A Novel RDC-Based Target Estimation Framework for Bistatic ISAC with AFDM-IM over Doubly-Dispersive Channels

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Abstract

This paper proposes a bistatic integrated sensing and communication (ISAC) employing affine frequency division multiplexing with index modulation (AFDM-IM) to enhance target detection and communication performance over doubly dispersive channels, particularly in dynamic environments with moving scatterers. A unified pilot design based on maximum length sequences (MLS) enables efficient channel estimation and radar sensing through the construction of a three-dimensional radar data cube (RDC), facilitating high-resolution range-Doppler processing. Furthermore, a hybrid ML-MMSE detection is introduced to effectively balance detection accuracy and computational complexity. Simulation results demonstrate that the proposed AFDM-IM scheme achieves superior range-Doppler estimation accuracy and significant bit error rate (BER) improvements compared to traditional multicarrier waveform designs.

1. Introduction

The vision for 6G wireless networks emphasizes the seamless integration of sensing and communication, establishing integrated sensing and communication (ISAC) as a key enabling technology. Delivering robust ISAC performance in such environments requires waveform designs that can withstand doubly dispersive channels, which exhibit both time and frequency selectivity [1]. High-mobility scenarios—such as vehicle-to-everything (V2X), satellite links, and aerial platforms—exacerbate channel variations, causing intercarrier interference (ICI) and degrading conventional orthogonal frequency division multiplexing (OFDM) performance.

Chirp-based multicarrier waveforms like orthogonal chirp division multiplexing (OCDM) offer improved resilience but are hindered by non-parameterizable transforms, limiting adaptability to time-varying channels. Affine frequency division multiplexing (AFDM) addresses this by using the discrete affine Fourier transform (DAFT) to modulate symbols in a twisted time–frequency domain. This results in delay–Doppler orthogonality and full diversity in doubly dispersive channels, making AFDM well-suited for beyond 5G ISAC applications. Moreover, index modulation (IM) further enhances spectral efficiency and energy savings by embedding information in the activation of transmission elements such as subcarriers or modulation formats. IM has gained traction for its versatility in next-generation wireless systems, including ISAC [2].

While prior pilot-assisted AFDM methods focus mainly on communication tasks, this work proposes a unified ISAC framework that extends pilot usage to both channel estimation and radar sensing. Unlike existing AFDM-based bistatic ISAC systems limited to static scatterers [3], our design supports moving targets in dynamic environments. The key contributions of this study are

- A novel index-modulated AFDM waveform for joint communication and radar sensing in doubly dispersive ISAC scenarios.
- A unified pilot structure using MLS for simultaneous channel estimation and radar processing, governed by time-domain pilot spacing M_t.
- A hybrid ML-MMSE detector combining maximum likelihood accuracy with MMSE efficiency for low-complexity, high-reliability communication.

2. System Model

This section presents the proposed AFDM-IM based ISAC framework, adopting a MIMO architecture with N_t transmit and N_r receive antennas. The AFDM-IM symbol, comprising N subchirps, is divided into G subblocks, each of length $g = N/G$. For each subblock, b incoming bits are split into b_1 index bits and b_2 modulation bits. The $b_1 = \lfloor \log_2(g/k) \rfloor$ bits select k active communication subchirps and r radar subchirps using a predefined lookup table, while $b_2 = k \log_2 Q$ bits map data to Q-ary modulation symbols.

MLS sequences are used for pilot design across transmit antennas. The inverse discrete affine Fourier transform (IDAFT) maps frequency-domain data to time-domain samples as:

$$s_n = \frac{1}{\sqrt{N}} \sum_{m=0}^{N-1} x_m e^{j2\pi\left(c_1 n^2 + \frac{mn}{N} + c_2 m^2\right)}, \tag{1}$$

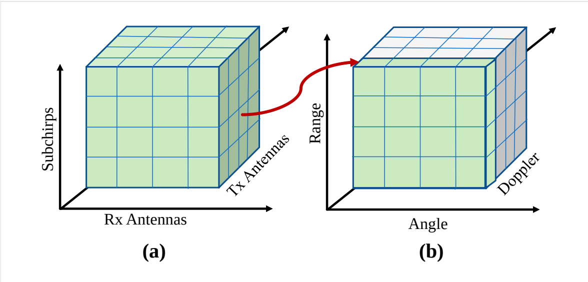

Figure 1. (a) Channel matrix estimates, (b) RDC formation by summing and stacking of (a), across Tx antennas.

where c_1 and c_2 are AFDM parameters. A chirp-periodic prefix (CPP) is added to mitigate channel delay spread effects.

The doubly dispersive channel is modeled as:

$$h(t,\tau) = \sum_{p=1}^{P} \alpha_p e^{j2\pi\nu_p t}\delta(\tau - \tau_p), \quad (2)$$

where α_p, τ_p, and ν_p represent the gain, delay, and Doppler shift of the pth path, respectively. The received signal passes through this channel, and the effective channel matrix is constructed for detection.

With M_t denoting the pilot spacing, a new channel matrix estimate of size $\mathrm{N_{sub}} \times N_\mathrm{t} \times N_\mathrm{r}$ is obtained every M_t symbols, as illustrated in Fig. 1(a). The RDC is then constructed by summing over the N_t dimension and stacking the results into a tensor of size $\mathrm{N_{sub}} \times N_\mathrm{r} \times N_\mathrm{frame}$, as shown in Fig. 1(b).

3. Simulation Results

The proposed AFDM-IM ISAC framework is evaluated with $N = 64$ subchirps and a carrier frequency of f_c = 6 GHz. The maximum target delay $\tau_{\max}$ is assumed to be less than the CP length.

Fig. 2 shows the range-Doppler response, where static scatterers are effectively suppressed, and moving targets are accurately detected at approximately 40, 70, and 90 meters with corresponding velocity estimates. Fig. 3 compares the BER performance of the proposed scheme with OFDM and OCDM-IM at a Doppler frequency of 1000 Hz. The AFDM-IM system with hybrid ML-MMSE detection achieves around a 1 dB gain over OCDM-IM and a 9 dB gain over OFDM at a BER of 10^{-3}, demonstrating superior robustness in high-mobility scenarios.

4. Conclusion

The proposed AFDM-IM framework enables robust joint sensing and communication over doubly dispersive channels using a communication-centric bistatic ISAC design. Future work will explore angle estimation and multi-target tracking.

5. Acknowledgment

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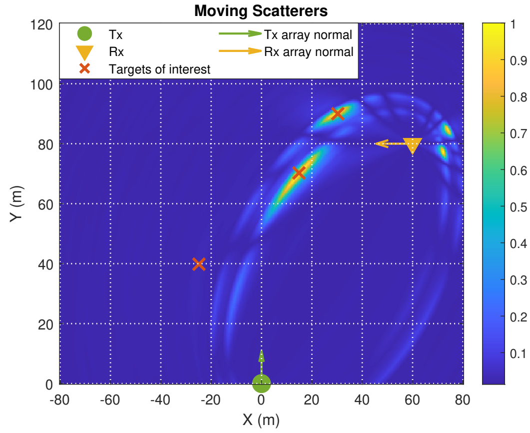

Figure 2. Range-Doppler response of the moving targets.

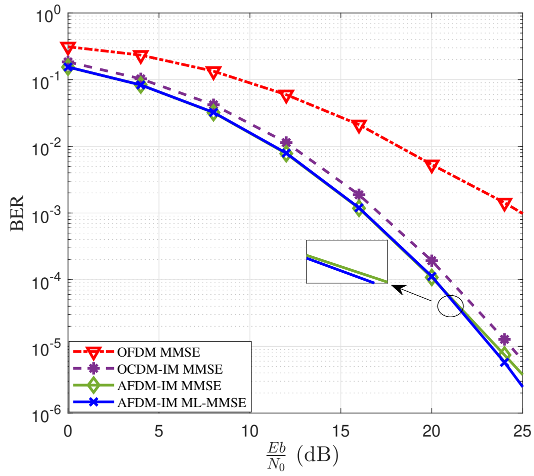

Figure 3. BER performance comparison of the proposed AFDM-IM with ML-MMSE detection against other schemes at $Q = 4$.

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