Integrated Sensing and Communication Signals Toward 5G-A and 6G: A Survey

IEEE Internet of Things Journal, 2023

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Agenda

- Introduction
- ISAC Signal Design
- ISAC Signal Processing
- ISAC Signal Optimization
- ISAC Future Trends

Overview

- **Emergence of ISAC** is not easy infact crucial for the future mobile communication 5G-A and 6G, enabling intelligent apps like machine type communication, connected robotics, autonomous driving and extended reality
- **Historical Development:** ISAC tech has evolved from early research by NASA and military initiatives, gaining significant attention from both academia and industry as a potential technology for 6G

Overview

- **Current Systems:** traditional separate designs for sensing and communication struggle to achieve high data rates and accurate sensing simultaneously, particularly as spectrum resources become scarce
- **Signal Design:** must provide a balance communication efficiency with radar performance, requiring advanced processing algorithms and flexible optimization to meet diverse scenario needs

Overview

- **Research Trend:** integrates radar sensing and communication, improving spectrum utilization, reducing equipment size and energy consumption, and meeting the demands of emerging services

https://www.youtube.com/watch?v=Y8oCRAqtUCk

Performance Metrics

- **Resolution** measures the ability of ISAC signals to distinguish multiple targets; lower values indicate better target distinction
- **Ambiguity Function** represents the time-frequency composite autocorrelation of ISAC signals, helping derive metrics like resolution, accuracy, and clutter suppression under optimal processing conditions
- **Doppler Sensitivity** indicates the error in radar and communication outputs due to Doppler frequency shifts. High sensitivity can lead to significant output errors and effect bit error rates (BER)
- **Doppler Tolerance** determines the maximum detectable velocity of the radar. Beyond this velocity, estimation errors become unacceptable
- **Peak-to-Average Power Ratio (PAPR)** high PAPR requires advanced power amplifiers and increasing hardware overhead
- **Mutual Information (MI)** evaluates channel capacity in communication and measures sensing performance through conditional MI between the sensing channel and echo signals
- **Data Information Rate (DIR)** assesses the information transmission rate, reflecting the communication efficiency of ISAC signals

OFDM

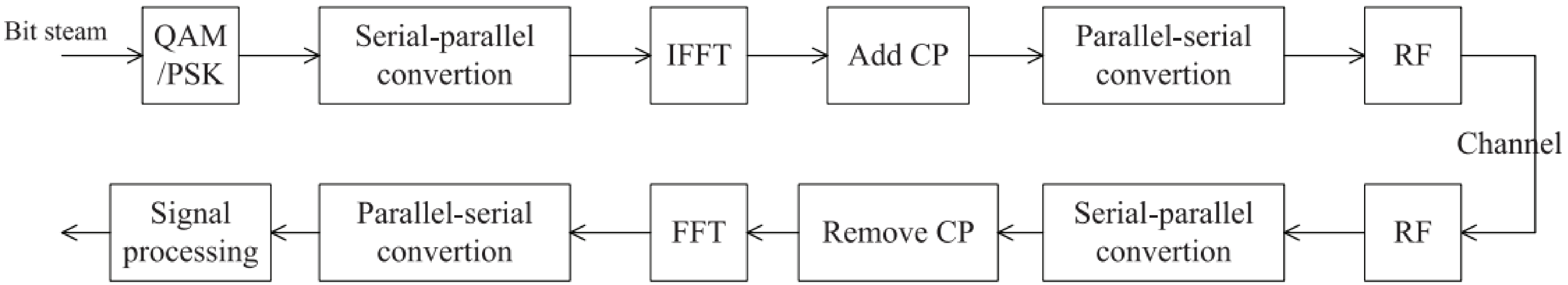

Fig. 3. Signal processing procedure for OFDM signal [8].

- **Orthogonality of Subcarriers**: reducing inter-carrier interference (ICI) and enhancing spectrum efficiency.
- **Synchronization and Equalization:** combat multipath fading facilitates synchronization and equalization in communication systems.
- **Flexibility in Design:** The number and spacing of OFDM subcarriers can be adjusted to meet the specific requirements of different scenarios, enhancing the sensing capabilities of ISAC.
- **Ambiguity Function:** A thumbtack-shaped ambiguity function is achieved with OFDM, aiding in reducing delay-Doppler ambiguity for moving target detection and high-resolution imaging.
- **High PAPR Issue:** OFDM signals have a high Peak-to-Average Power Ratio (PAPR), which can distort the RF front-end and negatively impact performance.
- **Interference Challenges:** Mutual interference between radar echo and communication signals, as well as self-interference between transmitter (TX) and receiver (RX), can degrade overall system performance, necessitating signal optimization.

OFDM

- **Modulation Combinations:** To enhance sensing performance, OFDM is often combined with other modulation techniques, including:
    1. Linear Frequency Modulation (LFM): Improves resolution for long-distance targets by increasing the time-bandwidth product.
    2. Phase Coding: Reduces PAPR.
    3. Spread Spectrum: Enhances anti-interference capabilities in low Signal-to-Noise Ratio (SNR) conditions.

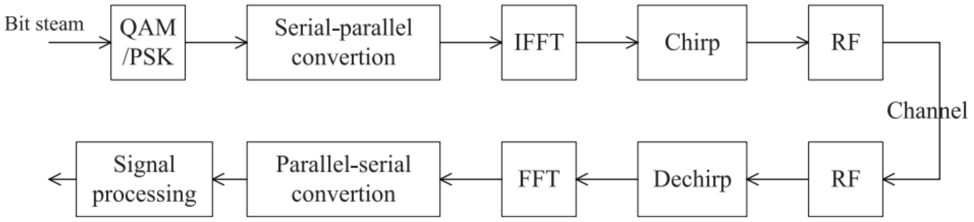

Fig. 4. Signal processing procedure for OFDM-LFM signal [52].

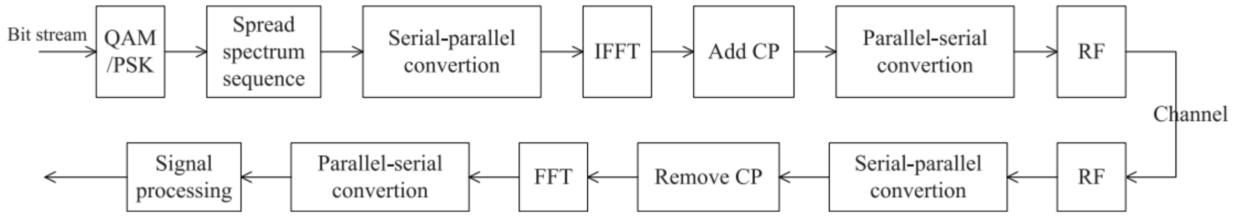

Fig. 6. Signal processing procedure for SS-OFDM signal [66].

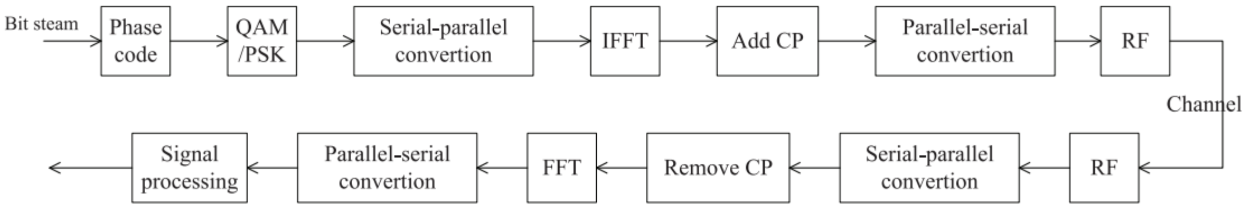

Fig. 5. Signal processing procedure for phase-coded OFDM signal [43].

Candidate Signals of 5G-A/6G

- **FBMC, GFDM, DFT-s-OFDM and OTFS** are proposed to solve the problems of Doppler sensitivity, high CP overhead, and high PAPR of OFDM, used to design ISAC signals.
- **Challenges**
  - **FBMC** the filters used in it can destroy the orthogonality between subcarriers, making it difficult to demodulate the QAM symbols carried by the FBMC signal. FBMC's narrow filter bandwidth and long tail in the time domain present challenges, impacting overall performance
  - **GFDM** achieves higher distance resolution and reduces mutual interference compared to OFDM, filter is easy to implement in comparison to FBMC, however, requires complex receiver algorithm to eliminate ISI and ICI
  - **DFT-s-OFDM** it has lower PAPR than OFDM, however, if used in combination to MIMO it generates high PAPR for high-order QAM modulation, as high-order modulation is a key factor to be implemented in 5G-A and 6G

Candidate Signals of 5G-A/6G

- **OTFS** is crucial for communication in a high mobile environment. While, in terms of radar sensing, OTFS is fully digitally modulated signal.
- OTFS and OFDM achieve the same sensing performance as FMWC while transmitting at high DIR. OTFS has shorter CP and achieves longer sensing distance and faster target tracking rate. Also, OTFS is ICI-free, which enables large Doppler frequency shift estimation and detects target with high velocity (Paper for details).

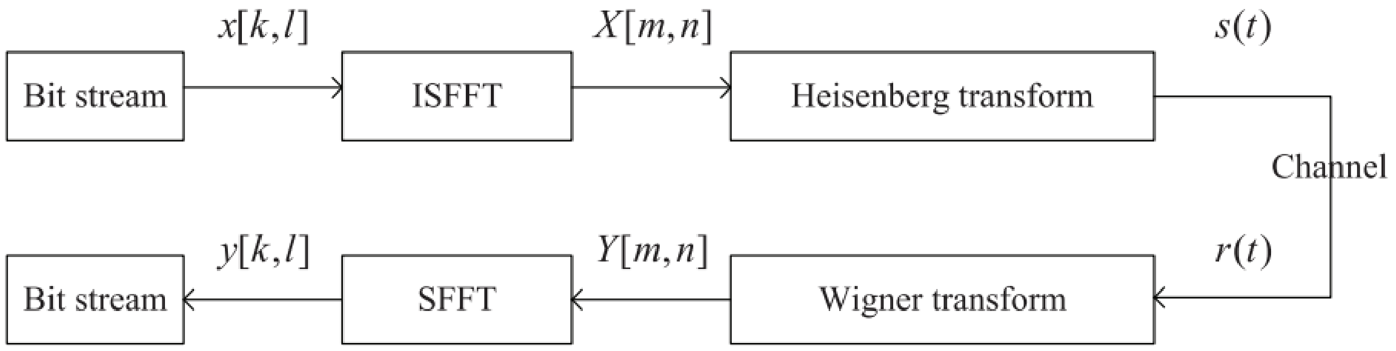

Fig. 7. Signal processing procedure for OTFS signal [30].

Performance Metrics

- **Computational Complexity** is about time consumption ISAC signal processing
- **Accuracy** reveals the difference between the sensing result and the real value
- **RMSE** since SNR affects the sensing results, RMSE reveals the anti-noise performance of the ISAC signal processing algorithm
- **Cramer-Rao Lower Bound** obtained by calculating the likelihood function of the observation value and the Fisher information matrix. Also reveals the accuracy of radar sensing

Methods

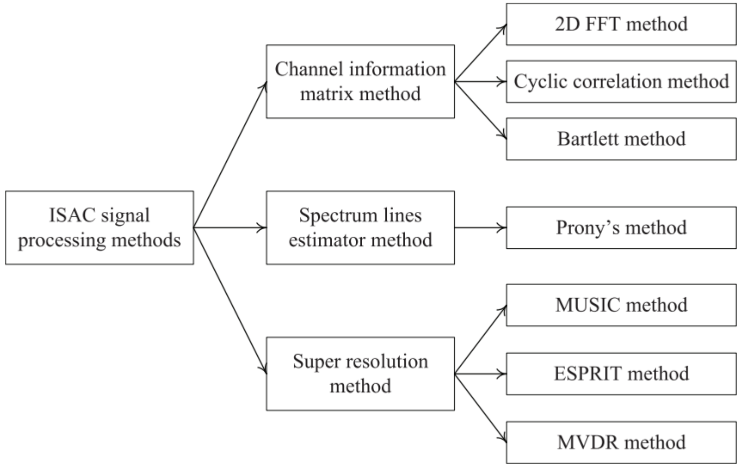

Fig. 8. ISAC signal processing methods.

1. **Channel Information Matrix Method** utilizes a constructed channel information matrix to extract sensing information. Key techniques include:
   - **2-D FFT Method** Fast Fourier Transform in two dimensions.
   - **Cyclic Correlation (CC) Method** Measures similarity between signals over time.
   - **Bartlett Method** Traditional approach for estimating power spectral density.

2. Spectrum Lines Estimator Method A prominent technique is **Prony's Method**, which estimates the spectral components of a signal.

3. Super-Resolution Method Focuses on estimating target distance and velocity by decomposing the received signal into noise and signal subspaces. Key techniques include:
   - **MUSIC (Multiple Signal Classification)** Identifies multiple signal sources.
   - **ESPRIT (Estimating Signal Parameters via Rotational Invariance Techniques)** Efficiently estimates parameters of signals.
   - **MVDR (Minimum Variance Distortionless Response)** Provides an optimal estimate of the signal while minimizing interference.

Categories to optimize

PAPR Optimization to reduce the Peak-to-Average Power Ratio (PAPR) to prevent signal distortion caused by the nonlinear operation of power amplifiers. Effective PAPR reduction schemes are necessary to maintain signal integrity.

Interference Management to addresses self-interference from the transmitter (TX) and mutual interference from other transmitters. Essential for maintaining the performance of both sensing and communication within ISAC systems.

Adaptive Signal Optimization involves optimizing signal parameters and structures to fit various application scenarios. Enhances the adaptability of ISAC signals, improving overall performance in different environments.

PAPR Optimization

- **Coding Method** to generate signals with low PAPR by using coding sequences to create multiple candidate sequences. This method is computationally intensive due to many subcarriers e.g. Golay code reduces PAPR by about 3dB and offers strong error correction and high sensing performance
- **Probability Method** an extension of the coding method that selects sequences with the lowest PAPR from a set. Include techniques such as partial transmission sequence (divides symbol into sub blocks, adjusts their phases and improves PAPR reduction with more sub-blocks), selected mapping (converts original symbols into low PAPR symbols and selects the best for transmission)
- **Tone Reservation Method** it reserves subcarriers to modulate LFM signals for peak cancelling, while other transmit communication signals. It is low complex but can waste spectrum resources. Combination with SM enhances PAPR reduction

Interference Management

- **Mutual-Interference Cancellation** arises when multiple ISAC users operate simultaneously in multipath or multiuser environments, lead to cross-interference among different users signals. Serial interference cancellation (involves demodulating the received signal, reconstructing the interference signal and subtracting it from the original echo signal, difficult in detection amplitude and phase rotation interference when their power level are similar), Selective interference cancellation (focus on strongest identified interference signal for reconstruction and cancellation as it is less complex)
- **Self-Interference Cancellation** occurs when the transmitter signal interferes with the echo signal returning to the receiver before transmission is completed incase when Tx and Rx are close to each other. Adaptive interference cancellation (generates a cancellation signal with the opposite phase and equal amplitude to the self-interference signal to eliminate it)

Adaptive Signal Optimization

ISAC systems require careful optimization of both signal parameters and structures to balance the dual demands of effective communication and accurate sensing

- **Signal parameter optimization** focus on various performance metrics such as sensing mutual information (MI), detection improvement rate (DIR), PAPR and transmit power. Space domain (beamforming and precoding techniques are employed to optimize beam patterns while managing constraints such as transmit power and SINR), Time-frequency domain (focus on maximizing sensing and communication MI)
- **Signal structure optimization** typically divide into pilot and data components, with pilot signal playing a crucial role in synchronization and channel estimation. Pilot Signal Optimization (the pilot signals should have high power, excellent sensing performance, and strong anti-interference capabilities e.g. block, comb and discrete pilots)

ISAC Signal Design

- **Waveform Design** OFDM is dominant but emerging next generation systems are FMBC, GFDM and OTFS. However, optional candidate waveforms are DFT-s-OFDM and single carrier frequency domain equalization (SC-FDE) are promising for ISAC applications
- **Frame Structure** research has explored flexible frame structures, such as optimal allocation of pilot and data subcarriers to enhance both sensing and communication. Future work aim for joint optimization of parameters across space, time and frequency domains
- **Transmission Mode** with potential for both half and full duplex implementations to improve system performance

ISAC Signal Processing

- **High accuracy and low complexity** mmWave and THz band applications become more prevalent, developing high accuracy ISAC signal processing algorithms tailored for these frequencies will be a significant research focus
- **Cooperative signal processing** <u>enhancing sensing capability</u> (utilizing multiple base stations for cooperative sensing can dramatically improve both sensing, accuracy and operational range), <u>existing methods limitations</u> (design for traditional radar systems to synch frequency and phase to enhance SNR, such methods often require precise timing and phase alignment which makes them unsuitable for the dynamic nature of MCS)

ISAC Signal Optimization

- **Spatial Optimization** the objective is to design ISAC beams in optimal directions to enhance both sensing and communication performance. Effective beamforming techniques are crucial to maximize the effectiveness of ISAC signals.
- **Time-Frequency Domain Optimization** this involves subcarrier and power allocation for ISAC signals, which is vital for adapting to varying communication needs and channel conditions. Optimization should consider the dynamic nature of environments to ensure robust performance.
- **Multi-Domain Optimization**

Future efforts should aim to simultaneously optimize:

  - <u>Precoding Matrices</u>: Tailoring signal transmission for specific user requirements.
  - <u>Subcarrier Allocation</u>: Efficiently distributing resources among multiple users.
  - <u>Power Allocation</u>: Balancing the energy distribution to meet performance criteria.
  - <u>Frame Structures</u>: Designing flexible frame structures that adapt to the specific needs of communication and sensing applications.

- **Cooperative Sensing Optimization** current research on ISAC signal optimization largely overlooks cooperative sensing scenarios involving multiple BSs. Extending the sensing range and improving accuracy through collaborative approaches will be critical.

Experimental Details

- MATLAB provides phased array system toolbox with practical examples

https://www.mathworks.com/help/phased/examples.html?s_tid=CRUX_topnav

https://www.mathworks.com/help/phased/radar-and-wireless-coexistence.html

https://www.mathworks.com/help/comm/ug/otfs-modulation.html (OTFS)