Waveform Design for ISAC: Trends and Future Directions

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***Abstract*—As wireless networks evolve toward 6G, Integrated Sensing and Communication (ISAC) aims to unify radar sensing and data transmission within shared spectrum and hardware resources. This survey reviews ISAC waveform design with a focus on practical trade-offs and deployability. We adopt a design philosophy based categorization, grouping schemes categorize current approaches based on design philosophy, grouping them into communication-centric modifications, hybrid OFDM–chirp, and balanced OFDM–FMCW waveform designs. We then examine waveform, communication, and sensing metrics, highlighting how PAPR, spectral shaping, BER/EVM, and sensing accuracy jointly constrain design choices. Finally, we identify critical open challenges in multiple aspects and outline integration opportunities with emerging technologies such as reconfigurable intelligent surfaces, AI-driven optimization, and Open RAN. Our assessment indicates that moving from promising prototypes to robust NextG deployments will require waveform designs that are not only spectrally efficient, but also hardware-aware, interference-resilient, and aligned with privacy constraints.**

***Index Terms*—Integrated Sensing and Communication, ISAC, Waveform Design, OFDM, FMCW, 6G Networks**

I. INTRODUCTION

As 5G scales and NextG architectures advance, wireless systems confront dual imperatives: delivering high-throughput, reliable connectivity while maintaining real-time environmental awareness. For decades, radar and communication systems have evolved on separate spectra with distinct hardware stacks. This arrangement has become increasingly inefficient amidst device proliferation and spectrum scarcity. Consequently, *Integrated Sensing and Communication* (ISAC) [1] has emerged as a paradigm shift. By unifying spectrum, hardware, and algorithmic design, ISAC enables transmission and sensing to operate cooperatively within a shared resource pool. This represents both a technically viable path and an economic necessity under tightening resource and cost constraints.

A common implementation strategy is to extract sensing information from existing communication signals, particularly Orthogonal Frequency-Division Multiplexing (OFDM), by utilizing payload Channel State Information (CSI) or pilot tones. While this approach requires minimal standardization changes, it is fundamentally constrained. Hardware and synchronization bottlenecks, including oscillator instabilities, I/Q imbalance, and RF chain mismatches, limit performance. Furthermore, bandwidth and subcarrier allocations are fixed by standards, and pilot densities are optimized for throughput rather than sensing, thereby restricting observability and resolution. Conversely, radar-centric solutions like Frequency-Modulated Continuous Wave (FMCW) offer superior range and velocity resolution but typically necessitate dedicated high-frequency hardware and wide bandwidths (e.g., 60 or 77 GHz). This increases power consumption, cost, and spectrum coordination burdens. Therefore, simply reusing legacy communication or radar signals is unlikely to deliver reliable joint performance at scale, motivating the need for joint waveform design and holistic system-level co-optimization.

To achieve simultaneous communication and sensing, the signal must be co-designed to balance these conflicting requirements. Promising strategies move beyond simple multiplexing by inserting high-resolution chirps between OFDM data blocks, mapping orthogonal sensing sequences onto specific subcarriers, or employing phase modulation to encode communication symbols into FMCW ramps while preserving a constant envelope.

However, these design choices impose distinct system-level implications. The Peak-to-Average Power Ratio (PAPR) directly impacts amplifier efficiency and device power consumption; synchronization complexity introduces latency; and pilot density creates a fundamental trade-off between spectral efficiency and channel estimation quality. Practical designs must also respect spectral masks and adjacent-channel limits, maintain robustness against hardware impairments such as Carrier Frequency Offset (CFO) and Sampling Frequency Offset (SFO), and ensure Doppler tolerance under high-mobility conditions. Moreover, multi-antenna operation adds another degree of freedom, enabling joint beam scheduling and null placement to facilitate sensing while sustaining link reliability.

This survey reviews recent waveform design schemes for ISAC, discussing how designs are evaluated via key metrics and analyzing the inherent trade-offs between sensing and communication performance. We further examine open challenges for future systems and explore how ISAC waveform design can interface with emerging technologies, including Reconfigurable Intelligent Surfaces (RIS) for propagation shaping, Artificial Intelligence (AI) for online parameter tuning, and Open Radio Access Networks (O-RAN) for software-defined resource allocation. Our contributions are as follows:

- We classify ISAC waveform designs into three cate-

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gories: communication-centric, radar-centric adaptations, and balanced composite designs, summarizing key representative techniques in each class.

- We provide a comparative performance analysis considering implementation constraints, waveform characteristics, communication quality, and sensing accuracy. This reveals the essential trade-offs guiding the design of high-performance waveforms.
- We identify critical gaps and actionable research directions, including persistent self-interference, interference management, and privacy vulnerabilities. Furthermore, we highlight potential integrations with emerging technologies to address these issues.

The paper is organized as follows: Section II reviews ISAC waveform designs and trends across three categories. Section III details evaluation metrics, emphasizing practical trade-offs and measurement factors. Section IV discusses open challenges and future technology integrations, and Section V concludes the work.

II. ISAC WAVEFORM DESIGNS

As summarized in Table I, existing ISAC waveform designs can be classified into three categories: *communication-centric*, *radar-centric hybrid*, and *balanced composite*. We detail representative waveform designs in each category below.

A. Communication-Centric Designs (OFDM Radar)

These methods preserve the standard OFDM frame structure and demodulation process while introducing sensing capabilities via specific symbol, pilot, or subcarrier modifications. Coherent symbol integration enhances the sensing Signal-to-Noise Ratio (SNR) through symbol repetition and averaging, after which a standard 2D FFT yields a range–Doppler map [2, 3]. Alternatively, OFDM frame reconstruction leverages standard demodulation to recover the CSI stream, subsequently applying a 2D FFT for motion sensing; however, observability remains limited by pilot density and scheduler load [4]. Adaptive subcarrier weighting shapes the ambiguity function for Generalized Likelihood Ratio (GLR) target detection while maintaining compatibility with conventional OFDM receivers [5]. Recent advancements also employ Symbol-Level Precoding (SLP) to suppress range–Doppler sidelobes by optimizing per-symbol phases under constant-envelope, target-illumination, and communication Quality-of-Service (QoS) constraints. In SLP, receiver processing typically relies on a matched filter or 2D FFT, with optimization objectives solved via majorization-minimization (MM) or the alternating direction method of multipliers (ADMM) [6]. Finally, a stepped carrier frequency approach synthesizes a wider effective bandwidth across successive bursts to construct a least-squares time-domain response for finer range resolution [7]. While these schemes integrate seamlessly into existing Wi-Fi or 5G NR resource grids (using pilots like CSI-RS (Channel State Information Reference Signal) or PRS (Positioning Reference Signal)), they inherit fundamental communication constraints: range resolution is bounded by signal bandwidth, Doppler resolution is tied to subcarrier spacing and symbol duration, and synchronization overhead scales with pilot density.

B. Hybrid Structures (OFDM–Chirp)

These waveforms retain an OFDM-like structure but embed chirp characteristics to enhance sensing performance. Triangular-FM subcarriers introduce a triangular frequency modulation (FM) law into the OFDM spectrum, enabling a decoupled Doppler-then-range processing flow for higher resolution [8]. Similarly, applying a quadratic phase (frequency-domain chirp) can reduce the Peak-to-Average Power Ratio (PAPR) under specific parameter settings [9]. However, improper chirp rates, windowing mismatches, or insufficient power back-off may inadvertently increase the PAPR, imposing stricter linearity constraints on the power amplifier (PA). Multiple orthogonal chirps are transmitted via time-division multiplexing (TDM), enabling the use of frequency-domain processing (FDP) for separation and an inverse-FDP combined with a two-dimensional FFT (2D FFT) for range–Doppler estimation [10]. Overall, these designs preserve OFDM grids while injecting chirp structures to facilitate clearer Doppler–range processing and receiver separation.

C. Balanced Composite Architectures

Composite designs explicitly address the sensing-communication trade-off by exposing tunable control parameters (e.g., power ratio, allocation density), allowing operators to dynamically balance data throughput against sensing resolution. In the **frequency domain**, diagonal-IDFT embedding maps structured sensing energy along the subcarrier symbol diagonal. This preserves the legacy OFDM chain while managing mutual interference via optimized sensing density and power splits [14]. In the **time domain**, preamble or midamble embedding inserts chirps into training fields, enabling parallel demodulation and sensing with direct control over update rates and SNR [11]. Hybrid approaches combine random time-division scheduling with sensing-implanted OFDM to adapt spectral occupancy to varying traffic loads [12]. In the **spectral domain**, guard-band embedding utilizes the null subcarriers at channel edges; by placing narrowband FMCW signals within 5G NR guard bands, this lightweight approach enables simultaneous operation without modifying the core OFDM structure. Here, the trade-off is managed by constraining the sweep bandwidth and power ratio to prevent leakage into active data subcarriers [16]. Finally, phase-modulated FMCW maintains constant-envelope properties for efficient PA operation, while non-orthogonal superposition transmits waveforms simultaneously to maximize resource reuse, though this necessitates sophisticated interference cancellation at the receiver [13, 15].

III. EVALUATION METRICS AND TRADE-OFFS

Waveform designs in ISAC systems must satisfy diverse requirements, ensuring sufficient sensing granularity while maintaining high-quality communication. These designs span

Table I
CATEGORY OF ISAC WAVEFORM DESIGNS

Category	Mechanism	Signal Processing	Ref.
Communication-Centric (OFDM Radar)	Coherent symbol integration	Symbol repetition with 2D FFT for enhanced SNR and range–Doppler mapping	[2][3]
	OFDM frame reconstruction	Standard OFDM demodulation followed by 2D FFT on CSI for motion sensing	[4]
	Adaptive subcarrier weighting	GLR detection with iterative transmit-power optimization	[5]
	SLP for sidelobe control	Matched-filter or 2D-FFT range–Doppler; ambiguity-function (ISL) minimization via MM/ADMM under constant-envelope, target-illumination, and QoS constraints	[6]
	Stepped carrier frequency	Least-squares (LS) time-domain response estimation for range profiling	[7]
Hybrid Structure (OFDM–Chirp)	Triangular-FM subcarriers	Doppler–range decoupling: adjacent-column product + DFT for Doppler; IDFT-based rough delay + compensated fine delay	[8]
	Frequency-domain chirp modulation	IFFT-based waveform synthesis with quadratic-phase embedding for PAPR reduction	[9]
	Multiple orthogonal chirps via TDM	FDP for chirp multiplexing; inverse-FDP and 2D FFT for demodulation	[10]
Balanced Composite (OFDM–FMCW)	*TD:* Preamble embedding	FMCW chirps in training sequences; GLR-based detection with frame-level fusion	[11]
	TD: Random time-division	Flexible sensing-implanted OFDM with dynamic slot allocation	[12]
	SD: Phase modulation	FMCW carrier phase-modulated by the OFDM signal; preserves spectral peak for radar processing	[13]
	SD: Diagonal-IDFT embedding	FMCW samples placed on diagonal IDFT elements (pilot-like); phase continuity compensation	[14]
	SD: Non-orthogonal superimposition	Simultaneous FMCW+OFDM transmission; FMCW-derived channel estimation removes pilot overhead	[15]
	SD: Non overlapping superimposition	Simultaneous FMCW+OFDM transmission	[16]

Note: TD: Time Division; SD: Spectral Division; 2D FFT = Two-Dimensional Fast Fourier Transform; GLR = Generalized Likelihood Ratio; FDP = Frequency-Domain Processing; PAPR = Peak-to-Average Power Ratio; TDM = Time Division Multiplexing; ISL = Integrated Sidelobe Level; IDFT = Inverse Discrete Fourier Transform; MM = Majorization-Minimization; ADMM = Alternating Direction Method of Multipliers.

a broad spectrum, ranging from communication-centric architectures like OFDM Radar and OFDM-Chirp to sensing-centric hybrid schemes such as OFDM-FMCW composites. Regardless of the specific architecture, performance is generally evaluated across three primary dimensions: *waveform metrics*, *communication quality*, and *sensing accuracy*. We analyze these metrics and their associated trade-offs below.

A. Waveform Metrics

Waveform metrics quantify signal-level properties that determine an ISAC waveform's behavior in physical environments. Key characteristics include the amplitude envelope (e.g., PAPR), spectral occupancy, time–frequency structure, and ambiguity behavior. These factors dictate how efficiently a waveform utilizes hardware, coexists with other spectral users, and supports sensing resolution.

Peak-to-Average Power Ratio (PAPR) captures the fluctuation of a waveform's instantaneous amplitude relative to its average power. Standard OFDM typically exhibits high PAPR, driven by the number of subcarriers and the modulation scheme [17]. A lower PAPR is preferred because large amplitude peaks necessitate higher input back-off in power amplifiers, which degrades both communication coverage and radar sensing range. Consequently, many ISAC systems are moving beyond conventional OFDM designs toward chirp-integrated waveforms. This transition is driven by the near-constant envelope of chirp signals [3], which mitigates the high PAPR of OFDM. Several studies explicitly target PAPR reduction to jointly enhance communication and sensing performance [9, 10, 13].

Spectral Shaping is critical in ISAC waveform design to prevent energy leakage that disrupts subcarrier orthogonality and compromises spectral stability. Jia et al. [9] show that integrating chirp modulation within OFDM frames reduces the spectral leakage inherent to standard OFDM. Furthermore, Liu et al. [10] demonstrate that frequency-domain processing (FDP) modules can leverage carefully designed chirp patterns to meet specific communication requirements under varying environments. The OFDM-PM design [13] further illustrates the impact of phase modulation on spectral sidelobe suppression and sensing quality.

B. Communication Metrics

Communication metrics assess a waveform's ability to support reliable data transmission amidst environmental interference and sensing-oriented modifications. These metrics are particularly critical for communication-centric designs, where sensing often depends on reliable symbol decoding and stringent synchronization.

Bit Error Rate (BER) measures data reliability and is influenced by modulation order, coding rate, frame structure, SNR, and modifications for ISAC coexistence. OFDM Radar simulations in [2] indicate that higher modulation orders incur higher BER, while Dapa et al. [3] demonstrate target velocity can significantly degrade BER in such systems. In frame regeneration approaches [4], a single bit error can corrupt the reconstructed frame, severely impacting sensing performance. For composite designs like OFDM–FMCW, the choice of relative chirp power is critical to avoid excessive interference with communication symbols [14].

Error Vector Magnitude (EVM) quantifies the deviation of received constellation points from ideal positions, reflecting distortions from the transceiver chain or interference. It is highly sensitive to timing synchronization; even minor DFT window misalignments broaden the constellation. In OFDM-FMCW composites, the relative chirp power is a critical tuning parameter: excessive power distorts communication symbols, while insufficient power limits sensing range, necessitating a careful balance [16].

C. Sensing Metrics

Sensing metrics evaluate detection probability and estimation accuracy, governed by waveform constraints, SNR, and processing schemes.

Range Resolution and Accuracy define the capacity to distinguish adjacent targets and the precision of position measurement. Resolution relies on the occupied bandwidth B (where $\Delta R = \frac{c}{2B}$), meaning wider bandwidths yield finer granularity. Accuracy, in contrast, represents the error variance for a single target; it is theoretically bounded by the Cramér-Rao Bound (CRB) and improves as $\propto 1/\sqrt{SNR}$.

Doppler Resolution and Accuracy measure velocity estimation precision. Resolution is determined by the carrier frequency and Coherent Processing Interval (CPI) as $\Delta v = \frac{\lambda}{2\times\text{CPI}}$; thus, longer integration times refine separability. Accuracy improves with higher SNR and extended observation windows, provided the channel remains coherent.

Signal-to-Noise Ratio (SNR) governs the trade-off between the Probability of Detection (P_d) and False Alarm Rate (P_{fa}). Higher SNR not only improves estimation accuracy but also suppresses the noise floor and sidelobes, preventing weak targets from being masked by clutter [2, 8]. Performance is further enhanced by multipath exploitation, frequency diversity, and optimized CPI lengths [2, 5].

D. Design Trade-offs

Hybrid waveform designs, such as OFDM–chirp and OFDM–FMCW, require careful power allocation between sensing components and data symbols to avoid degrading either function [14]. In communication-centric schemes, parameters such as subcarrier spacing, symbol count, and coherent integration time must balance radar resolution and SNR against data rate and BER. Specifically, while larger subcarrier spacing and longer processing windows improve range–velocity estimation, they reduce throughput and BER robustness under high Doppler conditions [2]. Similarly, designs that sharpen spectral peaks or suppress sidelobes often trade sensing gains for increased computational complexity [6, 8]. Composite structures can improve spectral efficiency but risk stronger spectral interference; meanwhile, schemes relying on pilot sequences for joint synchronization and sensing must optimize pilot density to balance overhead with estimation performance [4]. Ultimately, ISAC waveforms are defined by interdependent trade-offs, where each design strikes a specific balance between communication reliability and sensing accuracy based on system priorities.

IV. OPEN CHALLENGES AND FUTURE DIRECTIONS

Next-generation ISAC systems will rely on robust waveform designs, particularly as they integrate with emerging network architectures. This section identifies promising directions for waveform-centric research and system integration, while highlighting critical open challenges.

A. Integration with Emerging Technologies

Reconfigurable Intelligent Surfaces (RIS), AI-native processing, and O-RAN define the primary trajectories for ISAC waveform evolution. **RIS** introduces the concept of programmable propagation. In this architecture, the transmitter, receiver, and surface can be co-configured to steer energy toward sensing regions of interest while suppressing interference. This is achieved by reshaping multi-path geometry under practical constraints, such as discrete phase shifts and limited control links. Consequently, RIS enhances both communication reliability and secrecy. **AI-native ISAC** pushes learning down to the waveform and resource-allocation level. It jointly tunes transmit signals and receive processing for task-aware objectives while respecting spectral and safety constraints. Within **O-RAN**, these capabilities can be deployed as xApps and rApps. This enables waveform-aware scheduling and cooperative sensing across cells. As a result, waveform structures and processing must be partitionable between edge and cloud. This requires clear interfaces to expose sensing features while enforcing privacy policies.

B. Critical Open Challenges

1. Non-orthogonal Coexistence and Self-Interference

In non-orthogonal ISAC, waveforms share time–frequency resources, allowing radar probing and data transmission to coexist without time-division multiplexing. While this maximizes resource reuse, it introduces persistent self-interference where each function acts as structured interference to the other. On the sensing side, residual communication components raise the noise floor, distort range–Doppler responses, degrade sidelobe behavior, and generate ghost targets that are difficult to distinguish in rapidly changing scenarios. Although cancellation algorithms show promise, most rely on controlled simulations or idealized hardware models. The lack of validation in realistic deployments leaves the practical viability of these techniques unproven, underscoring the urgent need for implementation-focused research.

2. Rich Interference Environments

In realistic deployments, ISAC waveforms are rarely isolated. They must coexist with base stations, user devices, legacy radars, automotive sensors, and uncoordinated emitters. This creates an interference-rich environment where communication, sensing, and unrelated systems compete for spectrum. ISAC waveform design is particularly fragile in this context, as it must simultaneously support high-throughput communication and high-fidelity sensing under aggressive spectrum reuse. Future research must prioritize the following areas:

- **Interference-aware waveform design.** Researchers must develop probing and data structures with signatures that remain distinguishable amidst structured interference.
- **Spatial and temporal shaping at scale.** Networks should apply coordinated beamforming and time–frequency shaping for network-wide interference management.
- **Statistical modeling and monitoring.** Models must treat interference as structured and non-stationary, utilizing continuous tracking of key indicators.
- **Benchmarks and worst-case testing.** Current evaluations often underestimate challenges by utilizing controlled interferers. Future work should establish datasets with heavy mutual interference.

3. Privacy and Potential Misuse

Most ISAC research optimizes waveforms for range, Doppler, and spectral efficiency, assuming a benign environment. However, the time–frequency–space structure of a waveform also determines privacy vulnerabilities and the potential for system misuse. Thus, waveform design is not merely an engineering optimization problem but a security decision.

When a waveform serves both communication and sensing, motion and location become intrinsic observables. High-resolution designs can reveal fine-grained motion, posture changes, and micro-Doppler patterns. Moreover, this monitoring often occurs passively and continuously. Such capabilities expose sensitive data, including health indicators like respiration or tremors. In hybrid or radar-centric designs, biometric-like signatures may even enable re-identification across time and locations. These privacy risks are intrinsic to the waveform physics rather than optional by-products. Therefore, mitigation strategies must be embedded in the physical layer. Key approaches include constraining the ambiguity function, limiting effective bandwidth, introducing controlled randomness in probing sequences, and jointly optimizing for rate, sensing quality, and privacy.

4. Cross-Standard Alignment

Cross-standard alignment is essential to prevent ISAC fragmentation. Currently, 802.11bf, 5G NR, and automotive radar introduce unique sensing pilots, midambles, and chirp structures, which often rely on incompatible time–frequency grids. While this diversity favors local optimization, it undermines interoperability, particularly for multi-band devices. Consequently, waveform-aware alignment should promote a compact set of shared primitives that can be instantiated across standards with predictable ambiguity functions. The challenge lies in defining these common building blocks without stifling innovation within individual standards.

V. Conclusion

This survey classifies ISAC waveforms into communication-centric, radar-centric, and composite architectures, each offering distinct trade-offs in rate, resolution, and complexity. While communication-centric designs align with current standards but face bandwidth constraints, hybrid and composite approaches enhance sensing flexibility through tunable parameters. Key challenges remain in self-interference, interference management, and privacy. Ultimately, integrating these waveforms with RIS, AI, and O-RAN is essential to transition ISAC from theory to robust real-world deployment.

Acknowledgment

This work is partially supported by the National Science Foundation grants ECCS-1923739 and OAC-2417890.

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