On Platooning Control using IEEE 802.11p in Conjunction with Visible Light Communications

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***Abstract*—The control of a platoon using IEEE 802.11p is an active research challenge in the field of vehicular networking and cooperative automated vehicles. IEEE 802.11p is a promising technology for direct vehicle to vehicle communication, but there are concerns about its usage for the control of platoons as it suffers packet losses due to congestion in highly dense scenarios. On the other hand, Visible Light Communication (VLC) recently gained attention as a short range technology for vehicular applications. VLC could be used to support or backup IEEE 802.11p, increasing reliability and scalability, and hence the safety of platooning systems. In this paper, we perform a large-scale simulation campaign using VLC integrated with IEEE 802.11p for platooning. We particularly demonstrate the benefits, but also the limitations, of such heterogeneous networking.**

I. Introduction

A multitude of applications is emerging in the broad scope of vehicular networking; for most of them cooperative awareness for enhanced road traffic safety has been the driving force [1]. At the same time, autonomous driving has become a hot topic. Combining both concepts, new applications in the domain of cooperative driving become possible. In this paper, we focus on Cooperative Adaptive Cruise Control (CACC) or *platooning*. This technology builds upon Adaptive Cruise Control (ACC), where a local controller maintains a desired speed while keeping a safe distance to the vehicle in front. The system is supported by local sensors for continuous measurement of the distance and relative speed from the vehicle in front, and by communications for coordination among vehicles. Initial projects towards CACC have been conducted in the U.S. as well as in Europe in the scope of large projects such as PATH and SARTRE [2], [3].

Information about the behavior of the car in front as well as about the head of the platoon is transmitted by means of wireless communications. Within the car, a controller maintains the acceleration or deceleration of the car based on this information. This way, the inter-vehicle gap can be minimized. The benefits of platooning range from improved road traffic throughput [4], [5] to reduced fuel consumption thanks to lower air resistance and lower unnecessary accelerations and decelerations [6]. Moreover, automated car following can improve safety and reduce driving stress.

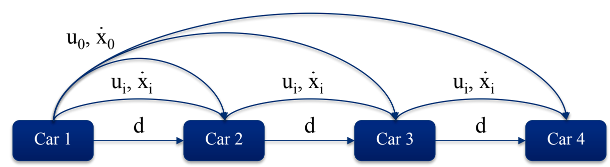

Figure 1. Input parameters for platooning controller

In general, IEEE 802.11p has been adopted for Inter-Vehicle Communication (IVC) applications, including platooning. A CACC requires frequent measurement samples for the local controller. A typical value discussed in the literature is an update rate of 10 Hz [7]. The general concept is shown in Figure 1. The cars measure the distance d to the car in front using radar and receive the speed $\dot{x}$ and the acceleration u of the car in front and the head of the platoon, respectively, using IEEE 802.11p. In previous work, we evaluated the applicability of IEEE 802.11p in this context and also developed a new protocol design using a combination of application layer Time Division Multiple Access (TDMA) and Transmit Power Control (TPC) to enable reliable communication even in heavily congested scenarios, i.e., having (too) many vehicles exchanging cooperative awareness messages and platooning measurement data [8].

In this paper, we use heterogeneous communication technologies to further improve both the reliability and the scalability of the system. We investigate the use of Visible Light Communication (VLC) for message exchange between pairs of adjacent vehicles, in order to: (a) reduce the load on the wireless channel, and (b) enhance the safety of the system as VLC uses direct line of sight communication.

Our main contributions can be summarized as follows:

- We design a new platooning system using heterogeneous communication technologies to improve both reliability and scalability;
- We evaluated the system in a set of simulation experiments to explore the benefits and drawbacks of VLC in comparison to IEEE 802.11p;
- We conclude that VLC increases delay (and thus the safety gap) but substantially improves scalability to hundreds of communicating cars.

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II. Background and Related Work

A. Platooning Control

We rely on the platooning controller used in the PATH project. In the following, we briefly describe the control formula, but a more detailed description can be found in [9], [10]. The objective of the controller is to maintain a distance d_d between each vehicle in the platoon. The CACC algorithm is based on the following measures (cf. Figure 1): The distance to the car in front measured by radar d_{radar}, the acceleration u_{i-1} and the speed $\dot{x}_{i-1}$ of the car in front, and the acceleration u_0 and speed $\dot{x}_0$ of the head of the platoon. The speed and acceleration measures are transmitted by means of wireless communication. Based on these inputs, the desired acceleration u_i is calculated to be fed into the Engine Control Unit (ECU) for actuation. In particular, PATH's CACC computes the control input u_i as follows:

$$u_i = \alpha_1 u_{i-1} + \alpha_2 u_0 + \alpha_3 \left(-d_{\text{radar}} + d_d\right) + \alpha_4 \left(\dot{x}_i - \dot{x}_0\right) + \alpha_5 \left(\dot{x}_i - \dot{x}_{i-1}\right), \quad (1)$$

where i is the index of the vehicle in the platoon (1 being the first follower) and $\dot{x}_i$ is the local speed. The α_i parameters are controller gains that can be configured to change the behavior of the controller (see [9] for further details). To mimic engine actuation delay effects, we use a first order low pass filter with a time constant τ, i.e., with the following transfer function:

$$\ddot{x}_i(s) = \frac{1}{1 + \tau s} u_i, \quad (2)$$

where $\ddot{x}_i$ is the actual vehicle acceleration.

B. VLC in Platooning

Platooning based on IEEE 802.11p suffers from two main problems. First, congestion on the wireless channel may lead to packet loss and, therefore, may require a substantial increase of the desired distance d_d between following vehicles to ensure safety. Secondly, security concerns need to be considered, from jamming of the channel (which translates to packet loss) to malicious attacks. The first problem has been addressed using application layer TDMA in conjunction with TPC [8]. To approach the second problem, more secure platooning solutions have been investigated using hybrid networks [11].

We consider VLC as a candidate technology for addressing both problems together. First studies investigated the use of infrared communication in the scope of platooning [12]. This technology is well understood but first requires additional components and is also rather sensitive to direct sun light [13]. On the other hand, VLC using modern LED technology is quite robust. Recently, new channel models have been described also taking VLC specific fading into account [14], [15]. Based on empirical measurements, simulation models have been realized and validated [16]. Taking all these advances into consideration, VLC emerges as a candidate technology for platooning [17], but also for simpler applications as emergency braking [18].

III. On the Applicability of VLC for Platooning

A. Modeling and Simulation

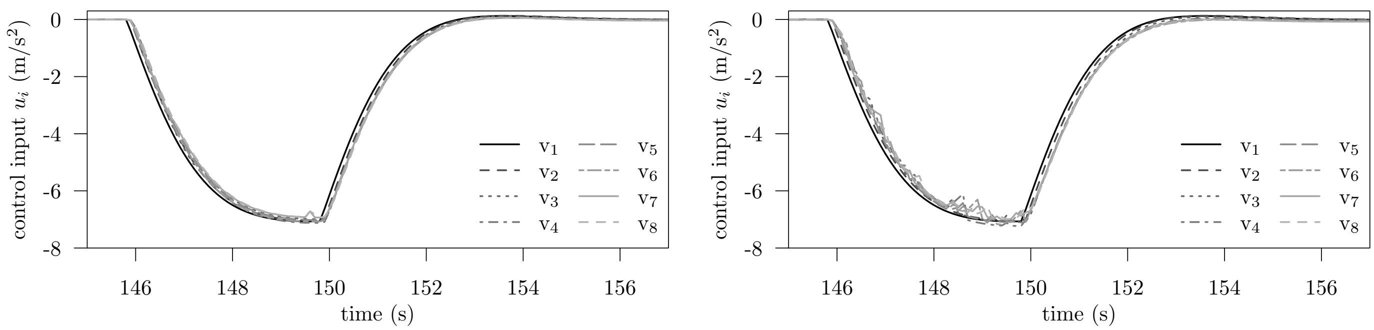
In order to test the combined IEEE 802.11p/VLC approach, we use a freeway scenario in a traffic jam situation as in [8]. In particular, using the Plexe simulator [9], we simulate a 4-lane freeway with 160, 320, and 640 cars divided in platoons of 20 cars. For a basic comparison, we also consider a single platoon scenario with 8 cars only. At the head of each lane, we add a vehicle generating traffic shockwaves by continuously changing its cruising speed every 30 s to mimic a worst case scenario for platooning. We keep jam vehicles desynchronized to have platoons on different lanes close to each other but misaligned over time. Each platoon leader is controlled by an ACC, while all the followers use the CACC controller described in Section II-A. In all scenarios, we consider two communication patterns. In the first one, all vehicles communicates using IEEE 802.11p. In the second, instead, only the leaders use IEEE 802.11p and communication between consecutive vehicles is realized through VLC

In order to stress the application, we consider a scenario with abrupt decelerations. In particular, jamming vehicles pass from 130 km/h to 30 km/h using a deceleration of $7\,\mathrm{m/s^2}$, and then accelerate back to 130 km/h at $1.5\,\mathrm{m/s^2}$. Each simulation lasts 180 s (about three traffic jam cycles), and we repeat each experiment 10 times for statistical confidence.

For this initial analysis we take a simplified, purely stochastic, VLC channel and physical layer model. In particular, we assume a maximum reception range of 25 m and consider decoding delay (i.e., processing time) to be distributed according to a truncated normal distribution (strictly positive) with a mean of 20 ms and a standard deviation of 1 ms. This is simplistic, but a possible source of delay might be the image processing in a

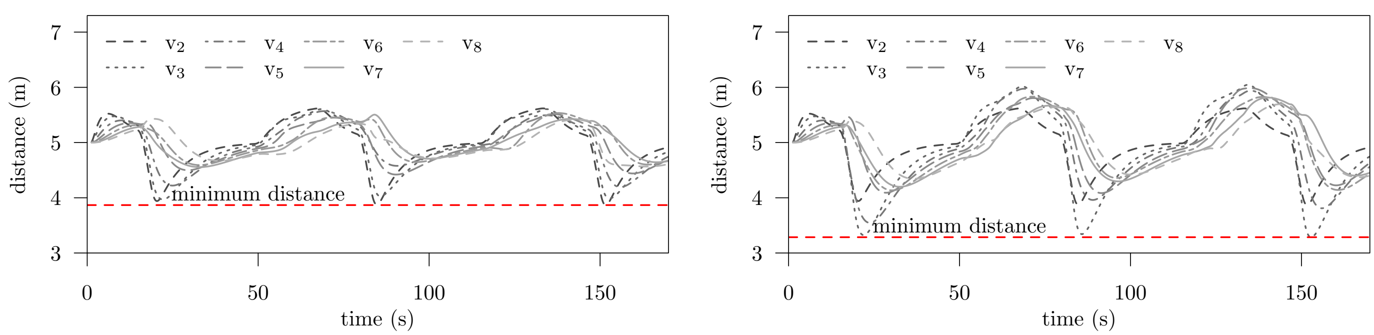
Table I
Network and road traffic simulation parameters.

	Parameter	Value
communication	Path loss model	Free space ($\alpha = 2.0$)
	Fading model	Nakagami ($m = 3$)
	PHY model	IEEE 802.11p
	MAC model	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
	$\max_{\text{bi}}$, $\min_{\text{bi}}$, $\Delta_{u_{\max}}$	1 s, 0.01 s, $2\,\mathrm{m/s^2}$
	p	0.1, 0.3, 0.5, 1, and 3
VLC	Max reception range	25 m
	Packet reception probability	Bernoulli, $p = 0.8$
	Decoding delay D	$D \sim N(\mu = 20\,\mathrm{ms}, \sigma = 1\,\mathrm{ms})$, $D \in (0, \infty)$
	Bitrate	1 Mbit/s
mobility	Max speed	130 km/h
	Min speed (harsh/gentle)	30 km/h and 110 km/h
	Deceleration (harsh/gentle)	$7\,\mathrm{m/s^2}$ and $3\,\mathrm{m/s^2}$
	Acceleration	$1.5\,\mathrm{m/s^2}$
	Platoon size	20 (and 8) cars
	Number of cars	160, 320, and 640 (and 8)
(C)ACC	Engine lag τ	0.5 s
	CACC's C_1, ω_n, ξ, d_d	0.5, 0.2 Hz, 1, 5 m
	ACC's T, λ	1.2 s, 0.1



(a) acceleration, IEEE 802.11p (b) acceleration, VLC

Figure 2. Control inputs u_i in the deceleration phases of the 8-car scenario, for both communication technologies.



(a) distance, IEEE 802.11p (b) distance, VLC

Figure 3. Distances over time for the 8-car scenario, for both communication technologies.

camera-based receiver. Finally, we assume a physical layer data rate of $1\,\mathrm{Mbit/s}$. Table I summarizes all simulation parameters.

B. Results and Discussion

Figure 2 shows the control inputs (i.e., the desired accelerations) computed by the CACC during the acceleration and the deceleration phases of the simulation, for the 8-car (single platoon) scenario and both communication technologies. The traces show that, when using VLC, we obtain a noisier control input because of the time varying decoding delay, but that the noise is limited. Moreover, the noise would be smoothed by the actuation dynamics. This, however, causes a larger positioning error, as witnessed by Figure 3. The plot shows the inter-vehicle distances during the entire simulation and, when using VLC for direct followers communication, the minimum distance reaches roughly $3.2/3.3\,\mathrm{m}$, while when using IEEE 802.11p only, this remains around $4\,\mathrm{m}$. It should be noticed, however, that VLC would be used as a backup technology, and for this purpose the results are definitely encouraging.

We now include into the picture the high density scenarios and we plot the minimum distance between any pair of consecutive vehicles in the simulations by grouping them into boxplots, i.e., plotting the median and a box showing the 1st and 3rd quartile plus whiskers indicating the minimum/maximum. Figure 4 shows that, due to the minimal interference domain typical of VLC, increasing the number of vehicle has nearly no impact on the performance of the control system. The minimum distance for a combined IEEE 802.11p/VLC system is smaller, but this is only due to the increased delay of VLC. Notice that, in a pure IEEE 802.11p communication network, the application layer would suffer from the larger amount of packet losses in such high density scenarios [8].

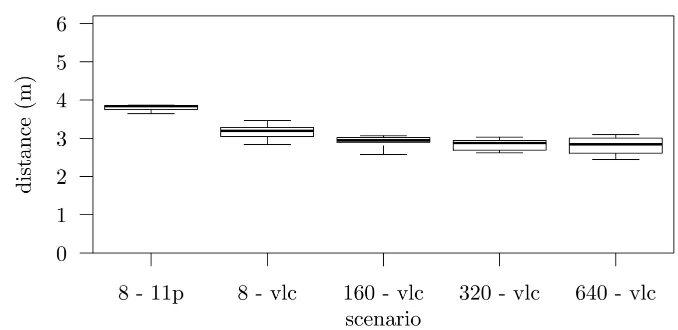
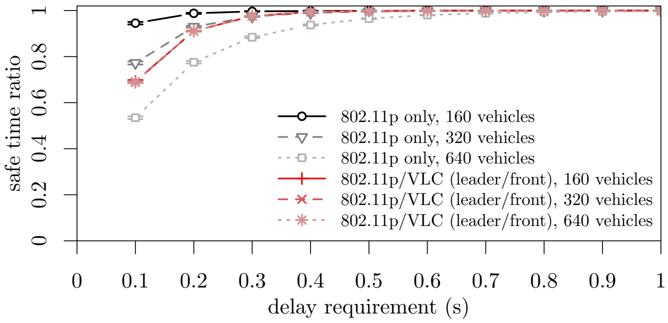


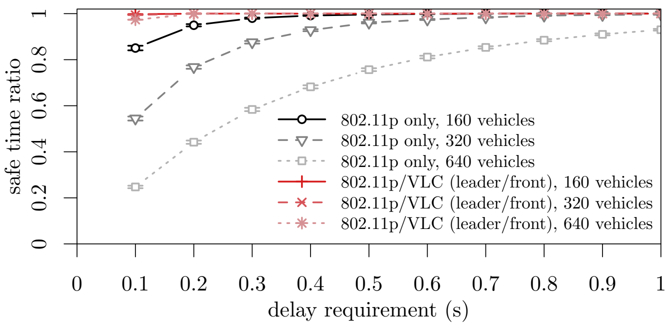
Figure 4. Minimum distances for all scenarios.

To conclude our analysis, we introduce an application layer metric which abstracts from application itself and measures the effectiveness of a protocol based on a parameterizable maximum delay requirement. More formally, let δ_{req} be the maximum tolerable delay, and let $\mathcal{D}$ be the set of all message inter-arrival times measured by a vehicle. We can define the set of all delays in $\mathcal{D}$ satisfying the requirement δ_{req} as

$$\mathcal{D}_{\text{safe}} = \{d : d \in \mathcal{D} \wedge d \leq \delta_{\text{req}}\}\,. \tag{3}$$



(a) Safetime ratio for front vehicle's beacons



(b) Safetime ratio for leader vehicle's beacons

Figure 5. Safetime ratio for front vehicle and platoon leader messages.

We then compute the safe time ratio metric r_{safe} as

$$r_{\text{safe}} = \frac{\sum_{d_s \in \mathcal{D}_{\text{safe}}} d_s}{\sum_{d \in \mathcal{D}} d}. \tag{4}$$

The r_{safe} metric indicates the fraction of time a vehicle was in a safe state given a particular delay requirement δ_{req}.

We study the safetime ratio in the different vehicle densities for both IEEE 802.11p only as well as for the combination with VLC. Figure 5 plots r_{safe} for messages received from the front and the leading vehicles, respectively. For what concerns front messages, we can confirm what we concluded in the analysis of the minimum distance: The performance of VLC is unaffected by the amount of vehicles in the scenarios due to the very limited interference domain. This is not the case for IEEE 802.11p. As can be seen in Figure 5a, the performance substantially degrades with the increasing number of cars, i.e., the increasing congestion on the wireless channel.

Looking at the communication between the leader and the platoon members, this trend becomes even more critical. Figure 5b indeed shows that the performance degrades as the number of vehicles increases, as the leaders are sharing the same communication channel. The results for VLC are however extremely promising, showing a safe time ratio above 95 % for the most demanding delay requirement. This holds thanks to the fact that VLC takes over the communication burden between consecutive vehicles, leaving the IEEE 802.11p channel free for leader communications. This means that VLC can be used not only as a backup technology, but also as an offloading technology that can partially take over IEEE 802.11p when the latter is not able to provide a certain quality of service.

IV. Conclusion and Future Work

We clearly outlined the potential of using VLC as a backup/offloading communication technology for the control of platooning systems. The results indeed show that, even though slightly larger communication delays need to be considered, VLC could improve the safety of the overall system by being coupled with IEEE 802.11p. Still, the results obtained in this work are preliminary for the simplistic assumptions we made for the physical and channel layer model. As a future work, we will consider a more realistic implementation that takes into account two-dimensional light propagation patterns together with a more sophisticated packet error rate model that we will be able to tune by means of real world experiments.

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