Towards Inter-Vehicle Communication Strategies for Platooning Support

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Abstract—**Platooning, the idea of cars autonomously following their leaders to form a road train, has huge potentials to improve traffic flow efficiency and, most importantly, road traffic safety. Wireless communication is a fundamental building block – it is needed to manage and to maintain the platoons. To keep the system stable, strict constraints in terms of update frequency and reliability must be met. We developed communication strategies by explicitly taking into account the requirements of the controller, exploiting synchronized communication slots as well as transmit power adaptation. The proposed approaches are compared to two state of the art adaptive beaconing protocols that have been designed for generic message dissemination. Our simulation models have been parametrized and validated by means of real-world experiments. We clearly show how taking into account specific requirements can be extremely beneficial even in very crowded freeway scenarios.**

I. INTRODUCTION

Since research on Vehicular Ad Hoc Networks (VANETs) started more than twenty years ago, many applications based on Inter-Vehicular Communication (IVC) have been proposed, and some have been implemented and tested. Among these applications, platooning, or Cooperative Adaptive Cruise Control (CACC), is often cited as one of the most visionary. Being investigated since the eighties, e.g., within the PATH project [1], it is still an active topic due to the challenging problems it raises. One of the core reasons behind such a huge interest are the benefits that platooning could provide once deployed.

Platooning can enhance the travel experience covering consumption issues, safety, and comfort: First, it has the potential to improve the traffic flow and to reduce the fuel consumption, reducing jams on freeways and decreasing pollution [2], [3]. Second, platooning can improve drivers' safety if a system fault is less likely than a human error, which is the main cause of accidents [3]. Last but not least, a vehicle autonomously following its leaders permits the driver to relax, as shown by the recent SARTRE project [4].

From a research point of view, platooning is extremely challenging, as it involves several research fields including control theory, communications, vehicle dynamics, and traffic engineering. For what concerns networking, any controller designed for supporting platooning, such as the CACC in [5], [6], needs frequent and timely information about vehicles in the platoon to avoid instabilities which might lead to vehicle collisions. A platooning system has a recommended information update frequency of 10 Hz [6]. Whether these communications requirements can be satisfied by the plain DSRC/WAVE stack [7] is still unclear, and further work is needed before platooning can become a reality.

In this paper, we study the suitability of state of the art beaconing protocols for platooning and highlight the challenges that are still open, proposing and investigating communication protocols that can help tackle them. We investigate the reliability of wireless communications for platooning under high channel load imposed by a large number of platoons, showing how the proposed approaches support applications' needs, and how they compare to two adaptive beaconing solutions: the current ETSI standard Decentralized Congestion Control (DCC) [8] and Dynamic Beaconing (DynB) [9]. Moreover, we report on an experimental validation of the simulation setup, using a platoon of four cars equipped with IEEE 802.11p compliant devices.

The contributions of this paper are the following:

- We define a set of different communication strategies, specifically taking into account CACC controller requirements (Section III).
- We show the result of a measurement campaign, which we used to calibrate our simulation models (Section IV).
- We compare the proposed approaches against state of the art adaptive beaconing strategies from a network and an application layer perspective, showing the substantial benefits of our approaches for platooning (Section V).

II. RELATED WORK

A. Platooning

The platooning research community focused initially on the problems connected to the automated control of vehicles, because the design of such a system is a non-trivial task. Indeed, the characteristic which makes a CACC different from a standard Adaptive Cruise Control (ACC) is the capability to *closely* follow the car in front by making use of wireless

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links in order to communicate with nearby vehicles. The CACC designed in [6] makes use of communication only between direct followers. In this case, the distance that can be maintained by the controller has to be speed-dependent as for ACC. Another type of controller uses data communicated from both the vehicle in front and the platoon leader [5]. The benefit is that the system can be proven to be stable under a constant-spacing policy, i.e., the inter-vehicle distance does not need to be speed-dependent. This means that the inter-vehicle gap can be chosen (almost) arbitrarily small, e.g., in the order of $5\,\mathrm{m}$ to $7\,\mathrm{m}$, as proven by Field Operational Tests (FOTs) in the PATH and SARTRE projects [4], [5].

Reducing channel congestion and dealing with packet losses in VANETs have been tackled with several proposals, which include transmit power control and adaptive beaconing techniques [8]–[10]. These approaches have proven to be extremely beneficial for the network, keeping the load under control and packet losses at an acceptable level. However, most of them are not application aware, hence they aim to improve the overall benefit instead of adapting to specific application requirements. This might harm single applications such as platooning, which requires a constant and reliable flow of information. As an example, Lei et al. [11] showed the impact of different packet loss rates on the string stability of CACC, considering a controller with constant time headway policy. Fernandes and Nunes [12] analyzed strategies to improve communications reliability considering five different protocols, all based on TDMA. Furthermore, they proposed a dynamic adaptation of CACC parameters to cope with different situations. Böhm et al. instead analyzed the co-existence of Cooperative Awareness Messages (CAMs) (used for platooning) with Decentralized Environmental Notification Messages (DENMs) (used for safety warning) messages, showing how the choice of different MAC layer priority classes for the two categories heavily affects the effectiveness of data dissemination [13].

It is clear that providing automated controllers with up-to-date information is still an open and very challenging topic. We propose a protocol specific to our purpose, evaluating it against existing solutions and showing how application awareness is extremely beneficial for the platooning controller.

B. Beacon-based IVC

Broadcast-based IVC, or beaconing, has been investigated in detail in the vehicular networking community. The consensus is to periodically send beacons to all vehicles in communication range in order to improve cooperative awareness in general. ETSI defined CAMs for this purpose. This line of research is still featuring very diverse proposals.

Most recently, ETSI ITS-G5 announced a new standard taking into consideration the network dynamics and the need for congestion control: DCC [8], which features a variety of protocol variants. In the scope of this paper, we are interested in the Transmit Rate Control (TRC) algorithm, which carefully adapts the beaconing rate to prevent channel congestion. As an alternative, DCC also supports Transmit Power Control (TPC), which does not work for the specific platooning controller we take as a reference [5], because the leading vehicle must be able to reach all other vehicles in the platoon. In the protocol variant we consider, the computation of the beacon interval I is based on the channel busy ratio b_t, i.e., the amount of time the channel was sensed as busy by the physical layer. The state change decision is taken by monitoring the busy ratio over two time windows, T_{down} and T_{up}. TRC supports three possible interval values, I_{min}, I_{def}, and I_{max}, which are $0.04\,\mathrm{s}$, $0.5\,\mathrm{s}$, and $1\,\mathrm{s}$, respectively. The protocol computes $b_{\text{down}} = \min\left\{b_{t-T_{\text{down}}}, \ldots, b_t\right\}$ and $b_{\text{up}} = \min\left\{b_{t-T_{\text{up}}}, \ldots, b_t\right\}$, and then performs a state change by comparing these values with thresholds b_{min} and b_{max}.

A more recent approach, DynB [9], tries to maintain network load at a fixed, predefined value. Similar to TRC, DynB monitors the channel busy ratio and computes the interval to be used for sending the next beacon accordingly, but adapts more aggressively to the current channel conditions. More formally, let N be the number of neighbors computed using frames received from nearby vehicles, I_{des} the desired (i.e., the minimum) beacon interval, and let b_t and b_{des} be the measured and the desired busy ratio respectively. The beacon interval I is computed as

$$I = I_{\text{des}}\left(1 + rN\right), \tag{1}$$

where $r = b_t/b_{\text{des}} - 1$, clipped in $[0, 1]$. The idea of the protocol is that if the channel load does not exceed a certain threshold, then the number of collisions should be small.

We rely on these state of the art protocols for comparing our approaches for platooning support.

III. COMMUNICATION PROTOCOLS

The set of communication protocols for platooning we propose are based on the IEEE 802.11p/IEEE 1609.4 PHY/MAC, hence scheduled messages will contend for the channel in a CSMA/CA fashion.

We adopt the platooning controller in [5] where the inputs to the system are the leader's and the front vehicle's speed and acceleration. For the design of the algorithms we exploit the specific requirements of the controller. In particular, we assume that each vehicle is aware of its position in the platoon, and uses this to decide *how* and *when* to send a beacon.

To decide *how*, we can exploit the fact that, besides the leader, each vehicle needs to communicate its speed and acceleration only to the vehicle immediately behind. The transmit power can thus be reduced in order to increase spatial reuse and avoid interfering with cars which are "not interested" in receiving such data. Leaders can instead use high transmit power in order to reach all vehicles within the platoon.

In general transmit power control is complex because it must cope with highly dynamic networks [10], but for the application we consider, the setup is simplified due to the linear topology of the platoon. Hence we set a fixed transmit power of $0\,\mathrm{dBm}$ for the followers.

To decide *when* to send, we exploit vehicle's position within the platoon. The leader can send its beacon first, then the others can follow in a cascading fashion, i.e., the second vehicle, the

Algorithm 1: SLB protocol.

```
onStartup():
    if myRole = leader then
        schedule(sendBeacon, beaconInterval);
    end
sendBeacon():
    sendBroadcast(getVehicleData());
    schedule(sendBeacon, beaconInterval);
onBeacon(beacon):
    updateCACC(beacon);
    if beacon.sender = leader then
        onLeaderBeacon(beacon);
    end
onLeaderBeacon(beacon):
    unschedule(sendBeacon);
    schedule(sendBeacon, myPosition $\cdot$ offset);
```

Table I
PARAMETERS EMPLOYED IN THE EXPERIMENTAL VALIDATION.

Parameter	Value
Beacon frequency	10 Hz, 20 Hz, and 25 Hz
Tx power (leader)	20 dBm
Tx power (followers)	20 dBm, 10 dBm, and 0 dBm
Modulation	QPSK R=1/2

third, and so on. Notice that this is different from a standard TDMA approach, as with TDMA every node participating in the communication obeys the same rules. In here, only nodes within a platoon cooperate in a TDMA-fashion in order to reduce intra-platoon channel contention.

The pseudo code of this slotted approach is listed in Algorithm 1. The idea is to divide the time after a beacon from the leader into slots, and have each vehicle send its beacon in the time slot corresponding to its position in the platoon. As shown in Algorithm 1, only the leader starts to send beacons at protocol startup. The followers use the beacon received from the leader for synchronization, computing the time at which they should send the beacon depending on their position and a time offset. To avoid that a lost beacon from the leader blocks the protocol, each vehicle, upon sending a beacon, always schedules another send event after one beacon interval. Upon reception of leader's beacon, this event is updated to synchronize with the leader.

The rationale behind this protocol is to reduce random channel contention by adding synchronization among nodes. Moreover, even if there is no inter-platoon collaboration, the leaders end up roughly synchronizing with other platoons when performing CSMA/CA at the MAC layer. In the remainder of the paper, we refer to this slotted beaconing protocol as SLB and SLBP (with and without transmit power control respectively).

In order to obtain a deep understanding of the benefits of each of the two contributions, we compare them with a baseline approach which uses standard static beaconing, as in the CAM concept [8]. This protocol uses only CSMA/CA, so nodes randomly contend for channel access. When a beacon from either the leader or the car in front is received, the updated information is passed to the CACC controller. The protocol versions of this static beaconing approach, with and without transmit power control, will be referred to in this paper as STB and STBP, respectively.

IV. EXPERIMENTAL VALIDATION

As a basic step, we performed a set of experiments with real cars. The goal is to validate and calibrate the network model we employ in simulations against real world measurements. In the experiment, we used four cars and drove on a private road to safely maintain a distance of 5 m when driving at 20 km/h.

For the communication, we used two Cohda Wireless MK2[1] and two Unex DCMA-86P[2] devices, both IEEE 802.11p compliant. We connected each device to a Mobile Mark ECOM9-5500 dipole antenna with a gain of 9 dBi, magnetically mounted on the rooftop of the vehicles.

We implemented STB and SLB, and tested them while repeatedly driving on a stretch of road of 2 km, using the parameters shown in Table I. Each experiment lasted roughly 30 s and has been repeated three times in order to collect results in different environmental conditions. The same conditions (number of cars, protocols, parameters, etc.) have been reproduced in simulation scenario, to calibrate the simulation setup.

In our experimental setup, we always received at least 99 % of frames sent, making frame error rate not valid for comparison. For this reason, only the distribution of the received power is presented in the following.

We model fading at the receiver with a Rice distribution with a strong Line Of Sight (LOS) component. We make this assumption as, for this paper, we only take into account cars: As stated in [14], if less than 40 % of the first Fresnel zone is unobstructed, then shadowing has no major impact on signal strength, and we experimentally verified the statement with another measurement campaign [15]. When a strong LOS component is considered in a Rician fading channel, the amplitude can be approximated by a Lognormal distribution [16], thus we assume lognormal fading with standard deviation $\sigma = 2\,\text{dBm}$.

Figure 1 shows the comparison between the simulation and the experimental results for 20 dBm and 0 dBm transmission power for the leader and the followers, respectively. Before the on-road experiments, we tested the equipment by pairing the cards using a cable with a 90 dB attenuator, and found that one device is transmitting with lower transmission power than selected, as well as reporting incorrect received signal strength. These tests were used to calibrate and equalize the received power values prior to analyzing the data.

The first aspect we want to focus on is the shape of the distribution. Different real world experiments show slightly different standard deviations; the one we choose for the simulation is a good compromise between all of them, matching also the LOS measurements we performed in [15].

The second aspect is the average received power. In the simulation we employed a *Free Space* path loss model with

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[1] http://www.cohdawireless.com/product/mk2.html

[2] http://unex.com.tw/product/dcma-86p2

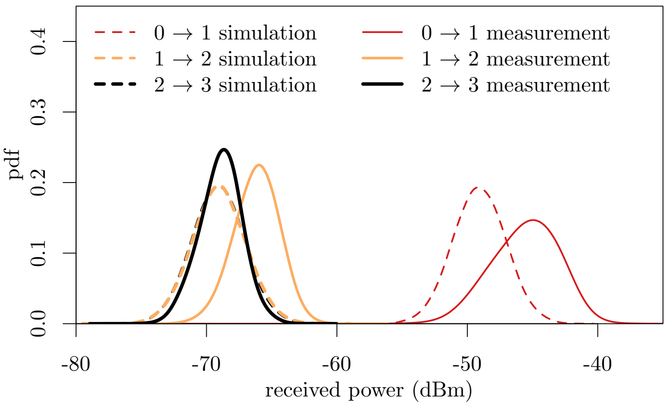


Figure 1. Comparison of received power distributions between the experimental testbed and the simulation environment, for the communication between immediate followers (0 being the leader, 3 being the last car). Transmission powers were 20 dBm for the leader and 0 dBm for the followers.

$\alpha = 2.0$. As can be seen, the average received power is slightly higher in the experiment. This is due to the antennas we used, as they provide high transmission gain. In the simulation we instead considered theoretical isotropic antennas with no gain, as frequently used in vehicular simulations. For the time being, we are mainly interested in the shape of the resulting curves rather than the exact quantities, thus ensuring better comparability with other simulation studies.

V. SIMULATIONS AND RESULTS

To compare the different approaches we use the platooning simulator we developed in [17]. The simulator, which is based on Veins [18], provides a high level of details and realism, featuring mixed scenarios with ACC and CACC controlled vehicles [5] and human controlled vehicles modelled with car-following models. The simulator provides a complete IEEE 802.11p/IEEE 1609.4 stack and has been extended to support all needed IVC protocols TRC, DynB, STB, STBP, SLB, and SLBP.

A. Simulation Model and Setup

To model channel phenomena, we employed a *Free Space* propagation loss model with $\alpha = 2.0$ plus log-normally distributed fading with $\sigma = 2.0$, as they match the experimental setup we performed in Section IV. For DSRC/WAVE, we disabled the switching between Control Channel (CCH) and Service Channel (SCH), using only the CCH. The bitrate is 6 Mbit/s, which has been reported to be optimal for highly demanding vehicular applications [19].

The leaders always transmit at 20 dBm, as they need to reach all cars in the platoon. When transmission power control is disabled, the followers use the same power value as the leaders. When power control is enabled, we tested the performance of the protocols for a fixed power value of 0 dBm, as the optimal transmission power is still unknown and an adaptive algorithm is beyond the scope of this paper.

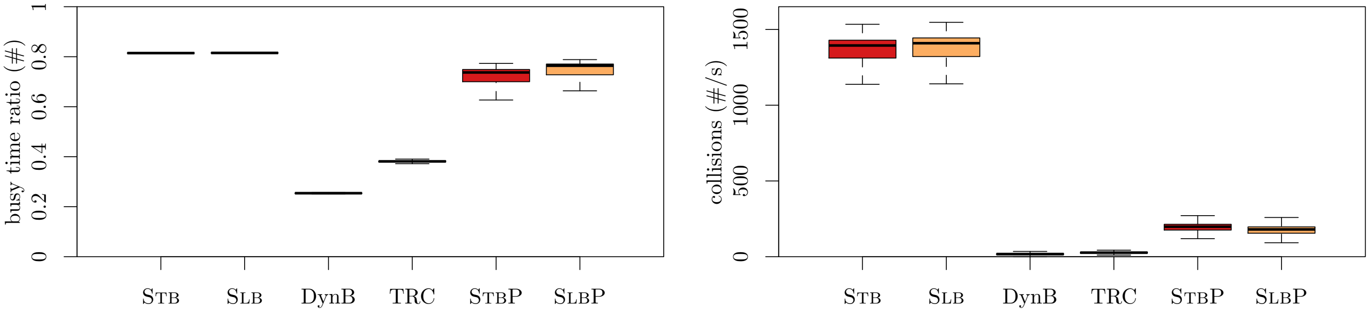
The fixed beacon interval value of 10 Hz and transmit power control capabilities only holds for STB and SLB. DynB and TRC compute their own beacon intervals, and always use 20 dBm as transmission power. The implementation and the parameters for these protocols are taken from [9] and listed in Table II.

Table II
NETWORK AND ROAD TRAFFIC SIMULATION PARAMETERS.

	Parameter	Value
communication	Path loss model	Free space ($\alpha = 2.0$)
	Fading model	Log-normal ($\sigma = 2.0$)
	PHY/MAC model	IEEE 802.11p/1609.4 single channel (CCH)
	Frequency	5.89 GHz
	Bitrate	6 Mbit/s (QPSK R = $1/2$)
	Access category	AC_VI
	MSDU size	200 B
	Transmit power	20 dBm and 0 dBm
mobility	Number of cars	160, 320, and 640
	Number of lanes	4
	Platoon size	20 cars
	Car length	4 m
	Intra-platoon distance	5 m
	Inter-platoon distance	$\simeq$ 41 m
	Speed	100 km/h
controllers	C_1	0.5
	ω_n	0.2 Hz
	ξ	1
	T	1.5 s
	λ	0.1
	τ	0.5 s
TRC	I_{min}, I_{def}, I_{max}	0.04 s, 0.5 s, 1 s
	b_{min}, b_{max}	0.15, 0.40
	T_{up}, T_{down}	1 s, 5 s
DynB	I_{des}	0.1 s
	b_{des}	0.25

We simulate a stretch of a 4-lane highway filled by platoons of 20 cars each, for a total number of cars of 160, 320, and 640, respectively. Such a high number of vehicles might seem unreasonable, but we choose it for two reasons. First, we want to understand if there is any upper limit, meaning that we want to know if the protocols are always behaving as expected, or if over a certain number of vehicles they simply cannot work. Second, such high densities are well possible on big freeways during rush hours, and platooning might exactly be the application we want to run in such situations. Understanding whether it can be supported or not is crucial. Other relevant parameters are the vehicle distance inside the platoon (gap_{des}), set to 5 m, and the speed of the platoons, set to 100 km/h. Table II summarizes simulation parameters. In this work we assume a constant speed because we focus on the analysis of the network.

Each simulation is divided in two phases. In the first part communications are disabled, and the data required by the CACC is supposed to be available and reliable. This way, the overhead due to network simulation is removed, speeding up the initialization phase. The second phase, where statistics about network performance are collected for 120 s simulation time, starts when all the platoons have formed properly and communications are enabled at this point. Moreover, we discard data during the initial transient time of 10 s in the statistic collection phase, after verifying that the network reaches a steady state. Each simulation experiment (each combination of density and protocol) has been repeated 10 times in order to improve the confidence in the results.



(a) Busy time ratio

(b) Collisions per second

Figure 2. The busy time ratio averaged every second and collisions per second for the 640 cars experiments.

B. General Networking Performance

First, we analyze the network behavior, changing the total number of cars in the simulation to vary the channel load. The goal is to understand behavior of the protocols based on typical networking metrics: *channel busy ratio* and *collisions*. The channel busy ratio is measured at the physical layer averaged every second: each node samples how much time the channel was declared busy by the network interface card. Collisions are estimated as the number of not correctly decoded frames (per second and car) due to interference.

Figure 2 shows these two statistics for the 640 cars scenario (the most demanding in terms of network resources) using boxplots, thus displaying the first and third quartiles as a box and the median as center line, as well as the minimum and maximum value with whiskers. The first evident difference between the proposed approaches and the dynamic protocols is in the channel busy ratio. DynB maintains channel load at the desired value of 25 %, independent of the number of vehicles, while TRC has a higher channel usage but still way lower than STB and SLB. In the 640 cars scenario STB and SLB completely saturate the channel as they do not employ transmit power control and hence cause a huge amount of collisions as can be witnessed in Figure 2b. In comparison, STBP and SLBP are able to avoid complete channel saturation and drastically reduce the number of collisions in the channel, suggesting that transmit power control can give a huge benefit. Notice anyhow that the usage of the slotted approach results in a better utilization, as shown by the increased channel busy ratio and the lower collisions. Yet, DynB and TRC definitely show better performance with respect to the considered metrics. Similar results and trends can be reported for lower vehicle densities (data not shown).

C. Application Layer Perspective

To assess the usability of the different protocols for platooning, we define a new metric which computes the amount of time a vehicle was in safe conditions compared to the overall simulation time. In other words, if the maximum tolerable delay for the CACC controller is 200 ms and the inter-message delay for a particular frame is 300 ms, then the system is assumed to be in an unsafe state for this whole time period.

It is clear that this metric requires a maximum tolerable delay in order to be computed. To obtain such a requirement we would need to perform an in-depth and dedicated study of the controller. We can circumvent the problem by computing the metric for a set of different tolerable delays. The choice of the protocol can then be made when such a value is known exactly.

More formally, let δ_{req} the delay requirement, i.e., the maximum allowable inter-message delay. Let $\mathcal{D}$ be the set of all inter-message delays collected by a vehicle. The set of all delays satisfying the requirement δ_{req} is defined as

$$\mathcal{D}_{\text{safe}} = \{d : d \in \mathcal{D} \wedge d \leq \delta_{\text{req}} + \Delta\}\,, \tag{2}$$

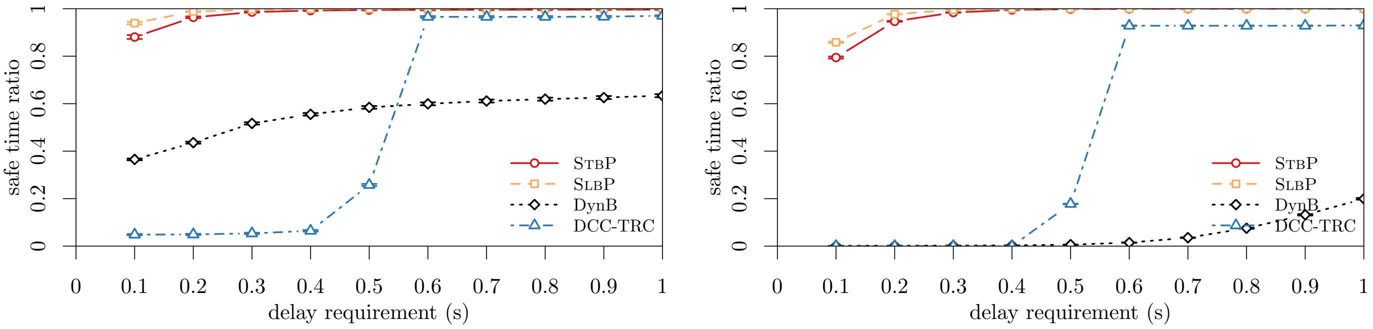
where Δ is a small grace period in which the information is still useful, which accounts for uncertainties such as MAC layer backoffs. In our computation, we set $\Delta = 10\,\text{ms}$. We define the safe time ratio r_{safe} as

$$r_{\text{safe}} = \frac{\sum_{d_{\text{s}} \in \mathcal{D}_{\text{safe}}} d_{\text{s}}}{\sum_{d \in \mathcal{D}} d}. \tag{3}$$

r_{safe} can then be computed for a set of possible delay requirements. What we display in the plots is the average r_{safe} over all cars and all simulation runs, for a particular protocol and delay requirement.

Figure 3 shows r_{safe} computed for leader messages, for 160 and 640 cars scenarios. From an application layer perspective it is clear that STBP and SLBP outperform DynB and TRC, with slightly better results for the slotted approach. When considering DynB with 160 cars, r_{safe} for $\delta_{\text{req}} = 100\,\text{ms}$ is only 40 %. Moreover, r_{safe} is still lower than 60 % for a δ_{req} up to 1 s, meaning that, on average, vehicles would be in an unsafe state for a non-negligible amount of time. TRC shows totally unsafe conditions for values of δ_{req} lower than 400 ms, and then quickly approaches an r_{safe} greater than 0.9 for a delay requirement of 600 ms, independently from the scenario. Again, the same behavior can be observed for medium vehicle density as well as for messages transmitted from the vehicle directly in front (data not shown).

We have shown how taking application-specific requirements into account can result in huge performance gains. A combination of transmit power control plus slotted scheduling can indeed provide frequent updates to the CACC controller,



(a) leader messages, 160 cars

(b) leader messages, 640 cars

Figure 3. Safe time ratios.

without incurring high packet losses. Power control keeps network utilization under control when the number of vehicles increases, and SLB reduces the number of collisions by avoiding random channel contention.

VI. CONCLUSION

In this paper, we discussed the communication technologies needed for automated platooning as well as the resulting challenges for beaconing protocols. We proposed a set of communication strategies by taking into account the specific requirements of the application, showing that a combined use of a slotted scheduling mechanism and transmit power control is highly beneficial, whereas dynamic approaches meant for generic information dissemination are not adequate. We performed experiments using real cars to validate our system architecture and the channel models used in simulations. Our simulation results clearly show the possible performance gain of our protocols compared to state of the art beaconing solutions. The concepts described therefore provide a solid basis for further developments of communication protocols supporting CACC. Further investigation is needed wrt. the interaction and possible integration with other applications based on standard CAM messages, which we assumed to operate on a separate wireless communication channel.

REFERENCES

[1] S. Shladover, "PATH at 20 – History and Major Milestones," in *IEEE Intelligent Transportation Systems Conference (ITSC 2006)*, Toronto, Canada, September 2006, pp. 22–29.

[2] B. van Arem, C. van Driel, and R. Visser, "The Impact of Cooperative Adaptive Cruise Control on Traffic-Flow Characteristics," *IEEE Transactions on Intelligent Transportation Systems*, vol. 7, no. 4, pp. 429–436, December 2006.

[3] A. Davila and M. Nombela, "Platooning - Safe and Eco-Friendly Mobility," in *SAE 2012 World Congress & Exibition*. Detroit, Michigan: SAE, April 2012.

[4] C. Bergenhem, Q. Huang, A. Benmimoun, and T. Robinson, "Challenges of Platooning on Public Motorways," in *17th World Congress on Intelligent Transport Systems*, Busan, Korea, October 2010.

[5] R. Rajamani, H.-S. Tan, B. K. Law, and W.-B. Zhang, "Demonstration of Integrated Longitudinal and Lateral Control for the Operation of Automated Vehicles in Platoons," *IEEE Transactions on Control Systems Technology*, vol. 8, no. 4, pp. 695–708, July 2000.

[6] J. Ploeg, B. Scheepers, E. van Nunen, N. van de Wouw, and H. Nijmeijer, "Design and Experimental Evaluation of Cooperative Adaptive Cruise Control," in *IEEE International Conference on Intelligent Transportation Systems (ITSC 2011)*. Washington, DC: IEEE, October 2011, pp. 260–265.

[7] "Wireless Access in Vehicular Environments," IEEE, Std 802.11p-2010, July 2010.

[8] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part," ETSI, TS 102 687 V1.1.1, July 2011.

[9] C. Sommer, S. Joerer, M. Segata, O. K. Tonguz, R. Lo Cigno, and F. Dressler, "How Shadowing Hurts Vehicular Communications and How Dynamic Beaconing Can Help," in *32nd IEEE Conference on Computer Communications (INFOCOM 2013), Mini-Conference*. Turin, Italy: IEEE, April 2013, pp. 110–114.

[10] T. Tielert, D. Jiang, H. Hartenstein, and L. Delgrossi, "Joint power/rate congestion control optimizing packet reception in vehicle safety communications," in *10th ACM International Workshop on Vehicular Internetworking (VANET 2013)*. Taipei, Taiwan: ACM, June 2013, pp. 51–60.

[11] C. Lei, E. van Eenennaam, W. Wolterink, G. Karagiannis, G. Heijenk, and J. Ploeg, "Impact of Packet Loss on CACC String Stability Performance," in *11th International Conference on ITS Telecommunications (ITST 2011)*, Saint Petersburg, Russia, August 2011, pp. 381–386.

[12] P. Fernandes and U. Nunes, "Platooning With IVC-Enabled Autonomous Vehicles: Strategies to Mitigate Communication Delays, Improve Safety and Traffic Flow," *IEEE Transactions on Intelligent Transportation Systems*, vol. 13, no. 1, pp. 91–106, March 2012.

[13] A. Böhm, M. Jonsson, and E. Uhlemann, "Co-Existing Periodic Beaconing and Hazard Warnings in IEEE 802.11p-based Platooning Applications," in *10th ACM International Workshop on Vehicular Internetworking (VANET 2013)*. Taipei, Taiwan: ACM, June 2013, pp. 99–102.

[14] M. Boban, T. Vinhosa, J. Barros, M. Ferreira, and O. K. Tonguz, "Impact of Vehicles as Obstacles in Vehicular Networks," *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 29, no. 1, pp. 15–28, January 2011.

[15] M. Segata, B. Bloessl, S. Joerer, C. Sommer, R. Lo Cigno, and F. Dressler, "Vehicle Shadowing Distribution Depends on Vehicle Type: Results of an Experimental Study," in *5th IEEE Vehicular Networking Conference (VNC 2013)*. Boston, MA: IEEE, December 2013, pp. 242–245.

[16] S. Abbas and A. Sheikh, "On understanding the nature of slow fading in LOS microcellular channels," in *47th IEEE Vehicular Technology Conference (VTC1997)*. Phoenix, AZ: IEEE, May 1997, pp. 662–666.

[17] M. Segata, F. Dressler, R. Lo Cigno, and M. Gerla, "A Simulation Tool for Automated Platooning in Mixed Highway Scenarios," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 16, no. 4, pp. 46–49, October 2012.

[18] C. Sommer, R. German, and F. Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," *IEEE Transactions on Mobile Computing*, vol. 10, no. 1, pp. 3–15, January 2011.

[19] D. Jiang, Q. Chen, and L. Delgrossi, "Optimal Data Rate Selection for Vehicle Safety Communications," in *5th ACM International Workshop on Vehicular Inter-Networking (VANET 2008)*, San Francisco, CA, September 2008, pp. 30–38.