Demo: A Software-Defined OFDM Radar for Joint Automotive Radar and Communication Systems

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***Abstract*—76-81 GHz millimeter-wave (mmWave) spectrum is allocated to automotive radar systems with 4 GHz bandwidth for better radar resolution and accuracy. Considering the increasing number of connected vehicles, a joint automotive radar and communication (JARC) system can support the current vehicular communication in the 5.9 GHz spectrum with higher data rates by exploiting large bandwidth in the mmWave radar spectrum. In this demo, we present a complete JARC system that is built as a proof of concept by using software-defined radio (SDR) and mmWave components to operate in the 76-81 GHz band. The proof of concept system uses pilot symbols in the OFDM waveform for radar sensing while simultaneously transmitting communication symbols in data subcarriers. We also implement video streaming capability to demonstrate the joint operation.**

I. INTRODUCTION

Automotive radars are critical radio-frequency (RF) sensors in advanced driver-assistance systems (ADAS). Thus, up to 4 GHz bandwidth is dedicated to automotive radar systems in the 76-81 GHz millimeter-wave (mmWave) spectrum. Wider bandwidth and smaller wavelength in the mmWave spectrum enable better radar resolution and accuracy. For vehicular communication, Dedicated Short-Range Communication (DSRC) is designed to improve road safety and traffic management via the exchange of safety messages in the 5.9 GHz spectrum band with 75 MHz bandwidth. Due to its limited bandwidth, the maximum data rate of DSRC is not sufficient for the exchange of raw sensor data required for emerging cooperation sensing and autonomous driving technologies [1]. A solution to attain higher data rates is to leverage the large bandwidth in the mmWave automotive radar spectrum.

Instead of occupying the RF spectrum only for radar sensing, a joint radar and communication system will utilize the limited spectrum more effectively by using the same RF waveform for both functions. In our previous work [2], we investigated the orthogonal frequency-division multiplexing (OFDM) signal as a joint waveform to leverage pilot symbols for radar processing and channel estimation while transmitting data in other subcarriers. Considering OFDM's spectral efficiency and robustness against frequency-selectivity, we proposed OFDM pilot-based radar processing methods for joint systems operating in the mmWave radar spectrum.

In this demo, we present a real-time operating OFDM pilot-based joint radar transceiver that is implemented using software-defined radio (SDR) and mmWave RF components. As the radar transceiver also operates as a communication receiver, we built two identical proof of concept systems to demonstrate communication capability.

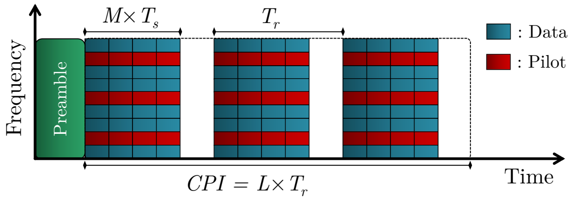

Fig. 1: The structure of the joint OFDM signal model

II. JOINT OFDM WAVEFORM AND RADAR PROCESSING

In this section, we briefly present the joint OFDM signal model and radar processing algorithm based on [2]. The transmitted OFDM waveform uses $N = 128$ subcarriers consisting of 42 pilot and 80 data subcarriers in which pilots are placed equally spaced in frequency. The joint radar transceiver transmits $L = 64$ OFDM pulses that are comprised of $M = 4$ symbols in a coherent processing interval (CPI) as depicted in Fig. 1. While transmitting data, it processes the reflections to generate a range-Doppler map. The baseband OFDM signal is formulated in the continuous-time domain as

$$x(t) = \sum_{l=0}^{L-1}\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} S[n,m,l]\exp\big(j2\pi n\Delta f(t - l\,T_r)\big), \quad (1)$$

where Δf is the subcarrier frequency spacing, $T_s = 1/\Delta f + T_{cp}$ is the total OFDM symbol duration with cyclic prefix, T_r is the pulse repetition interval (PRI) as depicted in Fig. 1. Also, $S[n,m,l]$ denotes the modulated symbols comprised of fixed pilot and random data symbols. The baseband signal is upconverted to the carrier frequency f_c for transmission.

Simultaneously, downconversion and sampling start to acquire reflected discrete signal. After the OFDM modulation is removed with the discrete Fourier transform (DFT) and pilot sequences are extracted and matched filtered for radar processing. The output of the matched filter is expressed as

$$\begin{aligned} D[n,l] = \sigma\Lambda_{mf}[n] \times \exp\Big(-j2\pi\big(f_c + n\beta\Delta f\big)2R/c\Big) \\ \times \exp\Big(j2\pi\big(f_c + n\beta\Delta f\big)(l\,T_r)2v/c\Big), \end{aligned} \quad (2)$$

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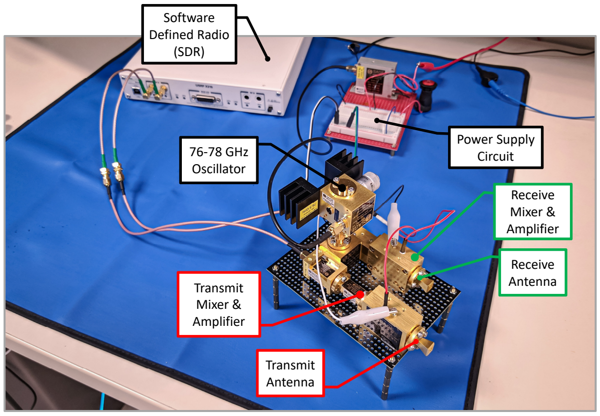


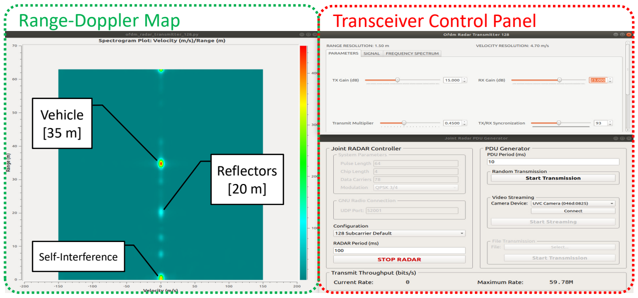
Fig. 2: The hardware part of joint radar transceiver

where σ is the the target's reflectivity, R is the target's distance, v is the target's velocity, and c is the speed of light. Also, n denotes the pilot's index and $\beta = \lfloor N/N_p \rfloor$ where N_p is the number of pilot subcarriers. As shown in (2), target's range and velocity introduce linear phase shifts along n (i.e., frequency) and l (i.e., time) axes, respectively. After matched filtering, we obtain range-Doppler map and target's parameters efficiently with inverse 2D-DFT.

III. PROOF OF CONCEPT IMPLEMENTATION AND RESULTS

In this section, we present our proof of concept system for joint mmWave radar transceiver that performs OFDM pilot-based radar processing and also works as a communication receiver. The proof of concept consists of two parts: (i) *hardware part* that handles RF signal generation, up/down-conversion, sampling and (ii) *software part* that handles the baseband digital signal processing. For the hardware part, we used USRP X310 equipped with UBX daughterboard that can operate with up to 6 GHz carrier frequency and 160 MHz bandwidth. To operate in the 76-81 GHz radar spectrum, we built an mmWave RF front-end transceiver board using commercial off-the-shelf components that consist of an oscillator, two mixers, two amplifiers, and two antennas. The hardware part of the system is shown in Fig. 2 and it is connected to a PC via 10 Gigabit Ethernet to attain the maximum sampling rate of 200 Msps for real-time processing.

For the software part, we implemented user interfaces (UI) and two signal processing systems: (i) *joint radar transceiver* and (ii) *communication receiver* using GNU Radio, which is an open-source framework to implement real-time signal processing systems. The joint radar transceiver comprised of message encoding, modulation, and radar processing blocks. While the radar processing blocks are implemented based on Section II, the communication blocks are designed based on IEEE 802.11p transceiver proposed in [3]. Since our OFDM waveform structure is different, the communication architecture is customized accordingly for frame detection, synchronization, and channel equalization. Besides GNU Radio implementation for signal processing, we also implemented UIs to control transmission rate, generate payload from a video stream, and display received video stream. Fig. 3 and 4 represent the UIs and control panels for the transmitter and receiver to display range-Doppler map and received video stream, respectively.



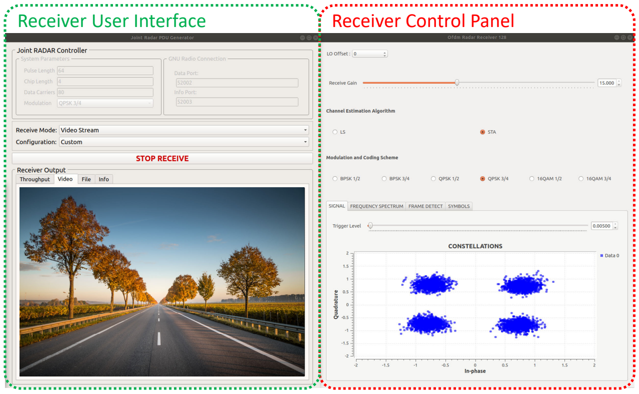
RANGE RESOLUTION: 1.50 m
VELOCITY RESOLUTION: 4.70 m/s
TX Gain (dB): 15.000
RX Gain (dB): 23.000
Transmit Multiplier: 0.4500
TX/RX Syncronization: 93

Joint RADAR Controller
System Parameters
Pulse Length: 64
Chip Length: 4
Data Carriers: 78
Modulation: QPSK 3/4
GNU Radio Connection
UDP Port: 52001
Configuration: 128 Subcarrier Default
RADAR Period (ms): 100

PDU Generator
PDU Period (ms): 10
Random Transmission
Video Streaming
Camera Device: UVC Camera (046d:0825)
File Transmission
File:

Transmit Throughput (bits/s)
Current Rate: 0
Maximum Rate: 59.78M

Fig. 3: User interface for joint radar transceiver



Joint RADAR Controller
System Parameters
Pulse Length: 64
Chip Length: 4
Data Carriers: 80
Modulation: QPSK 3/4
GNU Radio Connection
Data Port: 52002
Info Port: 52003
Receive Mode: Video Stream
Configuration: Custom
Receiver Output

LO Offset: 0
Receive Gain: 15.000
Channel Estimation Algorithm
○ LS ● STA
Modulation and Coding Scheme
○ BPSK 1/2 ○ BPSK 3/4 ○ QPSK 1/2 ● QPSK 3/4 ○ 16QAM 1/2 ○ 16QAM 3/4
Trigger Level: 0.00500

Fig. 4: User interface for communication receiver

With 100 MHz bandwidth, our joint radar system achieves around 1.5 m range resolution and 4.7 m/s velocity resolution with a maximum unambiguous range of 60 m. The left half of Fig. 3 shows the generated range-Doppler map for an outdoor experiment with a vehicle at 35 m and reflectors at 20 m. For the communication, maximum achievable bitrate is 60 Mbps with quadrature phase-shift keying (QPSK) and 3/4 code rate. However, current setup with a single PC achieves around 4 Mbps bitrate due to the limited processing power of the CPU. Nevertheless, we can stream video from a high definition camera in real-time with simultaneous radar processing.

IV. CONCLUSION

In this work, we present an SDR-based joint automotive radar and communication system that performs radar processing using the fixed pilot sequences in the OFDM waveform. At the same time, an identical receiver decodes transmitted symbols that are carried on data subcarriers. To demonstrate the simultaneous operation with high bitrate, we also implemented a video streaming interface along with the range-Doppler display.

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