Inband Full-Duplex Relaying for RADCOM-based Cooperative Driving

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***Abstract*—We explore the use of RADar based COMmunication (RADCOM) as a complementary communication technology for next-generation Intelligent Transportation Systems (ITS). RADCOM makes use of vehicular radar operating in the 77 GHz mmWave band. Using platooning of cars on the freeway as an example application, which could benefit substantially from mmWave high bandwidth transmissions with low latencies along the platoon, we propose to combine Full-Duplex Relaying (FDR) with RADCOM. Full-duplex relaying at the 77 GHz band benefits from the directionality of the signal, which leads to reduced Looped Self-Interference (LSI). We developed a real-time simulation model based on GNU Radio to study the mmWave propagation in platoons. In particular, we investigate the opportunities of inband FDR for RADCOM. Our first results clearly indicate the advantages of the proposed approach in terms of reduced physical layer latency and energy requirements while maintaining optimal channel link rates.**

I. Introduction

RADar based COMmunication (RADCOM) is an emerging communication method proposed for the use in Intelligent Transportation Systems (ITS) [1], [2]. By dual-purposing existing RADAR detection and ranging systems that operate in the mmWave frequency bands, high bandwidth, and low latency communication is enabled between vehicles on the road. Since such RADAR systems are already common in modern vehicles, the adaption for communication would be significantly less costly and complex compared to the integration of additional communication methods. Additionally, the properties of the electromagnetic waves in the mmWave spectrum (high directionality, strong Line of Sight (LOS) component, and substantially increased available bandwidth) differ from more established ones using sub-6 GHz frequencies. This enables the complementary use of both resources, improving the efficiency and reliability of the overall system.

Cooperative driving applications such as vehicular platooning can particularly benefit from RADCOM. In platooning, groups of wirelessly connected vehicles are controlled automatically to follow each other at short inter-vehicle distances [3]. This leads to a variety of improvements in road traffic, e.g., improved fuel economy. The safe operation of a platoon relies on the frequent exchange of information about kinematics of preceding vehicles, putting a high load on the communication network. Beyond basic operation of the platoon, also high-bandwidth applications are desirable to exchange sensor data, such as 4k video streaming of the leaders' front cameras to the other platoon members ('see-through' concept). Additionally, reliable and low latency communications are crucial in platooning: delayed and outdated information is essentially less useful, or even disadvantageous to the safety of the system, as the reaction time of the underlying control system increases.

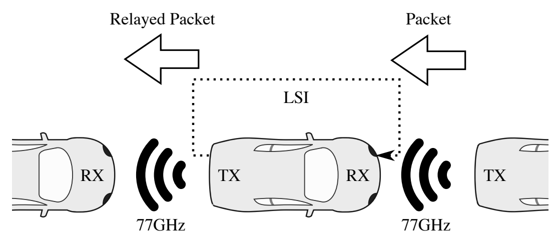

Figure 1. FDR in a platoon: The first vehicle transmits a packet via RADCOM. The signal is amplified by the intermediate vehicle and transmitted from its back. Due to reflections, part of the signal can be received by the intermediate vehicle during relaying, inducing LSI.

RADCOM can potentially address these requirements in vehicular platoons and beyond. To guarantee reliable packet reception, especially at the furthest vehicle in a platoon with RADCOM, very high power transmissions would be required from the vehicle leading because of large propagation losses in mmWaves. This certainly results in an expanded interference domain, affecting the neighboring vehicles on the road, which are not part of this platoon. An alternative to high power transmissions is the use of multi-hop relaying to transport the data from the leading vehicle to the last vehicle. Existing Time Division Duplex (TDD)-based relays, which have been also adopted by the wireless standards such as WiMAX and LTE, are half-duplex in nature and require additional resources in time-domain for reliable communication. Inevitably, such Half Duplex Relaying (HDR) increases end-to-end latency that gets even worse in multi-hop relay scenarios such as in platooning.

Recent works, for example [4], [5], have demonstrated the practicability of Full-Duplex (FD) wireless systems, and have shown the potential gains of FD communications. As opposed to HDR, FD relays can receive and forward at the same time and frequency, which essentially reduces the end-to-end latency in a multi-hop relay networks. The major bottleneck in Full-Duplex Relaying (FDR) is the Looped Self-Interference (LSI), which exists as a result of simultaneous reception and forwarding, illustrated in Figure 1. Nevertheless, with the advancements in LSI cancellation techniques, FD communications have become more realistic, and it is even more effective in RADCOM because of high propagation losses in mmWaves that leads to weak reflected LSI and high passive (RF) isolation due to directionality.

In our previous work [6], for the first time, we investigated the potential of full-duplex relaying in vehicular platoons for the sub-6 GHz band. Building upon this work, we explore the potential of RADCOM for platooning with mmWave-based FDR. RADCOM platooning with FDR helps to reduce the latency in a platoon network and, at the same time, the huge unused spectrum allows high-speed data communication between vehicles. Our first results demonstrate the advantages of RADCOM at 77 GHz.

Our main contributions can be summarized as follows:

- For the first time, we investigate RADCOM-based FDR in cooperative driving networks and show its potential in vehicular platoons.
- We conduct real-time simulations in the open-source GNU Radio framework with both HDR and FDR using an NYUSIM [7]-based 77 GHz mmWave channel model.
- Our results demonstrate the significant gains with RADCOM FDR over HDR and in terms of energy requirements, physical layer latency, and channel link rates.

II. Related Work

In this paper, we rely on platooning as one of the most challenging applications in ITS. Platooning vehicles use controllers to compute their accelerations based on information of other platoon members. The dynamic, unreliable nature of vehicular communication poses a significant challenge to such a distributed controller [8]. Several proposals have been published to deal with these dynamics, e.g., controllers making use of shared consensus on the available information [9]. Also, different message dissemination strategies have been envisioned to provide frequent and recent updates to the vehicles of a platoon without overloading the channel. Some studies explore the use Long Term Evolution (LTE) Device to Device (D2D) communications, enabling spatial reuse of the communication channel [10]. Other researches have focused on data exchange using Dedicated Short Range Communication (DSRC), e.g., by using multi-channel FD communication among vehicles [11]. Still, the latency is a major factor in the performance of the platooning system, in particular in sub-6 GHz frequencies due to the limitted available bandwidth.

As an alternative to direct transmission of messages from the lead car to all platoon members, relaying the packets along within the platoon can be used to allow for better spectral efficiency (spatial reuse). However, even though infrastructure relays have been a key research domain for a couple of decades now, the literature on Full-Duplex Relaying (FDR) in both sub-6 GHz and mmWaves is still mostly based on analytical findings. For example, Lee et al. [12] experimentally demonstrated that the analog cancellation is not sufficient to suppress the reflected Self-Interference (SI) in mmWave and suggest an opportunistic full-duplex scheme to combat the impact of SI channel. More recently, we studied the potential of Decode and Forward (DF)-based FDR by comparing it with HDR, and presented FDR performance results in terms of Packet Delivery Ratio (PDR) and throughput [13], [14]. López-Valcarce and González-Prelcic [15] proposed a beamformer design for Amplify and Forward (AF)-based FDR in mmWave and analytically investigated the achievable upper bounds of spectral efficiency. Ma et al. [16] considered FDR in D2D communications for mmWave-based 5G networks and proposed an algorithm which reduces the required transmit power levels and improves throughput results. In our previous work [6], for the first time, we explored FDR using the sub-6 GHz band in cooperative driving and showed its feasibility in vehicular platoons.

The concept of RADCOM, which combines sensing and communication, has been investigated only recently. For example, Dwivedi et al. [17] demonstrate such a system, which is capable of joint sensing and communication in the vehicular 77 GHz mmWave band. Other approaches aim to use Orthogonal Frequency Division Multiplexing (OFDM), which necessitates finding waveforms that are suitable to both sensing, and communication, in the frequency selective automotive radar band [18]. In this paper, we go one step further combining FDR with RADCOM.

III. Toward RADCOM-based Full-Duplex Relaying

A. Concept of Relaying

With the growing demand for high-speed wireless connectivity among communicating devices, maintaining a reliable link with reasonable channel capacity has become a major challenge. Infrastructure relays, in this regard, have attracted a great deal of attention as a mean to increase both the capacity and range of a wireless system at the same time. A relay node interconnects a primary (source) node in a network (typically furthest away) with the last (destination) node while providing a reliable communication link and better coverage area.

In relay-based wireless networks, the two most widely adopted relaying schemes are Amplify and Forward (AF) and Decode and Forward (DF) relaying. An AF relay node simply amplifies the signal received from the source node and forwards it towards the destination. The implementation of AF relays is rather simple; nevertheless, they have an inherent disadvantage of forwarding the amplified noise component as well. On the other hand, the implementation of DF relays is relatively complex as they first have to decode the received packet, and then re-encode and forward it. The decoding and re-encoding of a packet in DF relays helps to remove the noise component entirely, however, this process requires additional signal processing at the relay node, which introduces decoding delays and complexity.

Most traditional relays (e.g., those in WiMAX and LTE) operate in half-duplex mode. This means that a typical Time Division Duplex (TDD)-based relay node requires at least two time-slots for interference-free operation. In the first slot, the node receives a packet from the source and in the next available slot, it forwards it towards the destination. Since high reliability and low latency are the fundamental requirements in safety-critical applications, the use of HDR certainly improves the reliability significantly. Nevertheless, the relaying of packets through every preceding node to the last node adds up significant latency.

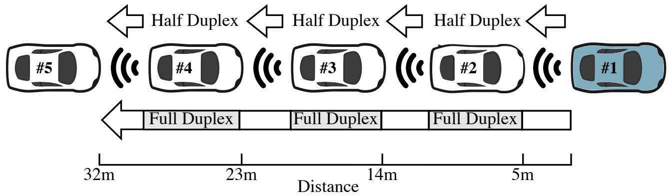

Figure 2. The simulation scenario: A platoon of five vehicles that uses either HDR or FDR. Arrows indicate transmissions. With HDR relaying four individual transmissions are needed, while FDR relaying only requires one. The scale at the bottom indicates vehicle distances from the leading vehicle.

B. Half Duplex Relaying in RADCOM-based Platooning

The formation of a platoon involves a leading vehicle and the following platoon members (cf. Figure 2). The currently practiced direct transmission approach would be needing high power transmissions and/or a lower order Modulation and Coding Scheme (MCS) [6], in order to reliably and timely communicate with vehicles on either end of a platoon communicating via mmWave link. These strong transmissions will produce large interference domain, which can especially be problematic in high vehicle density highways, where many vehicles are expected to be affected by these transmissions. By adopting a HDR approach, the leading vehicle now only needs to send the packet to the immediately preceding vehicle. This vehicle relays the packet to its preceding vehicle and in a successive manner, such that eventually the entire platoon receives the message.

The RADCOM-based HDR approach with highly directional antennas qualifies the leading vehicle to use less transmit power along with a higher-order MCS for the transmission of packets. Consequently, less interference (confined within the platoon region due to directionality of the antenna) is observed on the surrounding vehicles. Nevertheless, such HDR introduces excessive delays as each vehicle receiving the packet has to wait before forwarding to avoid the looped back SI at the same vehicle. In the best case of receiving the packet in the first time slot and forwarding it in the following slot, linearly incremental delays (depending on the platoon size) are to be anticipated. Moreover, for the channel access schemes such as CSMA/CA, which are subjected to randomized behavior, it is impossible to fully predict the introduced transmission delays. Therefore, higher latency and more jitters are expected in this multi-hop HDR.

C. Inband Full-Duplex Relaying with RADCOM

FDR, on the other hand, has the ability to simultaneously receive and forward the packet (cf. Figure 2). This property makes FDR an attractive alternative to overcome the latency issues with the traditional HDR while maintaining its merits of low transmit power requirements along with a stronger MCS. Moreover, the simultaneous reception and forwarding allows the relaying vehicles to not wait for channel access while relaying. The only factor, however, that limits the performance of FDR is the Looped Self-Interference (LSI). For optimum performance, it is essential to reduce it to the receiver's noise floor.

The LSI appears as a consequence of simultaneous reception and forwarding of the packet by the FDR vehicle at the same time and frequency. As a result, the packet forward by the leading vehicle experiences interference, unless the LSI is suppressed to the receiver's noise floor. Recent advances in mitigating the LSI [5] have shown to suppress the interference caused by LSI substantially, such that only a small to negligible amount of residual LSI power is experienced. LSI suppression is typically realized in three stages: passive suppression, analog domain cancellation, and digital domain cancellation [5].

The mmWave link in RADCOM already introduces high propagation losses. Moreover, the use of highly directional antennas, which are placed at the two ends of the vehicle for reception and forwarding, provides additional benefits in the case of RADCOM-based FDR. First, the interference domain is reduced as most of the power is confined within a platoon's communication region. Second, and most importantly, a huge passive suppression (antenna isolation) is introduced with no direct path for the Looped Self-Interference. As a result, the only possible source of LSI is through multi-path reflections, which in the case of RADCOM mmWave links, are even less because of high propagation losses. These LSI reflections can be easily suppressed in the digital domain using cancellation at baseband level. Although, the implementation of digital domain cancellation brings in more complexity at the relay node, there is no need for analog domain cancellation because of huge passive suppression.

In summary, we expect RADCOM-based FDR circumvent the channel access delays to timely deliver the packets to all platoon members while maintaining the high reliability of classic HDR. At the same time, the interference-domain for the neighboring vehicles is reduced.

IV. LSI Modeling in RADCOM-FDR

The highly directional antennas placed furthest apart, i.e., at the front and rear ends of the vehicle, offer maximal passive isolation of the looped back self-interference. The LSI typically observed in RADCOM at the relaying vehicle, is largely due to multi-path reflections, and can be easily modeled in the baseband. Additionally, due to high propagation loss in the mmWaves, no interference is observed from the transmissions of the vehicle preceding the relaying vehicle. Consider the model shown in Figure 3 as an example, the transmissions from the *Leading Vehicle* cannot reach the *Following Vehicle X1* because of extreme propagation losses occurring as the result of Non-line of Sight (NLOS) mmWave link between the two vehicles. The resultant multi-hop relay network can thus operate in a non-cooperative manners, which eventually reduces the signal processing requirements at each relaying vehicle.

To model the LSI at each relaying vehicle in the platoon, consider the system model shown in Figure 3, where the leading vehicle is forwarding the information to the *Vehicle X*, operating in FD relaying mode. The *Vehicle X* receives the

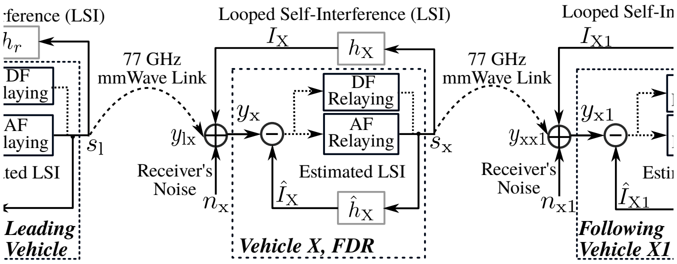

Figure 3. Block diagram for modeling the LSI in vehicle platoons. The model here shows three vehicles, i.e., leading vehicle, vehicle X, and following vehicle X1, in a multi-hop FD relaying network. Each relaying vehicle is capable of performing both AF and DF relaying schemes.

information, applies either AF or DF relaying scheme, and at the same time forwards it to the *Following Vehicle X1* over the 77 GHz mmWave link. This simultaneous reception and forwarding results in looped back self-interference at *Vehicle X* as illustrated in the figure.

The baseband signal at input of *Vehicle X* can be written as

$$y_{\mathrm{x}} = y_{\mathrm{lx}} + I_{\mathrm{X}} + n_{\mathrm{x}}, \tag{1}$$

where y_{x} is the combined received signal, y_{lx} is the signal from the leading vehicle, I_{X} is the LSI signal, and n_{x} is the receiver's noise.

The aim here is to model the LSI component (I_{X}) and eliminate it from the combined signal, which exist because of simultaneous reception and forwarding by the vehicle and can be obtained as

$$I_{\mathrm{X}} = s_{\mathrm{x}} * h_X. \tag{2}$$

Here h_X is the LSI channel between the relaying vehicle Tx and Rx ends, and s_{x} is the signal forwarded by the *Vehicle X*.

Since s_{x} is already available at the relaying vehicle, therefore, by acquiring an estimate of the LSI channel $\hat{h}_X$, an approximate looped SI signal $(\hat{I}_X)$ can be reproduced as

$$\hat{I}_{\mathrm{X}} = s_{\mathrm{x}} * \hat{h}_{\mathrm{X}}. \tag{3}$$

This regenerated LSI $\bar{I}_{\mathrm{X}}$ can then be subtracted from Equation (1) to extract the desired signal y_{lx} from the *Leading Vehicle* as

$$y_{\mathrm{x}} - \hat{I}_{\mathrm{X}} = y_{\mathrm{lx}} + I_{\mathrm{X}} - \hat{I}_{\mathrm{X}} + n_{\mathrm{x}}. \tag{4}$$

Using (2) & (3) Equation (4) can be rewritten as,

$$y_{\mathrm{x}} - \hat{I}_{\mathrm{X}} = y_{\mathrm{lx}} + s_{\mathrm{x}} * (h_{\mathrm{X}} - \hat{h}_{\mathrm{X}}) + n_{\mathrm{x}}. \tag{5}$$

The residual useful signal in Equation (5), after the subtraction can be transformed in terms of error vector as

$$y_{\mathrm{x}} - \hat{I}_{\mathrm{X}} = y_{\mathrm{lx}} + s_{\mathrm{x}} * e_{\mathrm{X}} + n_{\mathrm{x}}. \tag{6}$$

In Equation (6), e_X represents the error between estimated and actual LSI channels. Note that if this error is close to negligible, i.e., $e_{\mathrm{X}} \approx 0$, then the residual LSI is maximally suppressed, and the expression is reduced to

$$y_{\mathrm{x}} - \hat{I}_{\mathrm{X}} = y_{\mathrm{lx}} + n_{\mathrm{x}}, \tag{7}$$

i.e., only the signal of interest, which is fed to the relaying scheme (AF or DF) block. Also, the right-hand side of (7) is the equivalent form of typically received signal.

In practical full-duplex systems, e_X can be forced to a significantly small number but it is never zero. This error magnitude, certainly quantifies the performance of an FDR node, and for optimal performance, it is required to negligible. Nevertheless, because of the inaccuracies in LSI channel estimates, oscillator noise and amplifier's non-linear behavior at the forwarding relaying vehicle, it is hard to force this error close to zero. This is the very reason why, at best, a full-duplex relay can achieve performance similar to a half-duplex relay, given that the error is close to negligible.

A. Looped Self-Interference Channel Estimation

For the estimation of linear component of the LSI channel, we have considered the time-domain based least square estimation approach for error minimization. The least square technique utilizes the Long Training Sequence (LTS) symbol attached in the OFDM frame structure, to acquires the Channel Impulse Response (CIR) estimate $\hat{h}_X$. For most accurate estimates, the LSI channel estimation is performed only during the training transmissions period, when leading vehicle is in idle mode, i.e., $y_{\mathrm{lx}} = 0$. The received samples y_{x} under the stated condition can be obtained using Equations (1) and (2) as

$$y_{\mathrm{x}} = s_{\mathrm{x}} * h_X + n_{\mathrm{x}}, \tag{8}$$

i.e., only looped self-interference signal I_{X}. For a fixed and predefined LTS in s_{x}, the time-domain convolution in Equation (8) can be transformed into matrix multiplication as

$$y_{\mathrm{x}} = \mathbf{S}_{\mathrm{x}} \cdot h_X + n_{\mathrm{x}}, \tag{9}$$

which reduces the signal processing complexity of the estimation task. In (9), $\mathbf{S}_{\mathrm{x}}$ is the Toeplitz matrix, formed using the transmitted LTS symbol as detailed in [19]. Using Equation (9), the least-square based LSI channel estimate is obtained as

$$\hat{h}_X = \mathbf{S}_{\mathrm{x}}{}^{\dagger} \cdot y_{\mathrm{x}}, \tag{10}$$

where $\mathbf{S}_{\mathrm{x}}{}^{\dagger}$ is the Moore-Penrose (pseudo) inverse of $\mathbf{S}_{\mathrm{x}}$ and y_{x} is the received signal. Also, this inverse Toeplitz matrix $\mathbf{S}_{\mathrm{x}}{}^{\dagger}$ can be precomputed and stored prior to the beginning of training transmissions, which reduces the computational complexity of the overall estimation process. From Equations (9) and (10) mean square error can be calculated as

$$\|e_{\mathrm{X}}\|^2 = \|\hat{h}_{\mathrm{X}} - h_{\mathrm{X}}\|^2 = \sigma_x^2 \cdot \|\mathbf{S}_{\mathrm{x}}{}^{\dagger}\|^2. \tag{11}$$

By comparing (6) and (11), it can be concluded that the main source of residual LSI is the noise component σ_x^2 at the receiver. The lower this value is, the smaller error magnitude is there in the estimates, which consequently reduces the LSI strength and improves the performance of the relaying vehicle.

B. Looped Self-Interference (LSI) Regeneration

The regeneration process of the looped self-interference is equivalent to the equalization process. However, here, instead of equalizing the received signal y_{lx} at the relaying vehicle, the known forwarded signal s_{x} (as illustrated in Figure 3) is equalized with the estimated LSI channel $\hat{h}_{\text{X}}$. To force the channel impairment effects on the regenerated LSI signal I_{X}, the forwarded signal s_{x} is filtered with the estimated CIR, as expressed in (3). The regenerated looped self-interference signal $\hat{I}_{\text{X}}$ as a result, inherits the same channel characteristics as that contained by the received LSI signal I_{X}.

V. Performance Evaluation

A. mmWave Channel Model

To model the 77 GHz mmWave channel, we have considered the NYUSIM [7], which is a MATLAB-based open-source mmWave channel model simulator, developed by the NYU WIRELESS. The simulator uses a statistical spatial channel model build upon measurements conducted at frequencies from 28–140 GHz, in various outdoor environments such as urban microcell (UMi), urban macrocell (UMa), and rural macrocell (RMa). It supports a wide range of center frequencies from 500 MHz to 100 GHz, and RF bandwidth up to 800 MHz [20].

The 3D channel model generates omni-directional and directional CIRs and Power Delay Profile (PDP). The temporal and spatial statistics are divided by utilizing the time cluster spatial lobe (TCSL) approach. In NYUSIM, a time cluster is formed by a group of Multi Path Components (MPCs) arriving from different angles and traveling close in time. Whereas a spatial lobe is composed of MPCs traveling in the same direction over a longer time period, which can reach up to several hundreds of nanoseconds. The aforementioned approach is driven by the measurements and gives a slightly different definition on the time cluster compared to the concept of the cluster in the other existing channel models such as WINNER and 3rd Generation Partnership Project (3GPP) models.

Furthermore, NYUSIM is comprised of two modes [20], the drop based mode, and the spatial consistency mode. Under the drop based mode, subsequent simulation runs generate independent CIRs. However, in reality, a user moving in a local area, or multiple users in the vicinity, experience similar scattering environment, which can not be captured by such a model. For this reason, recently the simulator has been extended by the feature of the spatial consistency, for generating correlated CIRs as the receiver moves in a local area. Spatial consistency and other components such as human blockage and outdoor-to-indoor penetration loss have been acknowledged in the 3GPP Release 14 and therefore, are crucial for the mmWave communication systems.

For the evaluation of full-duplex relaying in RADCOM-based platooning, we have used this spatial consistency model in NYUSIM to obtain the CIRs and PDPs. The simulator is utilized to model the channel between every vehicle in the platoon for LOS scenario. Additionally, in the case FDR, it models the LSI channel between the transmitter and receiver of the same vehicle as well for NLOS case. The primary source of LSI in the mmWave-based platooning scenario are multi-path reflections, as there is a huge RF isolation of the direct component (leakage) between TX and RX front-ends because of antennas separation and their directionality. The channel coefficients between every vehicle and the LSI channel within vehicle (shown in Figure 3) from the NYUSIM are imported into GNU Radio framework, where the complete baseband system is implemented for real-time signal processing and evaluation.

B. Simulation Setup

For the performance evaluation of the traditional HDR and the novel FDR for the RADCOM communication link between vehicles in a platoon, we conducted a series of real-time simulations in the GNU Radio framework. GNU Radio is a widely utilized open-source platform, which allows rapid prototyping and supports real-time signal processing – not just in simulations but for real-world experiments using Software Defined Radio (SDR) as well.

Figure 2 shows our simulated scenario of a five-vehicle platoon. Our simulations investigate the impact of the 77 GHz mmWave channel and the residual looped-back SI in FDR on PDR, link capacity, and physical layer latency. The vehicles in the considered platooning scenario have a length of 4 m, and the inter-vehicle distance is 5 m. Each vehicle accommodates two highly directional antennas on the rear and front ends of the vehicle for transmission and reception, respectively. The Half Power Beam-Width (HPBW) of each antenna is 10° with an antenna gain of 24.6 dBi. The communication channel bandwidth is 800 MHz in the 77 GHz band, which generates a noise floor of −73.9 dBm for RF front-ends with an expected noise figure of 11 dB.

To perform baseband modulation/demodulation in both HDR and FDR, we have built upon the GNU Radio-based open source stack for the IEEE 802.11p standard developed by Bloessl et al. [21]. The core of this framework is a modular and flexible OFDM transceiver implementation, which is fully compatible with commercial WiFi cards. We implemented both AF and DF relaying schemes (we used this approach already for sub-6 GHz channels in [4]). Additionally, in the FD relaying case, the suppression of LSI is realized through an implemented core block for LSI cancellation. The LSI suppression block first estimates the LSI channel using the least square time-domain based estimation approach discussed in Section IV, and then uses the estimated channel coefficients to regenerate an approximate LSI signal at every vehicle to mitigate the LSI.

In our simulation, we transmitted 100 packets through the 77 GHz channel and measured the PDR, link capacity, and physical layer latency at each of the following vehicles in the platoon. The packet structure includes training sequences, 3 B header, 250 B payload, and 4 B CRC. The transmissions were repeated 20 times for each MCS and transmit power to obtain a 95 % confidence interval. Table I lists the most important parameters of our simulation settings. It is important to mention

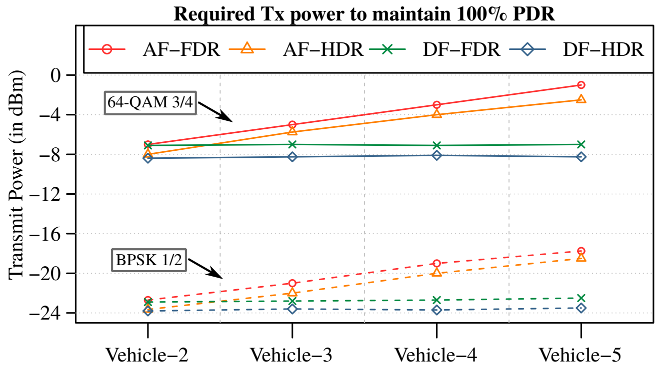

Figure 4. Required transmit power from the leading vehicle for the considered AF and DF relaying schemes, to maintain a 100 % PDR using a 77 GHz mmWave link, operating in both HD and FD mode. For visual clarity, the plot only shows the data for the lowest and highest MCS at each relaying vehicle.

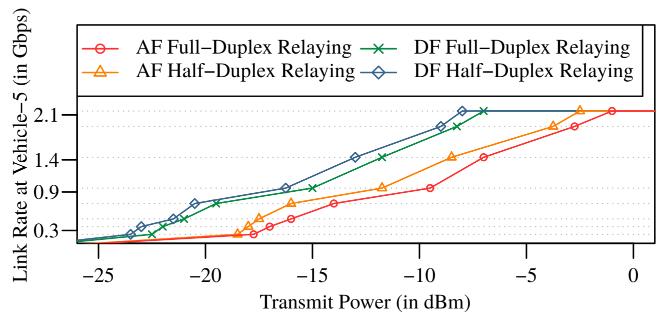

Figure 5. Achievable bit rates at the last vehicle (Vehicle-5) for 77 GHz mmWave link with 800 MHz bandwidth, in the considered Half Duplex Relaying (HDR), Full-Duplex Relaying (FDR) scenarios of vehicular platoon.

that, because of space limitations, some of the results presented here are just for the last vehicle in the platoon.

C. Packet Delivery Ratio

Figure 4 shows the transmit power required by the leading vehicle to maintain a 100 % PDR at each preceding vehicle in the platoon, for both AF and DF relaying schemes in HD and FD modes. For visual clarity, the plot only shows the transmit power requirements with the lowest (BPSK 1/2) and highest order (64–QAM 3/4) MCS. It is worth mentioning here, that the performance results with FDR are obtained with a non-negligible residual LSI of approx. 1.2 dB.

First, it can be seen in the plot that the 64–QAM 3/4 requires roughly 16 dB more transmit power as compared to BPSK 1/2 to achieve 100 % PDR at each vehicle. This would certainly increase the interference domain for the neighboring vehicles. Nevertheless, 64–QAM 3/4 carries 9 times more information than BPSK 1/2, which maps to 9× reduction in physical layer latency because of reduce packet size. Additionally, with highly directional antennas, this interference domain can be confined mostly within a platoon's communication region.

Table I
KEY PARAMETERS OF OUR SIMULATION SETUP.

OFDM Tx / Rx Settings	
FFT Size	64 points
Data Carrier / Pilots / Nulls	48 / 4 / 12
Modulations	BPSK, Q-PSK, 16-QAM & 64-QAM
Code Rates	1/2, 3/4, 2/3
PLCP (Preamble & Header)	(4 & 1) OFDM Symbols
Carrier Frequency	77 GHz
Bandwidth	800 MHz
Achievable Link Rates	0.24–2.16 Gbit/s
Antenna Gain (Tx & Rx)	24.6 dBi directional antennas
Antenna HPBW (Tx & Rx)	10° AZ, 10° EL
Receiver Noise Floor	−73.9 dBm
Residual Looped-SI	−72.7 dBm
Platoon Configuration	
Platoon Size	5 vehicles
Inter-Vehicle Distance	5 m
Vehicle Length	4 m

Secondly, with AF-HDR, the transmit power requirements increase from Vehicle-2 to Vehicle-5, whereas for DF-HDR, the power requirements remain almost the same regardless of the vehicle number. At the last vehicle in the considered scenario (Vehicle-5), AF-HDR requires roughly 5.5 dB more power to achieve similar performance. This degrading performance with AF-HDR is because of the simple forwarding of the received packet to the preceding vehicle, which gets further degraded (due to amplified noise) as it hops from vehicle to vehicle. On the other hand, the DF-HDR regenerates noise-free packets at every vehicle. Thus, there are no noticeable performance losses regardless of the vehicle number, but there is a cost of added up decoding delays. Intuitively, the performance of AF relaying will get worse in platoons with more members.

Finally, the transmit power requirements with AF-FDR and DF-FDR are showing a similar behavior as we have seen in the case of HD relaying, i.e., DF is outperforming AF but at the cost of decoding delay. Also, from the performance comparison of FDR with HDR (regardless of the relaying scheme), it can be seen that there is a performance drop of roughly 1 dB at every relaying vehicle with FDR. This 1 dB reduced performance with FDR is due to the residual-LSI, which essentially increased the noise-floor for the packets arriving from the leading vehicle, and thus, more transmit power is required to achieve similar performance. Nevertheless, the benefit of simultaneous reception and forwarding of FDR, i.e., no waiting for channel access before forwarding, should not be overlooked here.

Intuitively, with higher residual LSI, the transmit power requirement with FDR will further increase, which could lead to bigger interference domains. Thus, for optimum performance with FDR, maximal mitigation of the LSI is a crucial requirement. By establishing this requirement, FDR potentially solves the existing issues of reliability and better coverage without causing additional channel access delays, not just in cooperative driving applications but for wireless communications in general.

D. Achievable Link Rates

Figure 5 shows the achievable link rate at the last vehicle in the considered platooning scenario. In our simulations, a maximum link rate of 2.16 Gbit/s is achieved with 64–QAM 3/4

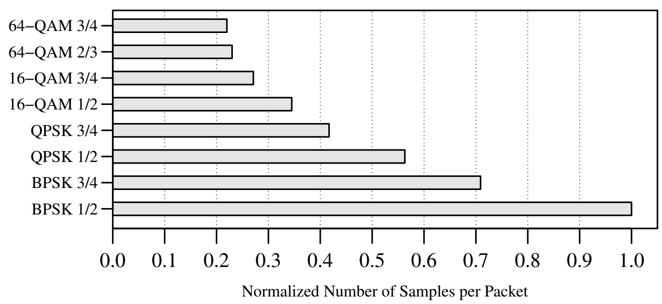

Figure 6. Normalized packet length for sending the same payload with different modulation and coding schemes.

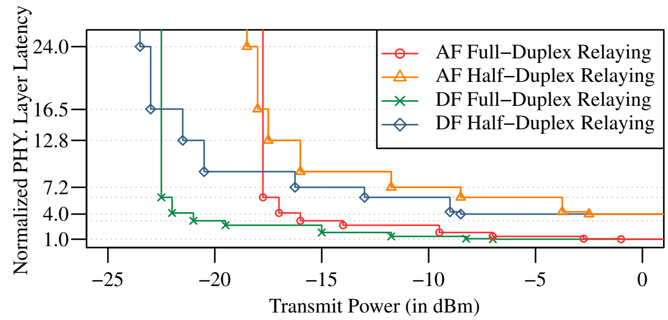

Figure 7. Normalized physical layer latency at the last vehicle (Vehicle-5) for 77 GHz mmWave link with 800 MHz bandwidth in the considered platooning scenario.

for the 77 GHz mmWave channel of 800 MHz bandwidth. The other link rates are listed in Table I. Both AF and DF relaying schemes in HD and FD modes acquire this link rate; AF-FDR however, is performing the worst and reaches 2.16 Gbit/s link rate at −1 dBm transmit power, whereas, DF-FDR establishes similar link rate with a transmission power of −7 dBm, i.e., a performance difference of 6 dB. This degraded performance with AF-FDR and AF-HDR is essentially because of the further channel distortion added while coursing through each relaying vehicle until the last vehicle (as AF relaying simply amplifies and forwards the received packet). Additionally, the link rate performance with DF-FDR is roughly 1 dB lower compared to DF-HDR, intuitively because of the residual LSI, as already discussed in the previous section.

E. Physical Layer Latency

Physical layer latency is the time for which a packet engages the channel while traveling from the leading vehicle to Vehicle-5, and it varies based on the chosen MCS. The plot shown in Figure 6 indicates the reduction in packet size, when a higher level modulation and coding scheme is employed. A higher order MCS basically encodes more information per sample, as a result less number of samples are required to send the same payload, and thus less occupancy of the actual physical channel duration while forwarding the packet. Nevertheless, to employ a higher order MCS, higher received Signal-to-Noise Ratios (SNRs) are required, and under similar receiver parameters, more transmit power is required to improve this received SNR. Therefore, the packet size is directly dependent on the transmit power levels.

Figure 7 presents the normalized physical layer latency estimated at the last vehicle with AF and DF relaying schemes in both FD and HD modes. The plot demonstrates that the physical layer latency introduced by HD relaying is the largest, even with the DF scheme which outperformed all others in terms of PDR. This is absolutely because of the waiting period involved in HDR for channel access to forward reliably. Also, these results are obtained for the most optimistic case of receiving and forwarding in the consecutive time slots, still, the latency with DF-HDR, for similar transmit power levels can be approx. 4 times higher than DF-FDR.

Additionally, although in AF-FDR there is no hops/waiting involved, still the physical layer latency experienced until −17.5 dBm transmit power level is more as compared to DF-HDR. This is due to the inherent precondition of accumulated channel distortion in AF relays imposed on the signal as it transverse through each relaying vehicle, and requires roughly 8 dB more transmit power just to start receiving the packets with the lowest MCS, i.e., BPSK 1/2. In essence, DF-FDR transcends all other relaying approaches in terms of physical layer latency. Even though there is a decoding delay and complexity involved in DF-FDR, its better PDR performance at low transmit powers allows to support a higher order MCS, which reduces the packet size and consequently lowers the physical layer latency.

F. Energy and Channel Busy-Time Comparison

Figure 8 compares the energy requirements and the channel busy-time of each relaying scheme in both FD and HD relaying operation. We first analyze the energy requirements in each case for optimal performance, i.e., maintaining the maximum link rate (2.16 Gbit/s) with 64–QAM 3/4, between every vehicle until the very last vehicle (Vehicle-5). In the figure, it can be seen that the AF-FDR scheme requires the most energy for optimal communication performance until the last vehicle. This is due to both noise amplification and residual LSI in AF-FDR, and can also be deduced from the previous results and discussions. The percentage energy reduction compared to this worst case, i.e., AF-FDR, is also shown in the plot, with DF-HDR demanding the least energy for optimal performance. The DF-FDR requires roughly 5 % more energy as compared to DF-HDR, quite evidently to overcome the residual LSI that

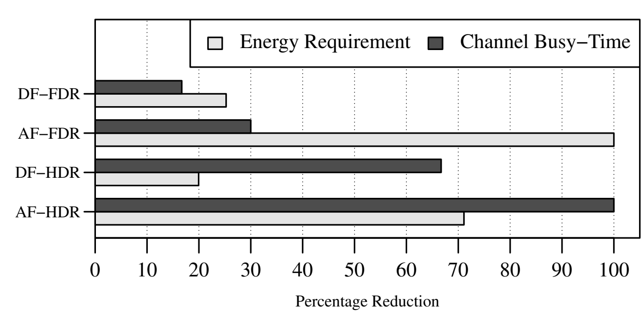

Figure 8. Reduction in the energy requirements and the channel busy-time in each employed relaying scheme under both FDR and HDR modes.

slightly increases the noise floor (by approx. 1.2 dB) for the incoming Signal-of-Interest (SoI). Additionally, since the AF-HDR does not have to deal with residual LSI, therefore, its energy requirement is lower (71 %) than AF-FDR. However, it is still higher than the DF schemes, intuitively because of the noise amplification factor introduced in each relay-hop until Vehicle-5 of the platoon.

In Figure 8, the percentage reduction in the channel busy-time of each case is obtained referencing the point when DF-FDR reaches its optimal performance, i.e., 2.16 Gbit/s with 64–QAM 3/4 MCS, until the last vehicle. The plot shows that with AF-FDR, the channel busy-time is 13 % more as compared to DF-FDR. This is due to the fact that when DF-FDR has adopted the highest MCS, the AF-FDR is still engaged with a relatively lower order MCS. Intuitively, AF-FDR as a result has a larger packet size to communicate, thus more channel busy-time. Likewise, the channel busy-time of DF-HDR and AF-HDR are far more, 51 % and 83 %, respectively. These large channel engaging durations are primarily because of the waiting period involved in HDR before forwarding the packet, at every relaying vehicle in the platoon. From these percent reduction plots, DF-FDR is by far the superior choice in terms of both less energy requirement and reduced channel busy-time.

VI. Conclusion

In this paper, we proposed the use of Full-Duplex Relaying (FDR) for RADar based COMmunication (RADCOM) systems operating in the 77 GHz mmWave band. FDR has the advantage of significantly reducing the latency of communication while maintaining optimal data rates. A prime application scenario is platooning, where cars drive with very short safety gaps on the freeway. In order to support such cooperative driving application, sensor data needs to be transmitted with very low delays from the head of the platoon to its tail. In addition, high data rate 4k video streaming would allow 'see through' applications that ease the drivers' driving experience. We evaluated the proposed inband FDR for RADCOM using real-time simulations in GNU Radio. It turns out that the directionality of the mmWave links already leads to reduced Looped Self-Interference (LSI), so that the remaining LSI due to multi-path components can be dealt with in the digital domain completely. The results obtained here clearly indicated a substantial reduction in both physical layer latency and energy requirements as compared to traditional half-duplex relaying operation, while maintaining optimal link capacity.

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