Improving Platooning Safety with Full Duplex Relaying and Beamforming

Tobias Hardes∗†‡, Florian Klingler†§, and Christoph Sommer∗

∗TU Dresden, Faculty of Computer Science, Germany
†Paderborn University, Dept. of Computer Science, Germany
‡TU Ilmenau, Dept. of Computer Science, Germany
§Software Innovation Campus Paderborn, Germany

https://www.cms-labs.org/people/ { hardes, sommer }
https://www.fklingler.net

Abstract—Platooning is a promising application in the field of vehicular networks. It has the potential to improve traffic flow, but also road safety. However, unreliable communication has strong negative effects on platoon stability and, thus, safety on roads. To improve reliability, in this work, we propose using multi-hop communication for platooning using the Decode and Forward (DF) Full-Duplex Relaying (FDR) scheme together with beamforming. We use computer simulations to demonstrate that FDR latency has no observable negative effect on string stability or safety even while performing an emergency brake. We further show that this combined approach reaches a constant Packet Delivery Ratio (PDR) of 100 % even in situations with high interference and/or congestion, where traditional approaches fail.

I. INTRODUCTION

Cooperative vehicular networks are an essential enabler for future transportation systems [1]. One of their most promising building blocks is platooning with Cooperative Adaptive Cruise Control (CACC) controllers like those by PATH [2] or Ploeg et al. [3], which require wireless communication.

This communication commonly follows a Device-to-Device (D2D) paradigm and only operates reliably if data is exchanged at fixed, high update rates. While some other countries favor Cellular vehicle to everything (C-V2X) for D2D communication of vehicles, the European ITS-G5 system is based on IEEE 802.11p, which employs CSMA/CA, i.e., listen before talk, for medium access. At very high node densities or interference, however, safe driving in such a platoon may no longer be possible because of lost or delayed packets [4].

Common approaches to combat this are: transmitting data less frequently to reduce channel load; reducing (or, indeed, increasing) the transmit power to improve Signal-to-Interference-plus-Noise Ratio (SINR); using additional wireless technologies (e.g., mmWave [5] or Visible Light Communication, VLC); or using traditional multi-hop communication so that only immediate neighbors need to be able to decode transmissions. Each of these, however, can have substantial drawbacks: Sending data more infrequently jeopardizes the safety and stability of the platoon, simply reducing (or increasing) transmit power requires tuning transmit power to specific scenarios, using additional wireless technologies increases cost and complexity, and using traditional multi-hop communication increases latency.

Multi-hop approaches, however, can not only be implemented in higher layers, as is traditional, but also in lower layers. Full-Duplex Relaying (FDR) is a relaying technique that operates at the Physical (PHY) layer and exploits simultaneous reception and transmission of data to lower the end-to-end delay caused by multi-hop transmissions. On its own, however, it does not solve the abovementioned problems as the platoon is very susceptible to interference.

In this paper, we present an analysis of multi-hop communication within a platoon using FDR and beamforming to keep the platoon in a stable configuration even under extreme interference. We propose to employ the proven FDR method Decode and Forward (DF) on the hardware layers without changing higher layer protocols. Since multi-hop communication within a platoon provides a well-defined communication topology (e.g., with the direct neighbor), we base our approach on beamforming to reduce interference for vehicles close by [6]. Together, these techniques form our proposed approach LUNA (full duplex relaying with beamforming).

We demonstrate that using LUNA within platoons enables large platoons subjected to considerable interference to operate collision-free compared to traditional approaches.

In brief, the key contributions of this paper are:

- We model and implement LUNA, an approach that integrates beamforming with a DF communication scheme for FDR in platoons.
- Based on extensive computer simulations, we investigate the effects of LUNA for platooning in traffic jam scenarios.
- We show that LUNA outperforms traditional approaches from related work and maintains a Packet Delivery Ratio (PDR) of 100 % even in highly congested scenarios.

II. RELATED WORK

Many publications have addressed reliable communication within a platoon. Various studies focus on higher layers, such as on protocols that optimize transmission times of Platooning Beacons (P-Beacons) [4] or on multi-technology approaches [7], e.g., using both VLC and Radio Frequency (RF)-based communication [8].

Focusing on lower layers, Campolo et al. [9] compare Full-Duplex (FD) communication for a Time-division multiple
access (TDMA) based protocol in a scenario where vehicles in a platoon transmit Cooperative Awareness Messages (CAMs), demonstrating that the required channel resources and delay can be reduced. Further work by Campolo et al. [10] proposes an FD-based multi-channel Medium Access (MAC) extension. Both works do, however, focus on lower layer effects and channel metrics. Amjad et al. [11] investigate the use of FDR for platoons. Simulations with GNU Radio showed a substantial improvement regarding the PDR or the physical layer latency. However, the work focuses only on channel metrics. Further work by Amjad et al. [12] uses FDR and radar-based communication as a complementary communication technology. The authors perform simulations with Matlab and GNU Radio for a platoon of 5 vehicles. Although the results are very positive, they focus on a static scenario of only a single platoon that is not affected by external interference.

López-Valcarce and González-Prelcic [13] propose a beamformer design for mmWave communication with no constraints regarding the self-interference, but treat this problem in isolation from higher layers. Our previous work investigated beamforming for platooning [6], but showed that, with beamforming alone, safe driving within a platoon required environment-specific calibration of transmission parameters.

Summing up, related work points to many potential advantages of using either FDR or beamforming for platooning. However, it often neglects to investigate application-layer effects or scenarios suffering from high interference. Moreover, to the best of our knowledge, a combination of FDR and beamforming has not yet been investigated.

In this paper, we close this gap by evaluating the effect of FDR DF and beamforming on platoons, modeling many aspects from physical effects up to the application layer behavior, including the impact on the CACC. In particular, we investigate properties like string stability, PDR, or the minimal maintained distance between two consecutive vehicles in emergency situations, since all these properties directly impact road safety.

III. LUNA: FULL DUPLEX RELAYING WITH BEAMFORMING

Several CACC designs available in the literature are suitable for the longitudinal control of vehicles. For example, the controller of Ploeg et al. [3] needs only data from the vehicle in front, but can only follow a constant time-gap policy, thus being not as efficient as other controllers. The more widely used PATH controller [2] needs to receive P-Beacons of both the leader and the vehicle in front of it, but can apply a constant spacing policy, which is why we base our work on it.

Protocols employing the PATH controller often configure a high transmission power (commonly: 100 mW) for the leader to reach all vehicles within the platoon. In addition, a roof-mounted omnidirectional antenna is often considered to support CSMA/CA [14]. As a downside, such transmissions inevitably lead to a considerable interference range. To overcome the disadvantage of 1-hop transmissions, multi-hop approaches are a possible solution. Using a multi-hop approach, the leader’s

P-Beacons only need to reach the following vehicle, allowing a lower transmission power. Thus, we base our work on a multi-hop approach.

Multi-hop approaches are usually Half-Duplex (HD) [15] which results in such relays being unable to transmit and receive data simultaneously. Besides inefficient channel utilization, HD communication introduces additional overhead for collision-free communication [16]. Also, Half-Duplex-Relaying (HDR) suffers from an increased end-to-end latency [11]. FDR is FD communication where incoming transmissions are forwarded simultaneously, so that it suffers from neither the increased end-to-end delay nor the increased overhead of HDR. Since we use a multi-hop approach in this work which relays a P-Beacon from the leader to all vehicles in the platoon, we rely on an approach that implements FDR.

Before forwarding, an incoming signal is either amplified (Amplify and Forward, AF) or decoded and again encoded (Decode and Forward, DF), depending on the relaying strategy. For an AF relaying scheme, the amplification factor strongly affects the performance [15]. Furthermore, it requires additional channel estimation to determine the source-relay gain or a complex method to calculate the necessary gain of the signal [17]. We rely only on a DF implementation since the potential advantages of AF are negated by the complex processing of transmissions [17], though such a scheme is still very susceptible to interference.

To reduce interference, we employ directed communication using beamforming for transmission and reception of P-Beacons, reserving omnidirectional transmission for non-platoon communication. Since beamforming uses directional radiation to radiate energy only in one direction, interference for vehicles in the surrounding is substantially lower. Furthermore, a strong antenna gain affects both transmit and receive characteristics due to reciprocity. A signal is, therefore, also received stronger by the gain factor. This property further reduces the necessary transmission power and thus also the caused interference [6]. However, due to this antenna reciprocity, directional receiving behavior also results in more interference being received. Related work has already shown [6] that this can have a strong negative effect on packet collisions. Here, we exploit the physical topology of a platoon and propose to mount a transmitter to the rear and a receiver to the front of the vehicle; each at a height of 0.5 m [14]. Figure 1 illustrates this setup. This arrangement also allows us to neglect Looped Self Interference (LSI).

We call this approach, which reduces latency in a multi-hop platoon while reducing interference for non-platoon vehicles by combining FDR and beamforming for platoon vehicles, LUNA.
Table I: Key parameters of the simulative evaluation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CACC implementation</td>
<td>PATH controller [2]</td>
</tr>
<tr>
<td>Vehicle speed</td>
<td>100 km/h</td>
</tr>
<tr>
<td>CACC desired gap $d_1$</td>
<td>5 m</td>
</tr>
<tr>
<td>CACC bandwidth $2\pi$</td>
<td>0.2 Hz</td>
</tr>
<tr>
<td>CACC damping ratio $\xi$</td>
<td>1</td>
</tr>
<tr>
<td>CACC weighting factor $C_1$</td>
<td>0.5</td>
</tr>
<tr>
<td>Technology</td>
<td>IEEE 802.11p</td>
</tr>
<tr>
<td>Shadowing</td>
<td>Vehicle Shadowing [20]</td>
</tr>
<tr>
<td>Transmit power ($LUNA$)</td>
<td>10 mW</td>
</tr>
<tr>
<td>Transmit power (Baseline)</td>
<td>20 mW / 100 mW</td>
</tr>
<tr>
<td>FDR forwarding delay</td>
<td>42 μs</td>
</tr>
</tbody>
</table>

We investigate the feasibility of LUNA for platoons using computer simulations. Our simulations are based on the OMNeT++ network simulator, on Veins 5.1 [18] for realistic modeling of wireless communication using IEEE 802.11p, Plexe 3.0 [19] for platooning support, and SUMO 1.8 for road traffic simulations. For Veins, we model and implement frame capture to allow decoding of the stronger signal in case several transmissions arrive in parallel. We model this by decoding the stronger signal and ignoring the weaker one.

For simplicity, we choose a freeway with 4 lanes as a scenario. This type of scenario is often used in related work concerning platooning. It allows us to study the effects of LUNA without additional effects due to buildings or non-straight roads. We consider homogeneous vehicles in the simulation, meaning all vehicles have the same height (1.5 m), the same width (1.8 m), and the same length (4 m). We use static beaconing [4] to transmit P-Beacons, i.e., periodic transmissions with a fixed frequency of 10 Hz. We furthermore subtract a uniform random time offset between 0.001 s and 0.005 s to model processing delays and to mitigate simulation artifacts. Table I highlights the key simulation parameters.

We compare three different approaches in our work:

1) **LUNA**: Vehicles use directional signal radiation and FDR with DF for all vehicles within a platoon. We model vehicles for LUNA as being equipped to use directed signal radiation [6] for transmitting and receiving P-Beacons (see Figure 1). Since we are using a multi-hop approach, one radio is located at the front and a second one at the rear of each vehicle at a height of 0.5 m. We do not use any channel access technique to forward P-Beacons of the leader (see Section III). The transmission power is reduced to 10 mW since only the following vehicle needs to be reached. The directional radiation pattern can be found in the literature [6].

2) **Baseline 100 mW**: Vehicles use omnidirectional signal radiation with a transmission power of 100 mW, a common value in related work [19]. We model vehicles as being equipped with a single non-ideal monopole antenna [21]. This is the default setup in related work. CSMA/CA is used for channel access.

3) **Baseline 20 mW**: Same as above, but with a transmission power of 20 mW, another common value in related work.

We use 3 metrics for our evaluation:

1) **PDR of leader beacons**: We measure the PDR of leader beacons as the ratio of successfully received packets to the total number of packets transmitted from the leader. We calculate the average PDR for each vehicle position in the platoon over all simulation runs.

2) **Minimum distance after an emergency brake**: We calculate the minimum distance between any pair of vehicles during the simulation while the platoon performs an emergency brake with a deceleration of $-8 \text{m/s}^2$. For each simulation run, we take the minimum distance over all vehicles in the platoon for our evaluation.

3) **String stability**: A CACC is string-stable when errors in acceleration, speed, or position are not amplified towards the end of the platoon [19]. String stability is a required property of a platoon to prevent vehicle collisions and thus a fundamental concept for the analysis of control algorithms for automated car following.

We perform all experiments with four scenarios, illustrated in Figure 2:

1) **Isolated Platoon**: We consider a single, isolated platoon consisting of 20 vehicles with no side effects.

2) **Large Jam**: We simulate a traffic jam consisting of 300 vehicles spaced 15 m apart on three lanes on the freeway. A platoon with 20 vehicles travels on the fourth lane. Non-platoon vehicles transmit status information with a frequency of 1 Hz and a packet size of 238 Byte. Interfering vehicles use omnidirectional signal radiation with a transmission power of 100 mW. With this scenario, we investigate the impact of additional interference on the success of the different approaches.

3) **Extreme Jam**: As Large Jam, but with 500 vehicles. We chose this scenario to investigate if there is an upper limit where LUNA might fail. Furthermore, such scenarios are realistic on large freeways with many lanes. Platooning is certainly conceivable for such a case [4].
4) Four Platoons: As Large Jam, but with 4 platoons of 20 vehicles each traveling on 4 out of 7 lanes. Through this scenario, we investigate the impact of direct channel access for LUNA.

We perform 20 independent repetitions for all experiments for statistical confidence and remove the transient phase from the beginning and the final phase from the end of the simulation.

A. Packet Delivery Ratio

In the Isolated Platoon scenario, the PDR is approx. 100 % for all approaches (data not shown). The differences between all approaches are negligible and safe driving in a platoon is possible in all cases.

Figure 3a shows the results for the Large Jam scenario. Here, the PDR for LUNA remains constant at 100 %. Since only communication with the direct neighbor is necessary, the received energy from the transmitting platoon vehicle is high compared to the received energy from interfering vehicles. The strong gain of the directional energy radiation further amplifies this effect. Thus, due to the frame capture effect, the P-Beacon of the preceding vehicle is decoded, and the PDR is correspondingly high. Accordingly, all incoming packets from the preceding vehicle are successfully received.

The PDR for both baseline approaches strongly decreases towards the end of the platoon. The last vehicle in the platoon receives approx. 44 % of all P-Beacons from the leader in both scenarios. The low PDR is due to the omnidirectional signal radiation and the resulting large interference range that affects a considerable fraction of other vehicles in the scenario. Further packet loss occurs as a result, and thus a lower PDR is achieved. The different transmitting powers for the two baseline approaches are not particularly noticeable here.

We repeat the experiment in the Extreme Jam scenario. Figure 3b shows the results of this experiment. Again, the PDR for LUNA remains high and constant at 100 % for all platoon vehicles. The PDR of both baseline approaches drops substantially and reaches approx. 19 % (100 mW) and approx. 17 % (20 mW).

Again, the highly directional transmit and receive behavior of LUNA has a positive effect since transmissions from the vehicle in front are received with a much higher power. Consequently, LUNA achieves a high PDR in all cases.

Figure 3c shows our simulation results for the Four Platoons scenario. The constant PDR for LUNA at 100 % is clearly visible. This data clearly shows that the lack of channel access for LUNA (for leader P-Beacons) has no negative impact on transmitting or receiving vehicles close to the platoon. On the other hand, the baseline approaches exhibit PDRs as low as approx. 22 % (20 mW).

Also, the resulting delay of 42 µs for the FD communication has no negative effects. Since the update rate for P-Beacons is set to 10 Hz [3], such a small additional delay does not substantially affect the update rate of the CACC. Accordingly, the resulting delay is negligible here.

In summary, our data show that LUNA and both baseline approaches are sufficient for an isolated platoon. However, the performance of both baseline approaches strongly decreases in case of interference. This degradation is due to the omnidirectional signal radiation and the resulting interference that increases packet loss at a high vehicle density. In contrast, LUNA achieves a constant PDR of 100 % even in extreme cases with 500 interfering vehicles. Furthermore, the missing channel access for LUNA (for leader P-Beacons) has no negative impact on other vehicles close to the platoon.

B. Minimum Distance after Emergency Brake

We simulate an emergency braking scenario to evaluate the effects of LUNA regarding safety in a platoon.

We examine platooning under extreme conditions by having the leader perform emergency braking at a speed of 100 km/h. We configure the maximum braking deceleration for platoon vehicles to $-8 \text{m/s}^2$ – a common value in related work [19].

We first investigate the Isolated Platoon scenario (data not shown). The three approaches do not differ in this scenario and maintain a minimum distance which also arises in the standard scenario of Plexe.

We repeat this experiment using the Large Jam scenario. Figure 4a shows the minimum distance of vehicles within the platoon for all performed simulation runs as an eCDF. The data show that the additional interference has no substantial effect on LUNA. Further investigations showed slight differences (in
In summary, our study shows that the proposed approach works [19], we perform this change in the velocity with a frequency of 0.2 Hz and an amplitude of 10 km/h. Our simulation results show that LUNA and both baseline approaches are string-stable for the Isolated Platoon scenario (data not shown). The stable platoon configuration is the same as in the default scenario of Plexe. We repeat the experiment with the Large Jam scenario (data not shown). The platoon using LUNA maintains a stable configuration over all performed simulation runs. Both baseline approaches can maintain a stable configuration, even though there are some minor deviations from the leader. We repeat the experiments for the Extreme Jam scenario. Figure 5 shows a typical simulation run for LUNA and the baseline approach with 100 mW. For LUNA, our data (Figure 5a) shows that the sinusoid is adopted by all the following vehicles, and no error occurs. Consequently, the platoon is string-stable. Figure 5b shows a typical simulation run for the approach with 100 mW. Because of the high transmit power and the introduced interference due to the omnidirectional signal radiation, the probability of successful decoding is further reduced [6], and platoons are not string-stable anymore. Baseline approaches lead to collisions in 10% (100 mW) and 5% (20 mW) of all simulations (data not shown).

C. String Stability

We examine all approaches regarding string stability using the existing approach from Plexe. The platoon leader changes its velocity by following a sinusoidal profile. Similar to related work [19], we perform this change in the velocity with a frequency of 0.2 Hz and an amplitude of 10 km/h. Our simulation results show that LUNA and both baseline approaches are string-stable for the Isolated Platoon scenario (data not shown). The stable platoon configuration is the same as in the default scenario of Plexe. We repeat the experiment with the Large Jam scenario (data not shown). The platoon using LUNA maintains a stable configuration over all performed simulation runs. Both baseline approaches can maintain a stable configuration, even though there are some minor deviations from the leader. We repeat the experiments for the Extreme Jam scenario. Figure 5 shows a typical simulation run for LUNA and the baseline approach with 100 mW. For LUNA, our data (Figure 5a) shows that the sinusoid is adopted by all the following vehicles, and no error occurs. Consequently, the platoon is string-stable. Figure 5b shows a typical simulation run for the approach with 100 mW. Because of the high transmit power and the introduced interference due to the omnidirectional signal radiation, the probability of successful decoding is further reduced [6], and platoons are not string-stable anymore. Baseline approaches lead to collisions in 10% (100 mW) and 5% (20 mW) of all simulations (data not shown).
LUNA shows no irregularities in the Four Platoons approach (data not shown). All platoons are in a stable configuration in all simulation runs. Both baseline approaches are no longer string-stable and lead to vehicle collisions. Again, the reason can be traced back to the high packet loss.

In summary, our results show that LUNA achieves a stable configuration for the platoon even under external interference. The baseline approaches only achieve a stable configuration up to the Large Jam scenario and lead to vehicle collisions in the Extreme Jam scenario.

V. CONCLUSION

In this work, we proposed LUNA (full duplex relaying with beamforming), a multi-hop communication approach for platooning using Full-Duplex Relaying (FDR) in combination with beamforming. We took advantage of FDR Decode and Forward (DF) as a lower layer implementation and exploited directional signal radiation to handle massive interference. In contrast to related work, we investigate a combination of FDR and beamforming. For this, we modeled aspects of the lower layer, investigated application layer metrics, and did not limit ourselves exclusively to channel metrics.

We investigated our approach using computer simulations and compared it to traditional approaches from the literature. For this, we investigated 4 different scenarios from isolated platoons to multiple platoons passing traffic jams. Using computer simulations, we showed that LUNA reaches a Packet Delivery Ratio (PDR) of 100 % in different scenarios. LUNA can substantially improve communication within a platoon in high congestion scenarios. Where traditional approaches fail, LUNA still reaches a PDR of 100 % and thus enables a platoon to perform emergency braking maneuvers with a strong deceleration without causing vehicle collisions. Our results also show that a platoon stays stable while the leading vehicle follows a sinusoidal profile. Finally, LUNA allows multi-platoon scenarios in traffic jam situations without any negative impact on road safety. The latency caused by multi-hop communication has no observable negative effect on string stability or safety while performing an emergency brake. Thus, the discussed effects lead to a stable platoon configuration and allow safe driving even in extreme scenarios.

Since LUNA, which employs FDR DF with beamforming, has proven to be very promising for platoons, there are different possibilities for future work. First, the introduced interference by the platoon could be further reduced by a more precise calibration of the transmission power. Second, first results show that LUNA is very promising for use for urban platooning. We will further elaborate this in future work.

REFERENCES


