Improving Platooning Safety with Full Duplex Relaying and Beamforming

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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

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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.

Figure 1. Each vehicle in a *LUNA* platoon is equipped with directional communication capabilities. Since vehicles employ a multi-hop approach, these radios are mounted at a height of 0.5 m to reach only the direct neighbor.

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.

Parameter	Value
CACC implementation	PATH controller [2]
Vehicle speed	100 km/h
CACC desired gap d_d	5 m
CACC bandwidth ω_n	0.2 Hz
CACC damping ratio ξ	1
CACC weighting factor C_1	0.5
Technology	IEEE 802.11p
Shadowing	Vehicle Shadowing [20]
Transmit power (*LUNA*)	10 mW
Transmit power (Baseline)	20 mW / 100 mW
FDR forwarding delay	42 µs

IV. EVALUATION

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.

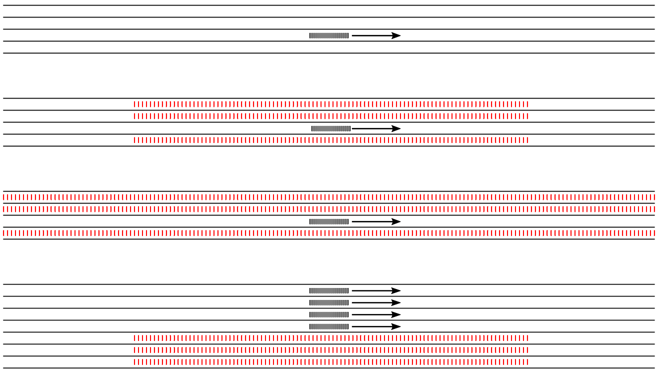


Figure 2. Investigated scenarios: *Isolated Platoon* (black with arrow), *Large Jam* (red, no arrow), *Extreme Jam*, and *Four Platoons*, respectively.

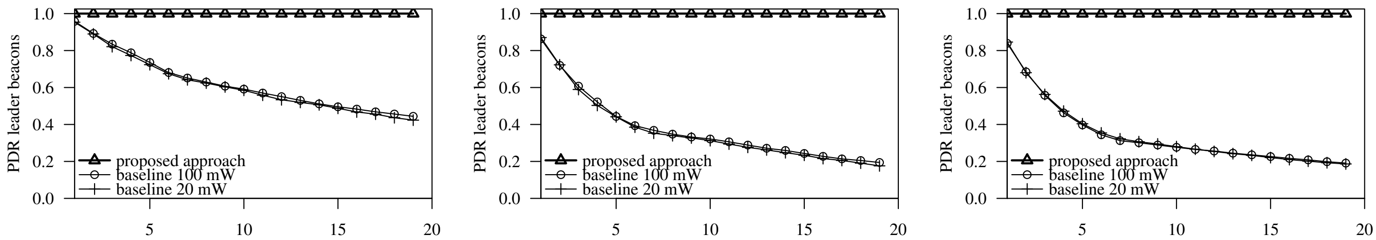
3) **Baseline 20 mW:** Same as above, but with a transmission power of 20 mW, another common value in related work.

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].



(a) *Large Jam* scenario; While *LUNA* maintains a PDR of 100 %, the PDRs of both baseline approaches decrease to approx.44 %.

(b) *Extreme Jam* scenario; While *LUNA* maintains a PDR of 100 %, the PDRs of both baseline approaches decrease to approx. 17 % to 19 %.

(c) *Four Platoons* scenario; *LUNA* maintains a PDR of 100 %. The PDR of both baseline approaches decrease to approx. 22 %.

Figure 3. Packet Delivery Ratio (PDR) for the *Large Jam*, *Extreme Jam*, and *Four Platoons* scenarios.

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.

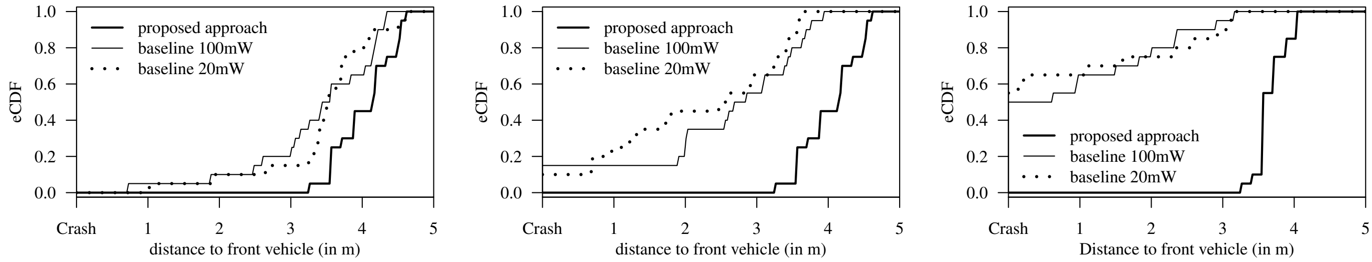
B. Minimum Distance after Emergency Brake

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 $-8\,\mathrm{m/s}^2$ – 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 affect on *LUNA*. Further investigations showed slight differences (in



(a) *Large Jam* scenario; all approaches operate collision-free. However, both baseline approaches achieve a substantially lower minimum distance after reaching standstill.

(b) *Extreme Jam* scenario; while *LUNA* reaches standstill collision-free in all simulation runs, both baseline approaches lead to vehicle collisions in 15 % and 10 %, respectively

(c) *Four Platoons* scenario; while *LUNA* reaches standstill collision-free in all simulation runs, both baseline approaches lead to vehicle collisions in 50 % and 55 %, respectively.

Figure 4. Minimum distance for a simulation run after the platoon reached standstill in the *Large Jam*, *Extreme Jam*, and *Four Platoons* scenarios.

terms of the minimum distance) compared to the case without interference, but these are negligible. Here, less interference and the exclusive radios for transmissions within the platoon have a positive effect.

The baseline approaches, however, now lead to substantially lower inter-vehicle distances, even though no vehicle collisions occur. The reason is provided by the huge interference range that is caused by the omnidirectional signal radiation. The probability of successful decoding of the transmission decreases and thus also the possibility to adapt to the leader's braking maneuver in a timely manner. However, even if this does not lead to collisions, such close driving can still have a negative effect on the comfort of the passengers, as the situation is subjectively assessed as very dangerous and uncomfortable.

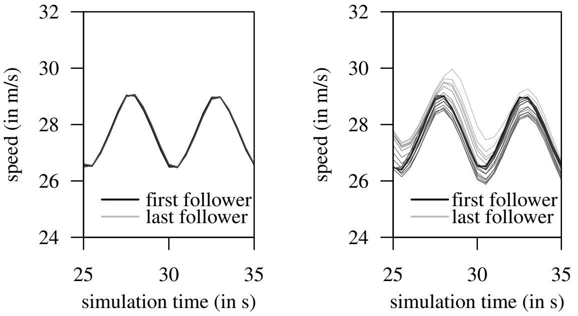
We repeat the experiment with the *Extreme Jam* scenario. Figure 4b shows the results of this experiment. *LUNA* is again not influenced by the strong interference and reaches standstill without any vehicle collisions. Compared to the previous experiments, the differences regarding the changes in the minimum distance are negligible. In contrast, 15 % (100 mW) and 10 % (20 mW) of all simulation runs for the baseline approaches now result in vehicle collisions.

The data for the *Four Platoons* scenario is shown in Figure 4c. *LUNA* achieves collision-free braking in all simulation runs. In contrast, both baseline approaches lead to vehicle collisions in 50 % (100 mW) and 55 % (20 mW) of all simulation runs. Thus, safe driving is no longer possible.

In summary, our study shows that *LUNA* provides safe emergency braking even under strong interference. There is not much difference regarding the minimum distance after reaching standstill between the *Large Jam* and *Extreme Jam* scenario. Missing channel access (for leader P-Beacons) for this approach shows no effect in the *Four Platoons* scenario. Both baseline approaches, however, suffer from strong interference and lead to vehicle collisions.

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.



(a) *LUNA*; The platoon maintains a stable configuration.

(b) Baseline approach; The platoon does not maintain a stable configuration.

Figure 5. Typical speed profile for *LUNA* and baseline approach in the *Extreme Jam* scenario. *LUNA* keeps the platoon in a stable configuration whereas both baseline approaches lead to non-stable platoons.

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

[1] C. Sommer and F. Dressler, *Vehicular Networking*. Cambridge University Press, Nov. 2014.

[2] S. E. Shladover et al., "Automated Vehicle Control Developments in the PATH Program," *IEEE Transactions on Vehicular Technology (TVT)*, vol. 40, no. 1, pp. 114–130, Feb. 1991.

[3] J. Ploeg, B. T. M. Scheepers, E. van Nunen, N. van de Wouw, and H. Nijmeijer, "Design and Experimental Evaluation of Cooperative Adaptive Cruise Control," in *14th International IEEE Conference on Intelligent Transportation Systems (ITSC 2011)*, Washington, D.C.: IEEE, Oct. 2011, pp. 260–265.

[4] M. Segata et al., "Towards Inter-Vehicle Communication Strategies for Platooning Support," in *7th IFIP/IEEE International Workshop on Communication Technologies for Vehicles (Nets4Cars 2014-Fall)*, Saint Petersburg, Russia: IEEE, Oct. 2014.

[5] C. Quadri, V. Mancuso, M. Ajmone Marsan, and G. P. Rossi, "Platooning on the Edge," in *23rd International ACM Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM 2020)*, Alicante, Spain: ACM, Nov. 2020.

[6] T. Hardes, F. Klingler, and C. Sommer, "Modern WLAN for V2X Applications: Exploiting Beamforming for Platooning," in *12th IEEE Vehicular Networking Conference (VNC 2020)*, Virtual Conference: IEEE, Dec. 2020.

[7] M. Segata et al., "Multi-Technology Cooperative Driving: An Analysis Based on PLEXE," *IEEE Transactions on Mobile Computing (TMC)*, Feb. 2022.

[8] S. Ucar, S. Coleri Ergen, and O. Ozkasap, "IEEE 802.11p and Visible Light Hybrid Communication based Secure Autonomous Platoon," *IEEE Transactions on Vehicular Technology (TVT)*, vol. 67, no. 9, Sep. 2018.

[9] C. Campolo, A. Molinaro, A. O. Berthet, and A. Vinel, "Full-duplex radios for vehicular communications," *IEEE Communications Magazine (COMMAG)*, vol. 55, no. 6, pp. 182–189, 2017.

[10] C. Campolo, A. Molinaro, and A. O. Berthet, "Full-duplex communications to improve platooning control in multi-channel VANETs," in *IEEE International Conference on Communications (ICC 2017), Workshops*, Paris, France: IEEE, May 2017.

[11] M. S. Amjad, T. Hardes, M. Schettler, C. Sommer, and F. Dressler, "Using Full Duplex Relaying to Reduce Physical Layer Latency in Platooning," in *11th IEEE Vehicular Networking Conference (VNC 2019)*, Los Angeles, CA: IEEE, Dec. 2019, pp. 236–239.

[12] M. S. Amjad, M. Schettler, S. Dimce, and F. Dressler, "Inband Full-Duplex Relaying for RADCOM-based Cooperative Driving," in *12th IEEE Vehicular Networking Conference (VNC 2020)*, Virtual Conference: IEEE, Dec. 2020.

[13] R. López-Valcarce and N. González-Prelcic, "Beamformer design for Full-Duplex Amplify-and-Forward millimeter wave relays," in *16th IEEE International Symposium on Wireless Communication Systems (ISWCS 2019)*, Oulu, Finland, Oct. 2019, pp. 86–90.

[14] M. Lübke, J. Fuchs, A. Dubey, M. Frank, R. Weigel, and F. Lurz, "Evaluation of Different Antenna Positions for Joint Radar-Communication at 77 GHz," in *2021 Kleinheubach Conference*, Miltengerg, Germany: IEEE, Sep. 2021.

[15] M. S. Amjad and F. Dressler, "Performance Insights on IEEE 802.11a/g Compliant Software-based In-Band Full Duplex Relay Systems," in *IEEE Wireless Communications and Networking Conference (WCNC 2019)*, Marrakesh, Morocco: IEEE, Apr. 2019.

[16] ——, "Software-based In-Band Full Duplex Relays for IEEE 802.11a/g/p: An Experimental Study," in *IEEE Wireless Communications and Networking Conference (WCNC 2021)*, Nanjing, China: IEEE, Mar. 2021.

[17] X. J. Zhang and Y. Gong, "A Simple Amplify-and-Forward Relaying Scheme Based on Clipping and Forwarding for Dual-Hop Transmissions," *Engineering and Technology Publishing Journal of Communications (JCM)*, vol. 5, no. 4, pp. 348–353, Apr. 2010.

[18] C. Sommer, R. German, and F. Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," *IEEE Transactions on Mobile Computing (TMC)*, vol. 10, no. 1, Jan. 2011.

[19] M. Segata, S. Joerer, B. Bloessl, C. Sommer, F. Dressler, and R. Lo Cigno, "PLEXE: A Platooning Extension for Veins," in *6th IEEE Vehicular Networking Conference (VNC 2014)*, Paderborn, Germany: IEEE, Dec. 2014, pp. 53–60.

[20] M. Boban, T. T. V. Vinhoza, M. Ferreira, J. Barros, and O. K. Tonguz, "Impact of Vehicles as Obstacles in Vehicular Ad Hoc Networks," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 1, Jan. 2011.

[21] D. Kornek, M. Schack, E. Slottke, O. Klemp, I. Rolfes, and T. Kürner, "Effects of Antenna Characteristics and Placements on a Vehicle-to-Vehicle Channel Scenario," in *IEEE International Conference on Communications (ICC 2010), Workshop on Vehicular Connectivity*, Cape Town, South Africa: IEEE, May 2010.