Context-Aware Retransmission Scheme for Increased Reliability in Platooning Applications

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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 vehicles, where reduced inter-vehicle gaps lead to considerable reductions in fuel consumption. This, however, puts high requirements on timeliness and reliability of the underlying exchange of control data. Considering the difficult radio environment and potentially long distances between communicating platoon members, as well as the random channel access method used by the IEEE 802.11p standard for short-range inter-vehicle communication, those requirements are very difficult to meet. The relatively static topology of a platoon, however, enables us to preschedule communication within the platoon over a dedicated service channel. Furthermore, we are able to set aside parts of the available bandwidth for retransmission of packets in order to fulfil the reliability requirements stated by the platoon control application. In this paper, we describe the platooning framework along with the scheduling algorithm used to assign retransmission slots to control packets that are most likely to need them. This retransmission scheduling scheme offers a valuable tool for system designers when answering questions about the number of safely supported vehicles in a platoon, achievable reductions in inter-vehicle gaps and periodicity of control packets.

Keywords: Platooning, cooperative driving, VANETs, real-time communication, vehicular communication, retransmission scheme, scheduling.

1 Introduction

Cooperative driving holds the potential of revolutionizing the way we travel on our roads today. With the exchange of status information and occasional warning messages between vehicles, a vehicle is no longer limited to its own sensor readings but is able to assess the current traffic situation within a radius of several hundred meters. This information is the foundation of a large variety of future cooperative driving applications targeting enhanced safety, efficiency and comfort on our roads. The feasibility and success of such applications rely entirely on the performance of the underlying communication network with fast and reliable information exchange

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over an unreliable wireless communication channel as a prerequisite. The timely and reliable treatment of safety-critical data is further complicated by the communication protocol choices made for the recently adopted IEEE 802.11p standard [1] 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 periodic status updates and event-triggered warning messages. In terms of Medium Access Control (MAC), IEEE 802.11p uses a decentralized random access protocol. A quality of service (QoS) differentiation of four priority classes for different message types is in place, whereas there is no mechanism to individually treat vehicles depending on their importance to the application or the current radio conditions at hand. Furthermore, the standard assumes broadcast to be the only communication model required in VANET applications. Acknowledgements are not feasible and therefore retransmissions of not successfully received packets are not considered, which considerably decreases the reliability and real-time properties of the standard compliant communication network. In order to fulfil the strict requirements of future safety-critical cooperative driving, application-specific and context-aware adaptations to the standard are needed. In this paper, we therefore propose and evaluate a context-aware retransmission scheme for time-critical status information exchange in a platooning application.

Platooning can be seen as the first step towards the realization of fully autonomous driving. Vehicles join a platoon lead by a designated driver and follow this leading vehicle with a minimal inter-vehicle spacing. A reduction in fuel consumption of 14% has been reported for a three-truck platoon with a 10 m gap between the trucks [2], while even higher savings are possible with shorter gaps. In practice, however, platooning requires an automated control loop to be constantly fed with up-to-date information about the status of each platoon member in order to be able to quickly adapt to changes and maintain safety. The basic status update messages used by the standard (defined as Cooperative Awareness Messages (CAM) in Europe and Basic Status Messages (BSM) in North America) include information about a vehicle's position, speed and driving direction. Due to the particularly strict requirements on status exchange within a platoon, we argue that simple periodic broadcast on the common control channel (shared with other vehicles within the platoon's radio range) is not a viable option. We therefore suggest the use of a dedicated service channel (SC) for intra-platoon communication only. Furthermore, compared to other VANET applications, platoons constitute a relatively static network topology where changes only happen in the comparably rare situation of a vehicle leaving or a new one joining the platoon.

In this paper, we present an analysis tool for the context-aware distribution of communication resources between platoon members. The goal is to improve the timing and reliability properties of periodic control data spread within the platoon for safety and maintenance purposes. This is done by introducing a retransmission phase shared by all real-time channels, i.e., all sender-receiver pairs with application defined timing and reliability requirements. This retransmission phase is divided into time slots and slots are assigned to real-time channels depending on their probability of successful packet reception. In other words, a packet to a far destination (and thereby with a lower probability to be successfully received) will receive more retransmission opportunities than a packet to a close destination. With this context-aware resource assignment the target packet reception probability required by the platoon control application is more likely to be met.

The rest of the paper is organized as follows: Chapter 2 provides a background to relevant aspects of the current standard and discusses related works. In Chapters 3 and 4, we introduce the system assumptions and provide details of the protocol framework, respectively. The scheduling optimization and evaluation are presented in Chapter 5, while Chapter 6 concludes this paper.

2 Background and Related Works

The amendment IEEE 802.11p [1] 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 [3] and considers two types of messages, periodic status updates, CAMs [4] and event-triggered warning messages, DENMs [5]. One dedicated control channel is reserved for data exchange in traffic-safety applications and shared between CAMs and DENMs. Additionally, service channels are available and can, e.g., be used for certain applications as platooning as long as mandatory listening periods to the control channel are kept. Alternatively, a second transceiver pair needs to be installed and tuned to the service channel (as employed for a platooning scenario in [6]), while the primary transceiver pair stays tuned to the control channel.

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 back-off time, which is counted down only during time periods when the channel is sensed free. When the back-off value reaches zero, the node transmits directly without any further delay. This random access protocol introduces unbounded delays, especially at high node density or high data loads as can be found in platoon control applications with its demand for frequent status updates. Slot-based, time division multiple access (TDMA) protocols have therefore been proposed for VANETs. In [7], the self-organizing TDMA protocol is adapted to a vehicular scenario, successfully providing guaranteed access to all nodes through distance-based slot reuse. [6] successfully uses a slotted, prescheduled approach for CAM exchange, making use of the predictability of the bandwidth needs of periodic status updates in a platooning scenario.

Timing and reliability issues in VANETs have been subject to many studies, where either channel access alone [6], [7] is targeted, or channel access in combination with retransmission schemes [8], [9]. Since the IEEE 802.11p standard assumes simple broadcast, no acknowledgements are used and thereby no collision detection is possible. Many papers concerned with improved reliability in VANETs disregard this fact and introduce acknowledgements to keep the sender informed about the success of a transmission. In a broadcast environment, this knowledge can even be used by other vehicles in the reception range of a packet to determine the best candidate to relay a packet without wasting valuable bandwidth by causing a broadcast storm [8] [9] [10]. As we assume every platoon member to be in each other's transmission range, multihop communication is not our concern and retransmissions are merely used to increase the probability of successful packet reception within the one-hop neighbourhood. Acknowledgements are bandwidth intensive. Acknowledging each broadcast packet, as, e.g., described in [10], introduces unnecessary overhead where the bandwidth should rather be used for data transmissions. In [11], Shafiq et al. design a block acknowledgement scheme for VANET broadcasts to reduce this overhead. We argue that the rather predictable link quality between sender and receiver pairs in a platoon make acknowledgements redundant. Boukerche et al. [12] describe a protocol to estimate the reliability of unicast links in a VANET and use that knowledge to group those links into QoS classes. As in our work, no acknowledgements are needed to achieve this classification. Boukerche et al. do however not make use of retransmissions to boost the success ratio of packets over a certain link.

While our proposed retransmission algorithm attempts to improve the packet reception probability through unicast retransmissions based on channel estimation, other studies are concerned with enhanced reliability by making the first transmission more likely to succeed. The authors of [13], e.g., look at the effect of transmit power and contention window adaptations to achieve a higher packet reception probability. Even [14] studies the correlation between reliability and transmission range in VANETs. Neither of those works takes their results one step further and studies further improvements to reliability through retransmission of the packet. In earlier work, [15], we designed a communication and real-time analysis framework over a dedicated frequency channel for platoon applications and show that our retransmission scheme is able to decrease the message error rate of control data exchange within a platoon. In the current work, we make a step further and propose an adaptive retransmission scheme, which explicitly takes into account different links qualities between platoon members.

3 System Assumptions

The special circumstances and prerequisites of platooning set this application apart from other less static and predictable VANET applications and enable us to make a number of choices that deviate from the specifications found in, e.g., the IEEE 802.11p standard.

1. We assume the presence of a dedicated service channel used for intra-platoon communication only, while a second transceiver is tuned to the common control channel shared with any other vehicles and VANET applications for the transmission of non-platoon specific CAMs, DENMs and service announcements as required by the standard. This separation of communication within the platoon and with surrounding vehicles has two important advantages. Firstly, the bandwidth of the platooning service channel is not shared with data from non-platoon vehicles with potentially lower timing and reliability requirements.

Secondly, by keeping intra-platoon communication separate from other VANET applications, we can make use of the comparably static topology of a platoon in the design of pre-scheduled, deterministic MAC and retransmission schemes.

2. Platoon members are assigned different roles, depending on their position within the platoon. The first vehicle, called platoon leader, has special responsibilities when it comes to the maintenance and control of the platoon, while all other vehicles, regular vehicles, merely follow. We assume that the platoon leader makes general control decisions concerning the entire platoon, while regular vehicles are simply required to maintain a constant gap to the vehicle in front and follow orders from the leader. This model requires that the entire platoon is within the leader's transmission range, restricting the feasible length of a platoon. The integration of longer platoons in the proposed retransmission scheme would require multihop communication, an aspect left as future work for now.
3. A platoon is maintained by an automated control loop that needs to be continuously fed with current status information. It is a realistic assumption that the following data will be needed and combined to make this possible:
   a. There is still a need for CAMs and DENMs broadcasted on the common control channel as specified by the standard. This ensures that the platoon is well integrated into other VANET applications and that its members are "visible" to surrounding non-platoon vehicles. Furthermore, the status information in periodically broadcasted CAMs is still useful to the platooning application, even if the CAM report rate of 2 - 10 Hz and the reliability offered by the standard do not satisfy the requirements of the platoon control loop.
   b. In addition to the afore-mentioned CAMs on the control channel, platoon vehicles are assumed to send out CAM-like status updates even on the service channel. As communication on the service channel is not restricted to the message types and report rates stated by the standard, both the content and the periodicity of those status messages can be adapted to the control requirements of the platooning application. Furthermore, we are able to make use of the periodic nature of such status updates and preschedule them in a slot-based MAC protocol, considerably increasing the packets' real-time and reliability properties.
   c. A platoon vehicle's distance to its immediate neighbours (most importantly to the vehicle in front) is constantly assessed by the means of radar. Combined with the afore-mentioned CAMs from both the control channel and the service channel, this provides each vehicle with a sufficient understanding of its neighbourhood to adapt to minor changes in speed and maintain a constant inter-vehicle distance.
   d. The control of the platoon as a whole requires a more centralized approach where a designated vehicle (preferably the leading vehicle) makes control decisions for the entire platoon and distributes these to the platoon members on a regular basis. As those packets contain individual information to specific platoon members, we view them as unicast transmissions. In other words, while they can still be overheard by other vehicles in the radio range, those unicast packets have one specified destination. Due to their safety-critical content, it is vital that the unicast control packets reach their destination within

a certain deadline and with a very high reception probability. This aspect is targeted by the retransmission protocol described below.

e. Unforeseen events might require the swift dissemination of warning messages within the platoon. Inter-vehicle gaps of merely a few meters put timing requirements on the warning dissemination that DENMs sent over the shared (and in emergency situations probably overloaded) control channel with its IEEE 802.11p random access MAC protocol will not be able to fulfil. We see, however, two ways of issuing event-triggered warning messages over the designated service channel. Firstly, a part of the bandwidth could be reserved for such kinds of spontaneous bursts of warning messages. During those event-based phases, no periodic control data transmissions are scheduled. Secondly, warning content could be integrated into the periodic control data transmissions (as described under c. above), i.e., hazard warnings would be spread inside control packets with the same real-time and reliability properties as guaranteed for control data. In the scope of this paper, we do not further explore the integration of event-based warnings into the platooning application.

4. Furthermore, we assume that every vehicle knows its position within the platoon. This information is provided by the control packets sent out by the platoon leader. The topology of a platoon is stable until a vehicle leaves the platoon or a new vehicle requests to join. A vehicle that wants to leave the platoon would have to announce this action to the leader who informs the concerned platoon members and instructs them to close the gap. In case a new vehicle requests to join, it has to make its intention known to the platoon leader (e.g. via communication on a control channel) and wait for instructions on its position within the platoon. (For fuel efficiency reasons, vehicles are expected to be sorted by size, which does not allow vehicles to simply join the end of the platoon.) Unicast messages to involved platoon members are used to organize this process.

Summarizing, we assume that the dedicated service channel is used by two message types enabling the control within a platoon: CAM-like status updates that are broadcasted periodically by every platoon member and unicast control packets issued by the platoon leader with individual vehicles as intended recipients. Due to the importance of the unicast control packets to the control loop of the platoon, this message type should be given the opportunity of retransmissions. Figure 1 explains the communication patterns considered.

4 Protocol Framework

We propose a collision-free slotted MAC protocol, where time is divided into superframes, SF, which in their turn are divided into time slots corresponding to the transmission time of one maximum-sized packet. A part of the SF is set aside for the retransmission of packets that are not fulfilling the packet reception probability requirement with only the regular transmission. The protocol framework in terms of SF design and retransmission scheduling is described below.

4.1 Superframe Design

We assume that a message never is longer than one packet and that both status updates and control packets are of comparable length, i.e., one time slot with duration T_{slot}. The first slot in the frame is used for a synchronization beacon transmitted by the platoon leader to all the members to announce the SF start. We divide the rest of a SF into three phases (see Figure 2):

a. The ***collection phase***, where the broadcast of CAM-like status messages is done. This information benefits both the platoon members in their assessment of their immediate neighborhood and the platoon leader in its assessment of the overall platoon status. The duration of the collection phase, $T_{collection}$, corresponds to the current number of ordinary platoon members (denoted as N) plus the platoon leader itself, i.e., $T_{collection} = (N + 1) \cdot T_{slot}$.
b. The ***control phase***, which is N slots long, is used by the platoon leader to send unicast control data to each of the other platoon members. The duration of the control phase is therefore $T_{control} = N \cdot T_{slot}$.
c. For increased reliability of the unicast control data, a third phase, the ***retransmission phase***, $T_{retrans} = K \cdot T_{slot}$, is present. Depending on the assessed need for retransmissions, a number of retransmission slots, $\leq K$, are assigned to different communication channels, where a communication channel is defined by a unique sender-receiver pair. Details on the choice and assignment of retransmission slots, RT slots, are given in the following subsection.

4.2 Retransmission Scheduling

While the length of the collection and control phases is determined by the number of vehicles in the platoon, the length of the retransmission phase depends on one of the following factors (See Figure 3):

1. The update frequency (periodicity) of control data required by the application. As we assume the update frequency to be identical to the SF length, this parameter determines the maximum SF length and consequently the number of available RT slots.
2. The level of reliability required by the application. The platoon control loop specifies a minimum or target Packet Reception Probability (PRP) that needs to be achieved by the underlying communication network in order to safely maintain a platoon of a certain length and with certain inter-vehicle gaps.

Although both a target PRP and a required update period might be requested by the application, it will not always be possible to fulfil both requests. The number of required RT slots to maintain a certain target PRP might, e.g., not fit in the RT phase available for the specified SF length for the current number of platoon members. We assume that, in most scenarios, the periodicity of control data is the fixed parameter. In that case, the requirements on the target PRP have to be relaxed, meaning that the safety of the platoon travelling with the current inter-vehicle gaps cannot be sufficiently supported any more, but that inter-vehicle gaps might have to be increased. Alternatively, the number of vehicles in the platoon has to be reduced to free more slots within the SF for retransmissions.

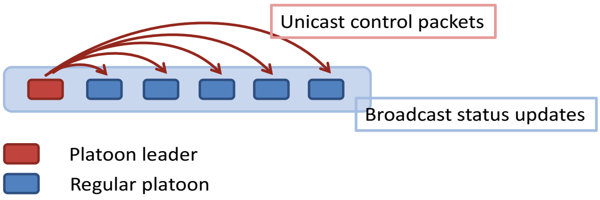

Fig. 1. Communication Pattern

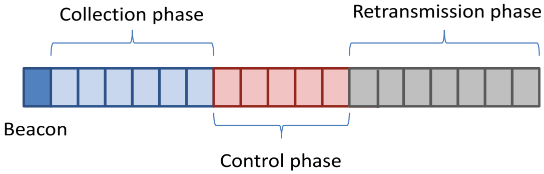

Fig. 2. Superframe Format

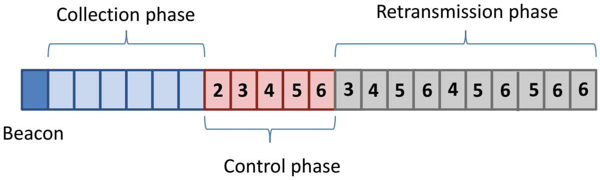

Fig. 3. Retransmission Phase Example

The PRP, P_i, $1 \leq i \leq N$, of packets from the leader to the i-th ordinary member depends on, e.g., the distance between them as well as the number and size of the intermediate vehicles (trucks or cars). Studies [16] have shown that the number of intermediate vehicles, blocking the line-of-sight path between sender and receiver, obviously plays an important role to the channel quality. Depending on the PRP for a particular member, unicast transmission to it is in more or less need of retransmissions. The number and actual assignment of slots needed in the retransmission phase depends on the current PRP values P_i on the platooning service channel. Members that are expected to suffer from more frequent packet loss should receive a higher number of retransmission attempts (i.e., assigned RT slots) than those who experience better channel conditions. This requires knowledge at the leader side of the currently achievable PRP for all the members for the assignment of slots in the RT phase.

The PRP values P_i used by the leader for the scheduling can be either computed beforehand using any model reflecting the configuration of the platoon or adapted during the operation by utilizing the estimations of current P_i values by the leader. In the first case, the scheduling is able to catch major propagation differences between the members caused by the different sizes and positions of the vehicles. This rather static assessment of the expected PRP is purely based on predetermined models and does not involve feedback from the platoon members about the actual experienced PRP at hand. Note that it is not necessary that the probability of packet errors in the platoon increases proportionally to the distance between sender and receiver even though there often is a correlation [16]. In the second case, adaptation will also tend to catch the influence of the actual propagation environment. The success and failure of recent transmissions between individual sender-receiver pairs give a more accurate and fine-grained picture of the current radio conditions. PRP P_i experienced by member i is included in the payload of the packet it broadcasts during the collection phase.

5 Scheduling Optimization and Evaluation

We assume that the control data to be transmitted by the platoon leader to each of the platoon members during the control phase is updated with a fixed interval not exceeding the application requirement T_{update}^{max}. The SF duration coincides with the actually chosen control data update interval duration, T_{update}, not exceeding T_{update}^{max}.

We propose the following scheduling approach for the retransmission phase:

Step 0. Make the following initializations:
- Set current slot index k in the retransmission phase to 1;
- Set current experienced PRP values for each ordinary vehicle (out of total N) in SF, denoted as p_i, equal to P_i;
- Set the current number of transmission attempts M_i for each ordinary vehicle to 1.

Step 1. Choose the vehicle with index j, which has the lowest p_j value and schedule it for retransmission in slot k.

Step 2. Increment M_j. Assign $1-\left(1-P_j\right)^{M_j}$ as new value for p_j.

Step 3. If there are more retransmissions to schedule, i.e., $k < K$, then increment k and go to Step 1, otherwise stop.

The PRP per SF achieved for a given number of vehicles in the platoon N+1 and a fixed control data update interval duration T_{update} can be computed as $P_{actual} = \min p_j$. If the requirement on a target PRP P_{target} is imposed, then the minimal SF duration $T_{update} \le T_{update}^{max}$, allowing to meet P_{target}, can be determined as follows.

Let $q_i^{(M)} = 1-(1-P_i)^M$ be the probability that the leader requires not more than M attempts for the successful delivery to the i-th member of the platoon (in other words this is the probability that at least one of M attempts of the leader is successful). Then $M_{min}^{(i)} = \arg\min_{q_i^{(M_i)} \ge P_{target}} q_i^{(M_i)}$ is the minimum number of transmission attempts that should be done by the leader for the i-th ordinary platoon member in order to provide the target PRP.

Therefore, the required SF duration is

$$T_{update} = \left(2 + N + \sum_{i=1}^{N} M_{min}^{(i)} \right) T_{slot} \leq T_{update}^{max}$$

where $2 + N$ signifies one synchronization slot plus the collection phase.

Above, we presented the scheduling algorithm for RT slots in a SF of predefined length. We thereby provide a scheduling tool where the required control update frequency is coupled to the supported platoon length and the achievable PRP. Figures 4 and 5 visualize that connection. The parameters used are a bit rate of 6 Mbps and a data packet length of 400 bytes, corresponding to a packet duration of 642 µs. In order to account for a deterioration of the channel quality due to fading and shadowing (by vehicles situated in-between sender and receiver), the simulated PRP is reduced by 5 percentage points for every intermediate vehicle. PRP is therefore calculated as $\text{PRP} = 1 - (N_{hop} \times 0.05)$, where $N_{hop} = 1$ if the sending and receiving vehicles are direct neighbours, $N_{hop} = 2$ if there is one vehicle in-between, etc.

According to earlier measurement campaigns [17], testing the achievable transmission range of IEEE 802.11p-enabled communication equipment, radio ranges beyond 500 m are not realistic, not even when considering direct line-of-sight (LOS) communication. Assuming an antenna-to-antenna spacing of 30 m, i.e., considering two trucks following each other, we therefore restrict the number of platoon members in our evaluation to 15, including the platoon leader.

In Figure 4 the packet reception ratio is plotted as a function of the platoon length, including the leading vehicle, for five different fixed SF durations. The SF durations simulated are 20 ms, 25 ms, 40 ms, 50 ms, and 100 ms. A SF duration of 20 ms will only provide the possibility of one retransmission attempt for a platoon length of 15 vehicles. This also means that SF durations shorter than 20 ms will not support 15 vehicles at all as not each vehicle will get a time slot for its ordinary transmission. Assuming a SF duration of 20 ms, a packet reception ratio of almost 1, i.e., almost no errors at all, can be achieved for a platoon length up to 7 vehicles. For 10 vehicles the packet reception ratio is still over 0.9, but for longer platoon sizes, the success rate decreases quickly. For the maximum platoon length supported, the reception rate is down to only 0.35. Increasing the SF duration by merely 5 ms to 25 ms will increase the packet reception ratio for the 15-vehicle platoon to 0.6, and to reach over 0.9, the platoon cannot be longer than 11 vehicles. For the three longest simulated SF durations, the packet reception rate never dropped under the 0.9 mark, and a 100 ms SF will result in nearly error free performance.

In Figure 5, the minimum SF duration as a function of the platoon length is plotted instead. Curves are given for different fixed target PRPs. The target PRPs simulated are 0.9, 0.99, 0.999 and 0.9999. As seen in the figure, the curves for the different target PRP values behave in a similar way. For the lowest PRP studied, 0.9, a maximum-sized platoon (15 vehicles) will need a SF duration of about 40 ms. The increase of the target PRP by one order of magnitude will add approximately 25 ms of SF duration, leading to a SF duration of about 120 ms for the highest target PRP of 0.9999.

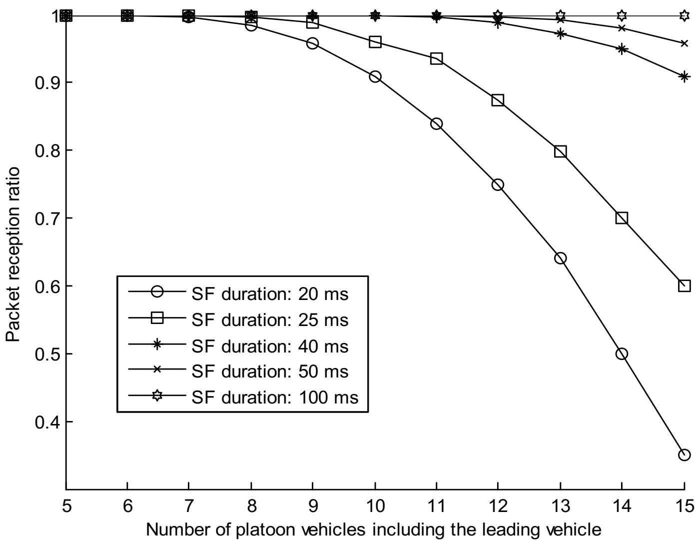

Fig. 4. PRP for various SF lengths and platoon sizes

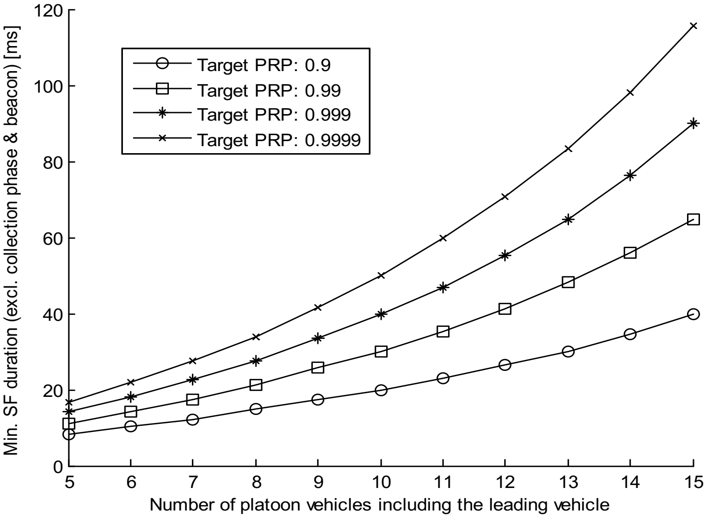

Fig. 5. Achievable SF length for various target PRPs and platoon sizes

According to our assumptions, the SF duration and the update rate of the application are identical, meaning that a longer SF would correspond to a lower update frequency. A more detailed study of a higher update rate versus more retransmission possibilities is, however, outside the scope of this paper, and left as on-going future work.

6 Conclusion

In this paper, we presented a communication framework and retransmission scheme for increased reliability of safety-critical control data transmissions in a platooning application. In order to provide the necessary update rate of status and control messages to maintain a platoon of heavy vehicles at inter-vehicle gaps of 10 meters or less, a target packet reception probability should be met even for sender-receiver pairs that are several hundred meters apart, with a potentially high number of intermediate vehicles deteriorating the signal quality. Our framework set aside a part of the available bandwidth for retransmissions of packets that can be assumed to experience packet errors. The lower the expected packet reception probability of a unicast link, the more retransmission slots are assigned to that link by the proposed retransmission scheduling algorithm. Our framework provides a tool that balances reliability requirements (a requested probability of packet reception), update frequency of periodic control messages and the number of vehicles and their inter-vehicle gap that can safely be supported in the platoon. This is done based on an estimation of the link quality, a value that is expected to remain fairly stable due to the stable topology found in a platoon. As no acknowledgements are needed, no additional overhead is added besides the bandwidth used for scheduled retransmissions.

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