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Phase-Coded FMCW Automotive Radar: Application and Challenges

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Abstract—Phase-Coded frequency-modulated continuous-wave (PC-FMCW) radar is an emerging radar system with its unique features such as enabling joint sensing and communication or advanced interference mitigation. Even though radars with phase coding capabilities are available in the automotive radar market today, there are some challenges in phase coded radar applications. With this paper we demonstrate multiple bit coding per single transmit chirp waveform in a FMCW automotive radar system for the first time. We concentrate on the sensing aspect of PC-FMCW radar and point out the challenges due to instantaneous phase change. To overcome these issues and improve sensing performance, this paper proposes a smart filtering method which consists of rejection filtering and signal recovery steps.

I. INTRODUCTION

The need for radar sensors in cars dramatically increased by the emerging autonomous driving technology since the radar has advantages compared to other sensors such as day-and-night and all-weather sensing capabilities. Some modern vehicles have already been equipped with large number of radar sensor. The co-existence of multiple radars in congested traffic will be an issue with the increasing number of radar-equipped vehicles on the roads. Since a lot of equal or similar waveforms and transmission strategies are presently used in automotive radar applications, interference will occur between multiple radar units [1], [2].

On the other hand, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2X) communication needs also increase due to autonomous driving as well as the internet of things (IoT). To address these needs, either modern cars must be equipped with multiple sensors or available sensors has to be reprogrammed/reconfigured for multi-purpose.

The radar is one of the unique sensors which can perform both sensing and communication tasks simultaneously. To realize these functionalities, phase coded radar waveforms are used instead of traditional ones. Phase coded radar systems take advantage of code orthogonality to mitigate interference or carry communication information.

In literature, there are different kinds of implementation of phase coded radar. Phase-modulated (or coded) continuous wave (PMCW) radar is the well known one which is not Doppler resilient; Another implementation may use a different kind of OFDM waveforms [3]; Or combination of phase coding with traditional linear frequency modulated (LFM) waveform which is known as Phase Coded LFM or shortly

PC-FMCW radar [4]–[7] (see details in Section-II). The realization of such waveforms in hardware is challenging due to the instantaneous phase change and needs very expensive equipment, thus it is not applicable to automotive radar domain straight forward. In this paper, according to the author’s best knowledge, PC-FMCW waveform is successfully implemented on an over-the-shelf commercial automotive radar sensor for the first time in which the success of the sensing performance is demonstrated after proposed smart filtering.

II. BACKGROUND AND SIGNAL MODEL

Transmit signal for a phase coded LFM radar with a duration of T can be written as [4], [5]

$$x_T(t) = C(t) \text{rect} \left(\frac{t - T/2}{T} \right) \cos(\phi(t)). \quad (1)$$

where $C(t)$ is a single period of a phase-code. For simplicity, assume the phase code is a binary sequence to realize binary phase shift keying (BPSK) which can mathematically be represented as,

$$C(t) = \sum_{n=1}^{L_c} e^{j\phi_n} \text{rect} \left(\frac{t - (n - 1/2)T_c}{T_c} \right), \quad (2)$$

where T_c is the duration of a chip and $\phi_n \in \{0, \pi\}$ denotes the phase corresponding to the n^{th} bit of the L_c bits sequence. While the instantaneous phase of the radio-frequency (RF) waveform is defined as,

$$\phi(t) = 2\pi \left(f_c t + \frac{1}{2} k t^2 \right) \quad (3)$$

where f_c is the carrier frequency and k is the slope of the LFM waveform (equal to the ratio of bandwidth, and the duration of the waveform $k = B/T$).

In a PC-FMCW radar systems, the received signal is directly mixed with the uncoded transmit signal to preserves the phase coding and low-pass filtered to eliminate the high frequency components before sampling [4]. This signal at sampling stage, is called beat signal, can be written as,

$$x_B(t) = \frac{C(t - \tau)}{2} \text{rect} \left(\frac{t - \tau - T/2}{T} \right) \cos(\phi(t) - \phi(t - \tau)). \quad (4)$$

where the round-trip time delay for a target at range R with a velocity of ν is

$$\tau = \frac{2(R + \nu t)}{c}. \quad (5)$$

III. EMBEDDED REAL-TIME CODING AND DATA ACQUISITION

In this section, one implementation of phase coding in FMCW radars is proposed. Such implementation has been realized using a radar module with the ability to change phase of the waveform inside a single chirp signal.

A communication channel or interference mitigation can be realized by phase coding the same chirp waveform that the radar uses for sensing. In this paper, only a single radar has been used to demonstrate the successful phase coding as well as the sensing performance of PC-FMCW radar. Real-time synchronization of multiple radars and extraction of communication information are not in the scope of this paper (the interested reader is referred to [8]).

A. System Setup

Experimental setup consists of a mmWave automotive radar, a microcontroller unit (MCU), a computer and multiple targets.

1) *Radar and MCU*: The radar platform, which is shown in Figure 1, integrates two credit card size PCBs for data acquisition and real-time processing. The first PCB contains an NXP-TEF810X radar transceiver as well as three transmission antennas and four receiving antennas (for MIMO applications), while the second hosts a S32R274 MCU with dedicated power supply, an Ethernet module, a CAN transceiver module and a small selection of general-purpose input/outputs (which can be used for GPS based synchronization).

Waveform generation, frequency modulation, transmission, reception, sampling, analog to digital conversion and down-sampling are handled by the TEF810X chip. This chip can be programmed for phase coding by changing the values of its registers. An operation performed real-time through the serial peripheral interface (SPI) from the MCU board.

2) *The MCU board*: Consist of S32R274 MCU which is dedicated to the transceiver control through SPI, to the real-time signal processing functionality as well as the transmission of samples through Ethernet or CAN bus.

The phase coding that will be coded on top of the sensing waveform can be provided by a user through a host computer. The data is transferred to the MCU in real-time through the transmission control protocol (TCP). The radar chip codes this communication data onto each transmit chirp waveform and transmits it.

The code data (for communication or interference mitigation) can be provided by a user through a host computer (as illustrated in Figure 2). The data is transferred to the MCU in real-time through Ethernet link using the transmission control protocol (TCP). The radar chip codes this data onto each transmit chirp waveform and transmits it.

To implement this phase coding scheme, we modified the provided firmware on the S32R274 MCU. We created an



Fig. 1. A credit card size automotive radar system that is used for experiments: NXP TEF810X / S32R274 Radar Chipset

additional information channel on the radar waveform by adding the following functionality to the software;

- To send a communication message, a TCP connection has been added from PC to radar on the same Ethernet port that is used to broadcast the ADC samples.
- A inter-core shared memory system with a semaphore access arbitration has been implemented on the multicore S32R274 MCU to realize real-time phase coding.
- On one of the cores of the S32R274 chip, the firmware has been modified to allow direct control of a specific pin connected to the TEF810X chip which can be used to trigger the phase inversion during chirp transmission.
- One hardware timer of the S32R274 chip has been designated to control the time between consecutive phase shifts.

After these modifications, the system is able to transmit phase coded LFM waveforms. After successful transmission, the waveform scattered from targets is received back by the radar chip; Mixed with the original (uncoded) sensing signal; Converted in digital samples which can be processed by MCU in real-time or transmitted back to the host PC for further

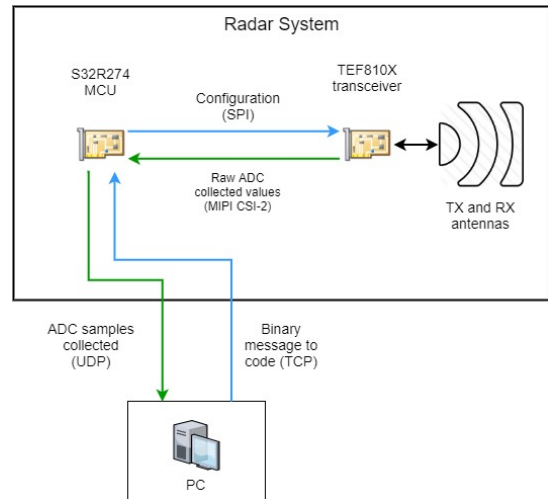


Fig. 2. Experimental setup diagram (the flow of information can be visualized following the arrows).

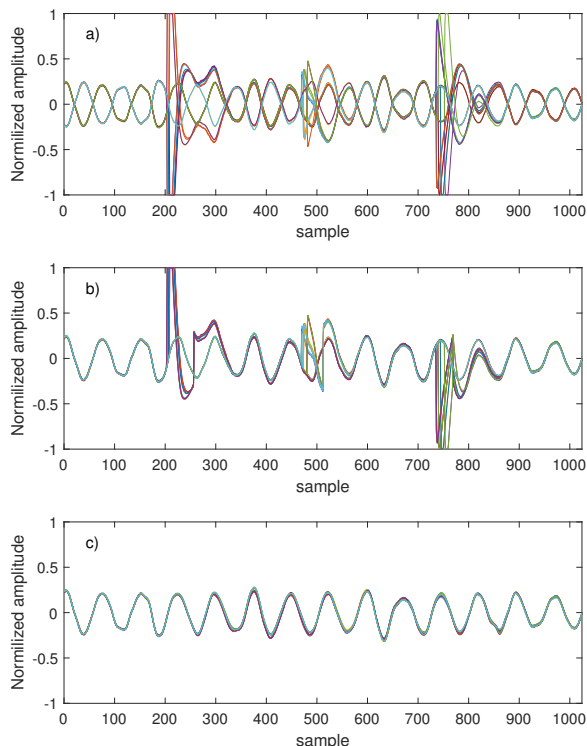


Fig. 3. Illustration of time domain beat signals for a coherent processing interval (512 pulses superimposed). a) Beat signals before processing. b) Beat signals after decoding. c) Beat signals after smart filtering

processing.

For step by step demonstration purpose, we perform processing at host PC which executes the decoding of the return signal and applies the smart filtering to achieve desired sensing performance.

IV. EXPERIMENTS AND CHALLENGES

Modified radar system, that is explained in Section III-A, is used to collect experimental data to evaluate sensing performance of the PC-FMCW radar system. Figure 3.a illustrates the collected beat signals of the form of (4) in which 512 pulses are superimposed on top of each other to demonstrate the effect of phase coding. As seen from the figure, there is a dominant beat signal which is due to a strong target at range of 1.7m. In this example, each chirp is coded by 4 bits of information (there are 4 bits of information in fast-time domain). System creates overshoots during the instantaneous 180° phase change due to the BPSK coding.

It should be noted that, collected beat signal needs to be decoded with the correct code sequence before range Doppler processing. Any other code sequence does not focus the targets in range domain. Thus, proposed system is not only good for joint sensing and communication but also preferred for active interference mitigation (see details at [4]).

Figure 3.b shows the result of decoding of the received signal with the proper code sequence. However the dominant beat signal from strong target is clearly observable, the distortion created by phase change hinder range processing (for

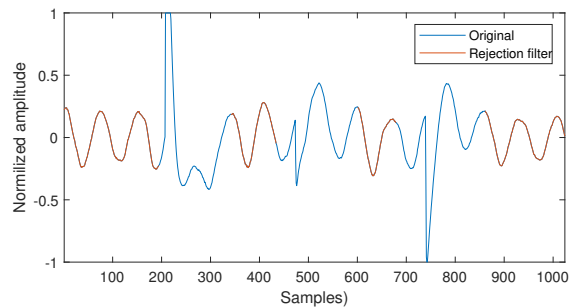


Fig. 4. Figure shows the original decoded signal (blue) and the result of rejection filter (red) for a code sequence [1 0 1 0].

instance corrupted signal in Figure 5). These distortions due to the abrupt phase changes need to be corrected before range processing to achieve acceptable sensing performance.

A. Smart Filtering

We propose a smart filtering approach, to mitigate the distortion created by phase changes, which is consist of two parts; rejection filter and signal recovery. First, a rejection filter is created based on the transmit code to reject distorted samples due to phase changes. It should be noted that rejection filter is dynamic (this is the where smart filtering name comes from) since the code sequence is known and the location of phase changes deterministic, we can estimate distorted signal location and reject only effected samples. For instance, the filter does not reject any samples if there is no phase change (i.e 4-bits code sequence [0 0 0 0]) since there is no distortion. On the other hand, if there is a phase change due to the coding sequence, the rejection filter rejects the distorted region which is known by to the transfer function of the system. For illustration purpose, Figure 4 shows the result of the rejection filter for a worse case scenario where the code sequence is [1 0 1 0]. As seen from the figure distorted regions are rejected, thus there are some gaps in filtered signal (red).

1) *Signal Recovery, Filling the Gaps:* Let x is the original sampled beat signal of length N which was not distorted by the phase changes of the transmit waveform. The distorted samples which are omitted by rejection filter, need to be recovered in according to the undistorted samples. Suppose only K samples of x are reliable, undistorted (such as shown by red in Figure 4). Then the filtered (incomplete) signal g can be written as;

$$g = Hx \quad (6)$$

where H is a matrix of size $K \times N$ which selects the reliable data samples. Note that matrix H represents the rejection filter operation which is dynamic based on the code sequence. Then the problem turns out estimating the undistorted signal (x) such that $g = Hx$, for the given filtered signal g and the rejection filter matrix H .

Even though there are many different methods in literature (such as interpolation etc...) to successfully achieve a reliable estimation, we select to exploit the sparsity feature of radar targets. It should be noted that radar targets are sparse in

frequency (range) domain since each (point like) target has a single beat frequency which can be represented with a Fourier coefficient in frequency domain. Thus, one can write the range domain signal \mathbf{r} as

$$\mathbf{r} = \mathbf{F}\mathbf{x} \quad (7)$$

where \mathbf{F} is a discrete Fourier transform (DFT) matrix. Then we can write the distorted signal as

$$\mathbf{g} = \mathbf{H}\mathbf{F}^{-1}\mathbf{r} \quad (8)$$

where \mathbf{F}^{-1} represents the inverse discrete Fourier transform (DFT) matrix. Any range response \mathbf{r} satisfying (8) can be considered as a valid target response. To find a meaningful solution we can use the sparsity assumption of target response and define an optimization problem as

$$\begin{aligned} & \arg \min_{\mathbf{r}} \|\mathbf{r}\|_1 \\ & \text{subject to } \mathbf{g} = \mathbf{H}\mathbf{F}^{-1}\mathbf{r} \end{aligned} \quad (9)$$

To solve this optimization problem which is a well-known basis pursuit problem [9], one may use proximal splitting methods, such as a Douglas-Rachford approach [10], or can use fast convergent split augmented Lagrangian shrinkage algorithm (SALSA) [11].

B. Results

Figure 3.c shows the result of the proposed processing approach for PC-FMCW radar system. As seen from the figure dominant beat signals for different pulses are successfully recovered. To demonstrate the improvement in sensing performance, we apply range processing which is illustrated in Figure 5.

After initial demonstration, we make a full scale controlled experiment to further evaluate the proposed approach which consist of multiple targets including but not limited to a controlled stationary target, a swinging pendulum and a walking person. The range Doppler output of the signals at different stages of processing are shown in Figure 6. Figure 6.a shows the input signal as received by the radar chipset. As seen from the figure without proper decoding, it is not possible to achieve any sensing information. It should be noted that this feature can be used for interference mitigation [4]. Range-Doppler output of the decoded signal is illustrated in Figure 6.b. Finally, smart filtered signal's range Doppler output is shown in Figure 6.c. Figure 6 qualitatively validates that the proposed PC-FMCW system as well as the proposed processing algorithms are able to achieve acceptable sensing performance even there are multiple moving targets in the scene.

V. CONCLUSION

This paper demonstrates for the first time the real-time implementation of multi bits condign of a single chirp waveform in a commercial automotive radar systems. The challenges due to the instantaneous phase change are investigated, demonstrated and successfully mitigated by a novel smart filtering approach to achieve the desirable sensing performance.

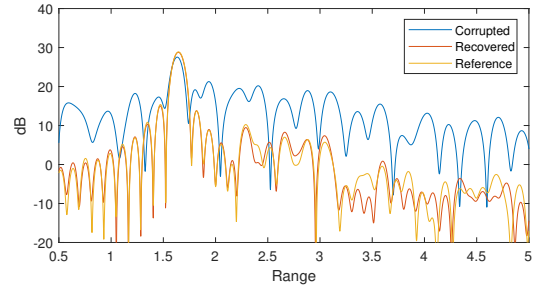


Fig. 5. Range response of the phase coded collected data is illustrated before (corrupted signal) and after processing (recovered signal). Reference signal is extracted when the phase code is [0000].

Application of proposed method for interference mitigation as well as the performance of the proposed approach in noisy environment are still in progress. The future work includes investigation of communication performance; investigation of different code such as Gaussian minimum shift keying (GMSK) to mitigate distortions due to instantaneous phase change.

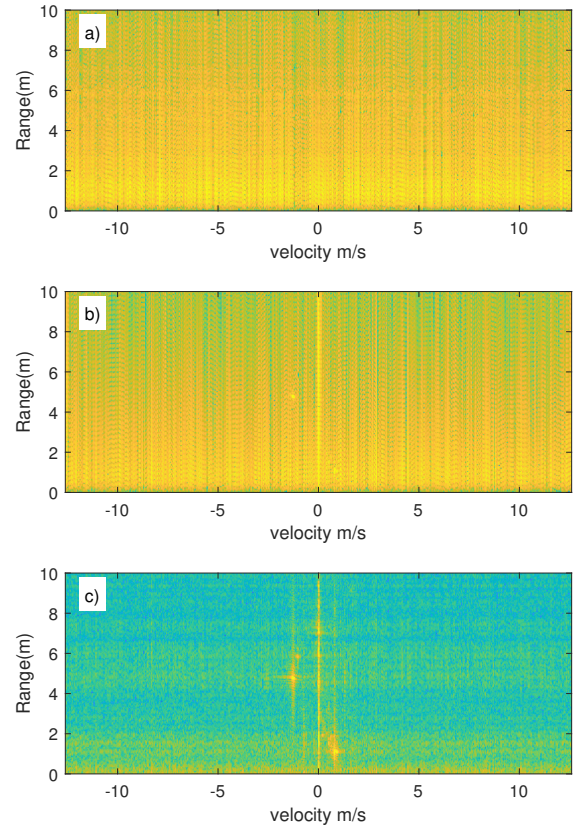


Fig. 6. Results of data processing for phase coded FMCW radar system. Range-Doppler snapshot of a) unprocessed received signal b) decoded signal c) signal after smart filtering. The full video associated this data processing, including a moving pendulum and walking person, can be seen at https://youtu.be/fL_f498Lz8A

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