Using Full Duplex Relaying to Reduce Physical Layer Latency in Platooning

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***Abstract*—Intelligent Transportation Systems (ITS) are changing the way cars will drive in the future – improving, at the same time, the safety and the efficiency of road traffic. Platooning is one of the considered applications, helping cars to drive with very short safety gaps to improve road traffic capacity and to reduce air drag. A fundamental building block for such cooperative driving solutions is reliable and fast wireless communication. Usually, information from the leader of the platoon needs to be broadcast to all members, resulting in large interference ranges, or being relayed from car to car, introducing additional delays. We introduce a Full Duplex Relaying (FDR) system for use in platooning to overcome these limitations. Concentrating on IEEE 802.11p, we implement the system to explore the feasibility and also to conduct a first performance evaluation. Our results clearly demonstrate the significant performance gain, which at the same time allows to further reduce communication overhead and, thus, to safely increase platoon sizes.**

I. Introduction

Platooning is an Intelligent Transportation System (ITS) application that addresses multiple issues in today's road traffic [1], [2]. Vehicles in a platoon autonomously follow each other by keeping a small safety gap (down to only a few meters) with the preceding vehicle. By using such small inter-vehicle gaps, platooning not only increases the effective road utilization and traffic flow, but also reduces the air drag.

To maintain an inter-vehicle gap of only a few meters, platooning requires a reliable wireless communication channel for vehicles to exchange their *platoon beacons*. Normally, technologies such as WLAN IEEE 802.11p/bd or 4G/5G Cellular V2X are considered. The platoon beacons essentially contain current status information of a vehicle, e.g., acceleration or speed. The exchange of such platoon beacons between vehicles enables the design of Cooperative Adaptive Cruise Control (CACC) systems, and allows cooperative driving. Based on the control principle of the CACC, the controller exploits the data received from other vehicles within a platoon to maintain consistent behavior of the platoon as a whole, while keeping small inter-vehicle gaps. A periodic beaconing transmission is required for the CACC to work effectively, and the transmission frequency is typically in the order of 10 Hz [3].

Related studies for platooning [2], [3] use the IEEE 802.11p stack as the fundamental basis for communications. Segata et al. [2] showed that especially real-time safety-critical applications like platooning suffer from high packet loss due to the unreliable Radio Frequency (RF) channel. This packet loss results in a lower update rate of the CACC and leads to an unstable platoon, which can cause vehicle collisions.

To ensure packet delivery at each member of a platoon, high power transmissions are typically configured for the leading vehicle, which naturally increases the interference domain for the nearby vehicles that are not part of the platoon. A possible solution to reduce this interference domain is to not use such a *Direct Transmission (DT)* scheme, but to use multi-hop relaying for the transportation of the beacons from the leading vehicle to the last vehicle of a platoon. Classical relaying, however, is based on Half Duplex (HD) communication, which requires additional resources in frequency or time domain, depending on whether a Frequency Division Duplex (FDD)-based or a Time Division Duplex (TDD)-based system is employed [4]. Consequently, Half Duplex Relaying (HDR) either has low spectral efficiency or increased end-to-end latency, which only gets worse in multi-hop scenario, as in platooning.

Recent studies, such as [5], [6], have shown the feasibility of Full Duplex (FD) wireless systems, and demonstrated the potential of FD communication to nearly double the spectral efficiency compared to HD systems. With the substantial improvements in Self-Interference (SI) suppression techniques, FD communications have become more realistic for mobile applications such as vehicular networking [6]. Unlike HDR, a Full Duplex Relaying (FDR) system can simultaneously receive and forward at the same time and frequency [7], which can significantly reduce the end-to-end latency in a multi-hop scenario, in particular compared to TDD-based HDR.

Combining platooning with FDR capabilities can further reduce the latency of the platooning beacons that are necessary to keep the desired inter vehicle gap and to ensure safety. In this work, we therefore build upon our GNU Radio-based implementation [8], which is compliant to the IEEE 802.11p standard, and consider a prototypic scenario of a five-vehicle platoon, exchanging beacons by means of HDR, FDR, and DT approaches. Our first results show the achievable Packet Delivery Ratio (PDR) and Physical Layer Latency (PLL) at the last vehicle for the three use cases.

Our main contributions can be summarized as follows:

- For the first time, we investigate full duplex relaying in vehicular networks, and show its feasibility in platooning.
- We perform an extensive set of real-time simulations for all scenarios, i.e., HDR, FDR, and DT.
- Our results demonstrate the significant gain of FDR over the traditional HDR and DT approaches in both Physical Layer Latency (PLL) and Packet Delivery Ratio (PDR).

II. Related Work

A considerable amount of research studies are focused on communication protocols for exchanging beacons within platoons. Most of these protocols do not operate on the PHY or MAC layer and are instead designed for higher layers.

Segata et al. [2] proposed an approach called *slotted beaconing* that uses a Time Division Multiple Access (TDMA) like approach to synchronize vehicles within the same platoon. The time slot to transmit a beacon is dependent on a vehicle's position in the platoon. The proposed protocol has been compared with generic approaches like Dynamic Beaconing (DynB), showing that is highly beneficial when used in combination with Transmit Power Control (TPC).

Fernandes and Nunes [9] proposed different application layer based strategies to address communication delays within a platoon. Based on the number of vehicles in a platoon, the channel is divided into different time slots according to the position of the vehicle in the platoon. This TDMA like approach has been considered by Campolo et al. [6] to analyze the protocol while using FD communication. Simulations show that the delay is almost halved, allowing high density platoon scenarios and higher update rates of the platoon controller.

For FDR, most of the research results are still based on analytical findings. Jiao et al. [10] are building an analytical model of Looped SI (LSI) to analyze the effect of an Amplify and Forward (AF) relaying system in terms of spectral efficiency. Likewise, an analytical model based on Markov chains is proposed in [11], which analyzes the outage probability in FD multi-relay channels. Bharadia and Katti [7] presented the first complete FDR design, implementation, and experimental evaluation. They introduced AF scheme based *construct and forward relaying*, which unlike typical AF relays, avoids noise amplification by efficiently choosing the amplification factor. Our previous work [8] demonstrates the potential gains of FDR in terms of packet reception ratio, spectral efficiency and end-to-end delay, measured at the physical layer. Simulative evaluation is performed with GNU Radio-based implementation for both the AF and Decode and Forward (DF) relaying strategies.

The aforementioned studies illustrate that the Full Duplex Relaying (FDR) is a hot topic in research currently. Yet, while FD communications has gained most attention with substantial volume of literature available, covering both theoretical and experimental works; FDR is still an unexplored topic, with most of the existing studies commonly based on analytical models without considering real application scenarios. Especially the consideration of cooperative and mobile networks is completely out of scope right now. In this paper, we take a first step towards closing this gap by providing a GNU Radio based simulation of an FDR system considering platooning as an example application with low latency requirements. However, our contributions can be seen as work in progress.

III. Beaconing in Vehicle Platoons

In platooning, timely and reliable communication is critical to transport the information for CACC controllers. Typically, every platoon member's controller requires information from

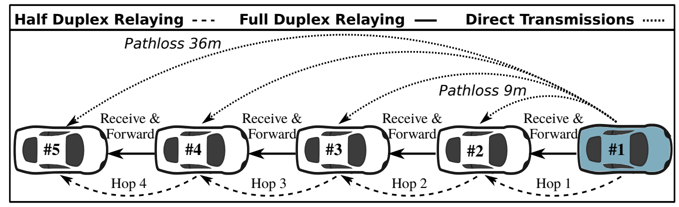

Figure 1. Overview of our five-vehicle platoon model. The figure illustrates the three considered communication scenarios of Half Duplex Relaying (HDR), Full Duplex Relaying (FDR), and Direct Transmission (DT), for beaconing in platooning.

both the platoon's leader and the immediately preceding vehicle (the *front vehicle*). The front vehicle's beacons can leverage TPC and a strong Modulation and Coding Scheme (MCS) due to the short distance, which greatly reduces the interference for uninvolved vehicles [2]. However, this is typically not the case for the leading vehicle, as illustrated in Figure 1.

The beacons from the platoon's leader are required to be received by all following vehicles. In existing approaches, this is usually achieved via Direct Transmission (DT). When doing so, a relatively strong transmit power and a weak MCS have to be utilized for two reasons: Firstly, transmitted beacons are not repeated to maintain tight timing constraints and low jitter. Accordingly, conservative assumptions are made to ensure their delivery. Secondly, all vehicles within the platoon have to be reached. In particular, the last vehicle is the furthest away, and the most affected by pathloss (illustrated in Figure 1), as well as shadowing introduced by the other platoon members. Consequently, the interference domain of the transmissions due to strong transmit power is large. This can be problematic in high vehicle densities as many vehicles are influenced by the transmission.

IV. Relaying for Beaconing in Platooning

An alternative to DT is to use the TDD-based HDR. In a platoon formation, all the platoon members follow the leader – and with HDR, the leader only needs to transmit its beacons to the immediately following vehicle. This vehicle in turn relays them to its following vehicle, such that, successively, the whole platoon receives the beacons, as shown in Figure 1. This allows to aggressively use less transmit power and/or a stronger MCS similar to the transmissions of front vehicle beacons. Hence, less interference is caused at neighboring vehicles. However, HDR introduces additional delays, as each vehicle has to wait while it is receiving (to avoid LSI at the same vehicle). Hence, linearly incremental delays based on platoon size are expected in the best case (i.e., receive a beacon in the first time slot and forward it in the following time slot). Additionally, if the channel access is subject to randomized behavior (e.g., of CSMA/CA), the delay introduced by each transmission cannot be fully predicted. Thus, increased end-to-end delays and higher jitter are anticipated in multi-hop HDR.

A. Proposed Full Duplex Relaying (FDR)

Given the merits of relaying in terms of reduced power requirements along with a stronger MCS, a possible solution to overcome the excessive delays in HDR is to use emerging FDR techniques. FDR has the capability to simultaneously receive and forward the signal almost immediately, as depicted in Figure 1. Only a short additional delay is introduced, which inherently exists in all relay systems and which depends on the employed relaying strategy (i.e., AF or DF). Additionally, with simultaneous reception and forwarding, the relaying vehicles do not need to wait for channel access while relaying. The only performance limiting factor in an FDR is the LSI, and it is required to be suppressed to the receiver's noise floor for optimal performance. The LSI exists because the signal forwarded by a relaying node is also received at the same node, and contributes largely to cause interference while receiving the Signal-of-Interest (SoI) from the source node. Recent advances in combating LSI [4], however, allow to reduce the interference caused by LSI drastically, such that only a small amount of residual interference power is experienced.

In summary, we expect FDR to combine the advantages of the other introduced beaconing mechanisms: timely delivery to all platoon members, as well as less interference induced at neighboring nodes.

V. Performance Evaluation

To compare the performance of multi-hop Full Duplex Relaying with the existing DT and possible TDD-based HDR for a vehicle platooning application, we conducted real-time simulation experiments with a DF relaying scheme in the GNU Radio framework. The framework is widely utilized because of its real-time signal processing and rapid prototyping capabilities, supporting not just simulation but real-world experiments via Software Defined Radios (SDRs) as well. The simulation results presented here are built upon our previous implementation [8] in GNU Radio.

A. Simulation Setup

Figure 1 describes our simulation model with a five vehicle platoon. Our simulative evaluation investigates the impact of key parameters, i.e., the residual LSI (in FDR) and the pathloss, on the PDR and PLL. For the channel modeling, we have implemented 4-taps frequency-selective Rayleigh fading channels for individual sub-paths between two vehicles within the platoon. Also, a linear 3-taps fading channel is implemented to model the LSI channel within a vehicle for the FDR case. It is worth pointing out here that the LSI channel resides within the same vehicle, i.e., both Tx and Rx are on the same vehicle. Therefore, it does not suffer from the Doppler shift, as the relative speed between Tx and Rx is zero, and can be estimated using basic least square estimation approach. Additionally, to keep LSI channel more realistic, among the three taps first one is kept strongest to maps the LSI through direct path, and the remaining paths model the weak multi-path environment. In the scenario of Direct Transmission, the further pathloss impact due to the additional distance between the second and last vehicle is also included in the simulation setup.

For the baseband modulation/demodulation, we have used the GNU Radio-based Open Source stack for IEEE 802.11p standard for WAVE. The core of this framework is a modular and flexible Orthogonal Frequency Division Multiplexing (OFDM) transceiver implementation, which is fully compatible with commercial WiFi cards, and has been developed and comprehensively evaluated by Bloessl et al. in [12]. Additionally, the cancellation of LSI in the FDR case for simultaneous reception and forwarding is achieved via the implemented core block for LSI suppression. The details of the complete implementation can be studied further in [8].

Table I
Key parameters of our simulation setup.

Modulations	BPSK, Q-PSK, 16-QAM & 64-QAM
Code Rates	1/2, 3/4, 2/3
Sampling Frequency [MHz]	10
Carrier Frequency [GHz]	5.9
Data Rates [Mbit/s]	3, 4.5, 6, 9, 12, 18, 24, 27
FFT/IFFT Size	64
Cyclic Prefix (CP) Length	16
PLCP (Preamble & Header)	$(4+1)$ OFDM Symbols
Payload Size	250 B
Platoon Size	5 Vehicles
Inter-Vehicle Distance	5 m
Vehicle Length	4 m
Pathloss Second Vehicle (9 m)	67 dB
Pathloss Last Vehicle (36 m)	79 dB
Transmit Power	0 dBm

In our simulation setup, we have transmitted 100 packets for each MCS defined in the IEEE 802.11p standard and measured the PDR based on received Signal-to-Noise Ratio (SNR). Each packet comprises a 250 B payload, a 3 B header, and a 4 B CRC. Each run of packets is repeated 20 times to obtain a 95 % confidence interval, which for the sake of clarity is not shown in the plots. Table I lists the key parameters of our simulation setup. It is important to mention here that due to space limitations, the results presented in this work are just for the last vehicle in the platoon.

B. Packet Delivery Ratio (PDR)

Figure 2 demonstrates the PDR performances at the last vehicle in the platoon for the HDR, FDR, and DT scenarios.

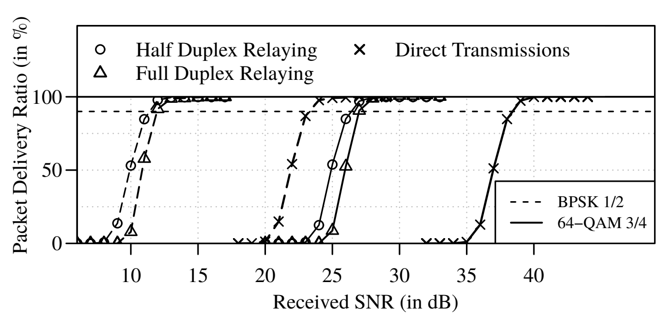

Figure 2. Packet Delivery Ratio (PDR) performances (last vehicle) with the lowest (BPSK 1/2) and highest (64–QAM 3/4) Modulation and Coding Scheme (MCS) in the three considered scenarios, i.e., Half Duplex Relaying (HDR), Full Duplex Relaying (FDR), and Direct Transmission (DT), for vehicular platooning. The horizontal dashed line marks 90 % PDR, with 100 % indicating that all the packets have been correctly detected and decoded. For visual clarity, the plot is showing the data for the lowest and highest MCS only.

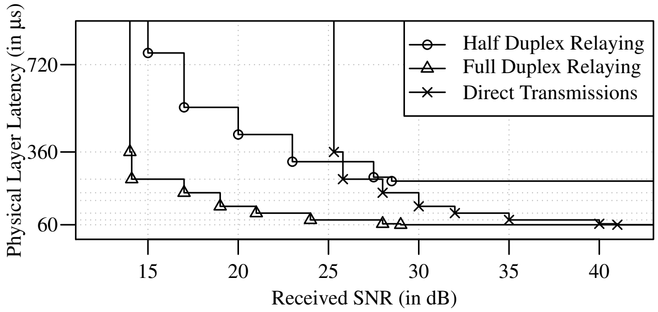

Figure 3. Computed Physical Layer Latency (PLL) in the considered scenarios of Half Duplex Relaying (HDR), Full Duplex Relaying (FDR), and Direct Transmission (DT).

For clarity reasons, the PDR for the intermediate MCS is not shown here; they also demonstrated similar performance behavior in the three considered scenarios. From the comparison of the HDR with FDR approach, it can be seen that the PDR performance is roughly 1 dB worse with FDR for both BPSK 1/2 and 64-QAM 3/4 MCS. This 1 dB lower performance with FDR compared to HDR is because of the residual LSI, which basically raised the noise floor for the SoI or leader beacons in this case, resulting in slightly reduced performance. It is worth mentioning here that for higher magnitudes of residual LSI, the performance with FDR could further worsen, as studied in [8]. Therefore, maximum suppression of LSI is a critical requirement for the optimal performance with FDR.

Similarly, the PDR performance with the DT scenario is roughly 11 dB poorer than FDR and over 12 dB worse as compared to HDR, for both BPSK 1/2 and 64-QAM 3/4 MCS. This degraded performance with DT is intuitively due to the additional pathloss from the second to the last vehicle, which does not exist in HDR and FDR cases. Since, the DF scheme regenerates noise-free packets at each intermediary vehicle, therefore, the relaying cases only suffers from the pathloss between two adjacent vehicles. Thus, the PDR performances with HDR and FDR (with sufficient LSI suppression) are anticipated to always outperform the DT case, especially for longer size platoons.

C. Physical Layer Latency (PLL)

Figure 3 shows the introduced PLLs in each scenario. Here, PLL is the time interval a payload takes to traverse from source to destination, and it hugely varies with the considered MCS. The plot here is for a 250 B payload, and indicates that the PLL introduced by HDR is the largest, even though it outperformed the other two in terms of PDR. This is because of the 4 hops involved with HDR in our simulation model (of a five-vehicle platoon), and in HDR, each vehicle has to wait for at least one time slot (to avoid Looped SI) for reliable forwarding of the beacons.

Additionally, although there are no hops involved with DT, still the PLL experienced in this scenario is significantly larger compared to FDR. This is due to the inherent precondition of additional pathloss in DT, and requires close to 12 dB more SNR just to start receiving the packets with the lowest MCS, i.e., 3 Mbit/s, where (with the same SNR) FDR is already supporting an 18 Mbit/s link for communications. In essence, the ability of FDR to simultaneously receive and forward collectively transcends both the HDR and the DT approach especially in terms of Physical Layer Latency (PLL), provided that the LSI is significantly suppressed.

VI. Conclusion

In this paper, we evaluated the performance of Full Duplex Relaying (FDR) in vehicular networks, and showed its feasibility for platooning application. For the first time, we compared the performance of existing Direct Transmission (DT) scheme and traditional Half Duplex Relaying (HDR) with the proposed FDR approach for the WLAN technology stack (e.g., IEEE 802.11p/bd), in particular for vehicle platoons. Our results demonstrated the significant performance gain with FDR over DT scheme and classical HDR in terms of Packet Delivery Ratio (PDR), and Physical Layer Latency (PLL). Our first results help paving the road towards FDR in platooning.

Acknowledgments

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