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A Framework for Reliable Exchange of Periodic and Event-Driven Messages in Platoons

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Abstract—Platooning is widely considered a promising approach to decrease fuel consumption by reducing the air drag. However, in order to achieve the benefits of aerodynamic efficiency, the inter-vehicle distances must be kept short. This implies that the intra-platoon communication must not only be reliable but also able to meet strict timing deadlines. In this paper, we propose a framework that reliably handles the co-existence of both time-triggered and event-driven control messages in platooning applications and we derive an efficient message dissemination technique. We propose a semi-centralized time division multiple access (TDMA) approach, which e.g., can be placed on top of the current standard IEEE 802.11p and we evaluate the resulting error probability and delay, when using it to broadcast periodic beacons and disseminating event-driven messages within a platoon. Simulation results indicate that the proposed dissemination policy significantly enhances the reliability for a given number of available time-slots, or alternatively, reduces the delay, in terms of time-slots, required to achieve a certain target error probability, without degrading the performance of co-existing time-triggered messages.

I. INTRODUCTION

In platooning, the air drag is reduced by forming a road train of heavy duty vehicles, which enables considerable fuel reductions [1]. Platooning applications rely on in-vehicle sensors but also inter-vehicle communications, where e.g., the leading vehicle sends information needed to enable automatic speed control of the trailing vehicles [2]. Delay-sensitive data traffic with requirements on high reliability is thereby generated.

Platooning applications is an example in a set of applications and services enabled by cooperative intelligent transport systems (C-ITS). Many C-ITS based applications will use IEEE 802.11p for short to medium range communication in vehicular ad hoc networks (VANETs) [3]. IEEE 802.11p uses carrier sense multiple access (CSMA), which has been shown to have problems with unbounded channel access delay and multiple consecutive packet drops [4, 5]. Excessive delays may prevent proper functionality of a platooning application or, alternatively, the required inter-vehicle distances between members in a platoon may have to be extended to the point where fuel reductions are no longer possible. One way to tackle this is through different congestion control mechanisms, e.g., [6–8]. However, while congestion control may increase the probability of timely channel access, channel access guarantees can still not be provided.

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For applications with high requirements on timely and reliable communications, centralized networks based on time division multiple access (TDMA) are often preferred as resources can then be scheduled to ensure an upper bound on the channel access delay, as in e.g., industrial control networks like WirelessHART[9]. While centralized access schemes are impractical for most VANET applications, they can be formed and managed quite easily in platooning due to the highly regular network topology. Even in networks based on IEEE 802.11p, TDMA can be adopted by, e.g., placing a time-slotted scheme on top of CSMA [10]. However, even if timely access to the channel is provided, the communications requirements of platooning applications are still challenging.

Standardization on C-ITS specifies two types of messages; time-triggered position messages, so-called beacons, and event-driven hazard warnings [11, 12]. Time-triggered messages are the foundation of most distributed control applications, but, since a platoon consists of a system of intelligent systems, event-driven messages will also be needed. Events may originate not only from the leading vehicle (the central control unit) but also from trailing vehicles, e.g., if a vehicle malfunctions and needs to perform emergency breaking. Depending on the type of event, the resulting message could either target a specific receiver within the platoon, e.g., the platoon leader or an emergency breaking message especially targeting the last vehicle which needs to start braking first, or concern all members of the platoon, e.g., the platoon leader adjusting the beacon update rate. Beacons and event-driven messages must likely co-exist on the same channel, without causing performance degradation to one-another.

Rather than tackling the problems that CSMA implies, we take advantage of the rather stationary network topology within a platoon and propose to use a time-slotted medium access scheme, which, e.g., could be placed on top of the IEEE 802.11p access layer. We reserve a subset of all available time-slots for periodic beacons, and adopt a hyperframe structure, such that all platoon members broadcast their beacons once in each hyperframe. This yields a bounded channel access delay for beacons, which results in a message age only depending on the beacon update rate and the packet error rate, as the jitter can be set to zero. Further, given a certain number of available time-slots, e.g., the set available in-between two successive beacon slots in the hyperframe, we propose an efficient message dissemination strategy especially tailored to

platooning applications. We consider two types of event-driven messages; the type that should be propagated to a specific receiver and the type that needs to be correctly received by all platoon members. The message itself can originate from any platoon member. The resulting message dissemination strategy is based on relaying, has a bounded channel access delay and we evaluate the error probability at the targeted receiver(s) after a fixed transmission delay. We benchmark the performance of our proposed scheme against a scheme where the message originator itself uses all time slots to repeat its own message. Simulation results indicate that the proposed dissemination policy significantly enhances the reliability for a given number of available time-slots, or alternatively, reduces the delay, in terms of time-slots, required to achieve a certain target error probability. Our framework can thus be used both to broadcast periodic beacons and to disseminate event-driven messages within a platoon, without one message type causing performance degradation to the other.

II. RELATED WORKS

European standardization on C-ITS specifies two types of messages; periodic and event-driven [11, 12]. Particularly for platooning, a high beacon update rate is required in order to maintain short inter-vehicle gaps and quickly react to variations in the surrounding environment. Performance of applications based on time-triggered messages is generally improved by providing timely channel access, increased reliability, increased update rate and reduced jitter. Kaul *et al.* [13] identifies the age of periodic status updates in vehicular networks as an important performance metric and propose a rate control algorithm to improve its properties. If the medium access control (MAC) algorithm has a bounded channel access delay, the message age is purely a function of the beacon update rate and the packet error rate (PER). If event-driven messages should co-exist with beacons, the update rate should be as low as possible while still providing enough data to control the process. The beacon update rate should then be adjusted based on the current PER [14].

In contrast, the communications requirements of event-driven messages are typically quite different from those of time-triggered messages. Jitter and message age is of no interest, but instead a low dissemination delay. A common approach to increase the reliability and reduce the dissemination delay of event-driven messages is to let all nodes repeat all messages and focus on mitigating broadcast storms. Different ways of mitigating broadcast storms associated with message dissemination within a certain geographical area in IEEE 802.11p based VANETs have been evaluated in [15] and in [16] where several selective broadcast algorithms are compared from an application perspective using simulations. An overview of information dissemination protocols for VANETs is given in [17]. In [14], the dissemination delay in platooning is considered as a performance measure, i.e., the delay between event detection (e.g., the leading vehicle in the platoon detecting an upcoming traffic jam) and the point in time when the entire platoon successfully received the warning.

Fig. 1: Hyperframe structure for a platoon of N trucks.

In order to maintain fuel-efficient inter-vehicle gaps within the platoon while providing the required levels of traffic safety, the need for efficient dissemination strategies of event-driven messages co-existing with high update rate beacons on the same channel emerges. Co-existence strategies for beacons and event-driven messages have been considered previously, both for VANETs in general in [7] and in platooning applications specifically in [14, 18]. All existing strategies aim to keep the network load of beacons below a certain threshold such that the remaining part of the bandwidth is made available for event-driven messages where, in turn, the main focus is to mitigate broadcast storms. In [18], a combined decentralized/centralized access approach is adopted, using real-time schedulability analysis to determine the ratio of bandwidth required for beacons and event-driven messages, respectively. The event-driven messages are, however, still using CSMA and the performance in terms of dissemination delay is not enhanced further, except to mitigate broadcast storms.

III. SYSTEM MODEL

We consider a platoon consisting of N vehicles, labeled by the integers $1, 2, \dots, N$, communicating through an ad hoc network as shown in Fig. 1. We adopt the use of a periodic hyperframe structure with time slotted medium access such that all platoon members broadcast their beacons once in each hyperframe. The channel gain h_{ij} between a pair of nodes (i, j) is real-valued, independent but not identical distributed (i.n.i.d.), characterized by its probability density function $f_{h_{ij}}(h_{ij})$. We assume that each packet is transmitted in exactly one time-slot, every node transmits with power P_t and the noise power level at each node is N_0 . Defining g_{th} as the correct decoding threshold, the probability that a message sent, directly from node i , cannot be successfully decoded at node j is derived as

$$p_{i,j} = \Pr \left[\frac{P_t |h_{ij}|^2}{N_0} \leq g_{th} \right] = \int_0^{\frac{g_{th} N_0}{P_t}} \frac{f_{h_{ij}}(\sqrt{x_{ij}})}{2\sqrt{x_{ij}}} dx_{ij}. \quad (1)$$

The channel packet error rates are represented by an $N \times N$ matrix $\mathbf{P}$, in which each element $p_{i,j}$ denotes the error probability on the link from node i to node j . We further assume that $f_{h_{ij}}(h_{ij})$ is known or can be estimated, and remains unchanged for the set of time-slots considered. This assumption is motivated by noting that the path loss and the slow fading characteristics will remain virtually unchanged, as long as the network topology and the inter-vehicle distances do not change.

IV. PROPOSED FRAMEWORK

We adopt the use of TDMA and a periodic hyperframe structure such that all platoon members broadcast their beacons once in each hyperframe, Fig. 1. This enables a bounded channel access delay. It should be noted that even though the channel access delay (i.e., the delay until channel access is granted by the MAC method) is bounded with TDMA, the delay until a message is successfully received (i.e., without errors) at its intended receiver(s) is still un-bounded. This is due to noise and interference encountered on the wireless channels. Therefore, to reduce the delay until a message is successfully received, it is not enough that the channel access delay is bounded – the reliability of each transmission (once granted by the MAC method) must also be maximized.

To ensure full reliability, a separate frequency channel is required to avoid interference from non-platoon vehicles using CSMA [18]. Using a separate channel for platooning has several advantages. The channel can be restricted to platoon members only and does not have to be shared by other vehicles. It enables adjusting the beacon update rate more freely as the overall traffic load is lower and thereby less affected by congestion control policies. In addition, a MAC method with guaranteed access such as TDMA can be used to avoid random channel access delays and packet collisions. However, according to European standard, all vehicles must listen to the control channel at all times. This implies that an extra transceiver would be needed if a separate platooning channel is to be used. The question is if the additional hardware cost implied by having a transceiver tuned to a separate channel at all times is justified. Two things indicate that the extra cost is well worth it. Firstly, in [18] it has been shown that the interference from non-platoon members is considerable. Secondly, platooning is now considered an extremely important application for the truck manufacturers as initial field trials have shown that platooning can reduce fuel costs considerably. The cost benefits of the fuel savings in combination with the problems displayed by pure CSMA of IEEE 802.11p have triggered serious discussions of using separate frequency channels for platooning, despite the risk of having to install twice the amount of hardware in the truck. Further, the TDMA scheme can be coordinated centrally by a platoon leader which also can grant entrance to new platoon members, by receiving requests sent by interested candidates using CSMA on another channel, e.g., the control channel.

A. Time-Triggered Messages

We assume that a subset of the available time slots is dedicated to periodic beacon messages. Each such message needs to be received reliably at least by the vehicle immediately behind, but likely also by the vehicle in front. If a high update rate can be kept, this implies a shorter inter-vehicle distance (i.e., better performance). The age of periodic status updates in vehicular networks has been outlined as an important performance metric as it captures the effects of channel access delay, packet error rate, beacon update rate and congestion – all in one measure. We define the data

Fig. 2: Eight vehicles are assigned slots for initiation of event-driven messages scheduled according to round robin. In this example, only vehicle 3 utilizes its opportunity.

age as the duration from the generation instance of the last correctly received beacon from a specific node, to the next beacon generation instance correctly received from the same node. If one time-slot is scheduled for each platoon member in each message period, the jitter is zero and the channel access delay is known and constant, Fig. 1. If the beacon update rate changes, the message period will change and thus the slot assignment and the hyperframe length needs to be updated. This is done by the platoon leader issuing an event-driven message targeting all platoon members, which contain the new slot assignment for time-triggered messages.

B. Event-driven messages

If a subset of all available time-slots is reserved for periodic beacons, the remainder of the slots in a cyclic hyperframe can be used for disseminating event-driven messages. The total number of time-slots available for dissemination thus depends on the number of platoon members, the beacon up-date-rate and the size of the messages/time slots. To minimize the delay until dissemination of event-driven messages can commence, we let the time-slots used for beacons be evenly distributed within the hyperframe similar to [18] and as shown in Fig. 1. This can be done without loss of performance in terms of message age for periodic messages. We consider two types of event-driven messages. The first type is a message that needs to be propagated from one end of the platoon to the other. The second type is a message that originates from one node and needs to be received by the entire platoon. Note that the message itself can originate from any platoon member.

In platooning, the dissemination delay, i.e., the delay between event detection (e.g., the leading vehicle in the platoon detecting an upcoming traffic jam) and the point in time when the entire platoon successfully received the warning, is particularly important. The aim here is to maximize the probability that the intended destination(s) correctly receive(s) each event-driven message, given a certain limited number of time slots that can be used for dissemination.

In each slot, not occupied by a beacon or an already initiated dissemination of an event-driven message, a specific vehicle (scheduled according to round-robin) is allowed to initiate dissemination of its event-driven message as shown in Fig. 2. Each such event-driven message, transmitted from a source node (message originator) to its final destination(s), is pre-assigned a set of $K + 1$ time-slots where the value of K depends on the application requirements on delay and

Algorithm 1: The relay selection algorithm

UNICAST

$R_0 \leftarrow \text{Source} ; D \leftarrow \text{Destination}; R_0 \neq D;$
 $K + 1 \leftarrow \text{Number of time slots};$
 $/\star [x]$ is the ceil function of x $\star /$
if $R_0 > D$ **then**
 for $i = 1$ **to** K **do** $R_i = S - \left\lceil i \left\lfloor \frac{R_0 - D}{K+1} \right\rfloor \right\rceil;$
else
 for $i = 1$ **to** K **do** $R_i = S + \left\lceil i \left\lfloor \frac{R_0 - D}{K+1} \right\rfloor \right\rceil;$

BROADCAST

$R_0 \leftarrow \text{Source} ; N \leftarrow \text{Platoon length};$
 $K + 1 \leftarrow \text{Number of time slots};$
 $K_L = \left\lceil \frac{(R_0 - 1)K}{N - 1} - \frac{1}{2} \right\rceil; K_R = K - K_L;$
 $i = 1; K_s = \min(K_L, K_R);$
while $i \leq K_s$ **do**
 $R_{2i-1} = R_0 + \left\lceil i \frac{N - R_0}{K_R + 1} \right\rceil; R_{2i} = R_0 - \left\lceil i \frac{R_0 - 1}{K_L + 1} \right\rceil;$
 $i++;$
if $K_L \neq K_R$ **then**
 for $j = 2K_s + 1$ **to** K **do**
 if $K_L = K_s$ **then** $R_j = R_0 + \left\lceil j \frac{N - R_0}{K_R + 1} \right\rceil;$
 else $R_j = R_0 - \left\lceil j \frac{R_0 - 1}{K_L + 1} \right\rceil;$

reliability for that particular type of event. The $K + 1$ slots can be granted since other vehicles, despite being scheduled for possible initiation of event-driven messages in a certain slot, are not allowed to interrupt an ongoing dissemination procedure. The first time slot is always allocated to the source R_0 , while the remaining K time slots are allocated to a set of K distinct relays $R_1, R_2, \dots, R_K$. After overhearing an event-driven message in the time-slots numbered $0, 1, \dots, k - 1$, relay R_k will transmit in time-slot k or, if it did not manage to overhear the message, remain quiet. We select the members for the set of K distinct relays, according to the Algorithm 1. The goal of Algorithm 1 is to get the relay nodes evenly distributed in the space between the source and the destination(s). In the unicast case, Algorithm 1 simply divides the number of hops in-between the source and the destination with the number of relay slots allowed (e.g., from node 1 to node 5 there are four hops and with two slots allowed, this gives two sets – hence node 1 and node $1 + 2 = 3$ get the relay slots). In the broadcast case, a similar reasoning is used, but the slots are divided among the two directions, in front of the source and behind the source. The number of slots given to each direction depends on the position of the message originator (hence, if the source is the first or the last vehicle, broadcast is equal to unicast).

Note that the unicast algorithm should be used for event-driven messages that need to be propagated to a specific receiver, whereas the broadcast algorithm targets a message that needs to be received by the entire platoon. Finally, note

that new relay nodes need to be selected using the broadcast or the unicast algorithm whenever something happens that affects the channel matrix $\mathbf{P}$, e.g., the platoon speed or intra-platoon distances change, or the slot assignment, e.g., the number of platoon members changes or the beacon frequency changes.

The total dissemination delay until a target PER has been achieved depends on the channel access delay and the number of time-slots required. The message dissemination delay once channel access is granted depends only on the number of time slots required to achieve a certain level of reliability (packet error probability). The channel access delay, in turn, depends on the number of ongoing events in the platoon, the preferred number of relay slots for each such event and the number of time-slots available for dissemination in the hyperframe (which primarily depends on the update rate of time-triggered messages). Consequently, for event-driven messages, the channel access delay is not constant, since it depends on the number of events that are active at the same time, but the worst case is known and occurs when all vehicles have an event and each such event is followed by a set of time slots for relaying. Hence, if the maximum number of relay slots allowed per event is known (centrally decided), the maximum channel access delay is known and thus bounded.

V. PERFORMANCE EVALUATION

To evaluate our framework, we use a Monte-Carlo simulator implemented in Matlab with the channel characteristics from [19]. The channels are represented by the pathloss exponent $\gamma = 2.32$ and a distance-dependent parameter m in the Nakagami- m distribution [19]. The probability density function of Nakagami- m distribution is

$$f_X(x) = \frac{2m^m x^{2m-1}}{\omega^m \Gamma(m)} \exp \frac{-mx^2}{\omega}, \quad (2)$$

where $\omega = \frac{P_t}{\delta^\gamma}$ and δ is the distance between the transceivers. We use the parameters suggested in [3] and [20], i.e., transmit power 20 dBm, noise floor -99 dBm and decoding threshold 8 dB, in our simulation to determine the matrix $\mathbf{P}$. The antenna-to-antenna distance between two subsequent vehicles is 25 meters, corresponding to an average truck length of about 18 meters. Given the characteristics of the matrix $\mathbf{P}$, we run 20 million trials to get sufficient confidence in the simulation results.

In Fig. 3, we present the probability of success as a function of the number of time-slots used for disseminating event-driven messages which are transmitted from node 1 to different receivers. Success is defined as the targeted destination correctly receiving the message. We compare the performance of our relaying scheme to a simple repetition scheme, in which the source R_0 uses all $K + 1$ time-slots. Note that both schemes will select the same relay (the message originator) if only one time slot is allowed. It can be seen that for platoon lengths above eight vehicles, the relaying scheme improves performance considerably, i.e., the success probability is 0.949 after two time-slots with relaying, but only 0.924 with repetition when the platoon length is 12.

Fig. 3: Success probability of an event-driven message reaching a certain destination (unicast), given a set of assigned time-slots and a platoon with 12 members.

Fig. 5: Success probability of an event-driven message originating from node 1 reaching all platoon members (broadcast), given a set of assigned time-slots and a platoon with 12 members.

Fig. 4: Success probability of an event-driven message originating from node 1 reaching all platoon members (broadcast), given a set of assigned time-slots and a platoon with 8 members.

In Fig. 4, we present the resulting probability of success for event-driven messages originating from node 1, the leading vehicle, to all platoon members, i.e., broadcast. Results are presented for a different set of time-slots ranging from one to four and the success probability is measured in each node as indicated on the x -axis. When three or more time-slots are used to disseminate the message, the success probability is approaching 1 for all platoon members. For two time-slots, we see an anomaly for node number 5 after the second time-slot. This is due to node 5 being selected as the relay and hence its own performance is not improved. The selected relay nodes are $\{1,4,6\}$ for three and finally $\{1,3,5,7\}$ for four time-slots. From Fig. 4 we can also derive the message age for time-triggered messages. The relaying scheme using only one time-slot is the same as broadcasting periodic beacons to the entire platoon. The average message age can be obtained by dividing the time between two successive beacon transmissions with the success probability. We can see from the figure that beacons are transmitted reliably to neighbors located two hops

Fig. 6: Success probability of an event-driven message originating from node 4 reaching all platoon members (broadcast), given a set of assigned time-slots and a platoon with 12 members.

away. For longer distances the message age will be higher than the beacon period.

In Fig. 5 we can also see the success probability of a message broadcasted from the leading vehicle to the entire platoon, but for 12 platoon members. It can be seen from Fig. 5 that the increased platoon length affects the success probability at several nodes, since the preferred relay node for two time-slots has moved from node 5 to node 7. In addition, we see that the success probability degrades linearly with the number of hops in the platoon, with two exceptions: after node 3 and after node 8. These distances correspond to the instances where the distance dependent parameter m in the Nakagami- m distribution changes.

In Fig. 6, the resulting success probability when broadcasting an event-driven message from node 4 to the entire platoon with 12 members is shown. We can see similar trends here as in Fig. 4–5, i.e., the success probability is close to one for for two nodes on each side of the message originator, even after one slot, and then performance reduces considerably for nodes

three hops away. Thereafter it degrades linearly again for nodes three to seven hops away, before the next considerable reduction at nodes located eight hops away. However, if four time slots are allowed for relaying, the success probability is close to one for all nodes.

The worst case channel access delay for event-driven messages is when a vehicle k generates an event right after its dedicated event-slot and all platoon members have events to disseminate. As illustrated in Fig. 2, the next opportunity for vehicle k does then not occur until all $N - 1$ vehicles have generated and sent their events, which all need to be followed by a set of relay slots. The maximum number of time-slots that can ever be assigned to an event is $N - 1$, i.e., each platoon member except the last one, relays the message e.g., to change the beacon update rate. Also note that event-driven messages and relay slots can only take place in slots not already used by time-triggered messages. We use the following numerical example: assume that the beacon update rate is 10 Hz, i.e., one periodic message is sent from each vehicle each 100 ms, and a time slot is 100 μ s. This implies that the hyper frame consists of 1000 slots and for a platoon length of $N = 10$ vehicles, a periodic message appear every 100 slot. If an event-driven message is generated in node 2 just after node 2's designated event-slot, the worst case is that node 3–10 and node 1 all have event-driven messages of the worst kind i.e., $N - 1 = 9$ slots. Then nine nodes will each use nine time slots, resulting in 81 slots before it is node 2's turn again. In the worst case one periodic message also appears, i.e., the worst case channel access delay becomes 82 slots, resulting in 8.2 ms when each slot is 100 μ s.

VI. CONCLUSIONS

In this paper, we have proposed a framework for reliable exchange of periodic and event-driven control messages in platooning applications together with an efficient message dissemination technique. We use a semi-centralized TDMA scheme, that can be placed on top of IEEE 802.11p, which includes designated time-slots for periodic beacons by all platoon members, evenly spread in a hyperframe, and in-between, a number of consecutive time-slots which can be used by event-driven messages. This yields a bounded channel access delay for beacons, which results in the message age only depending on the beacon update rate and the PER, and where the jitter can be set to zero. In our proposed dissemination algorithm, event-driven messages originating from any platoon member, are supported by a set of distinct relayers. We consider both the case with one targeted receiver and the case when the message should be received by all platoon members. The resulting message dissemination strategy uses relaying and has a bounded channel access delay. We can therefore evaluate the error probability at the targeted receiver(s) after a fixed transmission delay. Simulation results indicate that the proposed dissemination policy significantly enhances the reliability for a given number of available time-slots, or alternatively, reduces the delay, in terms of time-slots, required to achieve a certain target error probability. Our

framework can be used both to broadcast periodic beacons and to disseminate event-driven messages within a platoon, without one message type causing performance degradation to the other.

REFERENCES

- [1] A. Alam, A. Gattami, and K. Johansson, "An experimental study on the fuel reduction potential of heavy duty vehicle platooning," in *Proc. IEEE ITSC*, Madeira, Portugal, Sep. 2010, pp. 306–311.
- [2] C. Berghem, E. Hedin, and D. Skarin, "Vehicle-to-vehicle communication for a platooning system," *Procedia-Social and Behavioral Sciences*, vol. 48, pp. 1222–1233, 2012.
- [3] IEEE Std 802.11-2012, *IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, 2012.
- [4] S. Eichler, "Performance evaluation of the IEEE 802.11p WAVE communication standard," in *Proc. IEEE VTC-Fall*, Baltimore, MD, Oct. 2007, pp. 2199–2203.
- [5] K. Bilstrup, E. Uhlemann, E. G. Ström, and U. Bilstrup, "On the ability of the 802.11 p MAC method and STDMA to support real-time vehicle-to-vehicle communication," *EURASIP J. Wireless Commun. Netw.*, vol. 2009, 2009.
- [6] M. Sepulcre, J. Gozalvez, J. Harri, and H. Hartenstein, "Application-based congestion control policy for the communication channel in VANETs," *IEEE Commun. Lett.*, vol. 14, no. 10, pp. 951–953, 2010.
- [7] L. Le, R. Baldessari, P. Salvador, A. Festag, and W. Zhang, "Performance evaluation of beacon congestion control algorithms for VANETs," in *Proc. IEEE GLOBECOM*, Houston, TX, Dec. 2011, pp. 1–6.
- [8] G. Bansal, B. Cheng, A. Rostami, K. Sjöberg, J. B. Kenney, and M. Gruteser, "Comparing LIMERIC and DCC approaches for VANET channel congestion control," in *Proc. IEEE WiVeC*, 2014, pp. 1–7.
- [9] J. Akerberg, M. Gidlund, and M. Björkman, "Future research challenges in wireless sensor and actuator networks targeting industrial automation," in *Proc. IEEE INDIN*, Lisbon, Portugal, Jul. 2011, pp. 410–415.
- [10] A. Böhm and M. Jonsson, "Real-time communication support for cooperative, infrastructure-based traffic safety applications," *Int. J. Veh. Tech.*, vol. 2011, 2011.
- [11] ETSI EN 302 637-2 V1.3.2, *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service*, Nov. 2014.
- [12] ETSI EN 302 637-3 V1.2.2, *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specification of Decentralized Environmental Notification Basic Service*, Nov. 2014.
- [13] S. Kaul, M. Gruteser, V. Rai, and J. Kenney, "Minimizing age of information in vehicular networks," in *Proc. IEEE SECON*, Salt Lake City, UT, Jun. 2011, pp. 350–358.
- [14] A. Böhm, M. Jonsson, and E. Uhlemann, "Co-existing periodic beaconing and hazard warnings in IEEE 802.11p-based platooning applications," in *Proc. ACM VANET*, Taipei, Taiwan, Jun. 2013, pp. 99–102.
- [15] N. Wisitpongphan, O. Tonguz, J. Parikh, P. Mudalige, F. Bai, and V. Sadekar, "Broadcast storm mitigation techniques in vehicular ad hoc networks," *IEEE Wireless Commun. Mag.*, vol. 14, no. 6, pp. 84–94, Dec. 2007.
- [16] K. Bür and M. Kihl, "Evaluation of selective broadcast algorithms for safety applications in vehicular ad hoc networks," *Int. J. Veh. Tech.*, vol. 2011, 2011.
- [17] S. Panichpapiboon and W. Pattara-Atikom, "A review of information dissemination protocols for vehicular ad hoc networks," *IEEE Commun. Surveys Tuts*, vol. 14, no. 3, pp. 784–798, 2012.
- [18] A. Böhm, M. Jonsson, and E. Uhlemann, "Performance comparison of a platooning application using the IEEE 802.11p MAC on the control channel and a centralized MAC on a service channel," in *Proc. IEEE WiMob*, Lyon, France, Oct. 2013, pp. 545–552.
- [19] L. Cheng, B. E. Henty, D. D. Stancil, F. Bai, and P. Mudalige, "Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 GHz dedicated short range communication (DSRC) frequency band," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 8, pp. 1501–1516, 2007.
- [20] D. Jiang, Q. Chen, and L. Delgrossi, "Optimal data rate selection for vehicle safety communications," in *Proc. ACM VANET*, San Francisco, CA, Sep. 2008, pp. 30–38.