Towards Communication Strategies for Platooning

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***Abstract*—Platooning, the act of cars autonomously following their leaders to form a road train, has huge potentials to improve traffic flow efficiency and driving experience on freeways, and most importantly road traffic safety. The challenges of this application are numerous, as witnessed by the number of projects working on this topic from the eighties till nowadays. Platooning indeed encompasses control theory, vehicle dynamics, transportation engineering, and wireless networking, making it one of the widest and most challenging research topics. Wireless communication is a fundamental building block for this application, as it is needed to manage and maintain the platoons and, clearly, have strict constraints in terms of update frequency and reliability. While control theory and vehicle dynamics already provide strong theoretical and practical basis, questions regarding robust and timely communication are still open. In this paper we study concepts for platooning systems and identify specific challenges in wireless networking. In particular, we present a platooning simulation framework that can be used to analyze such systems, describe approaches for communication protocols, and present preliminary results outlining the potentials of our ideas.**

I. Introduction

Since the advent of Vehicular Ad Hoc Networks (VANETs) hundreds of applications have been proposed, analyzed and tested. Among these applications, platooning is often cited as one of the most visionary. It has been investigated since the eighties within the California PATH project [1], but due to the challenging problems it arises, it is still an active research topic. The reason behind such a huge interest by the community is most probably the benefit that this application could provide once deployed.

Platooning could enhance the driving experience in different ways, covering environmental, safety, and comfort aspects. First of all, it has the potential to improve the traffic flow and to reduce the fuel consumption, solving jams on freeways and decreasing pollution [2], [3]. Secondly, platooning could improve drivers' safety, if a system fault is less likely than a human error, which is the major cause of accidents [4]. Last but not least, a vehicle which autonomously follows its leaders permits the driver to relax, read news or emails, avoiding to waste driving time as shown by the recent SARTRE project [5].

From the research point of view platooning has always been extremely challenging, as it involves several research fields. The controller designed for supporting platooning, namely Cooperative Adaptive Cruise Control (CACC) [6, Chapter 7], needs indeed frequent and up-to-date information about vehicles in the platoon in order to avoid instabilities which might lead to collisions. This is where the networking community comes into play: a platooning system requires an information update frequency of at least 10 Hz [7]. Whether such communications requirements can be satisfied by the plain DSRC/WAVE stack [8] is still unclear, and further work is needed in order to complete the system, as highlighted in Section II. The aim of this paper is thus to study the current state of the art concerning communication strategies and protocols for platooning and to highlight the challenges that are still open, giving some ideas on how they could be tackled. We are interested in the analysis of the reliability of wireless communications for platooning under different network conditions, in particular high network load caused by several platoons, and interferences caused by background traffic. Furthermore, we want to design and analyze new information dissemination strategies to better support application's needs. This paper details the current status of our research, discussing some preliminary results we obtained regarding high network load conditions and new dissemination schemes. Finally, we outline what our future research plan will be in this challenging field.

II. Related Work

The platooning research community focused firstly on the problems connected to the automated control of vehicles, because the design of a system able to perform close following at high speed is a non-trivial task. The characteristic which makes a CACC different from a standard Adaptive Cruise Control (ACC) is the capability of closely (in the order of 5 m) following the car in front independently from the speed the vehicles are currently traveling at [6].

A CACC obtains the information about the leader and the vehicle in front by means of wireless communications: in this way a vehicle can know in advance what is happening at the head of the platoon and react earlier [6]. Such controllers have been investigated since the beginning by the pioneering projects PATH [1] and Auto21 CDS [9], but they are still under continuous improvement either by academic research [7] or by car manufacturers, as in the SARTRE project [5].

What differentiates pioneering projects from recent studies is the philosophy. In the case of PATH or Auto21 CDS, platoons were designed to run on dedicated highways, managed by a centralized system [10]. The idea in SARTRE instead, is that platoons form autonomously, and they can travel on public motorways mixed with human driven vehicles. In both cases, network conditions are a major concern. It is well known that 802.11-based networks can suffer of high packet loss ratios even in moderate channel load conditions. Given the frequent updates needed by the CACC in order to ensure string stability, the impact of the network performance on the safety of the overall system is non-marginal [6].

Due to this reason, the VANET community recently started to investigate the impact of communication characteristics on platooning performances. As an example, Lei et. al. [11] showed the impact of different packet loss rates on the performance of the CACC. Bergenhem et. al. [12] and Karlsson et. al. [13] instead focused on real world measurements, showing the impact of the antenna positioning on the packet error rate, and the impact of Non Line of Sight (NLOS) communications caused by obstructing vehicles. Fernandes and Nunes [14] analyze strategies to improve communications reliability considering five different protocols, all based on TDMA. Furthermore, they propose a dynamic adaptation of CACC parameters to cope with different situations.

These works provide a solid foundation which made it possible to raise challenging questions that we have identified.

- Under which channel conditions can a reliable communication still be ensured?
- How many platoons can co-exist without interfering?
- How does platooning cope with other applications generating background traffic?
- How can we deal with bad wireless channel conditions?

The answers to these questions are still missing. Thus, in the near future we intend to investigate on these problem.

III. Fundamental Research Problems

As first step we are interested in identifying to which extent plain IEEE 802.11p is able to support platooning. This can be done by performing network stress tests, either by simulating a highway with several platoons or taking background traffic into account. This way it will be possible to understand how many of the expected packets are received by vehicles in a platoon. We are working on this aspect, currently disregarding background traffic, in order to have an initial understanding of how the system behaves. This paper presents the simulation framework that we have developed to study these systems, together with preliminary results we have obtained.

Secondly, it would be interesting to make an analysis of the communication requirements needed to keep the CACC safe. For example we could let the leader perform an emergency braking and see what happens to the platoon by changing the beaconing frequency. This can be performed by means of simulations in order to obtain an empirical estimation. For a more theoretical analysis, a collaboration with other researchers is needed, as we are no experts in control theory.

Another important step is to analyze different communication protocols and strategies, in order to determine which one is best suited for platooning. For example, comparing static beaconing using pure CSMA/CA with TDMA approaches (as in [14]), as well as transmission power control algorithms. This can be done in conjunction with the initial stress tests, showing how different protocols behave. This is indeed what we are currently doing, and some first results are presented here.

As final step, even if the any of the approaches could not guarantee safety in all possible network conditions, it might be possible to determine network capabilities and react upon that, for instance by adapting the inter-vehicle distance. This step requires, however, an in-depth knowledge of control theory, as the system should be analyzed in order to guarantee that, given a certain inter-vehicle distance, a particular number of messages per second is enough to ensure system's stability. For this reason, we aim to collaborate with other research groups which are active in this area.

To the best of our knowledge, these are the issues that up to know have been left unsolved by the community and that we intend to tackle in our work. The simulations that we have performed in this paper provide some initial insights, and we think that they represent one step towards the implementation of platooning systems.

IV. Simulation Framework

The investigation of platooning systems under challenging conditions (i.e., high network and road traffic) can be performed by means of simulations. Our first contribution in this field is a platooning emulator [15] with a high level of details and realism, featuring ACC and CACC controlled vehicles [6] together with cars driven by well known human behavioral model, as well as a fully fledged IEEE 801.11p/IEEE 1609.4 network layer [16], [17] . This enables researchers to define highway scenarios, high level applications, and communication protocols. In such a way it is possible to investigate platooning strategies, for instance understanding what is the best way of organizing the vehicles, or determine networking metrics, such as packet loss rate, experienced channel load, etc. We also plan to publish the code as open source soon.

Fernandes and Nunes [18] also developed a simulator to investigate a completely automated and dedicated highway as in the idea of the PATH project. The one we developed is generalized to the SARTRE philosophy: it is indeed possible to simulate automated vehicles, together with vehicles controlled by well-known car following models, enabling the possibility of studying mixed scenarios.

We started from Veins [19] which relies on SUMO[1] for road traffic simulation and on OMNeT++/MiXiM[2] for network simulation. The definition of the logic of the applications and the protocols can be easily implemented like usual OMNeT++ modules, permitting the collection of data to the purpose of successive analysis. The results we present in this paper are obtained using our simulation framework.

V. Communication Protocols

As second contribution of the paper, in this section we describe the communication protocols in detail, to give insights on their behavior which is then analyzed in Section VI. Every protocol described here is working on top of IEEE 802.11p/IEEE 1609.4 PHY/MAC, hence scheduled messages will contend for the channel in a CSMA/CA fashion.

[1] http://sumo.sourceforge.net/

[2] http://www.omnetpp.org/

The first dissemination protocol is STATIC BEACONING, which is described in Algorithm 1. The protocol simply sends a message containing the own vehicle information every beacon interval. This protocol works in a pure CSMA/CA fashion, 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. Such protocol represents the most basic approach, as it just uses random dissemination without taking into account application's needs.

One improvement for this protocol is adding transmission power control, i.e., all the followers using a reduced transmission power. The idea is that there is no need for the followers to use the same transmission power as the leader, because the latter has to reach all the vehicles in the platoon, while the followers just need to communicate with the car immediately behind. Using less transmission power reduces interference caused to other nodes and enables spatial reuse of the channel, i.e., nodes which are far from each other can transmit concurrently without interfering.

A different approach opposed to pure CSMA/CA is TDMA, where each node does not transmit at random but at a defined time slot. The pseudo code of the protocol, named SLOTTED BEACONING, is listed in Algorithm 2. The idea is to divide a beacon interval into slots, and have each vehicle sending its beacon in the time slot corresponding to its position in the platoon. For example, the leader will send in the first slot, the second car in the second slot, and so on. As shown in Algorithm 2, 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. For example, if the time offset is 10 ms, then the second car in the platoon will send its beacon 10 ms after having received the message from the leader, the third after 20 ms, and so on. To cope with packet loss, after sending a beacon each vehicle schedules another send event after one beacon interval so that, even if the message from the leader is lost, the followers do not remain silent. This sending event is then canceled if the message from the leader is received.

The idea behind this protocol is to reduce random channel contention by adding synchronization among nodes. Moreover, even if there is no inter-platoon collaboration, one leader might still synchronize with another platoon by performing CSMA/CA at the MAC layer. As further improvement, active synchronization might be performed among the leaders, but for this initial analysis we stick to the simple version. Notice that this algorithm uses TDMA on top of CSMA/CA, there is no real slot reservation. Nevertheless, it might still provide some benefits, but this is discussed in detail in Section VI-B. As for static beaconing, this can be improved by adding transmission power control.

Algorithm 1: STATIC BEACONING protocol.

```
onStartup():
    schedule(sendBeacon, beaconInterval);
sendBeacon():
    sendBroadcast(getVehicleData());
    schedule(sendBeacon, beaconInterval);
```

Algorithm 2: SLOTTED BEACONING protocol.

```
onStartup():
    if myRole = leader then
        schedule(sendBeacon, beaconInterval);
    end
sendBeacon():
    sendBroadcast(getVehicleData());
    schedule(sendBeacon, beaconInterval);
onLeaderBeacon(beacon):
    unschedule(sendBeacon);
    schedule(sendBeacon, myPosition · offset);
```

VI. SIMULATIONS AND RESULTS

In this section we describe the simulation study we performed, providing and discussing initial results.

A. Models

To obtain an initial understanding of the characteristics and the behavior of the protocols and network, we performed a set of simulations in a "stressful" configuration. A summary of the simulation parameters is shown in Table I.

In particular, we have simulated a stretch of a 4-lane highway filled by platoons made by 20 cars each, for a total number of cars of 160, 320, and 640. This scenario is unrealistic but it gives initial insights about how the network is behaving under heavy load, and allows to evaluate which of the aforementioned protocols perform better and for which reason. After this initial evaluation, more realistic scenarios can be explored, for example taking into account non-platooning enabled cars, as well as interference caused by different applications. Other relevant parameters are the vehicle distance inside the platoon, set to 5 m, and the speed of all the platoons, set to 100 km/h.

Regarding network simulation, as physical and MAC layer we have used the IEEE 802.11p and IEEE 1609.4 presented in [17]. However, we did not enable the switching between Control Channel (CCH) and Service Channel (SCH), using only the CCH. The bitrate we have chosen is 6 Mbit/s, which is optimal for high demanding vehicular applications [20]. For transmission power control, we have chosen different power values. The leaders always transmit at 20 dBm, as they need to reach all the cars in the platoon. When transmission power control is disabled, the followers use the same power value as the leaders. When enabled instead, we tested the performances of the protocols for power values of 10 dBm and 0 dBm, as the optimal transmission power is still not known.

Since our first goal is to gain some fundamental insights, we decided to employ a simple path loss model in order to ease the interpretation of the results. In this step we want to avoid the introduction of noise in the results due to complex stochastic phenomena. We then aim to validate the derived conclusion in a

Parameter	Value
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	$\simeq$ 28 m
Speed	100 km/h
PHY/MAC model	IEEE 802.11p/1609.4 single channel (CCH)
Frequency	5.89 GHz
Bitrate	6 Mbit/s
Transmit power	20 dBm, 10 dBm and 0 dBm
Path loss model	Free space ($\alpha = 2.0$)
Access category	AC_VI
MSDU size	200 B

Table I
ROAD TRAFFIC AND NETWORK SIMULATION PARAMETERS.

more realistic setup, using models which consider fading effects, such as the Nakagami [21] or the Two Ray Interference [22] model. For the simulations we performed in this paper, we employed the Free Space model with an α parameter of 2.0.

Regarding the application layer, we are sending packets with an MSDU size of 200 B, and using the AC_VI access category, with a beacon frequency of 10 Hz, the minimum required by CACC [7].

The simulation is divided in two phases. In the first part communications are disabled, and data required by the CACC is "manually" fed into the system. This way, the overhead due to network simulation is removed, speeding up the simulation. When all the platoons are formed, communications are enabled, and statistics about network performances are collected for 2 min (simulation time). When performing post-processing, we discard data about the first 10 s of simulations, after having verified that this amount of time is enough for the network to reach a steady state. Each simulation has then been repeated 10 times in order to improve the confidence of the results.

B. Preliminary Results

The first analysis we perform regards the overall conditions of the network. The aim is to understand what is the impact of the protocols on general and well-known network metrics. In particular we have considered channel busy time and number of collisions. Channel busy time is measured at the physical layer: every second, each node samples how much time the channel was declared busy by the network card. In addition the nodes sample the number of collisions per second, i.e., the number of not correctly decoded frames due to interference.

These two statistics are plotted in Figure 1 in the form of boxplots. Figure 1a shows the busy time ratio for the different protocols and simulations. The first evident result is the increase in network load with the number of cars, as expected. In particular, with 640 cars and no transmission power control, the network is completely saturated as shown by the dense boxes around 0.8. What it is interesting to notice is the effectiveness of transmission power control, which is able to keep the network in a non-congested state both in the 320 and in the 640 cars experiments. For 160 cars, the benefits are instead marginal.

Regarding SLOTTED BEACONING, it can be seen that it always cause a slight increase in busy time, which is due

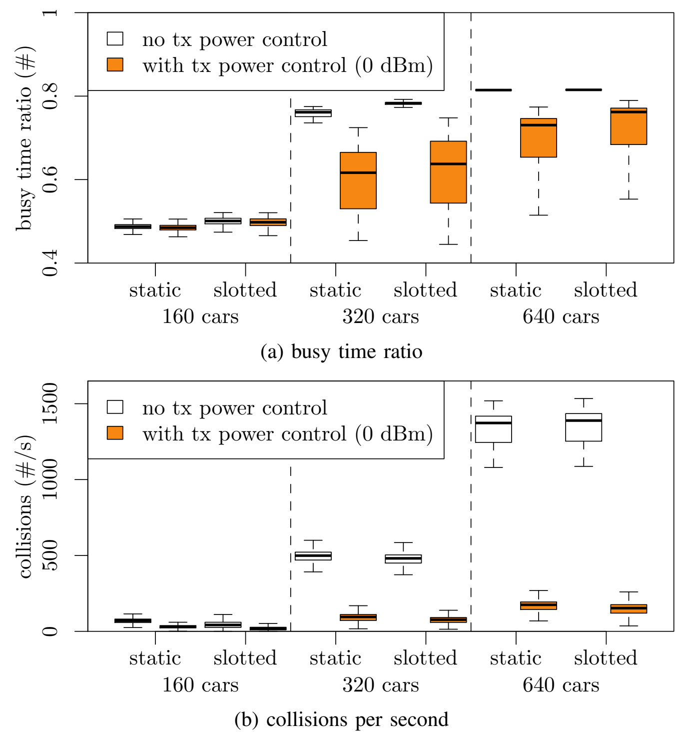

Figure 1. Overall network conditions under the different protocols, for different total number of cars.

to a better channel utilization. This fact can also be seen in Figure 1b, where the number of collisions for the TDMA approach is lower than for the standard CSMA/CA. The benefits provided by TDMA, however, are marginal with respect to the ones provided by transmission power control, suggesting that TDMA might not be the best solution. An improvement which could lead to better results is to have inter-platoon synchronization, i.e., leaders communicating among them and decide a scheduling strategy to avoid random contention.

The analysis we made so far considers the network in general, but it is also important to analyze the performances from the application perspective. The platooning application expects to receive 20 packets per second, 10 from the leader and 10 from the vehicle in front. What we can observe is the distribution of the actual number of received packets per second. An example for STATIC BEACONING, 640 cars, with and without transmission power control, is shown in Figure 2. The plot shows the ECDF of the number of messages per second received from the leader. When transmission power control is not employed (20 dBm), it can be seen that the application would suffer from network congestion, as the it seldom receives all 10 messages. Transmission power control instead provides a huge benefit with respect to application's needs. For the scenario with 0 dBm, the application is able to receive 10 messages per second 50 % of the times, going lower than 5 received messages with a negligible probability.

C. Discussion and Open Issues

Whether a probability of 50 % of receiving all 10 messages is enough to support platooning is still an open question that we want to address in our future work. It is still unclear what

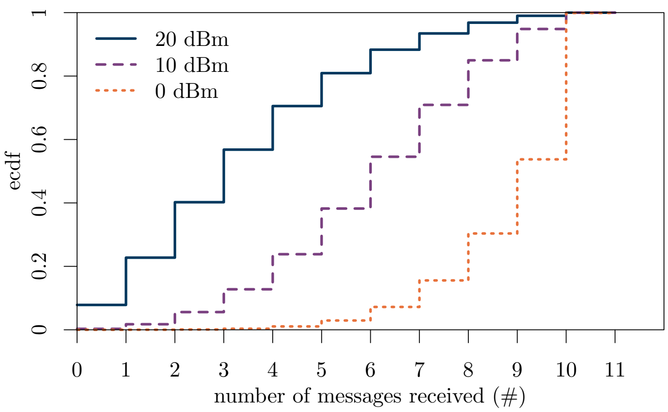

Figure 2. ECDF of the number of messages received per second from the leader, for different transmission powers, STATIC BEACONING protocol, 640 cars.

are the requirements of this application in terms of networking, and we would like to assess under which conditions CACC might not properly work. We were assuming that a beacon frequency of 10 Hz is enough, while higher frequencies might be required. This would have a huge impact on the network. We aim to investigate the protocols we presented in this paper in a realistic setup, so considering *i)* a better channel model, *ii)* automated and human driven cars together, and *iii)* background traffic generated by human driven cars. In this paper we indeed considered platooning to be the only application using the network. The result might however be completely different when other protocols are disturbing platooning. In our future work we aim to understand further benefits and weaknesses of the presented protocols in order to improve them to better support platooning.

VII. CONCLUSION

In this paper we described the technologies necessary for automated platooning and the resulting challenges related to wireless networking. Some issues remain open and must be carefully investigated and understood before the actual systems can be deployed. We proposed possible solutions and described a simulation framework that we have developed, which we used to obtain preliminary results. These results clearly indicate the opportunities of the investigated communication strategies. Based on these initial findings, which will guide us in the next steps of our research towards platooning strategies, we aim to develop more advanced protocols that integrate seamlessly with other vehicular networking concepts.

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