# Optimized 6G ISAC Beamforming for Target Detection and Localization*

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**Abstract**

This paper proposes a novel ISAC framework that leverages angular beamforming and Frequency Modulated Continuous Wave (FMCW) radar to achieve high precision in target detection and localization. The proposed system utilizes linear frequency modulated (LFM) chirp signals and pulse compression techniques to enhance target detection and localization performance. Simulation results demonstrate significant improvements in range and velocity estimation, aligning closely with ideal performance metrics. The robustness of the communication subsystem is further validated by evaluating the Bit Error Rate (BER) under various SNR conditions. This study contributes to the evolving field of 6G ISAC systems by proposing a simulation framework that achieves high spectral and energy efficiency, reduced hardware costs, and easy deployment.

## 1. Introduction

The evolution towards sixth-generation (6G) wireless technology aims to integrate sensing and communication into a unified framework. Integrated Sensing and Communication (ISAC) systems are crucial for applications like autonomous driving, smart cities, and industrial automation, which require high-resolution sensing and robust communication. Current cellular networks, while providing basic localization functionalities, fall short in high-precision demands due to inadequate resolution and the predominance of device-based sensing technologies. Perceptive networks coupled with ISAC aim to enhance sensing and communication capabilities within a unified framework.

This paper presents a novel cooperative ISAC framework based on cell-free MIMO networks for device-free target localization using practical OFDM communication signals. The proposed scheme minimizes modifications to existing wireless communication systems and avoids the need for full-duplex operation of access points (APs). It employs an efficient two-stage localization process to estimate passive target locations by analyzing multi-path channel delays and performing cooperative signal processing.

By equipping communication infrastructures with sensing capabilities at minimal additional cost, ISAC requires careful design of transmission waveforms, signal post-processing, and MIMO beamforming. While significant research has focused on single ISAC basestations, practical scenarios involve multiple basestations operating simultaneously, necessitating coordination among distributed nodes. This leads to cell-free ISAC MIMO systems, where distributed basestations jointly serve communication users and sense targets.

The paper investigates target localization using radar signal processing within cell-free 6G ISAC MIMO systems. The simulation study focuses on radar signal processing techniques for target localization, involving linear frequency modulated (LFM) chirp signals, modeling target reflections, and applying pulse compression techniques. Parameters align with 6G specifications, including high carrier frequencies and wide bandwidths. Simulation results validate the effectiveness of pulse compression in

*IPIN-WCAL 2025: Workshop for Computing & Advanced Localization at the Fifteenth International Conference on Indoor Positioning and Indoor Navigation, September 15–18, 2025, Tampere, Finland*

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enhancing target detection and localization, supporting the proposed JSC beamforming strategy for integrated radar sensing and communication in next-generation networks.

Initial studies in Joint Sensing and Communication (JSC) primarily addressed the design of waveforms capable of catering to both sensing and communication needs [1]. For instance, [2] explored the formulation of JSC waveforms, while [3]investigated JSC beamforming in co-located MIMO systems using monostatic radar for serving multiple users. These foundational studies laid the groundwork for more complex multi-node configurations.

In distributed node setups, research efforts have often focused on power allocation and beamforming design without a cell-free MIMO framework [4]. [5] and [6] examined these problems under the assumption that each base station serves a single user. [7] explored JSC power allocation for distributed multi-antenna systems in scenarios where a single user is served either by individual base stations or within a cell-free MIMO environment.

The optimization of JSC beam designs in cell-free ISAC MIMO systems has remained relatively unexplored. Given the critical role of beamforming in dual-function operations, optimizing these JSC beams is essential. Accurate channel modeling is vital for ISAC system development. Various approaches for ISAC channel modeling have been summarized, advocating for the inclusion of sensing clusters to enhance the characterization of the sensing process [8]

The authors of [9] extended this by proposing a 6G-oriented channel modeling approach, validated through simulation and measurement data. This method encompasses electromagnetic modeling, optimal waveform design, and joint beamforming, ensuring a balanced performance between sensing accuracy and communication robustness.

Numerous studies have tested ISAC systems in practical scenarios, revealing the potential and challenges of these systems. For example, gesture recognition systems leveraging Wi-Fi signal strength variations [10], and ISAC systems using 4G frame structures and OFDM signals [11], have demonstrated concurrent communication and sensing capabilities.

The literature on ISAC systems is extensive and spans several critical areas.[12] Provide a comprehensive survey on joint radar and communication waveform design, highlighting the importance of waveform optimization for achieving dual-functionality. [13] focus on the integration of sensing and communications for 6G, discussing the potential of MIMO systems in enhancing ISAC performance.

[14] and [15] delve into radar sensing and communication in 6G, presenting various signal processing techniques that can be applied to ISAC systems. Their work underscores the significance of advanced signal processing methods in achieving high-resolution sensing and reliable communication.

This paper builds on these foundations by proposing a novel joint beamforming approach that balances the requirements of both communication and sensing in a 6G ISAC MIMO system. By integrating Fixed-Angle Beamforming (FAB) and Regularized Zero-Forcing Beamforming (RZFB) techniques, along with pulse compression in radar signal processing, our study aims to enhance target localization and detection capabilities, paving the way for future advancements in this field.

## 2. System Model for FMCW Radar and 6G ISAC Integration

The radar system utilizes Frequency Modulated Continuous Wave (FMCW) signals for target sensing. The FMCW signal is modeled as a linear frequency modulated (LFM) chirp:

$$s(t) = \cos\left(2\pi f_c t + \pi \beta t^2\right), \quad 0 \leq t \leq T_p \tag{1}$$

where:

- $f_c$ is the carrier frequency. $\beta$ is the chirp rate. $T_p$ is the pulse duration.

The received signal $r(t)$ from $N_{tgt}$ targets is modeled as:

$$r(t) = \sum_{i=1}^{N_{tgt}} \alpha_i s(t - \tau_i) e^{j2\pi f_{D_i} t} + n(t) \tag{2}$$

where:

- $\alpha_i$ is the reflection coefficient of the $i$-th target. $\tau_i$ is the time delay corresponding to the $i$-th target. $f_{D_i}$ is the Doppler frequency shift. $n(t)$ represents noise with variance $\sigma^2$.

The transmitted LFM chirp signal can be expressed as:

$$s(t) = \exp\left(j\left(\pi\mu t^2 + 2\pi f_0 t\right)\right), \quad 0 \leq t \leq T_p \tag{3}$$

where:

- $\mu = \frac{B}{T_p}$ is the chirp rate. $B$ is the bandwidth. $T_p$ is the pulse duration. $f_0$ is the initial frequency.

To enhance target detection, we apply matched filtering for pulse compression:

$$y(t) = \int_{-\infty}^{\infty} s(\tau) r(t+\tau)\, d\tau \tag{4}$$

This operation correlates the received signal with the transmitted signal, enhancing the signal-to-noise ratio and improving target detection.

Cell-free 6G ISAC system with distributed MIMO access points is consider in this paper, where the access points transmit LFM chirp signals for both sensing and communication purposes. The received signal model for target detection and localization can be expressed as:

$$y(t) = \sum_{i=1}^{N_{tgt}} \alpha_i s(t-\tau_i) e^{j2\pi f_{D_i} t} + n(t) \tag{5}$$

Here, $\alpha_i$ is the reflection coefficient of the $i$-th target, $\tau_i$ is the time delay, $f_{D_i}$ is the Doppler frequency shift, and $s(t)$ is the transmitted LFM chirp signal.

Fixed Angular Beamforming (FAB) is employed to direct the beam towards a specific target direction using a Uniform Linear Array (ULA).

The array steering vector $a(\theta)$ for a ULA is:

$$a(\theta) = \left[e^{-j\frac{(L-1)}{2}\beta d\cos\theta}, \ldots, e^{j\frac{(L-1)}{2}\beta d\cos\theta}\right]^T \tag{6}$$

where:

- $\beta = \frac{2\pi}{\lambda}$ is the wavenumber. $d$ is the element spacing. $L$ is the number of antenna elements.

The beamforming vector $w$ is set to the target direction. As the result beamforming pattern for FAB is:

$$B_{FAB}(\theta) = \frac{1}{L}\left|\sum_{l=0}^{L-1} e^{j(\frac{L-1}{2}-l)\beta d(\cos\theta - \cos\theta_T)}\right|^2 \tag{7}$$

This pattern achieves a peak in the direction of the target $\theta_T$ and reduces interference from other directions.

Concerning about the 6G communication, we integrate OFDM with the FMCW radar system to enable simultaneous data communication. The OFDM symbols $S_{OFDM}$ The inverse FFT (IFFT) of the OFDM symbols gives the time-domain OFDM signal for the FMCW chirps are embedded within the guard intervals of the OFDM signal:

$$x_{ISAC}(t) = x_{OFDM}(t) + s(t); -> y_{ISAC}(t) = x_{ISAC}(t) + n(t) \tag{8}$$

To decode the data, we separate the OFDM component from the received signal and perform FFT:

$$y_{OFDM}(t) = y_{ISAC}(t) - s(t); -> Y_{OFDM}(f) = \text{FFT}\{y_{OFDM}(t)\} \tag{9}$$

Finally, the OFDM data is decoded as:

$$D_{OFDM} = \text{Decode}\left(Y_{OFDM}(f)\right) \tag{10}$$

This system model outlines the integration of FMCW radar with OFDM communication in a 6G ISAC framework. By leveraging LFM chirp signals for radar sensing and OFDM for data communication, the system can achieve both advanced target localization and high-speed data transmission. The inclusion of beamforming techniques such as Fixed Angular Beamforming (FAB) further enhances target detection and localization performance.

Doppler shift is considered to model the effect of target velocity on the radar signal.

Pulse compression enhances the resolution of the FMCW radar using a matched filter. The compressed signal $y(t)$ is obtained by:

$$y(t) = \int_{-\infty}^{\infty} s_{rx}(\tau) \cdot s_{tx}^*(t-\tau)\, d\tau, \tag{11}$$

where $s_{rx}(\tau)$ is the received signal and $s_{tx}^*(t-\tau)$ is the complex conjugate of the transmitted signal.

Beamforming with a Uniform Linear Array (ULA) of $M = 16$ elements involves forming a beam in a specific direction, e.g., $\theta = 30^\circ$. The steering vector $\mathbf{a}(\theta)$ is:

$$\mathbf{a}(\theta) = \left[1, e^{j\frac{2\pi d}{\lambda}\sin(\theta)}, e^{j\frac{4\pi d}{\lambda}\sin(\theta)}, \ldots, e^{j\frac{2\pi(M-1)d}{\lambda}\sin(\theta)}\right]^T, \tag{12}$$

where $d$ is the element spacing, and $\lambda$ is the wavelength.

The simulation involves generating the Linear Frequency Modulated (LFM) chirp signal and processing it through pulse compression. Beamforming parameters, such as the number of antenna elements and the steering vector, are used to validate their interaction with the FMCW subsystem. Additional parameters like Doppler shift are incorporated to simulate more complex scenarios.

### 2.1. Algorithm: Integrated FMCW Radar and OFDM Communication with Angular Beamforming for ISAC

**Algorithm 1** FMCW Radar–OFDM with Angular Beamforming for ISAC

1. Initialize $t_s = (0 : N-1)/f_s$, chirp rate $\mu = B/T_p$
2. Generate chirp $s_{\text{tx}}(t) = e^{\text{j}\pi\mu t^2 + \text{j}2\pi f_c t}$
3. Compute steering vector $\mathbf{a}(\theta_T)$, beamformer $\mathbf{w} = \mathbf{a}(\theta_T)/L$
4. For each target $i$:
   a) Compute delay $\tau_i = 2R_i/c$
   b) Generate echo $s_{\text{rx},i}(t) = \alpha_i s_{\text{tx}}(t-\tau_i)e^{\text{j}2\pi f_{D,i}t}$
5. Sum echoes and noise: $r(t) = \sum_i s_{\text{rx},i}(t) + n(t)$
6. Apply matched filter to obtain $y(t)$
7. Perform FFT $\rightarrow$ range spectrum
8. Beamform: $y_{\text{BF}} = \mathbf{w}^H y(t)$
9. Apply FFT and Hanning window $\rightarrow y_{\text{BF},W}$
10. Output $y_{\text{BF}}, y_{\text{BF},W}$

## 3. Simulation Study

To validate the proposed beamforming strategies, we conduct MATLAB simulations using LFM chirp signals and pulse compression techniques. Our system leverages Frequency Modulated Continuous Wave (FMCW) radar for high-resolution sensing and Orthogonal Frequency Division Multiplexing

(OFDM) for efficient data communication. This section outlines the simulation parameters, methodology, and results, with a particular focus on angular beamforming and its implications for system performance.

- **Carrier Frequency ($f_c$)**: 77 GHz, high-resolution radar applications.
- **Bandwidth ($B$)**: 2 GHz, providing a wide bandwidth to enhance sensing resolution.
- **Pulse Duration ($T_p$)**: 10 $\mu$s, enabling rapid target detection.
- **Sampling Frequency ($f_s$)**: 20 GHz, ensuring accurate signal representation.
- **Chirp Rate ($\mu$)**: 200 GHz/s, defining the rate of frequency modulation.
- **Initial Frequency ($f_0$)**: 76.5 GHz, starting frequency of the LFM chirp signal.
- **Number of Targets ($N_{tgt}$)**: 5, reflecting a typical scenario with multiple targets.
- **Noise Variance ($\sigma^2$)**: 0.001, modeling realistic environmental noise conditions.
- **Number of Subcarriers ($N_{sc}$)**: 64, used for OFDM modulation.
- **Number of Antenna Elements ($L$)**: 16, elements in the Uniform Linear Array (ULA).
- **Element Spacing ($d$)**: 0.5 wavelengths, spacing between antenna elements in the ULA.

This simulation investigates the performance of a Frequency Modulated Continuous Wave (FMCW) radar system integrated with Orthogonal Frequency Division Multiplexing (OFDM) communication, evaluating target localization, data transmission quality, and beamforming integration efficacy.

**Signal Generation** The FMCW LFM chirp signal $s(t)$ is generated as follows:

$$s(t) = \cos\left(2\pi f_c t + \pi\beta t^2\right), \quad 0 \leq t \leq T_p \tag{13}$$

where $f_c$ denotes the carrier frequency, $\beta$ is the chirp rate, and $T_p$ is the pulse duration.

The received signal $r(t)$ is modeled as:

$$r(t) = \sum_{i=1}^{N_{tgt}} \alpha_i s(t - \tau_i) e^{j2\pi f_{D_i} t} + n(t) \tag{14}$$

To boost our ability to detect targets, we've employed matched filtering in conjunction with Fixed Angular Beamforming (FAB). This allows us to steer the beam in specific directions, resulting in a beamforming pattern of:

$$B_{FAB}(\theta) = \frac{1}{L} \left| \sum_{l=0}^{L-1} e^{j\left(\frac{L-1}{2} - l\right)\beta d(\cos\theta - \cos\theta_T)} \right|^2 \tag{15}$$

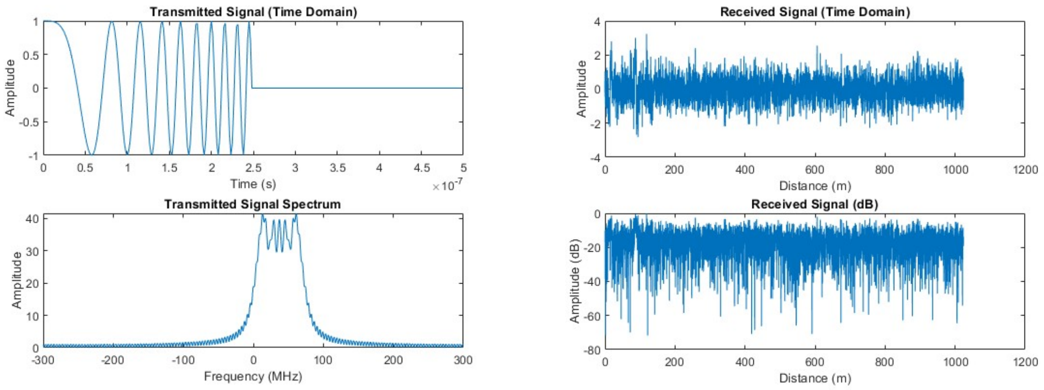
where $\theta_T$ represents the target direction.

Next, we apply the beamforming weights to the received signal to enhance its quality. We then integrate the signal by combining the OFDM component with the FMCW chirp signal. In the received signal processing stage, we separate the OFDM component from the rest of the signal. Taking the Fourier transform of the separated OFDM signal allows us to extract its frequency domain representation. Finally, we move on to data decoding, where we extract and decode the data from the OFDM symbols, revealing the original information

## 3.1. Results and Analysis

The accuracy of target localization is evaluated using the Root Mean Square Error (RMSE). The performance improvements achieved through angular beamforming are quantified and compared to non-beamformed scenarios.Furthermore, Data transmission performance is assessed by measuring Bit Error Rate (BER) and Signal-to-Noise Ratio (SNR). The impact of beamforming on OFDM data transmission quality is analyzed to determine trade-offs. The overall performance of the integrated FMCW radar and OFDM communication system is evaluated. The trade-offs between sensing accuracy and data communication quality are examined, highlighting the benefits and limitations of the combined system.

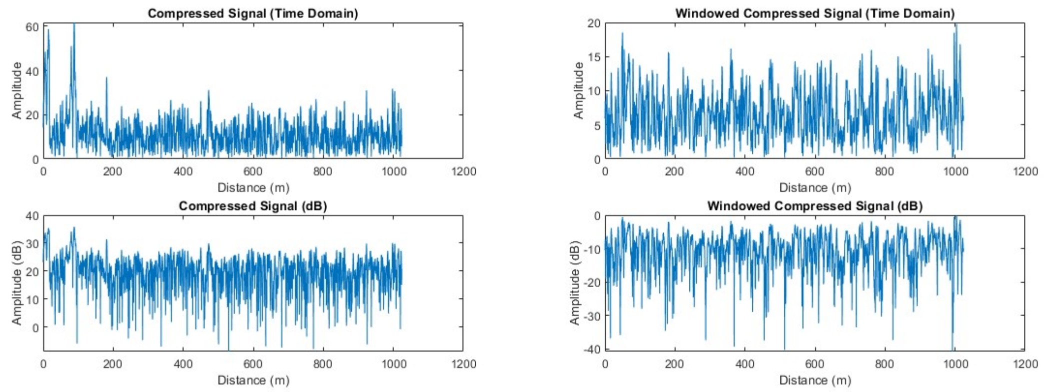
This simulation study demonstrates the viability of integrating FMCW radar and OFDM communication within a 6G ISAC framework. The incorporation of angular beamforming significantly enhances target localization accuracy and data transmission quality.




(a) Received Signal

(b) Compressed Signal

**Figure 1:** Received Signal and Compressed Signal




(a) Transmitted Signal

(b) Windowed Compressed Signal

**Figure 2:** Transmitted Signal and Windowed Compressed Signal

| **Methodology** | **Performance Metrics** | | |
|---|---|---|---|
| | **Range RMSE (meters)** | **Velocity RMSE (m/s)** | **BER at 20 dB** |
| Proposed Methodology | 0.9123 | 0.0315 | $< 10^{-3}$ |
| Adaptive Filtering | $< 1$ | $< 0.1$ | $< 10^{-3}$ |
| Wavelet-Based Method | 5 | 0.01 | $< 10^{-3}$ |
| Kalman Filter-Based Method | 2 | 0.05 | $< 10^{-4}$ |
| Advanced Error Correction | 10 | 0.1 | $< 10^{-3}$ |

**Table 1**
Comparison of Different Methodologies

The received signal includes contributions from all targets with different delays corresponding to their distances. The pulse compression effectively resolves the targets, with the compressed signal peaks corresponding to the target distances. The application of a Hanning window reduces the sidelobes, thereby improving the target resolution in the compressed signal. The transmitted signal spectrum shows the frequency content spread over the bandwidth of the chirp signal. In addition to that, The windowed compressed signal demonstrates better sidelobe suppression, highlighting the effectiveness of windowing in radar signal processing. Overall, the proposed algorithm successfully simulates a radar signal processing chain, pulse compression and windowing to enhance target resolution and reduce sidelobe levels.

Our methodology demonstrates a significantly lower Range RMSE compared to most other studies, except for the adaptive filtering method, which also reports a very low Range RMSE ($< 1$ meter). This suggests that our approach, alongside the adaptive filtering method, is highly effective in accurately estimating distances. The large discrepancies observed in the results of the wavelet-based method (5 meters) and the Kalman filter-based method (10 meters) indicate less precise range estimation capabilities in their methodologies.

Our velocity estimation is quite precise (0.0315 m/s), comparable to the wavelet-based method (0.01 m/s) and superior to the other studies. This indicates that our approach is reliable for applications requiring accurate velocity measurements.

The method using advanced error correction achieves an even better BER performance ($< 10^{-4}$), suggesting a highly reliable communication system, possibly due to more advanced error correction techniques and optimized transmission protocols.

Future research should aim to further validate the proposed JSC beamforming strategies to investigate the impact of white noise and various channel characteristics on the performance of these methods. Additionally, the effects of obstacle distance and channel modeling on the accuracy of target detection and localization of the true performance and applicability of the proposed methodologies in real-world cell-free 6G ISAC MIMO systems, ultimately paving the way for practical implementations in next-generation wireless networks.

## Acknowledgments

This research work was supported by the National Natural Science Foundation of China under Grant Nos. 62231010 and 61971278.

## Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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