event to report (a sudden deceleration, an icy spot on the road etc.) accesses the channel during the event phase in competition with other nodes using the standard's CSMA/CA protocol. Even packets exchanged between platoon coordinators for the safe and efficient integration of multiple platoons into the SF structure make use of the event phase (for details see Section IV). Periodic data traffic (SUs and CPs) can be scheduled in advance and assigned individual time slots for unique access to the channel.

We define two phases, a Collection Phase (Coll-P) and a Control Phase (Con-P), each with retransmission opportunities, if time allows: During the Coll-P each vehicle has a fixed time slot to send its SUs followed by a Retransmission Phase (Re-P) where unsuccessful packets can be retransmitted. Retransmissions are initiated by a short polling message from the master followed by an immediate retransmission attempt of that vehicle. Based on SU information, the coordinator sends individual CPs back to each platoon member during the Con-P. Even the Con-P offers the possibility of retransmissions based on ACKs returned by the receiving nodes. The ratio of Coll-P and Con-P is (initially) set to 50/50. The length of a Re-P depends on the number of vehicles in the platoon, i.e. the number of slots needed for ordinary transmissions and the overall length of the SF, which in its turn is dependent on the update period required by the platooning control application.

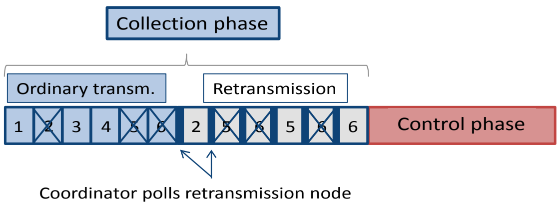

Figure 3a: The Collection Phase

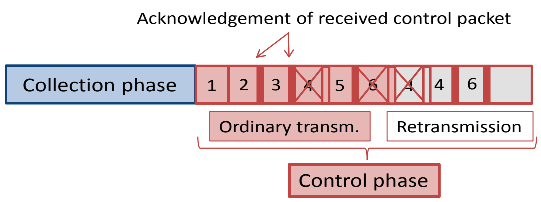

Figure 3b: The Control Phase

B. Retransmission Scheduling

The DA is used to assign retransmission opportunities to the nodes that need it the most. The coordinator keeps a table with the reception time of the latest SU from each individual node. From this table, the DA is deducted. It even keeps track of the CPs' DA at the individual nodes with the help of received ACKs. Fig. 3a explains the assignment of ordinary and retransmission slots during the Coll-P. Synchronized by the beacon and based on its position in the platoon, each vehicle sends an ordinary status update to the coordinator during its pre-scheduled time slot. Using the wireless medium, every transmission can be considered a broadcast transmission. We see the coordinator as the main recipient and the only node that asks for retransmissions. All platoon members within transmission range can however receive and utilize each other's SUs. We therefore also assign a slot for the coordinator during the ordinary transmission phase. In Fig. 3a, the transmissions of vehicles 2, 5 and 6 were not received by the coordinator and are therefore scheduled for retransmission in the order of DA. Retransmissions are initiated by a polling from the coordinator followed by an immediate retransmission attempt from that individual vehicle. If needed and if time allows, another round of retransmissions is initiated, again in DA order. This process continues until either the end of the Coll-P is reached or one successful SU was collected from each platoon member and the Con-P takes over.

Based on the collected SUs the coordinator sends individual CPs back to all nodes during the Con-P (see Fig. 3b). Ordinary transmissions are sent in order of vehicle ID, each followed by an ACK informing the coordinator of a successful CP reception. Amongst the nodes that have not sent an ACK (vehicles 4 and 6 in the figure) the coordinator chooses the one with the highest DA, retransmits its CP, awaits the ACK and repeats the process.

IV. EXTRA-PLATOON COMMUNICATION

Staying connected, both within the platoon, between platoons and with non-platoon vehicles, is vital to the safe operation and integration of a platoon into a broader C-ITS context. We define two types of interaction between the platoon and its surrounding: non-platoon communication to stay connected to non-platoon vehicles and inter-platoon communication to connect multiple platoons.

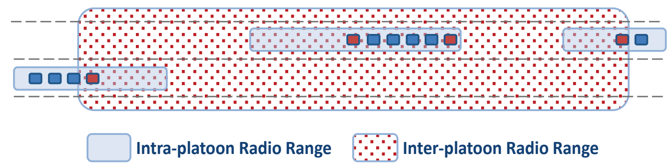

Figure 4: Inter- and intra-platoon communication

A. Non-Platoon Communication

Each platoon member communicates both on the CCH and the dedicated platooning SCH (see Fig. 4). To all surrounding traffic participants on the CCH a platoon vehicle looks like any 802.11p-equipped vehicle sending periodic CAMs. The presence of a platoon is only announced by the first and last vehicle of the platoon through Platoon Announcements (PAs). (By sending alternating PAs from the leading and the last vehicle, we get maximum broadcast coverage both in front of and behind the platoon.) PAs are broadcasted periodically (e.g. at 20 Hz) at the highest allowed output power (23 dBm) and inform about the platoon's length, number of members, position, speed and driving direction, so non-platoon vehicles can incorporate the platoon into their individual safety applications. Furthermore, a PA states the frequency band of the platoon's SCH and the current SF structure, so a vehicle that wants to join the platoon can make contact during the platoon's event phase once per SF. While PAs always are broadcasted at the highest allowed output power, the output power of intra-platoon communication is reduced to the one-hop coverage of the platoon (see below). Furthermore, it is desirable to make the SCH available to any application as long as no platoon resides within radio range. PAs alert any nodes on the SCH of an approaching platoon, hereby making maximal use of the available ITS frequency channels with minimal interference with the time- and safety-critical intra-platoon data exchange.

B. Inter-Platoon Communication

As the number of available SCHs is limited, it is not always possible to assign different frequency bands to individual platoons. Platoons consequently might have to share a single SCH for a limited amount of time. Depending on the type of meeting (overtaking or merging in case the platoons drive in the same direction; passing in case they travel in opposite directions) the channel sharing duration can amount to several minutes. To ensure the safe operation of both platoons a temporary switch to a random access MAC scheme is not an option. Maintaining the proposed DA-RE protocol, on the other hand, requires coordination between the platoons before they enter each other's transmission range.

C. Early Platoon Detection

Whenever several platoons occupy the same transmission range they need to negotiate how to temporarily share the SCH. Ideally, meeting platoons have already agreed upon a common schedule before they even get close enough to interfere with each other's intra-platoon transmissions. Early detec-

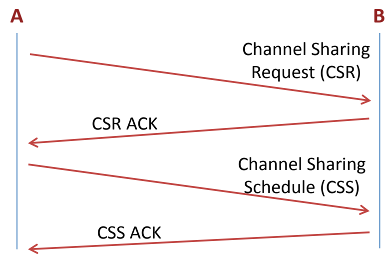

Figure 5: Channel sharing negotiation

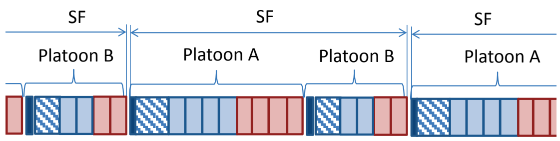

Figure 6: Superframe sharing

tion is based on the 23 dBm PAs (on the CCH) and negotiation messages (on the SCH). The lower the power level of intra-platoon packets, the higher the probability that the two platoon leaders detect each other and agree on a common schedule before any intra-platoon interference will occur. The choice of output power for intra-platoon communication is based on the required radio range for one-hop platoon coverage with reasonable reliability.

$$R_{intra} = (N \times d_{antenna}) + \alpha$$

where N is the number of vehicles in the platoon, $d_{antenna}$ is the antenna-to-antenna distance between platoon vehicles, R_{intra} is the transmission range for regular intra-platoon transmissions (in m) and α is a factor to regulate R_{intra}. The output power of the PAs on the CCH as well as all inter-platoon negotiation, R_{extra}, is set to the maximum allowed output power of 23 dBm.

Reducing the transmission range for intra-platoon data exchange leads to a lower PDR. If the ratio between SF length and platoon members allows a sufficient number of retransmissions, this negative effect can be counteracted. A certain PDR required by the application can therefore be met by balancing the number of platoon members, their inter-vehicle distances and the SF length (and thereby the number of retransmission opportunities).

D. Channel Sharing

Consider two platoons, A and B, approaching each other from opposite directions. As soon as the leading vehicle of A has received a PA from B on the CCH it knows B's SF structure. The platoon leader of A can now send a Negotiation Message (NM) during B's event phase. As SFs are not necessarily synchronized – their start might be out of synch or have different SF lengths – we cannot assume that the event phases of our two platoons overlap. This means that the NM from leader A might has to be sent during the Coll-P or Con-P at the expense of an intra-platoon data packet. Our time-slotted protocol is implemented on top of IEEE 802.11p hardware. Consequently, each packet – CDMA/CA based or pre-scheduled – has to adhere to the mandatory waiting time before channel access. We make use of the available priority classes of IEEE 802.11p to assure that NMs get priority over intra-platoon packets. Lower maximum backoff windows values for higher priority message types further increase a NM's chances of channel access. Table I summarizes the priority settings.

TABLE I: PRIORITY LEVEL ASSIGNMENT

Message type	**802.11p priority**	**AIFS**	**Backoff Window**	**Total transmission time**
Negotiation packet	1	58 µs	3	611 µs
Intra-platoon poll or ACK	2	58 µs	7	150 µs
Intra-platoon SU or CP	3	71 µs	15	624 µs

A handshake procedure of 4 NMs is required for the successful negotiation of channel sharing (see Fig. 5). First leader A sends a Channel Sharing Request (CSR) to leader B. As long as no ACK is received during A's event phase a new CSR is transmitted once per superframe. After the reception of a CSR ACK leader A answers with a Channel Sharing Schedule (CSS), specifying the division of the shared SF into two parts. A successfully received CSS is acknowledged by a CSS ACK from B.

The channel sharing algorithm is simple and directly related to the ratio of platoon members in A and B. A platoon gets access to the share of the SF that corresponds to its share of the total number of vehicles. By default a 20 ms SF is assumed. This means that two short platoons can share the SF at the expense of retransmission opportunities. The standard data rate is 6 Mbit/s and the packet size of 400 byte is assumed both for data packets. A 71 µs AIFS is used for SUs and CPs, 58 µs for beacons, polling and ACKs, resulting in a transmission time of 624 µs for data packets and 150 µs for polling and ACK messages. Assuming that two platoons share a 20 ms SF with a beacon each and an event phase of ⅕ of their share of the SF, a total of 12 slots are available for the two platoons. Shared by a 4-vehicle platoon A and a 2-vehicle platoon B (see Fig. 6) this would leave no slots for retransmission. If the total number of vehicles exceeds the number of ordinary slots the SF size must be increased. This, on the other hand, leads to a lower update rate of periodic control data and might require an increased inter-vehicle gap for maintained safety.

V. SIMULATOR DETAILS

The proposed retransmission and early detection schemes are evaluated in a comparative simulation study implemented in Matlab. The packet level simulator consists of a decentralized CSMA/CA implementation according the IEEE 802.11p standard and a slot based scheme as described in Section III. The data rate is 6 Mbit/s, the transmission times for different packet types can be found in Table I and the simulated platoon sizes are 3, 5 and 7 vehicles. The default SF length and antenna-to-antenna spacing are 20 ms and 30 m (truck with trailer and 5 m inter-vehicle gap), respectively. The channel model is derived from [17] with a distance-dependent parameter in the Nakagami-m distribution.

First, we evaluate the performance of our protocol by comparing five cases, representing different MAC schemes and retransmission capabilities (all employ a Coll-P and Con-P):

1) *The proposed DA-RE protocol*. The Coll-P starts in fixed (SF based) intervals while the Con-P starts whenever no more retransmissions of SUs are required.

2) *Slotted channel access with ID based retransmissions* - This scheme assumes retransmissions but applies no intelligent algorithm to schedule them. Retransmission slots are added in round robin fashion as time permits.

3) Slotted channel access without retransmission - No retransmissions are granted and any remaining time in the Coll-P or Con-P remain unexploited.

4) CSMA/CA without event based data - Channel access is granted according to IEEE 802.11p MAC. Each vehicle starts transmitting its first SU with a random initial offset and continues then sending one packet every 20 ms. A dropped SU is not repeated. During the Con-P the coordinator will send its CP one after another without competition from other nodes. Therefore, the Con-P resembles the one for the slotted channel access without retransmissions. No event based packets are assumed.

5) CSMA/CA with event based data – The only difference to case 4 is the existence of event based packets (400 byte) that compete for channel access with the periodic control data. We randomly inject 5 event messages per 20 ms period to study their effect on the performance. (In DA-R, event-based traffic would not affect the control data exchange as they are only sent during the event phase.)

We study the effect of different platoon lengths and intra-platoon output power levels on the PDR and DA. In the case of two platoons sharing the common SCH, we even extend the SF length and antenna-to-antenna distances to see how it affects the performance. Finally, we study how well our protocol manages to deal with the presence of NMs during the Coll-Ps and Con-Ps. All results are obtained over 10 000 SFs at a constant vehicle speed of 90 km/h.

VI. Simulation Results

First, we evaluate the performance of DA-RE compared to other MAC/retransmission schemes. We show figures for SUs only as CPs produced comparable results. Figure 7 shows the PDR of SUs sent by individual vehicles of a 3, 5 and 7 vehicle platoon from the coordinator's point of view. (Packets sent by the coordinator itself that were denied channel access are counted as unsuccessful although sender and intended receiver coincide.) The lower the output power of intra-platoon communication, the higher is the probability of early platoon detection without interference. In Fig. 7a we see that an output level of −10 dBm very well supports a 3-vehicle platoon as long as retransmission opportunities are offered. The DA-RE protocol slightly outperforms ID based retransmissions due to its context-aware choice of retransmission candidates. A scheme without retransmissions only reaches a PDR of 50% for the last vehicle, showing that packet loss is an issue even in short platoons and that retransmissions fill a purpose. Due to the small number of packets, the difference between CSMA/CA and the slotted scheme without retransmission is small.

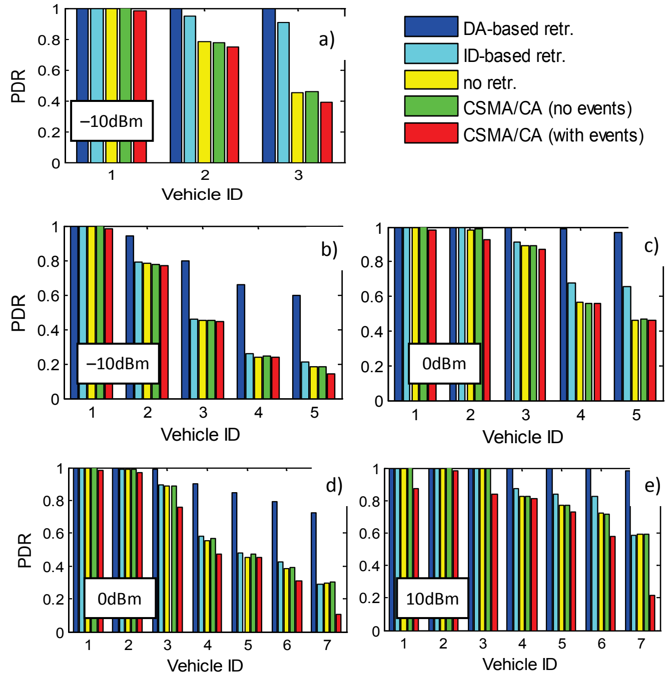

Figure 7: PDF for different MAC/retransmission schemes for various platoon lengths and output power levels

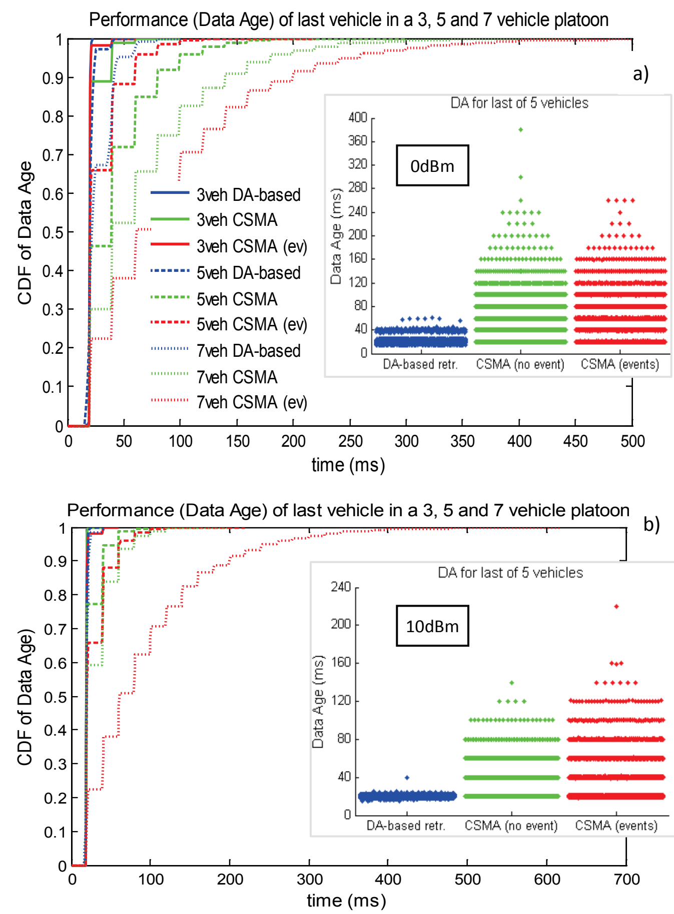

Figure 8: DA for different platoon sizes and output power levels for the data age based retransmission scheme

Increasing the platoon length to 5 or 7 vehicles increases the communication distance and thereby decreases the PDR. Even the DA based retransmissions are not able to counteract the dropped packets at −10 dBm (Fig. 7b) with a PDR of 60% for vehicle 5, while the same vehicle experiences a PDR of 97% for a power level of 0 dBm (Fig. 7c). A further increase from 0 to 10 dBm is required to support a 7 vehicle platoon (Fig. 7d,e), a power level that is still comfortably below the 23 dBm of the PAs and NMs used for inter-platoon communication. Especially for longer platoons, where retransmission opportunities are scarce, the context-aware retransmission assignment of DA-RE outperforms ID based retransmissions.

From the control application's point of view, it is vital that the DA of SUs is kept close to one SF. In Figure 8, we therefore study the DA of SUs for different platoon lengths for a 0 dBm and 10 dBm output level, comparing DA-RE to CSMA/CA. For each power level, the DA is shown for the last vehicle of the platoon (the vehicles with the toughest radio conditions), both as Cumulative Distribution Function (CDF) (large figure) and represented by a dot per simulated packet (small figure). Looking at 5 vehicles at 0 dBm (Fig. 8a), a DA of around 20 ms was recorded for 97% of the SFs (slight variations around the 20 ms mark are due to retransmissions). A DA of 60 ms, i.e. two unsuccessful packets in a row, was recorded in less than 0.1% of the SFs. The corresponding DA for CSMA packets, on the other hand, shows a worst case of 380 ms, a suite of 18 consecutive packet losses. In Fig. 8b, we see the performance at 10 dBm where DA-RE shows a success rate of 99.99% for a 5 vehicle platoon, whereas only 78% and 67% of the SF reported a successful SU reception for CSMA without and with event based traffic, respectively, with a worst case DA of 140 and 220 ms.

In Fig. 9 we study the effect of SCH sharing on the PDR of the individual vehicles of two 5-vehicle platoons. Comparing Fig. 9 to Fig. 7 for comparable power levels, we clearly see that a shared SF of 20 ms shows a considerable decrease in performance. To fit the second platoon with its ordinary transmission slots into the SF leaves no room for retransmissions (Fig. 9a-b). Therefore the differences between the time slotted and the random access schemes are merely due to channel access collisions, not retransmission. Even for DA-RE an increase in output power to 10 dBm is required to achieve a reasonable reliability for both platoons. In order to allow for retransmissions, we double the SF size in Fig. 9c and the effect of the retransmission scheme immediately becomes evident. Increasing the period of control data from 20 ms to 40 ms will most probably require an increased inter-vehicle gap. We therefore study the PDF for a 40 ms SF with an additional 5 m between the vehicles and reach a PDF of 100 for all vehicles. This shows that for a reasonable platoon length of 5 vehicles, the SF can be shared between 2 platoons with maintained reliability as long as the platoons adapt their inter-vehicle distance to the temporarily lowered control data update rate.

Fig. 10 shows the effect of the shared 40 ms SF on the DA of SUs reported per SF using the proposed DA-RE scheme. We assume two platoons of equal length (3, 5 or 7 vehicles) driving with an increased inter-vehicle gap (+5 m). For the DA-RE

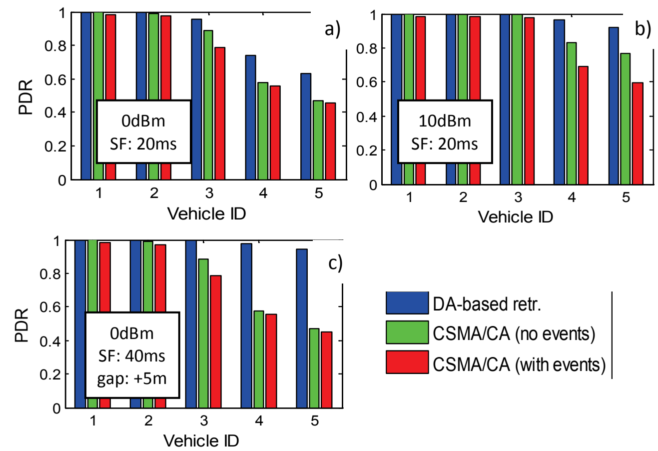

Figure 9: PDF for a SCH shared by two 5-vehicle platoons at various output power levels

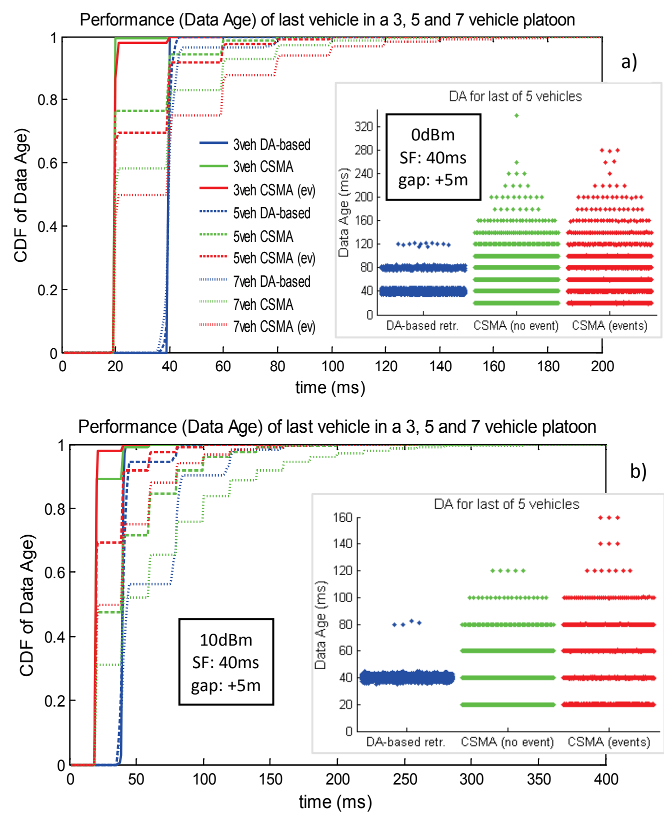

Figure 10: DA for different platoon sizes and output power levels for the DA-RE scheme on a SCH shared by 2 platoons

scheme the SF was doubled to 40 ms while we kept the SF length of the CSMA cases at 20 ms. For 5+5 vehicles and an output power of 0 dBm (Fig. 10a), we can see that for CSMA (with events) close to 70% of the SF produced a data age of around 20 ms, outperforming the 40 ms data age of the DA-RE scheme. If we look at the worst case performance, however, DA-RE does not exceed 120 ms (i.e. 3 SFs) while CSMA produces DA values of up to 300 ms. Considering the platooning application's demands for high reliability and low jitter and the increased inter-vehicle safety distance, the proposed scheme is to be preferred over the randomness of CSMA. Fig. 10b shows similar results for a 10 dBm output level, where (for two 5-vehicle platoons) 99.96% of the SFs produce a DA of around 40 ms for DA RE, while the value for CSMA (with events) is 91.8% with a worst case DA of 160 ms. We conclude that, with an appropriately adapted SF length and inter-vehicle gap, the DA-based retransmission method can support two platoons on a shared SCH, even at power levels safely below 23 dBm. This means that co-existence between intra- and extra-platoon communication can still be maintained.

Next, we investigated the delay of the early detection and channel sharing negotiation. We place the two platoon leaders 1000 m apart, let the platoons drive towards each other and measure the time until the negotiation handshake was successfully completed. The CDF of the detection and negotiation delay is shown in Fig. 11. We can see that in 50% of the runs the negotiation process was completed after 200 ms (i.e. after each platoon moved 5 m at 90 km/h), for 99% after 600 ms (15 m). Varying the power level (not shown in the figure) and platoon length had minimal effect on the delay.

Fig. 12 compares the DA achieved by DA-RE with and without the presence of NMs. Negotiating requires sacrificing intra-platoon control packets for inter-platoon NMs. As can be seen in Fig. 12a and 12b (for a power level of 0 and 10 dBm, respectively), this manifests itself in a slightly decreased performance, i.e. a slightly increased DA value. The results differ less for short platoons where the higher number of retransmission opportunities is able to counteract the interference from inter-platoon NMs. The results assume completely unsynchronized platoons. In reality, it is possible that platoons attempt to synchronize their SFs, resulting in partially or completely overlapping event phases and eliminating the interference with intra-platoon control data.

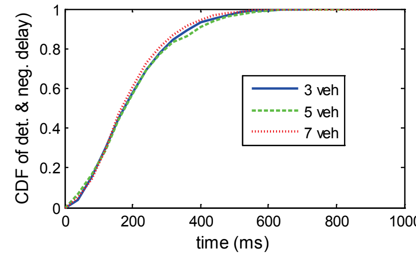

Figure 11: CDF of detection and negotiation delay

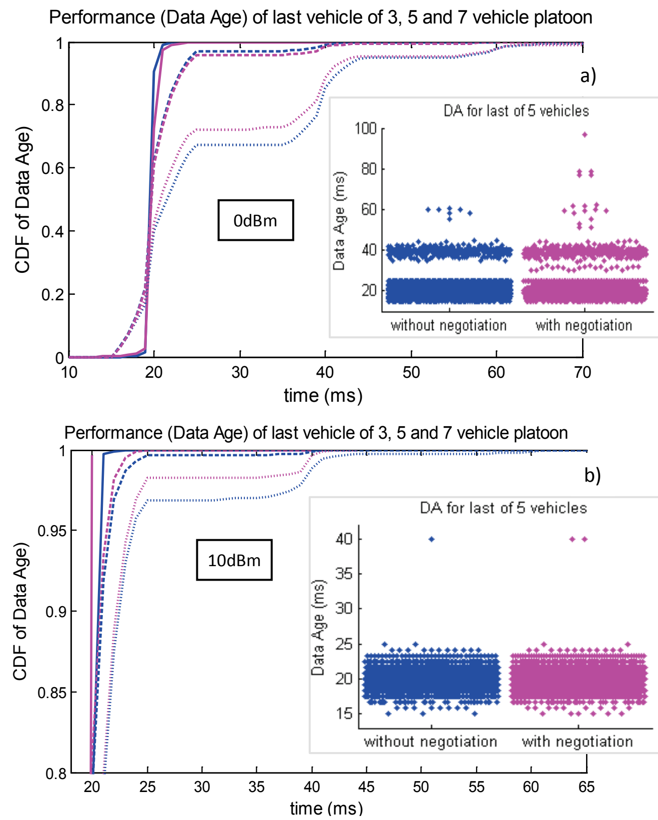

Figure 12: Data Age for different platoon sizes and output power levels for the data age based retransmission scheme with and without the presence of negotiation messages

VII. Conclusions

In this paper we presented a framework for intra- and inter-platoon communication based on a slotted, pre-scheduled MAC scheme with DA based retransmission opportunities. The purpose was to provide an alternative to the IEEE 802.11p standard's CSMA/CA random access MAC protocol that fails to support the very high timing and reliability requirements of a typical platooning application. Furthermore, we proposed an early detection and negotiation method based on power control. This enables other applications to use a platooning SCH as long as no platoon is in the vicinity, as well as multiple platoons to divide the channel without any negative impact on the safety-critical intra-platoon control data exchange. By simulation, we studied the feasibility of the proposed scheme in a realistic platooning scenario where more than one platoon temporarily share the SCH and showed that we are able to maintain a stable DA value for both platoons by adjusting SF length and output power level. Future work include a more detailed investigation of the interdependencies of factors like platoon length, output power, control data period, antenna-to-antenna distance and inter-vehicle gap to find the preferred settings to fulfil the requirements for a safe and reliable platoon operation.

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