<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper published in *IEEE Communications Letters*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Hoang, L., Uhlemann, E., Jonsson, M. (2015)

An Efficient Message Dissemination Technique in Platooning Applications.

IEEE Communications Letters, PP(99)

<http://dx.doi.org/10.1109/LCOMM.2015.2416174>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:hh:diva-28228>

An Efficient Message Dissemination Technique in Platooning Applications

Le-Nam Hoang, Elisabeth Uhlemann, and Magnus Jonsson

Abstract—Autonomous driving in road trains, a.k.a. platooning, may reduce fuel consumption considerably if the inter-vehicle distances are kept short. However, to do this, the intra-platoon communication must not only be reliable but also able to meet strict deadlines. While time-triggered messages are the foundation of most distributed control applications, platooning is likely to also require dissemination of event-driven messages. While much research work has focused on minimizing the age of periodic messages, state-of-the-art for disseminating event-driven messages is to let all nodes repeat all messages and focus on mitigating broadcast storms. We derive an efficient message dissemination scheme based on relay selection which minimizes the probability of error at the intended receiver(s) for both unicast and broadcast, without degrading the performance of co-existing time-triggered messages. We present a full analysis of the resulting error probability and delay, when relayers, selected by our algorithm, are used to disseminate messages within a platoon. Numerical results indicate that the proposed relaying policy significantly enhances the reliability for a given delay.

I. INTRODUCTION

Platooning, i.e., forming a road train of heavy duty vehicles with small inter-vehicle gaps, is considered a promising method to decrease fuel consumption by reducing the air drag [1]. Platooning applications rely on in-vehicle sensors, but also inter-vehicle communications, where, e.g., the leading vehicle sends information to the trailing vehicles to enable automatic control of the speed of the platoon [2]. Intra-platoon communication therefore requires delay-sensitive data to be transmitted and received with high reliability. While time-triggered messages, or so-called beacons, are the foundation of most distributed control applications, platooning is likely to also require dissemination of event-driven messages. Events may originate not only from the leading vehicle (the central controller) but from any platoon member. Depending on the type of event, the resulting message could either target a specific receiver within the platoon (e.g., an emergency breaking message targeting the last vehicle which needs to brake 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 affecting the performance of one another, as proposed by ETSI [3, 4].

Platooning is one example in a set of applications enabled by cooperative intelligent transport systems (C-ITS). Most

C-ITS based applications requiring short to medium range inter-vehicle communication will use IEEE 802.11p [5], operating in so-called vehicular *ad hoc* networks (VANETs). 802.11p uses carrier sense multiple access (CSMA), which has shown problems with unbounded channel access delay and multiple consecutive packet drops [6, 7]. For platooning, excessive delays may jeopardize the safety of the platoon or, alternatively, the inter-vehicle gaps may have to be extended to the point where fuel reductions are no longer possible.

Rather than tackling the problems implied by CSMA, we use a time division multiple access (TDMA) approach, which is placed on top of the CSMA scheme of 802.11p [8]. While centralized schemes such as TDMA are impractical for most VANET applications, they can be formed and managed quite easily in platoons due to the highly regular network topology. However, to ensure full reliability, a separate frequency channel is likely required to avoid interference from non-platoon vehicles using CSMA. 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) is still unbounded. This is due to noise and interference encountered on the wireless channels. To reduce the delay until a message is successfully received, it is not enough with an upper bounded channel access delay, the reliability of each transmission (once granted by the MAC method) must also be maximized.

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 problem of how to maximize the reliability of event-driven messages, given a fixed deadline, can then be reformulated as how to make best use of a set of available time-slots. Given a certain number of available time-slots, we select a set of relayers to aid the dissemination such that the probability of error is minimized at the targeted receiver(s) for broadcast as well as unicast. Our algorithm can also be used to determine the maximum delay required (in terms of time-slots) to achieve a certain reliability. We show that our proposed relaying policy significantly enhances the probability of receiving event-driven messages, without jeopardizing the performance of periodic beacons. To the best of our knowledge, our approach is the first of its kind as state-of-the-art for dissemination of event-driven messages is to simply let all nodes repeat all event-driven messages and focusing on mitigation broadcast storms.

II. RELATED WORKS

Performance of applications based on beacons is generally improved by providing timely channel access, increased reli-

This work is funded by the Knowledge Foundation (KKS) through the ACDC project and by the ELLIIT network. The authors are with CERES, Halmstad University, Halmstad, Sweden. Email: {le-nam.hoang, elisabeth.uhlemann, magnus.jonsson}@hh.se. E. Uhlemann is also with Mälardalen University, Västerås, Sweden.

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

ability, increased update rate or reduced jitter. The communications requirements of event-driven messages are typically quite different, as jitter is of no interest, but instead a low dissemination delay. Kaul *et al.* [9] identifies the age of periodic beacons in vehicular networks as an important performance metric and propose a rate control algorithm to improve its properties. In [10] several information dissemination protocols for VANETs in general are reviewed and in [11], the dissemination delay in platooning is specifically considered. The dissemination delay is defined as 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. Note that the dissemination delay therefore includes both the channel access delay as well as the delay due to packet errors. Different ways of mitigating broadcast storms associated with message dissemination within VANETs have been evaluated in [12] and in [13] where several selective broadcast algorithms are compared from an application perspective using simulations.

Co-existence strategies for beacons and event-driven messages are considered in [14] for VANETs in general and in [11, 15] for platooning applications. In [15], a combined decentralized/centralized channel 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 performance in terms of dissemination delay is not enhanced further, except to mitigate broadcast storms. In addition, [15] compares the performance of a platooning application by itself on a service channel, to a platooning application co-existing with other C-ITS based applications on the control channel. Interference from non-platoon members on the control channel is evident. Consequently, all existing strategies aim to keep the overall network load of beacons below a certain threshold such that a large part of the bandwidth is made available for event-driven messages where, in turn, the main focus is to mitigate broadcast storms.

III. SYSTEM MODEL

Consider a platoon of N vehicles, labeled by the integers $1, 2, \dots, N$, communicating through an *ad hoc* network, as in Fig. 1. We use a periodic hyperframe structure with time slotted MAC such that all platoon members broadcast their beacons once in each hyperframe. The number of time-slots remaining for disseminating event-driven messages thus depends on the number of platoon members, the beacon update-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 according to [16] and as seen in Fig.1.

The channel gain h_{ij} between a pair of nodes (i, j) is 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 has the noise power level N_0 . Defining η_{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

$$P_{i \rightarrow j} = \Pr \left[\frac{P_t |h_{ij}|^2}{N_0} \leq \eta_{th} \right] = \int_0^{\frac{\eta_{th} N_0}{P_t}} \frac{f_{h_{ij}}(\sqrt{\gamma_{ij}})}{2\sqrt{\gamma_{ij}}} d\gamma_{ij}. \quad (1)$$

The channel error rates are represented by an $N \times N$ matrix $\mathbf{P}$, in which each element $P_{i \rightarrow j}$ denotes the error probability on the link from node i to node j . We assume that $f_{h_{ij}}(h_{ij})$ is known or can be estimated, and remains unchanged during the set of time-slots considered. This assumption is not unreasonable as 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.

In each slot, not occupied by a beacon or an already initiated event-driven message, a specific vehicle (pre-allocated through round-robin) is allowed to initiate dissemination of its event-driven message. 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 reliability for that particular type of event. The $K + 1$ slots can be granted since other vehicles, despite being pre-allocated for possible initiation of event-driven messages in a certain slot, are not allowed to interrupt an ongoing dissemination procedure. Time-slot 0 is always allocated to the source R_0 and the remaining K time-slots to a set of K distinct relays $R_1, R_2, \dots, R_K$. After overhearing in the time-slots numbered $0, 1, \dots, k - 1$, relay R_k will transmit at time-slot k or, if it did not manage to overhear the message, remain quiet. Our aim is to select members of the set of K relays, given a certain limited number of time-slots.

IV. MESSAGE DISSEMINATION IN PLATOONS

Denoting the event

$$e_i = \begin{cases} T & \text{if } R_i \text{ transmits at time-slot } i \\ Q & \text{if } R_i \text{ remains quiet at time-slot } i, \end{cases}$$

we consider the probability of a sequence of K consecutive events $\mathbf{e} = \{e_i\}_{i=1}^K \in \{T, Q\}^K$, and apply the chain rule

$$\Pr [\cap_{i=0}^K e_i] = \Pr [e_0] \prod_{k=1}^K \Pr [e_k | \cap_{i=0}^{k-1} e_i]. \quad (2)$$

The probability that relay R_k transmits in its designated time slot, conditioning on $\{e_i\}_{i=0}^{k-1}$, is determined by

$$\Pr [e_k = T | \cap_{i=0}^{k-1} e_i] = 1 - \prod_{\substack{l \in \Phi_T(\mathbf{e}) \\ l < k}} P_{R_l \rightarrow R_k}, \quad (3)$$

where $\Phi_T(\mathbf{e}) = \{0\} \cup \{i | e_i = T\}$ is the ordered set of all time-slots in which transmissions take place. Assuming that $\{e_i\}_{i=0}^{k-1}$ is defined, the probability that relay R_k remains quiet:

$$\Pr[e_k = Q | \cap_{i=0}^{k-1} e_i] = \prod_{\substack{l \in \Phi_T(\mathbf{e}) \\ l < k}} P_{R_l \rightarrow R_k}. \quad (4)$$

Defining the complimentary set $\Theta_Q(\mathbf{e}) = \{j | e_j = Q\}$ of time slots where the corresponding relay nodes remain quiet, the sequence of events $\mathbf{e}$ occurs with probability as follows

$$\Pr[\mathbf{e}] = \prod_{\substack{\forall l \in \Phi_T(\mathbf{e}) \\ k \in \Theta_Q(\mathbf{e}) \\ k > l}} P_{R_l \rightarrow R_k} \left(1 - \prod_{\substack{u \in \Phi_T(\mathbf{e}) \\ u < l}} P_{R_u \rightarrow R_l} \right), \quad (5)$$

assuming that $P_{R_u \rightarrow R_l} = 0$ when $l = 0, u < l$. The event $e_{K+1} = Q$, i.e the destination cannot receive the packet after $K+1$ transmission attempts, has the probability

$$\begin{aligned} \Pr[e_{K+1} = Q] &= \sum_{\forall \mathbf{e} \in \{T, Q\}^K} \Pr[e_{K+1} = Q | \mathbf{e}] \Pr[\mathbf{e}] \\ &= \sum_{\forall \mathbf{e} \in \{T, Q\}^K} \prod_{\substack{\forall l \in \Phi_T(\mathbf{e}) \\ k \in \Theta_Q(\mathbf{e}) \cup \{K+1\} \\ k > l}} P_{R_l \rightarrow R_k} \left(1 - \prod_{\substack{u \in \Phi_T(\mathbf{e}) \\ u < l}} P_{R_u \rightarrow R_l} \right). \end{aligned} \quad (6)$$

Note that (6) can be used for two types of event-driven messages. The first type is a message that needs to be sent to a specific receiver. We then calculate the resulting error probability at this receiver after a certain number of time-slots. Alternatively, we can use (6) to calculate the delay, in terms of time-slots, required to achieve a certain target error probability. The second type of event is a message that originates from one node and needs to be received by the entire platoon. In this second scenario, (6) is used to calculate the resulting error probability for all platoon members, except the relays. To calculate the final error probability at a relay node R_k after $K+1$ time-slots, $1 \leq k \leq K$, we note that

$$\Pr[e_{K+1} = Q | \cap_{i=0}^{k-1} e_i \cap \{e_k = T\} \cap \cap_{i=k+1}^K e_i] = 0, \quad (7)$$

$$\begin{aligned} \Pr[e_{K+1} = Q | \cap_{i=0}^{k-1} e_i \cap \{e_k = Q\} \cap \cap_{i=k+1}^K e_i] \\ = \Pr[e_{K+1} = Q | \cap_{i=k+1}^K e_i]. \end{aligned} \quad (8)$$

Equation (7) means that it is impossible that a relay node transmits in its designated time-slot, k , but then does not possess a correct copy of the packet after $K+1$ slots. On the other hand, equation (8) indicates that a relay node remaining quiet in its assigned relaying slot k has the opportunity to receive the packet by overhearing in time-slot $k+1$ to time-slot K . Finally, note that new relay nodes need to be selected using (6) – (8) whenever something happens that affect the channel matrix, e.g., the platoon speed or intra-platoon distances change, or the slot assignment, e.g., the number of platoon members change or the beacon frequency change.

V. NUMERICAL RESULTS

To evaluate our solution, we use the channel characteristics from [17] to numerically calculate the elements in (1). The

Fig. 2: Probability of error at a certain destination, given a set of assigned time-slots and a platoon with 12 members.

Fig. 3: The dissemination delay in a platoon with 12 nodes.

channels are represented by the path loss exponent $\gamma = 2.32$ and a distance-dependent parameter m in the Nakagami- m distribution [17]. The Nakagami- m distribution is

$$f\{x; m, \omega\} = \frac{2m^m x^{2m-1}}{\omega^m \Gamma(m)} \exp \frac{-mx^2}{\omega}, \quad (9)$$

where $\omega = \frac{P_t}{d^\gamma}$, P_t is the transmitted power and d is the distance between the transceivers. We use the parameters suggested in [18] and [5], i.e., transmit power 20 dBm, noise floor -99 dBm and decoding threshold 8 dB in our simulation to determine the matrix $\mathbf{P}$. We use this channel model both in the analytical expressions from Section IV and, to verify its correctness, in a Monte-Carlo simulation using MATLAB.

In the following numerical example, we consider a platoon where the antenna-to-antenna distance between two subsequent vehicles is 20 meters, corresponding to an average truck length of about 15 meters. In Fig. 2, we present the resulting probability of error as a function of the number of time-slots for a platoon with $N = 12$, when messages are sent from the leading vehicle to a specific destination, i.e.,

TABLE I: Performance comparisons for different platoon lengths N

		$N = 6$			$N = 8$			$N = 10$			$N = 12$		
		ES	R	GS	ES	R	GS	ES	R	GS	ES	R	GS
Number of time-slots	1	0.0695	0.0695	0.0695	0.0986	0.0986	0.0986	0.2019	0.2019	0.2019	0.2338	0.2338	0.2338
	2	4.4e-6	0.0048	4.4e-6	0.0054	0.0097	0.0054	0.017	0.0407	0.017	0.0264	0.0547	0.0264
	3	7.8e-11	3.4e-3	7.8e-11	1.6e-7	1e-3	0.3e-3	1.9e-6	8.2e-3	1.9e-6	0.2e-3	0.0128	0.2e-3
	4	9.3e-14	2.3e-5	2e-12	2.4e-10	9.4e-5	2.4e-8	1.7e-8	1.7e-3	9e-8	2.2e-7	3e-3	3.8e-6
	$N - 1$	1.5e-18	1.6e-6	1.1e-13	1.3e-20	9e-8	5.5e-13	2.9e-22	5.6e-7	3.7e-14	1.5e-23	1.1e-7	7.5e-13

vehicle 8 or vehicle 12. We compare the performance of our Exhaustive Search (ES) scheme to that of two other schemes: “Retransmission” (R), in which the source R_0 uses all K time-slots, and “Greedy Search” (GS) which selects the best relay node for one time-slot at the time. Note that all schemes will select the same relay (the message originator) if only one time slot is allowed. From the plot, we can see that a transmission from the first to the last vehicle in a platoon of 12 vehicles can reach an error probability of 2×10^{-4} when using three time-slots. In this case, our ES algorithm employs nodes 4 and 9 to relay the message in time slots 2 and 3, respectively. As can be seen from Fig. 2, the analytical expressions perfectly match the simulations.

In Table I, we compare the performance of our ES scheme with R and GS for different number of time slots allowed and different platoon lengths. As can be seen, the performance advantage of the ES scheme increases for longer platoons and when more relaying time slots are allowed.

Finally, Fig. 3 illustrates the result in the second dissemination scenario in which the message originator needs to broadcast information to the entire platoon. Fig. 3 shows that our proposed solution is efficient for broadcast as well as unicast dissemination of event-driven messages in platoons.

VI. CONCLUSIONS

In this paper, we have proposed a relay selection policy suitable for platooning applications using a TDMA-based setting. The overall TDMA scheme includes designated time-slots for periodic beacons, sent by all platoon members, evenly spread in a hyperframe, and in-between, a limited number of consecutive time-slots which can be used by event-driven messages. In our proposed algorithm, event-driven messages originating from any platoon member, are supported by a set of distinct relayers. We have derived analytical expressions for how to select the set of relayers among the platoon members, such that the resulting error rate is minimized at the targeted receiver(s). We consider both the case with one targeted receiver and the case when the message should be received by all platoon members. Numerical results show that the benefits of using our algorithm increase as more time slots are allowed and also for longer platoons. Consequently, using our proposed relaying algorithm implies a lower delay when delivering emergency event-driven messages in platooning applications, or alternatively, provides more reliable dissemination of event-driven messages, given a fixed number of time-slots. In addition, the dissemination of event-driven messages do not compromise the timely transmission of beacons.

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] 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.
- [4] 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.
- [5] 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.
- [6] S. Eichler, “Performance evaluation of the IEEE 802.11-p WAVE communication standard,” in *Proc. IEEE VTC Fall*, Baltimore, MD, Oct. 2007, pp. 2199–2203.
- [7] 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.
- [8] A. Böhm and M. Jonsson, “Real-time communication support for cooperative, infrastructure-based traffic safety applications,” *Int. J. Veh. Tech.*, vol. 2011, 2011.
- [9] 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.
- [10] 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.
- [11] A. Böhm, M. Jonsson, and E. Uhlemann, “Co-existing periodic beaconing and hazard warnings in IEEE 802.11 p-based platooning applications,” in *Proc. ACM VANET*, Taipei, Taiwan, Jun. 2013, pp. 99–102.
- [12] 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.
- [13] 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.
- [14] 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.
- [15] A. Böhm, M. Jonsson, and E. Uhlemann, “Performance comparison of a platooning application using the IEEE 802.11-p MAC on the control channel and a centralized MAC on a service channel,” in *Proc. IEEE WiMob*, Lyon, France, Oct. 2013, pp. 545–552.
- [16] L.-N. Hoang, E. Uhlemann, and M. Jonsson, “A framework for reliable exchange of periodic and event-driven messages in platoons,” in *Proc. IEEE ICC Workshops 2015 (accepted for publication)*, Jun. 2015.
- [17] 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.
- [18] 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.