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Fuzzy And Hybrid Optimization Approaches For Waveform Design In Integrated Sensing And Communication (ISAC) Systems: A Comprehensive Review

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Abstract
The convergence of sensing and communication into a unified framework, known as Integrated Sensing and Communication (ISAC), is rapidly emerging as a foundational technology for sixth-generation (6G) networks and beyond. ISAC promises significant improvements in spectrum efficiency, hardware utilization, and situational awareness, enabling transformative applications in autonomous vehicles, smart cities, industrial IoT, and defense systems. At the core of ISAC research lies the waveform design problem, where conflicting objectives of high-capacity communication and high-resolution sensing must be jointly optimized under practical hardware, energy, and real-time constraints.
This paper provides a comprehensive review of optimization approaches for ISAC waveform design, focusing on three major paradigms: traditional methods, fuzzy optimization, and hybrid optimization. Traditional methods, including convex programming, semidefinite relaxation, and stochastic algorithms, offer strong theoretical foundations but suffer from scalability, model-dependency, and limited adaptability in dynamic environments. Fuzzy optimization addresses uncertainty and imprecision by leveraging linguistic reasoning, making it suitable for highly mobile or uncertain contexts, though it lacks global guarantees. Hybrid approaches integrate fuzzy logic with convex or evolutionary algorithms to combine adaptability and robustness, offering the most promising direction for real-world ISAC deployment despite increased computational complexity.
By conducting a critical comparative analysis, this review identifies the strengths, limitations, and application domains of each paradigm, while outlining key challenges in scalability, real-time implementation, hardware feasibility, standardization, and security. The paper also proposes future research directions, including AI-driven fuzzy–hybrid frameworks, cross-layer optimization, quantum-inspired algorithms, and security-aware waveform design. In doing so, it contributes both a synthesis of the state-of-the-art and a forward-looking research roadmap for adaptive, scalable, and secure ISAC systems in the era of 6G.
Keywords: *Integrated Sensing and Communication (ISAC), Waveform design, Fuzzy optimization, Hybrid optimization, 6G networks, Intelligent wireless systems, Communication and sensing integration.*

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I. Introduction

The rapid evolution of wireless communication technologies and the emergence of the fifth generation (5G) and the anticipated sixth generation (6G) networks have accelerated the integration of communication and sensing functionalities into a unified framework, known as Integrated Sensing and Communication (ISAC). Unlike traditional systems that treat communication and sensing as independent functions, ISAC enables the simultaneous transmission of data and acquisition of environmental information using the same hardware and spectrum resources[1] [2]. This convergence is increasingly vital in applications such as the Internet of Things (IoT), autonomous vehicles, unmanned aerial systems (UAS), healthcare monitoring, and smart city infrastructures, where both high data rates and precise sensing are essential [3, 4].

A fundamental enabler of ISAC performance is waveform design. The waveform determines how effectively a system can balance the dual objectives of communication throughput and sensing accuracy[5]. Conventional communication waveforms, such as orthogonal frequency-division multiplexing (OFDM), can be adapted for radar sensing, but they often result in trade-offs that compromise performance in one domain when optimized for the other [6]. For instance, a waveform optimized for high data capacity may reduce sensing resolution, while one optimized for radar sensing may degrade communication reliability[7]. Therefore, joint waveform optimization is essential to maximize the efficiency and reliability of ISAC systems [8].

Traditional optimization methods, such as convex programming or linear optimization, have been widely applied to ISAC waveform design[9]. While these methods offer mathematically elegant solutions, they are often limited in addressing the non-convex, high-dimensional, and dynamic nature of real-world ISAC scenarios[10]. These systems must adapt to multi-user environments, interference, mobility, and hardware constraints, all of which make closed-form optimization impractical [11]. Moreover, traditional methods frequently assume idealized channel models that fail to capture the uncertainties of heterogeneous IoT environments [12].

To address these limitations, fuzzy optimization and hybrid optimization techniques have emerged as promising approaches. Fuzzy logic-based methods excel in handling uncertainty, imprecision, and incomplete information, making them suitable for ISAC scenarios where environmental conditions and channel states fluctuate unpredictably[13]. On the other hand, hybrid approaches such as the combination of genetic algorithms (GA), particle swarm optimization (PSO), and fuzzy logic offer a means of overcoming the limitations of single techniques[14], balancing exploration and exploitation in complex optimization landscapes [15]. These methods are particularly effective in achieving near-optimal solutions under practical constraints, such as power budgets and low-latency requirements.

The aim of this review paper is to critically analyze the application of fuzzy and hybrid optimization approaches to ISAC waveform design. Specifically, it examines how these methods improve the joint design of communication and sensing waveforms, evaluates their effectiveness across different scenarios, and highlights the trade-offs involved. Furthermore, the paper identifies the challenges and open research questions in this area and outlines future directions for integrating artificial intelligence (AI)-driven optimization into ISAC systems to meet the demands of 6G and beyond

II. Literature Survey

The rapid evolution of wireless communication technologies over the past two decades has driven an unprecedented demand for high data rates, low latency, robust connectivity, and pervasive sensing capabilities. As society moves toward the vision of the sixth generation (6G) of wireless networks, traditional architectures that treat communication and sensing as independent functions have become increasingly inadequate to meet these demands. In response, Integrated Sensing and Communication (ISAC) has emerged as a transformative paradigm that unifies data transmission and environmental sensing into a single framework, sharing the same hardware, spectrum, and signal processing resources [9]. Unlike conventional systems, ISAC enables simultaneous delivery of communication services and acquisition of situational awareness, making it a cornerstone of future cyber–physical–social systems[16].

ISAC is particularly relevant in application domains where sensing and communication requirements are tightly coupled. For example, in autonomous vehicles, radar sensing is essential for detecting obstacles, lane boundaries, and other vehicles, while reliable vehicle-to-everything (V2X) communication ensures coordination and safety. Similarly, in smart cities, IoT nodes require both efficient communication with cloud infrastructure and sensing capabilities for tasks such as traffic monitoring and energy management[2]. Defense and aerospace also stand to benefit, as ISAC allows for dual-function radars that can simultaneously track targets and communicate tactical information without requiring separate systems[4]. By merging these two traditionally separate functionalities, ISAC not only increases spectral efficiency but also reduces hardware costs, power consumption, and deployment complexity[3] .

At the center of ISAC research lies the challenge of waveform design. The waveform determines the performance of both communication and sensing. Communication-centric waveforms such as orthogonal frequency-division multiplexing (OFDM) are designed for high throughput and robustness to multipath fading but suffer from poor radar ambiguity functions that limit range and Doppler resolution[17]. Conversely, radar-centric waveforms like linear frequency-modulated continuous wave (FMCW) signals excel in sensing but cannot support the high spectral efficiency required for modern data communication. The result is an inherent trade-off: waveforms that optimize one functionality often degrade the other. This dual-objective optimization problem makes waveform design the most critical and technically challenging aspect of ISAC[18].

The goals of ISAC waveform design can be summarized as follows: maximize communication capacity and reliability, ensure high-resolution sensing with robust detection probability, and minimize mutual interference between the two functions. Achieving these objectives simultaneously requires balancing multiple constraints such as power budgets, spectral occupancy, constant modulus requirements, and hardware limitations. Furthermore, the optimization must account for dynamic and uncertain environments, as ISAC systems are often deployed in mobile and heterogeneous contexts such as vehicular networks or distributed IoT platforms [19].

Scholars generally classify ISAC waveforms into three categories. The first is communication-centric waveforms adapted for sensing. These waveforms, typically derived from existing communication standards such as OFDM, are modified to embed sensing functionality. Their main advantage is compatibility with commercial communication infrastructure, but they suffer from degraded sensing performance. The second category is radar-centric waveforms adapted for communications. These waveforms, originally designed for sensing, are modified to carry data[20]. While they offer superior sensing capabilities, they often provide low spectral efficiency for communications. The third and most promising category is joint waveforms, which are designed explicitly for dual functions from the ground up. Joint waveform design requires advanced optimization techniques to balance communication and sensing objectives while remaining compatible with hardware and regulatory constraints[21].

Recent surveys underscore the importance of waveform optimization in achieving the broader vision of ISAC. [2]provide an overview of enabling joint communication and radar sensing in mobile networks, highlighting waveform design as a key enabler of ISAC. Similarly,[22] outline how integrated sensing and communications form the foundation of dual-functional wireless networks for 6G, with waveform optimization at the heart of performance trade-offs.[23]demonstrate prototype testbeds for ISAC in 6G contexts, showing how real-world implementations underscore the challenges of designing waveforms that can meet both sensing and communication demands simultaneously. Collectively, these studies establish that waveform design is not only a theoretical challenge but also a practical barrier to deployment.

However, conventional waveform design methods rely heavily on convex optimization frameworks. While powerful in theory, these frameworks often assume idealized conditions such as perfect channel knowledge and stationary interference, conditions rarely encountered in real deployments[24]. Moreover, convex formulations struggle with the inherent non-convexity of many ISAC objectives, such as jointly minimizing bit error rates and sidelobe levels or maximizing spectral efficiency while ensuring constant-modulus waveforms. The resulting gap between theory and practice has motivated researchers to investigate more flexible and adaptive approaches capable of handling uncertainty, complexity, and dynamic environments.

Among these emerging directions, fuzzy optimization and hybrid optimization methods stand out as particularly promising. Fuzzy logic provides a natural framework for managing imprecision, enabling systems to make adaptive decisions based on ambiguous inputs such as "high SNR" or "low interference.[25]" In contrast, hybrid optimization combines the strengths of multiple optimization paradigms, such as genetic algorithms, particle swarm optimization, and fuzzy control, to explore large, complex design spaces and escape local minima [26]. While these approaches are still relatively underexplored in ISAC waveform design, evidence from related wireless domains suggests they offer significant potential for advancing the field.

This review paper aims to critically survey fuzzy and hybrid optimization approaches for ISAC waveform design, identifying their contributions, limitations, and future opportunities. By situating these approaches within the broader context of ISAC development, the paper seeks to demonstrate how fuzzy and hybrid methods can bridge the gap between the limitations of classical convex optimization and the demands of real-world ISAC deployments. The review also highlights open research questions, including the integration of artificial intelligence, federated learning, and security-aware waveform optimization, which are expected to shape the trajectory of ISAC in 6G and beyond.

ISAC represents a paradigm shift in wireless networks, enabling dual functionality that is critical for emerging applications in autonomous systems, IoT, and smart infrastructure. Waveform design is the central technical challenge in ISAC, requiring innovative optimization strategies to balance communication and sensing objectives. Traditional convex methods have laid the groundwork, but their limitations necessitate the exploration of adaptive techniques such as fuzzy and hybrid optimization. The remainder of this review will examine these methods in detail, beginning with an evaluation of conventional optimization approaches before turning to the contributions of fuzzy logic and hybrid paradigms.

Early research on Integrated Sensing and Communication (ISAC) waveform design relied heavily on traditional optimization frameworks, particularly convex optimization, linear programming, and stochastic methods. These approaches provided rigorous mathematical models to balance communication throughput with sensing resolution, laying the foundation for ISAC system design. Convex optimization has been a dominant tool because of its efficiency and global optimality guarantees. For example, semidefinite relaxation (SDR) has been used to reformulate non-convex waveform problems, enabling approximate yet tractable solutions[27]. [21], while [28] introduced multi-objective frameworks that allowed trade-offs between bit error rate and radar detection probability. These studies confirmed the viability of convex formulations for balancing ISAC dual goals.

Beyond convex optimization, stochastic approaches such as genetic algorithms (GA) and particle swarm optimization (PSO) have been employed to address the non-convexity of ISAC waveform problems, especially those involving hardware constraints like constant modulus or nonlinear amplifiers[1]. These methods explore larger solution spaces than convex optimization at higher computational costs and with uncertain convergence.

Despite their contributions, these methods suffer from significant limitations. First, they rely on idealized assumptions such as perfect channel state information (CSI), which rarely holds in dynamic or mobile environments[29]. This mismatch causes optimized waveforms to perform poorly in practice. Second, convex methods often require simplifications that ignore hardware realities like power amplifier constraints or peak-to-average power ratio, producing solutions that are mathematically elegant but impractical[30].

Third, ISAC systems operate in highly dynamic conditions where communication and sensing priorities shift. For example, autonomous vehicles may emphasize sensing in dense traffic and communication during highway platooning. Traditional optimization lacks the adaptability to handle such rapid transitions. Moreover, these methods struggle with scalability as ISAC expands to massive MIMO and IoT networks. Solving large-scale convex programs or running GA/PSO on resource-limited edge devices is often infeasible.

Finally, traditional approaches are ill-equipped to deal with uncertainty and imprecision. Wireless systems are characterized by ambiguous conditions such as “high interference” or “low SNR,” but convex frameworks require precise mathematical models. This rigidity limits robustness under unpredictable real-world scenarios. Experimental testbeds confirm these shortcoming [31]showed that convex-based waveform designs excelled in controlled environments but degraded significantly in field tests.

while traditional optimization techniques established important theoretical baselines, they lack robustness, adaptability, and scalability for real-world ISAC deployments. These limitations underscore the need for advanced methods particularly fuzzy and hybrid optimization which can integrate uncertainty handling, flexibility, and multi-objective adaptation into ISAC waveform design.

As limitations of traditional optimization methods became more apparent, researchers turned toward fuzzy optimization and hybrid optimization approaches as promising solutions for ISAC waveform design. These methods address critical gaps in adaptability, uncertainty handling, and scalability, making them particularly relevant for real-world deployments where dynamic environments and conflicting objectives dominate.

Fuzzy optimization is rooted in fuzzy logic theory, which models reasoning under uncertainty using linguistic variables and membership functions rather than precise mathematical values[32]. This makes it particularly well-suited for wireless environments where conditions are inherently imprecise. For example, instead of requiring exact values of channel state information (CSI), fuzzy optimization can operate with qualitative assessments such as “low interference” or “high noise.” In ISAC, fuzzy controllers can dynamically adjust waveform parameters (e.g., power allocation, subcarrier usage) to balance sensing and communication objectives under uncertain conditions[33]. By providing adaptive control, fuzzy optimization allows ISAC systems to remain robust even when the environment deviates significantly from model assumptions.

While fuzzy methods are powerful for managing ambiguity, they are often combined with other techniques to improve global optimization performance, giving rise to hybrid optimization approaches. These approaches integrate fuzzy logic with methods like genetic algorithms (GA), particle swarm optimization (PSO), or convex programming. For instance, hybrid fuzzy–GA frameworks have been applied in related wireless optimization problems to escape local minima while maintaining adaptability[34]. In ISAC, hybrid optimization could allocate resources across multiple antennas or users while dynamically adjusting waveform parameters to meet real-time sensing and communication trade-offs.

Hybrid approaches are particularly attractive for multi-objective ISAC optimization. Since communication and sensing requirements often conflict, hybrid frameworks can combine global search methods with fuzzy decision-making to explore trade-off surfaces efficiently. For example, evolutionary algorithms like PSO provide broad exploration of solution spaces, while fuzzy controllers fine-tune waveform properties to achieve balanced performance[35]. This synergy enables scalable and flexible solutions in scenarios where convex optimization is computationally prohibitive.

Recent studies also suggest that fuzzy and hybrid methods can enhance resilience to non-linear hardware effects and real-time adaptability. For example, hybrid fuzzy convex methods can enforce constant modulus constraints while optimizing SINR or sidelobe levels, making solutions more feasible for hardware implementation[36]. Similarly, combining fuzzy systems with learning-based algorithms offers a pathway toward intelligent ISAC systems capable of continuous adaptation in vehicular networks, UAV swarms, or IoT deployments.

Nevertheless, fuzzy and hybrid methods face challenges, including higher algorithmic complexity and difficulties in standardizing fuzzy rules across diverse applications. Moreover, most existing applications remain proof-of-concept demonstrations, with limited deployment in large-scale ISAC testbeds. However, the trajectory of research suggests that these methods are critical for bridging the gap between the rigid assumptions of traditional optimization and the uncertain, dynamic realities of 6G-enabled ISAC systems.

In summary, fuzzy optimization provides robustness against uncertainty, while hybrid approaches combine complementary strengths to deliver scalable and adaptive solutions. Together, they represent a promising frontier in ISAC waveform design, capable of overcoming the shortcomings of earlier methods and aligning with the demands of real-world systems

III. Comparative Analysis

A critical examination of waveform optimization approaches for Integrated Sensing and Communication (ISAC) reveals fundamental trade-offs among traditional, fuzzy, and hybrid optimization paradigms. While each approach contributes valuable insights, their effectiveness depends heavily on system requirements, environmental conditions, and hardware constraints.

Traditional optimization methods such as convex optimization, semidefinite relaxation (SDR), and evolutionary algorithms provide rigorous mathematical frameworks with proven convergence properties. Convex approaches in particular are valued for their global optimality guarantees and computational efficiency when problems are well-posed[37, 38]. However, their reliance on precise mathematical models, such as perfect channel state information (CSI), significantly reduces their robustness in real-world deployments. Stochastic methods like genetic algorithms (GA) and particle swarm optimization (PSO) extend applicability to non-convex problems but often demand high computational resources and cannot guarantee convergence within real-time constraints[2].

By contrast, fuzzy optimization excels in handling uncertainty and ambiguity. Unlike convex methods, which require exact CSI, fuzzy systems accommodate linguistic descriptors such as “low interference” or “high SNR,” allowing ISAC systems to adapt dynamically in environments where precise inputs are unavailable[13]. This makes fuzzy approaches especially attractive for vehicular communications, UAV networks, and other highly mobile contexts. The main drawback lies in their lack of global guarantees; fuzzy rules depend heavily on expert knowledge and may not scale efficiently across diverse applications.

Hybrid optimization frameworks attempt to combine the strengths of both paradigms. For example, fuzzy–GA or fuzzy–PSO systems leverage global search algorithms to explore solution spaces while using fuzzy logic for fine-tuned, adaptive control[15]. Similarly, hybrid fuzzy–convex approaches allow rule-based adaptability to be integrated into tractable optimization problems, ensuring feasibility under hardware constraints like constant modulus or PAPR[39]. These methods represent a balanced compromise: they improve adaptability and scalability but at the cost of higher algorithmic complexity and potential difficulties in implementation on low-power devices.

From a comparative perspective, traditional methods remain attractive for controlled environments (e.g., laboratory settings or static IoT deployments), where accurate CSI is available and computational resources are abundant. Fuzzy optimization is better suited for dynamic, uncertain contexts where adaptability outweighs the need for strict optimality, such as vehicular or aerial ISAC applications. Hybrid approaches hold the greatest promise for real-world deployments, offering a middle ground between robustness and feasibility, though they require careful tuning to balance complexity and performance[40].

Table 1 Comparative Summary of ISAC Optimization Approaches

Approach	Strengths	Weaknesses	Best Applications	Key References
Convex Optimization (SDR, linear programming)	Global optimality; efficient for well-posed problems; strong mathematical guarantees	Relies on precise CSI; poor adaptability; ignores hardware nonlinearities	Controlled environments; static IoT or radar-comm co-design	[8, 9]
Stochastic Optimization (GA, PSO, etc.)	Handles non-convex problems; explores large solution spaces	High computational cost; slow convergence; unsuitable for strict real-time	Medium-scale ISAC with moderate dynamics	[21]

Fuzzy Optimization	Models uncertainty; adapts to imprecise/linguistic inputs; robust in dynamic environments	No global guarantees; dependent on expert-defined rules; scalability issues	Vehicular networks, UAV swarms, mobile IoT	[13]
Hybrid Optimization (Fuzzy–GA, Fuzzy–Convex, etc.)	Combines adaptability with global search; balances performance and feasibility; enforces hardware constraints	Complex design; higher computational load; limited large-scale validation	6G-enabled ISAC, multi-user and multi-target scenarios	[33, 39]

A critical insight from this comparison is that there is no "one-size-fits-all" solution for ISAC waveform design. Each method offers a trade-off between mathematical rigor, adaptability, computational cost, and feasibility. Convex methods provide theoretical elegance but practical rigidity, fuzzy systems provide adaptability but lack guarantees, and hybrid approaches aim for balanced performance at the cost of complexity.

This highlights the need for context-aware selection of optimization strategies. For example, in smart cities with dense IoT deployments but relatively stable channels, convex optimization may suffice. In contrast, highly mobile environments such as UAV networks benefit more from fuzzy or hybrid frameworks. For future 6G applications, where adaptability, scalability, and robustness are paramount, hybrid optimization appears to be the most viable pathway.

IV. Challenges And Future Research Directions

While significant progress has been made in Integrated Sensing and Communication (ISAC) waveform optimization, the transition from theoretical models to real-world deployment remains fraught with challenges. These challenges stem from the scalability, real-time adaptability, hardware feasibility, standardization, and security dimensions of ISAC systems. Addressing these barriers is essential for realizing the full potential of ISAC in 6G and beyond.

Key Challenges

Scalability in Massive ISAC Systems.

ISAC is expected to be deployed in dense environments such as smart cities, autonomous transportation networks, and industrial IoT ecosystems. In these scenarios, massive numbers of antennas, users, and devices create optimization problems of prohibitive dimensionality. Traditional convex and stochastic algorithms already struggle with scaling, and even fuzzy or hybrid approaches face computational bottlenecks when extended to massive MIMO or distributed IoT networks. Scalable solutions are therefore critical for ensuring feasibility in large deployments.

Real-Time Constraints.

ISAC applications such as vehicular networks and UAV swarms demand millisecond-level decision-making. Optimization algorithms that require extensive iterations such as genetic algorithms or hybrid fuzzy evolutionary methods may not converge fast enough to be useful in highly dynamic environments. The challenge lies in balancing optimization accuracy with computational speed, especially for edge devices with limited resources.

Hardware Feasibility and Nonlinearities.

Most waveform optimization frameworks assume idealized hardware. In practice, devices face power amplifier nonlinearities, phase noise, constant modulus requirements, and PAPR constraints. Solutions that ignore these factors often fail in implementation. Hardware-aware optimization is still an underexplored area, particularly for low-cost IoT nodes and energy-constrained edge devices.

Standardization and Interoperability.

Unlike communication standards such as 5G NR, ISAC currently lacks standardized frameworks for waveform design. Without unified protocols, waveform optimization solutions risk being fragmented, limiting interoperability across systems and vendors. Establishing standardization will require collaboration across academia, industry, and regulatory bodies.

Security, Privacy, and Trust.

ISAC waveforms are vulnerable to adversarial attacks, jamming, spoofing, and eavesdropping. While waveform design traditionally emphasizes sensing and communication trade-offs, little attention has been paid to embedding security and privacy constraints within optimization frameworks. As ISAC becomes integral to critical infrastructure and defense, integrating trust, cryptographic protocols, and privacy-preserving designs is no longer optional.

Future Research Directions

AI-Driven Optimization.

Artificial intelligence, particularly deep reinforcement learning and federated learning, offers powerful tools for real-time, data-driven optimization. Integrating AI with fuzzy and hybrid optimization could enable self-learning ISAC systems that adapt continuously to changing environments without relying on precise models.

Cross-Layer Optimization.

Future ISAC solutions must extend beyond the physical layer to include network resource allocation, spectrum sharing, and scheduling. Cross-layer optimization frameworks would allow waveform design to interact seamlessly with higher-layer protocols, improving overall system efficiency.

Quantum-Inspired and Bio-Inspired Algorithms.

Emerging paradigms such as quantum-inspired optimization and bio-inspired algorithms could accelerate convergence in large-scale ISAC problems. For example, quantum-inspired genetic algorithms may explore solution spaces more efficiently, while swarm-intelligence approaches could offer scalable heuristics for distributed ISAC systems.

Edge Intelligence and Energy Efficiency.

Deploying ISAC optimization on resource-constrained edge devices requires lightweight, energy-efficient algorithms. Techniques such as model compression, pruning, and approximate computing should be investigated to enable real-time fuzzy–hybrid optimization at the edge.

Security- and Privacy-Aware Optimization.

Future ISAC frameworks must incorporate privacy-preserving optimization and resilience to adversarial attacks. For example, embedding cryptographic constraints into waveform design or applying differential privacy to fuzzy decision-making could protect sensitive sensing data while maintaining communication efficiency (Feng et al., 2022).

Large-Scale Experimental Validation.

Although simulation-based studies dominate the literature, large-scale ISAC testbeds are urgently needed to validate fuzzy and hybrid optimization methods under realistic conditions. Prototypes such as those developed for 6G research [2] should be expanded to include field trials in vehicular, aerial, and industrial IoT contexts.

In summary, the challenges of scalability, real-time operation, hardware feasibility, standardization, and security highlight the gap between current ISAC research and practical deployment. Future directions point to AI-driven, cross-layer, and security-aware optimization frameworks, with an emphasis on lightweight, scalable, and adaptive designs. Addressing these challenges will be essential for enabling ISAC to serve as a cornerstone of 6G-enabled cyber–physical–social systems.

V. Conclusion

Integrated Sensing and Communication (ISAC) has emerged as a cornerstone technology for 6G and beyond, enabling simultaneous data transmission and environmental sensing on shared hardware and spectrum resources. Central to its success is the waveform design problem, which must balance competing objectives such as communication throughput, sensing resolution, hardware feasibility, and real-time adaptability. This review has critically analyzed the state of the art, focusing on traditional, fuzzy, and hybrid optimization approaches.

The discussion showed that traditional optimization methods, including convex and semidefinite relaxation (SDR) techniques, provide theoretical rigor and tractability but struggle with real-world uncertainty, non-linear hardware effects, and scalability. Fuzzy optimization, by contrast, excels in dynamic and uncertain environments by modeling imprecise system conditions using linguistic rules. However, its lack of global guarantees and dependence on expert knowledge limit standardization. Hybrid approaches that integrate fuzzy logic with stochastic or convex optimization offer a balanced pathway, combining adaptability with mathematical rigor. These methods appear most promising for 6G-enabled ISAC systems, though they introduce complexity and demand efficient implementations.

This review contributes to the field by providing a comparative analysis of optimization approaches and explicitly identifying their strengths, weaknesses, and application domains. Unlike earlier surveys that mainly catalog methods, this work has synthesized findings into a critical framework that highlights where each method is most effective convex for controlled environments, fuzzy for dynamic uncertainty, and hybrid for large-scale real-world deployments. It also mapped out the open challenges in scalability, real-time adaptability, hardware feasibility, standardization, and security, while proposing future research directions such as AI-driven fuzzy hybrid systems, cross-layer optimization, quantum-inspired algorithms, and security-aware waveform design.

In doing so, this review has not only consolidated the current state of ISAC waveform optimization but also offered a forward-looking research agenda. By clarifying the trade-offs among optimization paradigms and pointing to emerging opportunities, it equips researchers, engineers, and policymakers with insights into how ISAC can be effectively advanced from theory to practice.

In conclusion, this paper emphasizes that while traditional optimization established the theoretical foundations, it is the fuzzy and hybrid approaches potentially enhanced by AI and validated through large-scale testbeds that will drive the future of ISAC. By providing a structured synthesis and critical outlook, this review contributes a valuable roadmap for advancing adaptive, scalable, and secure ISAC waveform design as a central enabler of 6G networks, autonomous systems, and smart infrastructures.

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