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CDM-MIMO in Next-Generation mmWave Automotive Radar Sensors

(Invited Paper)

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Abstract

The goal of this paper is to provide a study about code division multiplexing (CDM) technique in the next-generation Multiple-Input-Multiple-Output (MIMO) millimeter wave (mmWave) automotive radar sensors. In particular, we highlight the performance advantages that can be leveraged through the flexibility in transmit waveform when performing conventional signal processing techniques. Further, we provide numerical examples for comparison between a mmWave automotive radar sensor equipped with CDM-MIMO and its conventional frequency modulated continuous wave (FMCW) phased-array counterpart.

1 Introduction

Next-generation millimeter wave (mmWave) automotive radar sensors should have high range and spatial resolutions to clearly distinguish objects and enhance safety and comfort in self-driving/autonomous vehicles [1, 2]. High range resolution can be obtained by deployment of very high signal bandwidth while larger effective antenna aperture yields desired spatial resolution. However, increasing the bandwidth can increase the probability of distortion by other radio frequency (RF) systems transmitting at the same time. Orthogonal waveforms are a key to overcome these difficulties and improving the angle resolution (spatial resolution) of mmWave-radars. In fact, the orthogonal waveforms, dealt in the context of multiple-input multiple-output (MIMO) radar systems, enable the receivers to separate waveforms [3]. This, enhances spatial resolution, improves detection performance, and refines parameter identifiability [3–8].

Recently, automotive MIMO radar sensors are commercially introduced to enhance resolution and parameter estimation [9, 10]. Hopefully, in the immediate future; the $76-81$ GHz frequency band will be widely deployed and add high-resolution radar performance [10–12]. In this respect, different multiplexing strategies are introduced in the literature [4, 5, 13–20], each having its own advantages and shortcomings; hence, the next-generation radar systems are provided with a plethora of waveforms requiring judicious selection to enhance the performance.

It is clear that in a MIMO radar system, receive (RX) antennas must be able to separate the signals corresponding to different transmit (TX) antennas (for example, by having different TX antennas transmit on orthogonal channels). There are different ways to achieve this separation, and four such techniques will be discussed below.

2 Different Multiplexing Strategies for Automotive MIMO Radar Sensors and CDM-MIMO

In order to achieve the waveform orthogonality needed for the MIMO radar systems, several approaches including code-division-multiplexing (CDM) [4, 5, 13–15], Doppler-division multiplexing (DDM) [16–18], frequency-division-multiplexing (FDM) [18–20], and time-division-multiplexing (TDM) [9, 21–25] have been developed. Among them, DDM, FDM, and TDM can provide almost perfect orthogonality. However, in comparison to CDM, they suffer from strong azimuth-Doppler coupling, lower amount of maximum Doppler frequency and shorter target detection range, respectively [15].

DDM-MIMO waveform means the center frequencies of the signals transmitted by different transmit antennas are shifted slightly so that these signals can be separated in Doppler domain. The frequency gap between two adjacent antennas should satisfy two requirements: (i) it should be equal or larger than $\frac{1}{T_p}$, where T_p is the pulse width of transmit signal, to satisfy the orthogonal requirement; (ii) it should be equal or larger than two times of the possible Doppler shift caused by the fastest moving target to guarantee the signals transmitted by different antennas can be separated in Doppler domain [15].

In FDM-MIMO, the signals transmitted by different antennas are modulated by different carrier frequencies. This technique can be implemented in single pulse (fast-time) or a pulse train (slow-time). In fast-time FDM-MIMO, each antenna transmit a signal and the frequency gap between two adjacent antennas is equal to the signal bandwidth transmitted by each antenna. However, due to the linear relationship between the carrier frequency and the index of antenna element, a strong range-azimuth coupling will occur after MIMO beamforming [15].

TDM-MIMO is the most simple way to separate signals from the multiple TX antennas and is therefore commercially used [9]. In conventional TDM-MIMO (alternative transmitting approach), each transmit antenna transmits its own waveform alternatively, and there is no overlap between any two transmissions [15]. In this method, ideal orthogonality can be achieved and the conventional radar waveform (e.g., chirp waveform, Barker sequences, etc.,) can be directly used in all transmitters. The more effective implementation of TDM-MIMO is recommended in [21] where time-staggered frequency modulated continuous wave (FMCW) waveform is used. In this case, setting the transmitting time proportional to the maximum unambiguous range, the transmission capabilities of all transmit antennas can be fully utilized.

CDM-MIMO waveform means the signals transmitted by different TX antennas are modulated by different series of orthogonal sequences, either in fast time or in slow time, so that these signals can be separated/decoded in radar receiver. Let us consider a fast-time CDM-MIMO radar system with N_T transmit antennas. The m-th antenna transmits a code vector composed of N sub-pulses that can be expressed as,

$$x_m = [x_m(1), x_m(2), \ldots, x_m(N)]^T \in \mathbb{C}^N, \;\; m \in [1, N_T], \quad (1)$$

where $x_m(n)$ is the n-th sub-pulse of the transmit code vector x_m. Let $\{x_m\}_{m=1}^{N_T}$ be columns of the code matrix X, viz.,

$$X = [x_1, x_2, \ldots, x_{N_T}] \in \mathbb{C}^{N \times N_T}. \quad (2)$$

The aperiodic cross-correlation [26] of $\{x_m(n)\}_{n=1}^{N}$ and $\{x_l(n)\}_{n=1}^{N}$ at lag k is defined as,

$$r_{ml}(k) = \sum_{n=1}^{N-k} x_m(n) x_l^*(n+k) = r_{lm}^*(-k),$$
$$m, l = 1, \ldots, N_T, \quad -N+1 \le k \le N-1, \quad (3)$$

when $m = l$, (3) becomes the aperiodic auto-correlation of $\{x_m(n)\}_{n=1}^{N}$. Notice that, the in-phase lag of auto-correlation function (i.e., $k = 0$), represents the energy component of the sequence whereas the out-of-phase lag (i.e., $k \neq 0$) represent the sidelobes. Since the ideal orthogonal code sequence with good auto- and cross-correlation properties does not exist [5], the CDM-MIMO waveforms can just approximately satisfy the orthogonality requirement. In the sequel, we numerically show that how CDM-MIMO can achieve higher angular resolution and target identifiability in comparison with its FMCW phased-array counterpart.

CDM-MIMO has some advantageous performance characteristics. The waveform generation is very simple; being that the chips can directly modulate the local oscillator. The phase modulation in the transmitter can be used to add information in the signal, which could be very useful to avoid interferences of twin systems that at some point could interfere between each other. CDM-MIMO radars also can deliver high interference robustness and accomplish one of the short range radar high resolution requirements, which is the range resolution. This performance can be achieved with many fewer constraints than using FMCW phased-array radar. Unfortunately, there are also some disadvantages in CDM-MIMO radars to be taken into account. The baseband bandwidth of CDM-MIMO radars is very big, being its half of the RF bandwidth. As an example, there can be named a system at 79 GHz using the 4 GHz of the spectrum with possible range resolution of 3.75cm, but there will be needed an ADC sampling at 4Gsps.

3 Numerical Examples

Let we consider a radar system with a uniform linear array (ULA) and half-wavelength spacing between adjacent antennas is used for both transmitting and receiving. We assume $N_T = 10$ number of transmit antennas, $N_R = 10$ number of receive antennas and M transmit waveforms are utilized which are random binary sequences with length $N = 64$. We study three different cases:

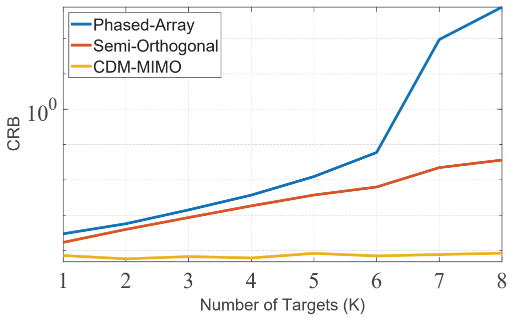
1. $M = 1$, which shows the phased-array radar system.
2. $M = 3$, which shows the semi-orthogonality in the radar system.
3. $M = 10$, which shows the CDM-MIMO radar system.

Similar to the [27], we assume that K targets are located at $\theta_1 = 0°$, $\theta_2 = 10°$, $\theta_3 = -10°$, $\theta_4 = 20°$, $\theta_5 = -20°$, $\theta_6 = 30°$, $\theta_7 = -30°$, ... , with identical complex amplitudes, $\beta_1 = \ldots = \beta_K = 1$.

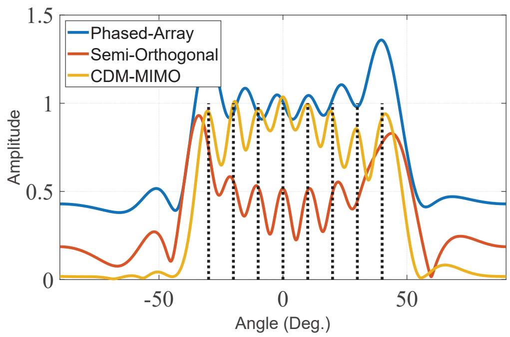
The received signal is corrupted by a spatially and temporally white circularly symmetric complex Gaussian noise with mean zero and variance 0.01 (i.e., SNR = 20dB) and by an interference source located at 45° with an unknown waveform (uncorrelated with the waveforms transmitted by the radar) with a variance equal to 1 (i.e., INR = 20dB).

Figure 1a, shows the Cramer-Rao bound (CRB) of θ_1 for the phased-array ($M = 1$), semi-orthogonal MIMO ($M = 3$), and CDM-MIMO ($M = 10$) radar as a function of K keeping the same all the other parameters as for the MIMO radar and its counterparts. The transmitted waveform is adjusted so that the total transmission power does not change. Note that the phased-array CRB increases rapidly as K increases from 1 to 6. The corresponding MIMO CRB, however, is almost constant when K is varied from 1 to 8. We next consider a simple nonparametric data-independent least-squares (LS) method [27]. Figure 1b shows the LS spatial spectrum as a function θ, when $K = 8$. Note that all 8 target locations can be approximately determined from the peak locations of the LS spatial spectrum whereas they can not be separated in phase-array or semi-orthogonal cases.

To further investigate the effect of designed sequences on the spatial resolution, let we consider a conventional receiver processing unit (i. e., matched filter, Doppler and angle processing) for the waveforms emitted by a ULA phased-array/MIMO radar system employing 3 transmit antennas with 4×0.5-wavelength interelement space and 4 receive antennas with 0.5-wavelength interelement spacing. Precisely, the radar with $N_T = 3$ and $N_R = 4$, would compute $4 \times 3 = 12$ range-Doppler matrices and the 2D-FFT



(a) Cramer-Rao bound of θ_1 versus K.



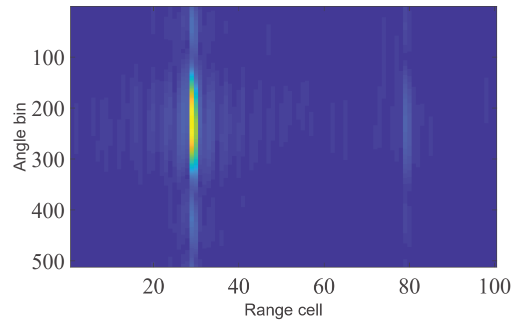
(b) LS spatial spectrum when $K = 8$.

Figure 1. Comparison between performance of FMCW phased-array and CDM-MIMO automotive radar system. Semi-Orthogonal is the case when number of orthogonal sequences is $M = 3$ and in the case of CDM-MIMO, $M = N_T$. Both phased-array and MIMO radar systems use a ULA with $N_T = N_R = 10$ antennas, and 0.5-wavelength interelement spacing is used for both transmitting and receiving.

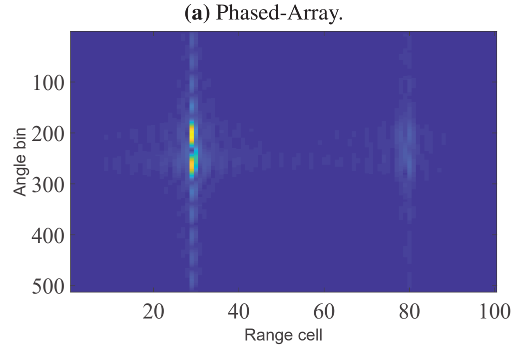
matrices are then summed to create a pre-detection matrix, and then a detection algorithm identifies peaks in this matrix that correspond to valid objects. For each valid object, an angle-FFT is performed on the corresponding peaks across these multiple 2D-FFTs, to identify the angle of arrival of that object. In Figure 2, the range-angle plots of the two targets moving toward the radar system is depicted for both cases of the phased-array and MIMO radar systems, when the angle-FFT is applied. This figure depicts that the better spatial resolution of the CDM-MIMO radar system lead to the better spatial separation. The input SNR utilized for this simulation is $\text{SNR} = 10$ dB.

4 Conclusion

In this paper, we briefly described various techniques of waveform design for next-generation automotive radar sensors including CDM, DDM, FDM and TDM. In case CDM-MIMO, we numerically illustrated that how this technique can enhance parameter identifiability and angular resolution of a mmWave automotive radar sensor in comparison with its FMCW phased-array counterpart.



(a) Phased-Array.



(b) MIMO.

Figure 2. Comparison between range-angle separation of phased-Array and CDM-MIMO automotive radar systems where a ULA with $N_T = 3$ and $N_R = 4$ is used.

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