JPIM-OCDM: Chirp-Grouped Index Modulation for Integrated Deep-Space Sensing and Communication with OCDM

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Abstract

This paper introduces a novel joint precoded index modulation technique tailored for orthogonal chirp division multiplexing (JPIM-OCDM), where grouped index bits are embedded into chirp-domain resource blocks. The approach supports both non-overlapping and overlapping configurations through symbol-wise phase-rotated precoding. By leveraging the inverse discrete Fresnel transform (IDFnT), the proposed waveform demonstrates strong resilience to Doppler effects in high-mobility, doubly dispersive channels. Simulation results reveal that the non-overlapping mode offers an improved bit error rate (BER), while the overlapping mode achieves higher spectral efficiency (SE). Additionally, enhanced delay-Doppler resolution in the ambiguity function confirms the scheme's effectiveness for both communication and sensing, making it a promising dual-purpose candidate for next-generation integrated sensing and communication (ISAC) systems.

1. Introduction

Integrated sensing and communication (ISAC) is gaining momentum as a key enabler for B6G networks, aiming to merge radar and communication within a unified spectrum- and hardware-efficient framework [1]. At the same time, index modulation (IM) is drawing attention for its ability to boost spectral efficiency without increasing power demands. Unlike traditional modulation, IM encodes information not just in signal amplitude or phase but in the selection of subcarriers, antennas, or time slots, offering a new way to convey data and sensing cues simultaneously [2].

Recent studies have explored incorporating IM into MIMO-OFDM systems, leveraging spatial and frequency diversity for improved resilience in fading environments [3]. Hybrid beamforming and various precoding strategies, such as EVD-based or spatial-domain techniques, have been proposed to manage inter-user interference and reduce detection complexity [4]. While schemes like PIM have pushed index detection toward the receiver side to improve BER, they typically treat subcarriers in isolation.

This work advances the current state of index modulation by introducing a joint precoded IM (JPIM) framework over orthogonal chirp division multiplexing (OCDM), a waveform known for its inherent resilience to Doppler spread and suitability for sensing tasks [5]. Unlike conventional PIM approaches that modulate indices independently over subcarriers, our method organizes subcarriers into coordinated space-frequency groups, allowing index bits to be jointly encoded across multiple dimensions. This not only enhances diversity and robustness against multipath and mobility-induced distortions but also enables the reuse of index patterns for sensing, effectively eliminating the need for separate radar pilots. The resulting JPIM-OCDM design achieves seamless integration of data transmission and radar functionality, marking a significant step toward practical and efficient ISAC waveform design.

2. System Model

This section presents the system model of the proposed Joint Precoded Index Modulation over Orthogonal Chirp Division Multiplexing (JPIM-OCDM), designed to support integrated sensing and communication (ISAC) in high-mobility, resource-constrained environments.

A binary input stream is split into index and symbol bits. The index bits activate K out of $V = R_g N_g$ space-frequency blocks, yielding $b_1 = \left\lfloor \log_2 \binom{V}{K} \right\rfloor$ bits. The remaining symbol bits are mapped to M-ary constellation symbols, providing $b_2 = K \log_2 M$ bits. In overlapping JPIM (O-JPIM), symbol-specific phase rotations $\theta_g = \frac{2\pi(g-1)}{G}$ are used to separate overlapping resources and maximize angular diversity:

$$\tilde{q}_m = q_m e^{j\theta}, \quad d_{\min} = 2|q_m| \min_{g\neq g'} \left| \sin \frac{\theta_g - \theta_{g'}}{2} \right|. \tag{1}$$

ZF precoding $\mathbf{P}_n = \mathbf{H}_n^H (\mathbf{H}_n \mathbf{H}_n^H)^{-1}$ is applied for each active subcarrier. The precoded signal is converted to time-domain using the inverse discrete Fresnel transform (IDFnT):

$$x_t = \frac{1}{\sqrt{N}} \mathbf{\Theta}_2 \cdot \mathrm{IFFT}(\mathbf{\Theta}_1 \mathbf{X}), \tag{2}$$

where $\mathbf{\Theta}_1$ and $\mathbf{\Theta}_2$ are chirp phase matrices ensuring unitary transformation.

An X-band ($f_c = 8.45\,\text{GHz}$) Rician fading model with $K = 25\,\text{dB}$ is used. Based on lunar terrain and orbital dynamics, the delay spread is $\tau_{\text{rms}} \in [0.1, 2]\,\mu\text{s}$ and Doppler spread $\nu_{\max} \approx 50\,\text{kHz}$, corresponding to a coherence time $T_c \simeq 10\,\mu\text{s}$. The received signal is transformed back using the discrete Fresnel transform:

$$\hat{\mathbf{x}} = \mathbf{\Theta}_1^* \cdot \text{FFT}(\mathbf{\Theta}_2^* \mathbf{r}), \tag{3}$$

and detected via MMSE or ML:

$$\hat{\mathbf{s}} = \arg\min_{\mathbf{s}} \|\mathbf{y}_n - \mathbf{H}_n \mathbf{P}_n \mathbf{s}\|^2. \tag{4}$$

For sensing, matched filtering is applied using the known JPIM index pattern:

$$F_{\text{Rx}}(n, m) = A(n, m) F_{\text{Tx}}(n, m) e^{j2\pi\nu n T_s} e^{-j2\pi\tau m\Delta f}. \tag{5}$$

This reuses the communication waveform for target delay-Doppler estimation without added pilots. Because the transmitter already knows the activated resource set, the receiver forms the matched filter directly with that mode-indicator pattern; the ensuing 2-D FFT therefore recovers $(\hat{\tau}, \hat{\nu})$ without extra training overhead or ambiguity with other mode bits used for data signalling. The communication process is accomplished through the combined use of constellation modulation, index activation patterns, spatial precoding, and Fresnel-domain waveform transformation, ensuring high data throughput with resilience to multipath fading and Doppler spread.

3. Simulation Results

Figures 2 and 3 illustrate the BER and SE performance of the proposed JPIM-OCDM system under both non-overlapping (NO-JPIM) and overlapping (O-JPIM) configurations using QPSK and 16-QAM, compared against OFDM-PIM. NO-JPIM consistently delivers the lowest BER due to orthogonal activation and OCDM's Doppler resilience, while O-JPIM, though slightly higher in BER, achieves better SE by exploiting index diversity, especially evident with 16-QAM. At high SNR, SE saturation is observed across all schemes, attributed to fixed subcarrier activation and modulation constraints.

For sensing evaluation, the ambiguity function of the JPIM-OCDM waveform demonstrates high delay-Doppler resolution with low sidelobe levels, thanks to the chirp-domain transformation and structured index modulation. At $\tau = 6,\mu s$ and $f_D = 2$,kHz, peak ambiguity values remain above -35,dB with sidelobes below -10,dB, confirming strong robustness and precise target localization. These results highlight JPIM-OCDM's effectiveness as a unified ISAC waveform in high-mobility environments.

4. Conclusion

This work presented JPIM-OCDM, a dual-purpose waveform combining joint precoded index modulation with chirp-based OCDM for integrated sensing and communication. By supporting both non-overlapping and overlapping configurations, the system balances BER and spectral efficiency while maintaining robustness in high-mobility, doubly dispersive channels. Simulation and ambiguity analysis confirmed JPIM-OCDM's effectiveness in delivering reliable communication and precise sensing, highlighting its potential for next-generation ISAC applications.

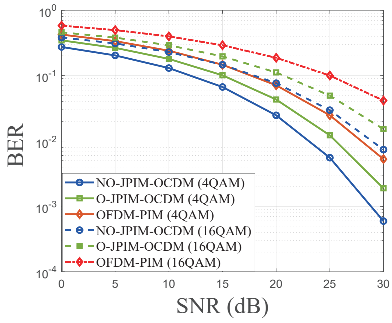

Figure 1. BER comparison of JPIM-OCDM and OFDM-PIM with QPSK and 16-QAM.

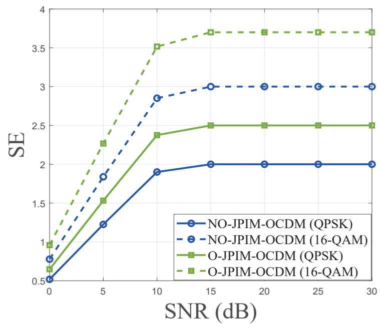

Figure 2. SE performance of NO-JPIM and O-JPIM with QPSK and 16-QAM.

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References

[1] X. Cheng, D. Duan, S. Gao, L. Yang, Integrated sensing and communications (isac) for vehicular communication networks (VCN), *IEEE Internet of Things Journal* 9 (23) (2022) 23441–23451.

[2] J. A. Zhang, F. Liu, C. Masouros, R. W. Heath, Z. Feng, L. Zheng, A. Petropulu, An overview of signal processing techniques for joint communication and radar sensing, *IEEE Journal of Selected Topics in Signal Processing* 15 (6) (2021) 1295–1315.

[3] C. Qi, W. Ci, J. Zhang, X. You, Hybrid beamforming for millimeter wave MIMO integrated sensing and communications, *IEEE Communications Letters* 26 (5) (2022) 1136–1140.

[4] X. Chen, V. Savaux, M. Crussière, P. Savelli, K.-C. Yao, ZF precoding-based spatial domain sic method for MIMO full duplex systems: A performance analysis under CSI errors, *IEEE Wireless Communications Letters* (2024).

[5] S. Ahmad, M. Ahmad, S. Y. Shin, Dual PHY layer multiple access transceiver for next generation 6G networks, in: *2024 15th International Conference on Information and Communication Technology Convergence (ICTC)*, IEEE, 2024, pp. 1187–1192.