A Survey on Massive MIMO ISAC 6G UAV Joint Communication and Sensing Waveform Optimization and Spectral Efficiency

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Abstract

This survey paper explores the integration of advanced wireless technologies, including Massive MIMO, Integrated Sensing and Communication (ISAC), 6G networks, and Unmanned Aerial Vehicles (UAVs), highlighting their potential to enhance spectral efficiency, resource allocation, and overall network performance in next-generation systems. The study emphasizes the transformative impact of these technologies, particularly in optimizing communication and sensing functionalities within ISAC frameworks. Key advancements include the use of Reconfigurable Intelligent Surfaces (RIS) for improved sensing accuracy and the development of innovative beamforming and power allocation strategies. The paper also addresses significant challenges such as balancing communication and sensing trade-offs, managing interference, and ensuring security and privacy. Future directions suggest a focus on adaptive algorithms, multi-sensory integration, and enhanced security protocols to further advance ISAC capabilities. The findings underscore the necessity for standardization and continued innovation to realize the full potential of these technologies in future wireless networks. By systematically analyzing current methodologies and proposing new research avenues, this survey provides a comprehensive understanding of the challenges and opportunities in optimizing communication and sensing trade-offs in next-generation wireless systems.

1 Introduction

1.1 Context and Relevance

The transition to sixth-generation (6G) networks is driven by the need to overcome the limitations of fifth-generation (5G) systems, particularly in environmental sensing and communication. Integrated Sensing and Communication (ISAC) is emerging as a crucial technology for future wireless networks, enabling simultaneous sensing and communication tasks. By utilizing a shared hardware platform, ISAC enhances spectral and energy efficiencies, leading to improved network quality and expanded service scenarios. Multi-point and multi-beam ISAC systems further optimize performance through advanced beamforming techniques, addressing challenges such as fading and interference. This approach maximizes hardware and spectrum resource utilization while offering greater flexibility in managing communication and sensing trade-offs, which is essential for achieving the high throughput, reliability, and low latency required for ubiquitous connectivity and advanced sensing capabilities [1, 2, 3]. The integration of radar and communication functionalities enhances equipment efficiency in terms of size, weight, cost, power consumption, and spectrum efficiency, which is vital for 6G networks.

ISAC systems facilitate spectrum and hardware resource sharing for dual functionalities within the same time-frequency block, optimizing resource allocation [4]. The incorporation of unmanned aerial vehicles (UAVs) and reconfigurable intelligent surfaces (RIS) further enhances this integration, addressing challenges in next-generation mobile networks [5]. Multi-beam ISAC technologies are

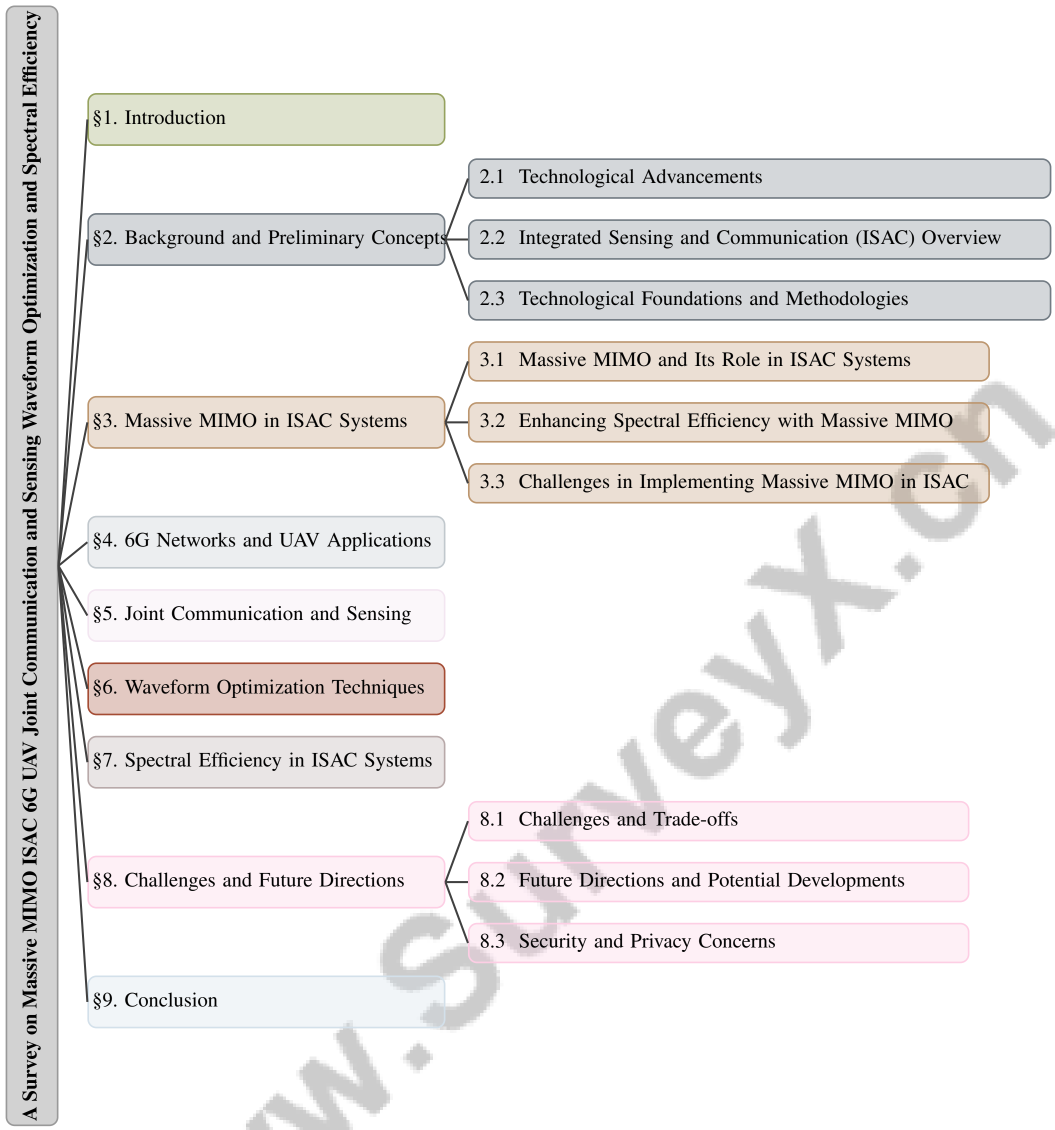

Figure 1: chapter structure

critical for concurrent location/motion detection and communication, essential for high-precision sensing applications.

The growing demand for Internet of Everything (IoE) applications has led to spectrum congestion, prompting research into ISAC as a means to alleviate spectrum scarcity and interference issues [6]. A carrier aggregation (CA)-enabled MIMO-OFDM ISAC system, utilizing multiple frequency bands, has been proposed to overcome the limitations of communication and sensing capabilities within a single frequency band [7]. Furthermore, embedding sensing capabilities into communication systems is crucial for enhancing sensing services and reducing costs [8].

The integration of sensing and communication functionalities is vital for the sustainability of 6G networks, supporting smart city initiatives, connected vehicles, and healthcare advancements by leveraging existing wireless infrastructures such as WiFi and 4G/5G [9]. Machine learning techniques in ISAC systems are being explored to address existing knowledge gaps, emphasizing the need for innovative approaches to optimize communication and sensing performance simultaneously [10].

In the rapidly evolving technological landscape, ISAC systems are pivotal in addressing challenges related to efficient spectrum utilization and minimizing hardware costs. These systems tackle significant knowledge gaps in ISAC signal design and optimization while leveraging advanced beamforming techniques to improve metrics such as outage probability, communication rate, and sensing rate. By adopting network-level approaches that incorporate interference mitigation strategies, ISAC systems can effectively manage various types of interference, including self-interference and multiuser interference, thus maximizing operational efficiency across diverse scenarios [11, 12]. Sparse MIMO is identified as a promising architecture for ISAC in future 6G networks, addressing the limitations of conventional compact MIMO systems. Advances in multi-antenna technology significantly enhance both wireless communication reliability and radar sensing performance, underscoring the potential of fixed and movable antenna technology in 6G networks. This survey systematically explores the evolutionary path and current research status of ISAC technologies, particularly in resource allocation, providing insights essential for supporting emerging wireless services, such as unmanned vehicles and holographic communication.

1.2 Objectives of the Survey

This survey aims to develop a comprehensive understanding of Integrated Sensing and Communication (ISAC) systems, focusing on optimizing communication and sensing functionalities through advanced resource allocation and waveform design techniques. By leveraging massive MIMO, 6G, UAVs, and waveform optimization, the survey seeks to enhance spectral efficiency and joint communication and sensing capabilities, addressing inter-functionality interference and optimizing trade-offs between communication and sensing performances [5].

A significant aspect of the survey is the exploration of joint sensing and communication (JSC) beamforming designs that optimize both functionalities under severe channel conditions and resource constraints. The capabilities of intelligent reflecting surfaces (IRS) to enhance millimeter-wave ISAC system performance, especially in obstructed line-of-sight (LoS) scenarios, are thoroughly examined. The study highlights the advantages of IRS deployment, such as improved coverage, interference suppression, and enhanced parameter estimation, while exploring innovative IRS-assisted ISAC protocols that utilize beam scanning and reflective beamforming to optimize both communication and sensing functionalities [13, 14, 15].

This survey also aims to enhance the sensing quality of service (QoS) in communication-assisted sensing (CAS) systems by leveraging communication functionalities to improve sensing performance, particularly for targets beyond the line of sight. It investigates a dual-functional signaling strategy within an information-theoretic framework that connects achievable distortion, coding rate, and communication channel capacity. The survey discusses optimal channel input design and waveform optimization for Gaussian signals in multi-input multi-output (MIMO) CAS systems, addressing trade-offs between sensing and communication processes. Additionally, it presents a waveform design framework for 6G perceptive networks that optimizes sensing QoS through innovative transmission schemes, achieving a performance improvement of approximately 25

The survey also focuses on minimizing average power consumption in UAV-enabled ISAC systems while ensuring communication QoS and successful sensing, particularly in scenarios with limited backhaul capacity. It addresses security challenges in ISAC systems, emphasizing the enhancement of communication security against threats like malicious Sybil attacks, reducing latency for improved system efficiency, and increasing identity mapping accuracy in UAV networks to facilitate reliable interactions across dual identity domains [8, 16, 17].

By examining network-level ISAC strategies, the survey seeks to enhance communication and sensing capabilities through multi-cell cooperation, addressing inefficiencies in dense multi-cell ISAC networks due to inter-cell interference. It highlights the critical need for improved spatial resolution and operational efficiency in ISAC applications, particularly by overcoming the limitations of traditional compact MIMO systems. Sparse MIMO architectures offer larger array apertures, improving performance in both wireless communication and sensing, thereby paving the way for advanced applications in future 6G networks [10, 18, 19, 20].

Finally, the survey explores the optimization of multi-user MIMO ISCPT systems, balancing the performance requirements of sensing, communication, and power transfer. It aims to ensure physical layer security in multi-user multi-input single-output communication systems coexisting with colocated MIMO radar systems. The survey provides a comprehensive understanding of the challenges and opportunities associated with optimizing communication and sensing trade-offs in next-generation wireless networks, particularly in the context of ISAC for 6G. By integrating advanced sensing capabilities at both the network infrastructure and user equipment levels, the survey demonstrates how these technologies can enhance resilience to channel-dependent effects and adapt to dynamic environments. It offers an analytical toolkit for modeling ISAC system performance, identifies key performance indicators, and discusses practical constraints and potential scenarios for future deployment, thus paving the way for more effective communication and sensing integration in cellular networks [21, 22].

1.3 Structure of the Survey

This survey is organized into several sections, each addressing critical aspects of Integrated Sensing and Communication (ISAC) systems and their interplay with advanced wireless technologies. The paper begins with an introduction that establishes the context and relevance of ISAC in the evolving landscape of 6G networks, emphasizing the necessity for efficient resource utilization and the integration of sensing and communication functionalities. Following this, a detailed discussion of the survey's objectives aims to enhance spectral efficiency and joint communication and sensing capabilities through the application of massive MIMO, UAVs, and waveform optimization techniques.

The second section delves into the background and preliminary concepts, providing an overview of core technologies such as massive MIMO, ISAC, 6G, UAV, joint communication and sensing, waveform optimization, and spectral efficiency, explaining their interrelations and significance in modern wireless communication systems.

The third section focuses on massive MIMO in ISAC systems, exploring its role in enhancing ISAC capabilities, improving spectral efficiency, and enabling joint communication and sensing. This section reviews existing literature on massive MIMO implementations in ISAC contexts, examining performance trade-offs and signal processing aspects [23].

The fourth section examines 6G networks and UAV applications, discussing the potential of 6G technologies to support advanced UAV applications and facilitate enhanced communication and sensing capabilities. It reviews case studies and current research on UAV-enabled ISAC systems, categorizing research into various stages, including monostatic, bistatic, and multistatic sensing [21].

The fifth section analyzes the integration of joint communication and sensing functionalities in wireless networks, emphasizing the benefits and challenges of this integration. It includes a comparative analysis of different ISAC techniques and their effectiveness.

The sixth section explores various waveform optimization techniques used in ISAC systems to enhance performance. This section discusses how these techniques contribute to improved spectral efficiency and effective joint communication and sensing, reviewing recent advancements and methodologies in waveform design.

The seventh section discusses the importance of spectral efficiency in ISAC systems, analyzing strategies to maximize spectral efficiency while maintaining robust communication and sensing capabilities, along with a review of current research and potential future directions.

The eighth section identifies key challenges faced in the integration of massive MIMO, ISAC, 6G, UAV, joint communication and sensing, waveform optimization, and spectral efficiency. It discusses potential solutions and future research directions, exploring the application of machine learning and optimization techniques to improve ISAC performance [21].

The survey concludes with a comprehensive summary of key findings, emphasizing the critical importance of integrating advanced technologies such as ISAC in future wireless communication systems. It discusses the implications of these technologies for enhanced spectrum utilization, reduced latency, and improved network resilience, while outlining the potential for innovative applications and services. Furthermore, the survey identifies key performance indicators and open research questions that need to be addressed to facilitate the successful deployment of these technologies in the evolving landscape of 6G and beyond [23, 24, 25, 21, 22].The following sections are organized as shown in Figure 1.

2 Background and Preliminary Concepts

2.1 Technological Advancements

Advancements in wireless communication, particularly in massive MIMO, Integrated Sensing and Communication (ISAC), 6G, and Unmanned Aerial Vehicle (UAV) systems, have significantly reshaped technological landscapes. The integration of massive MIMO with ISAC addresses the complex challenge of simultaneous channel state information (CSI) and target parameter estimation, a task complicated by numerous antennas and the need for precise training resources. This complexity is especially notable in UAV communications, where pilot contamination and accurate CSI and beam tracking are critical [24].

Progress in 6G focuses on integrating terahertz (THz) communications with sensing, enhancing energy efficiency and high-resolution capabilities essential for next-generation applications [25]. UAV-enabled ISAC systems investigate joint sensing and communication protocols, UAV motion control, and resource allocation, though deploying UAV base stations raises security concerns due to potential eavesdropping on line-of-sight transmissions [26].

ISAC integration with smart propagation engineering shows promise in dynamic environments, enhancing communication and sensing functionalities [9]. However, the scalability and implementation of cell-free massive MIMO systems present challenges in maintaining system complexity and cost as dimensionality increases, a gap that current methods have yet to effectively address [27].

Optimization frameworks for MIMO-ISAC systems focus on transmit beamforming and resource allocation strategies [27]. Sparse MIMO architectures significantly improve spatial resolution and sensing capabilities, enhancing communication and radar functions [10]. Integrating sensing, communication, and power transfer (ISCPT) is vital for enhancing radio resource efficiency and enabling effective data communication [28].

Collectively, advancements in massive MIMO, ISAC, 6G networks, and UAV technologies illustrate a significant transformation in wireless communication systems. These innovations enhance performance through improved coverage and resilience against channel-dependent effects, optimize resource allocation via advanced signal processing and machine learning techniques, and facilitate the seamless integration of communication and sensing functionalities. UAVs serve as aerial platforms for enhanced sensing and communication services, while ISAC systems enable simultaneous high-resolution sensing and robust communication, paving the way for a more perceptive and adaptive network infrastructure in future wireless environments [23, 21, 29, 30].

2.2 Integrated Sensing and Communication (ISAC) Overview

Integrated Sensing and Communication (ISAC) systems represent a paradigm shift in wireless communication, merging sensing and communication functionalities within a unified framework to enhance spectral and energy efficiencies, pivotal for sixth-generation (6G) networks. ISAC utilizes a single waveform to serve radar and communication functions simultaneously, optimizing resource usage and system performance [31].

ISAC systems leverage cooperative use of multiple transceivers to optimize communication throughput and sensing accuracy, facilitated by advancements in stochastic geometry and coordinated beamforming [4]. This cooperative approach enhances system performance while addressing critical challenges such as resource allocation and interference management, essential in densely populated wireless environments [4].

The integration of ISAC with UAVs extends its applications, enabling coordinated transmit beamforming at Ground Base Stations (GBSs) and optimizing UAV trajectories to maximize communication performance while fulfilling sensing requirements [5]. This synergy facilitates periodic execution of sensing tasks alongside communication services, optimizing overall system performance [5].

A critical aspect of ISAC is the design of dual-function waveforms that balance radar sensing and communication performance, focusing on enhancing radar capabilities while achieving beamforming gains for communication. These designs are crucial for maintaining Quality of Service (QoS) in scenarios involving multi-target interference and effective sidelobe suppression [7]. Joint secure transmit beamforming designs enhance communication security without compromising radar performance, ensuring robust operation in adversarial environments [4].

2.3 Technological Foundations and Methodologies

The foundational technologies and methodologies underpinning ISAC systems are essential for optimizing the dual functionalities of sensing and communication within a unified framework. A primary challenge is the efficient allocation of limited wireless resources to simultaneously accommodate both functions, maximizing system performance and ensuring effective utilization of spectrum and hardware resources [32].

Symbol-level precoding (SLP) plays a crucial role in waveform design for ISAC systems, enabling simultaneous optimization of radar and communication functions. This technique efficiently manages trade-offs between these functionalities, enhancing overall system performance [33].

Movable Antenna Enhanced Networked Full-Duplex ISAC (MA-FD ISAC) optimizes beamforming, power allocation, receiving filters, and movable antenna configurations, maximizing communication sum rate while ensuring high radar sensing quality [34]. The concept of Multi-Point Integrated Sensing and Communication (MPISAC) exemplifies the integration of multiple dual-functional radars (DFRs) to enhance sensing performance, effectively managing the trade-off between sensing and communication [1].

Reconfigurable Intelligent Surfaces (RIS) have emerged as a significant advancement in ISAC systems, offering additional degrees of freedom and improving signal propagation. The dual-sided STAR-RIS design facilitates simultaneous communication and sensing, enhancing system efficiency and performance [35].

Cooperative ISAC frameworks utilize Orthogonal Frequency-Division Multiplexing (OFDM) signals for communication and target localization, highlighting the potential of cooperative networks to enhance system performance through coordinated tasks [36]. Optimizing training and transmission signals in MIMO ISAC systems aims to minimize the weighted sum of mean-squared errors (MSEs) for both communication and radar target response matrix estimation, demonstrating the intricate balance between these dual functionalities [37].

IRS-enabled sensing architectures are categorized into fully-passive, semi-passive, and active systems, each offering distinct capabilities and limitations, emphasizing diverse approaches to integrating IRS into ISAC systems based on specific application scenarios [38].

The technological foundations and methodologies of ISAC systems are crucial for optimizing resource allocation, managing interference, and enhancing integration techniques. These methodologies facilitate the advancement of 6G networks and future wireless technologies, supporting simultaneous data transmission and environmental sensing, and driving the evolution of next-generation wireless infrastructures [23, 39, 40, 41, 21].

In recent years, the integration of Massive MIMO technology into Integrated Sensing and Communication (ISAC) systems has garnered significant attention due to its potential to enhance performance and efficiency. Figure 2 illustrates the hierarchical structure of the role, enhancements, and challenges of Massive MIMO in these systems. This figure categorizes the contributions of Massive MIMO to ISAC, outlines strategies to enhance spectral efficiency, and highlights the challenges faced during implementation. By examining these aspects, we can better understand the multifaceted impact of Massive MIMO on ISAC, paving the way for future research and development in this critical area.

3 Massive MIMO in ISAC Systems

3.1 Massive MIMO and Its Role in ISAC Systems

Massive Multiple-Input Multiple-Output (MIMO) technology plays a pivotal role in enhancing Integrated Sensing and Communication (ISAC) systems by leveraging extensive antenna arrays to augment spatial resolution, sensing precision, and spectral efficiency. This integration addresses the architectural challenges of unifying communication, localization, and sensing in distributed MIMO networks [42], enabling simultaneous optimization of these functions and enhancing system performance.

As depicted in Figure 3, the figure illustrates the role of Massive MIMO in ISAC systems, highlighting key advancements such as sparse MIMO systems for improved spatial resolution, joint secure beamforming to enhance communication security, and UAV-enabled ISAC for optimized resource

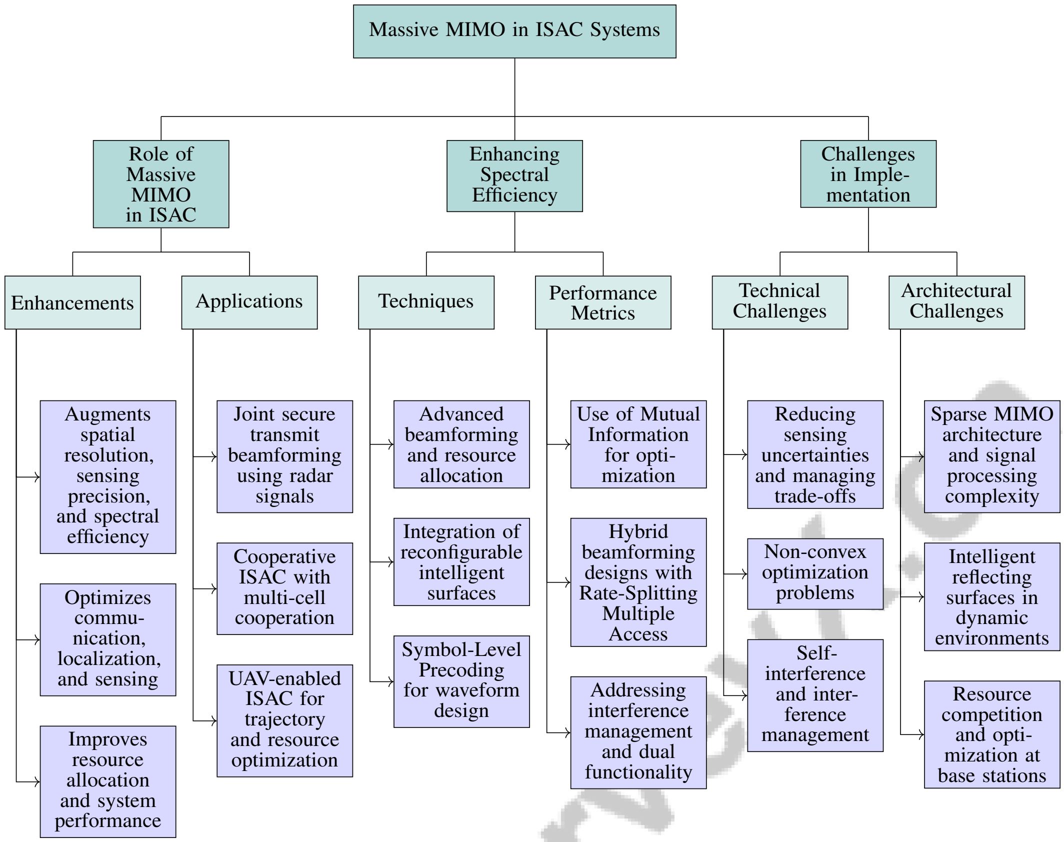

Figure 2: This figure illustrates the hierarchical structure of the role, enhancements, and challenges of Massive MIMO in Integrated Sensing and Communication (ISAC) systems. It categorizes the contributions of Massive MIMO to ISAC, strategies to enhance spectral efficiency, and challenges faced in implementation.

allocation and power savings. Sparse MIMO systems, particularly effective in near-field scenarios, surpass compact MIMO systems by achieving superior spatial resolution and efficiency [10]. They adeptly balance the trade-offs between communication and sensing, optimizing resource allocation and overall performance [31]. The multi-point ISAC framework exemplifies this balance by enhancing sensing accuracy through data fusion and adaptive task selection [1].

Joint secure transmit beamforming in massive MIMO ISAC systems utilizes radar signals as jamming signals to bolster communication security, illustrating the multifaceted benefits of massive MIMO [6]. The Cooperative ISAC (C-ISAC) approach, leveraging multi-cell cooperation, further optimizes resource allocation and mitigates interference [9].

In UAV-enabled ISAC systems, massive MIMO optimizes trajectory and resource allocation, yielding substantial power savings and enhanced capabilities [26]. The networked ISAC approach integrates functionalities, effectively managing interference and outperforming isolated systems [5].

Massive MIMO is thus crucial for ISAC evolution, providing infrastructure for improved spatial resolution, efficient resource allocation, and better integration of functionalities. As research progresses, massive MIMO's role is expected to expand, facilitating innovations in next-generation wireless networks. This integration leverages spatial beamforming gains, enhancing communication rates and sensing capabilities. Studies indicate that massive MIMO-ISAC systems manage multi-user interference while optimizing performance metrics like the Cramér-Rao lower bound and spectral efficiency. Emerging architectures like sparse MIMO and decentralized hybrid precoding promise to enhance hardware efficiency and power consumption, essential for the transition to 6G networks. These advancements improve ISAC operational characteristics and enable new functionalities vital for future applications [20, 43, 44, 19, 45].

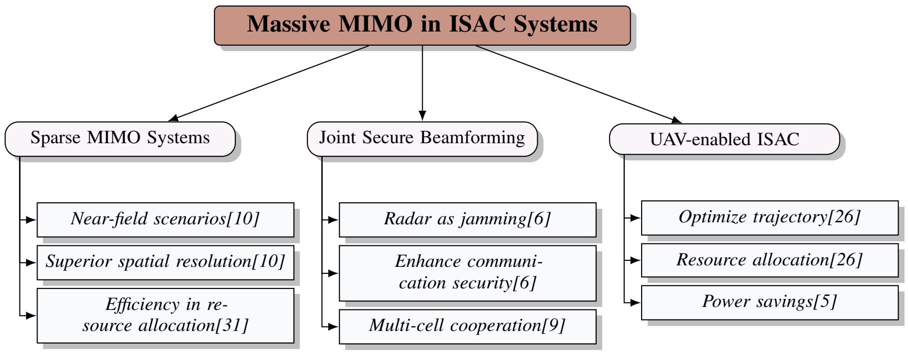

Figure 3: This figure illustrates the role of Massive MIMO in ISAC systems, highlighting key advancements such as sparse MIMO systems for improved spatial resolution, joint secure beamforming to enhance communication security, and UAV-enabled ISAC for optimized resource allocation and power savings.

3.2 Enhancing Spectral Efficiency with Massive MIMO

Benchmark	Size	Domain	Task Format	Metric
ISAC[46]	1,000,000	Radar Sensing	Object Detection	Localization Accuracy, Detection Rate
MaMIMO-UAV[47]	5,000,000	Wireless Communications	Channel Characterization	Spectral Efficiency, RMS Delay Spread
MIMO-ISAC[20]	1,000	Wireless Communications	Performance Analysis	SR, CR
ISAC[48]	1,000	Radar Sensing	Object Detection	SNR, Range Standard Deviation
ADB[49]	100,000	Dynamic Systems	Adaptability Assessment	Accuracy, Robustness Score

Table 1: This table presents a comprehensive overview of representative benchmarks utilized in the evaluation of Integrated Sensing and Communication (ISAC) systems. It details key attributes such as benchmark size, domain of application, task format, and performance metrics, providing insights into the diverse methodologies employed in ISAC research.

Enhancing spectral efficiency in ISAC systems via massive MIMO involves advanced beamforming, resource allocation, and innovative waveform designs. The integration of reconfigurable intelligent surfaces (RISs) significantly improves beamforming, optimizing radar mutual information (MI) and communication rates [50]. This optimization is critical for achieving high spectral efficiency by managing trade-offs between communication and sensing.

Symbol-Level Precoding (SLP) for low-range-sidelobe waveform design enhances spectral efficiency by minimizing interference and improving signal quality [33]. This technique underscores the potential of innovative waveform designs in maximizing massive MIMO performance.

Joint UAV Maneuver and Beamforming Design (JUMBD) significantly contributes to spectral efficiency by maximizing communication rates while satisfying sensing constraints in UAV-enabled ISAC systems [51]. This approach highlights the importance of dynamic resource allocation and trajectory optimization.

Utilizing Mutual Information (MI) as a performance metric streamlines optimization, providing a unified framework for evaluating communication and sensing performance. This approach allows simultaneous maximization of communication and sensing MI, addressing domain interactions. Simulations show ISAC systems leveraging MI outperform traditional techniques, leading to enhanced performance [52, 53, 54]. Hybrid beamforming designs, particularly those aided by Rate-Splitting Multiple Access (RSMA), further reduce interference, enhancing performance in mmWave ISAC schemes.

These strategies address challenges like interference management and dual functionality integration. Performance analyses reveal ISAC systems achieve larger high signal-to-noise ratio slopes and broader sensing rate-communication rate regions compared to traditional methods. Sparse MIMO architecture enhances spatial resolution and performance, paving the way for advancements in 6G

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technology [19, 20, 55]. As research progresses, these strategies will be crucial in developing next-generation networks, facilitating efficient integration of communication and sensing functionalities. Table 1 provides a detailed overview of the benchmarks used in the performance analysis of ISAC systems, highlighting their size, domain, task format, and evaluation metrics.

3.3 Challenges in Implementing Massive MIMO in ISAC

Implementing Massive MIMO in ISAC systems involves addressing challenges from the dual functionalities of communication and sensing. A major obstacle is reducing sensing uncertainties while managing the trade-off between sensing and communication, complicated by binary functionality selection [1]. This trade-off is exacerbated by severe self-interference (SI), complicating radar echo detection despite existing SI cancellation techniques.

The non-convex nature of optimization problems presents additional challenges, particularly in optimizing transceiver beamforming and UAV trajectories in dynamic environments [16]. The coupling of downlink and uplink transmissions introduces interference from both desired target echoes and undesired signals, complicating optimization [56].

Sparse MIMO architectures enhance spatial resolution but introduce challenges like managing grating lobes from larger inter-antenna spacing and the complexity of signal processing needed for effective communication and sensing [10]. These challenges are compounded by limited degrees of freedom (DoF) for concurrently optimizing performance metrics, necessitating innovative approaches [50].

Implementing intelligent reflecting surfaces (IRS) in dynamic environments presents further complications, including joint signal processing, accurate channel estimation, and managing multiple signal paths [13]. Mixed-integer optimization problems from having fewer RF chains than antennas complicate efficient antenna selection and covariance matrix optimization [57].

In cooperative ISAC networks, increased signaling overhead and resource consumption impact efficiency, while UAV motion introduces variations in angle of arrival (AoA) and departure (AoD) that current methods struggle to address. The trade-off between communication and sensing performance in complex environments leads to significant losses in communication efficacy [34].

Finally, competition for system resources at the base station complicates effective utilization of communication channels to enhance sensing performance, emphasizing the need for advanced strategies [58]. These challenges highlight the necessity for innovative solutions to optimize massive MIMO integration in ISAC systems, advancing next-generation wireless networks.

4 6G Networks and UAV Applications

4.1 6G Networks and UAV Integration

Integrating sixth-generation (6G) networks with Unmanned Aerial Vehicles (UAVs) marks a significant advancement in Integrated Sensing and Communication (ISAC) systems, enhancing both communication and sensing through sophisticated resource management. This synergy notably improves UAV performance in low-altitude environments by merging communication and sensing capabilities [5]. Air-integrated sensing and communication (Air-ISCC) within the 6G framework facilitates ubiquitous Internet of Things (IoT) services, bolstering both communication and sensing capabilities [7].

A key innovation is the deployment of cell-free massive MIMO systems, which utilize a distributed network of access points to ensure seamless coverage, especially in densely populated urban areas. This approach optimizes resource allocation by effectively combining cell association with the distribution of communication and sensing power, significantly enhancing both the system's average sum rate and localization quality of service (QoS). The alternating iteration algorithm based on optimal transport theory (AIBOT) has achieved a nearly 12% increase in system sum rate and a 29% reduction in localization Crámer-Rao bound (CRB) compared to traditional methods [59, 30]. Sparse MIMO technology also offers a cost-effective approach to achieving 6G ISAC objectives, enhancing spatial resolution and capabilities for both communication and sensing.

Integrating UAVs with 6G networks presents complex optimization challenges, particularly regarding energy efficiency and trajectory planning. The non-convex nature of these optimization problems

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necessitates innovative strategies for maximizing energy efficiency and overall system performance. Hybrid beamforming and trajectory optimization techniques are crucial for enhancing UAV operational efficiency within ISAC systems. These strategies enable optimal resource utilization by maximizing user achievable rates through the joint optimization of UAV trajectories, transmit precoders, and sensing parameters, while adhering to constraints such as sensing frequency and beam pattern gain. By effectively managing trade-offs between communication and sensing functionalities, these approaches significantly enhance system capabilities, ensuring high-quality data acquisition and communication performance under limited backhaul capacity and stringent QoS requirements [17, 60, 51, 61, 62].

Carrier Aggregation (CA)-enabled MIMO-OFDM ISAC systems are anticipated to play a vital role in the evolution of 6G mobile communication systems, offering improved performance through resource sharing and optimized signal processing. Despite advancements, challenges such as limited coverage for sensing services, synchronization complexities among multiple UAVs, and scalability issues in distributed systems persist. These challenges are exacerbated by UAV size, weight, and power constraints, necessitating effective motion control and resource management for optimized performance in dynamic environments. Addressing these challenges is essential for unlocking the full potential of UAV-enabled ISAC in next-generation wireless networks, such as 6G [8, 30, 63].

The integration of 6G networks with UAVs represents a transformative opportunity for advancing ISAC systems. By employing UAVs as aerial platforms, this integration enhances coverage and improves the efficiency of sensing and communication services while addressing challenges related to size, weight, and power constraints. Furthermore, it enables innovative applications such as communication-assisted sensing and sensing-assisted communication, ultimately driving significant advancements in next-generation wireless communication networks and paving the way for more secure and efficient multi-functional networks [23, 30, 39]. This integration is expected to play a crucial role in the evolution of wireless communication, unlocking new possibilities for enhanced performance and resource utilization in ISAC systems.

4.2 Applications of UAVs in 6G Networks

Incorporating UAVs within the sixth-generation (6G) networks framework creates new opportunities for enhancing Integrated Sensing and Communication (ISAC) capabilities, particularly in Joint Communication and Sensing (JCAS) systems. Combined with MIMO technology, UAVs significantly improve spatial resolution and communication reliability, essential for effective JCAS deployment [64]. This integration allows UAVs to function as mobile base stations or relay nodes, enhancing coverage and connectivity in remote or challenging environments.

A notable application is UAVs' role in Backscatter Integrated Sensing and Communication (B-ISAC) systems, which leverage low-power backscatter communication to enhance IoT scenarios where energy efficiency is critical. UAVs equipped with B-ISAC technology can provide ubiquitous sensing and communication services, particularly in energy-constrained environments, by reflecting existing signals to convey information without active transmission [65].

UAVs also facilitate advanced power allocation strategies within massive MIMO ISAC systems. Their strategic deployment enables dynamic power distribution and beamforming techniques that optimize communication and sensing performance. In a mono-static massive MIMO ISAC system simulation, UAVs can be positioned to maximize coverage and signal quality, with users distributed within a 1000m radius and targets at varying distances. This configuration allows performance evaluation under different signal-to-noise ratio (SNR) conditions, demonstrating UAVs' potential to enhance ISAC capabilities across diverse operational scenarios [43].

The applications of UAVs in 6G networks are diverse and impactful, significantly enhancing ISAC systems through improved mobility, flexibility, and resource management. As research in wireless communication advances, integrating UAVs into 6G networks is expected to enhance both communication and sensing capabilities. This expansion will drive innovations through advanced technologies such as non-terrestrial networks, cell-free architectures, and ISAC systems, enabling UAVs to provide improved coverage and resilience in dynamic environments while addressing challenges related to size, weight, and power constraints, as well as interference management. Moreover, the synergy between sensing and communication will unlock new applications and optimize performance, paving the way for transformative use cases in the coming decade [21, 24, 30].

As illustrated in Figure 4, this figure illustrates the diverse applications and future directions of UAVs within 6G networks, highlighting their roles in enhancing ISAC systems, functioning as mobile base stations and relay nodes, and their potential in non-terrestrial networks and cell-free architectures. The first image depicts a UAV and terrestrial-based sensor (TBS) communication system designed for emergency areas, facilitating robust communication links and efficient data transmission through fronthaul links, thereby enhancing situational awareness and response times in critical scenarios. The second image showcases an antenna array configuration, emphasizing its significance in communication and signal strength analysis. The aerial view of the grid-patterned antenna array linked to a centrally located base station highlights the importance of strategic antenna placement for optimal signal coverage and strength. These examples underscore the transformative potential of UAVs in 6G networks, enhancing communication capabilities and improving data management across diverse applications [66, 47].

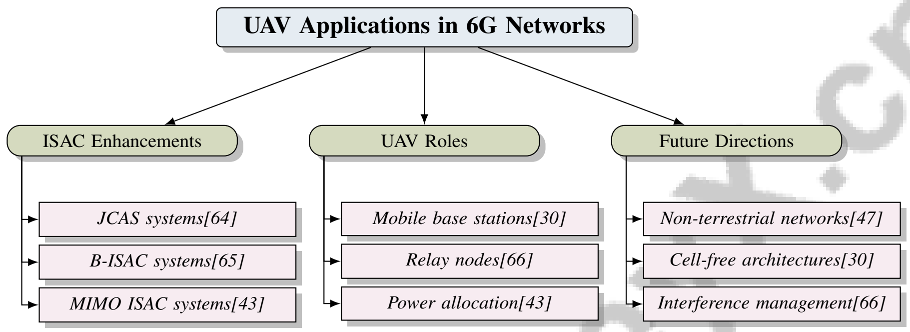

Figure 4: This figure illustrates the diverse applications and future directions of UAVs within 6G networks, highlighting their roles in enhancing Integrated Sensing and Communication (ISAC) systems, functioning as mobile base stations and relay nodes, and their potential in non-terrestrial networks and cell-free architectures.

4.3 Challenges and Solutions in UAV-Enabled ISAC Systems

Implementing UAV-enabled Integrated Sensing and Communication (ISAC) systems presents unique challenges and opportunities, particularly in optimizing communication and sensing functionalities. A primary challenge is the complexity of non-convex optimization problems associated with UAV trajectory planning and resource allocation, significantly affecting the computational efficiency of algorithms and complicating real-time optimization in dynamic environments [14].

Variability in the limitations of proposed methods, contingent on the specific characteristics of communication and sensing channels, poses another challenge. This variability necessitates the development of adaptive algorithms capable of dynamically adjusting to changing channel conditions to maintain optimal performance [67]. Additionally, integrating UAVs with ISAC systems raises security and privacy concerns, as UAV mobility can increase vulnerability to eavesdropping and unauthorized data interception.

To address these challenges, several solutions have been proposed. One approach involves employing advanced machine learning techniques to enhance the adaptability and efficiency of optimization algorithms, enabling better management of the non-convex nature of the problems and variability in channel characteristics. The integration of intelligent reflecting surfaces (IRS) significantly improves wireless communication and sensing systems by modifying signal propagation characteristics, leading to enhanced coverage, reduced interference, and better parameter estimation. This is particularly beneficial in ISAC frameworks, where IRS can create virtual line-of-sight links for sensing in obstructed environments. Jointly optimizing transmit and reflective beamforming strategies allows IRS-assisted systems to achieve superior sensing performance while satisfying communication requirements, thus maximizing overall system efficiency and reliability [13, 14].

Developing robust security protocols is essential to mitigate risks associated with UAV mobility. These protocols should focus on securing data transmission and ensuring the integrity of sensing information. Implementing robust encryption and authentication mechanisms is critical for safeguarding sensitive information against unauthorized access and data breaches, particularly in advanced communication systems like UAV-enabled ISAC networks, where dual identity mapping and prevention of malicious attacks are vital for secure and efficient data transmission [8, 16].

While implementing UAV-enabled ISAC systems presents several challenges, adopting innovative solutions and advanced technologies can significantly enhance their performance and reliability. As research in ISAC progresses, these systems are expected to play a crucial role in shaping the next generation of wireless communication networks, particularly in 6G. By leveraging extensive data from network infrastructure and user equipment, ISAC technologies will enhance resilience against environmental challenges, support dynamic network reconfiguration, and enable a wide array of new services that transcend traditional communication capabilities. This evolution is anticipated to improve performance through innovations such as Extremely Large-Scale Antenna Arrays (ELAA), non-terrestrial networks, and artificial intelligence, ultimately transforming how wireless networks operate and interact with their environments [23, 21, 24, 68].

5 Joint Communication and Sensing

5.1 Joint Communication and Sensing

The convergence of communication and sensing in Integrated Sensing and Communication (ISAC) systems represents a pivotal advancement in wireless networks, enhancing spectral efficiency and reducing hardware expenses. Leveraging existing communication infrastructures, ISAC systems facilitate concurrent communication and sensing tasks, optimizing resource utilization and system performance. A key advantage is the integration of radar and communication functionalities into a single waveform, enhancing task performance [31].

Distributed Multiple-Input Multiple-Output (D-MIMO) systems significantly enhance communication and localization performance by improving spectral efficiency through superior spatial resolution and resource distribution [42]. The Multi-Point Integrated Sensing and Communication (MPISAC) framework exemplifies this by improving detection accuracy via multi-view fusion and optimizing functionality selection to balance sensing and communication needs [1].

In UAV-enabled networks, dynamic optimization of UAV positions greatly enhances sensing capabilities in joint communication and sensing scenarios, effectively balancing these requirements and improving performance in low-altitude applications [5]. Additionally, utilizing radar signals to thwart eavesdropping while maintaining communication quality enhances security and efficiency [6].

Air-ISCC exemplifies the integration of sensing and communication by enabling concurrent operations, significantly reducing latency and improving spectrum efficiency [7]. Joint beamforming and power allocation strategies further enhance communication and sensing capabilities, leading to improved overall system performance [4].

As illustrated in Figure 5, which depicts the key frameworks and strategies in ISAC systems, the integration of UAV-enabled ISAC and various optimization strategies is crucial for enhancing system efficacy. Despite advancements in ISAC technologies for next-generation networks like 6G, challenges remain in balancing trade-offs between communication and sensing functionalities. These include optimizing resource allocation, managing interference, and addressing constraints of platforms such as UAVs, all while ensuring resilience in dynamic environments and enhancing overall network performance [21, 30, 69]. Developing comprehensive frameworks that systematically address interference through various mitigation techniques and optimization methods is crucial for overcoming these challenges. The integration of communication and sensing in wireless networks offers significant benefits, including improved spectrum utilization, enhanced performance metrics, and adaptability to dynamic conditions, positioning ISAC systems as foundational elements of next-generation wireless networks.

5.2 Comparative Analysis of ISAC Techniques

A comparative analysis of Integrated Sensing and Communication (ISAC) techniques reveals diverse approaches, each with unique strengths and limitations depending on the application context. Evaluating these techniques highlights their effectiveness in scenarios requiring precise positioning and resilience against environmental changes [21].

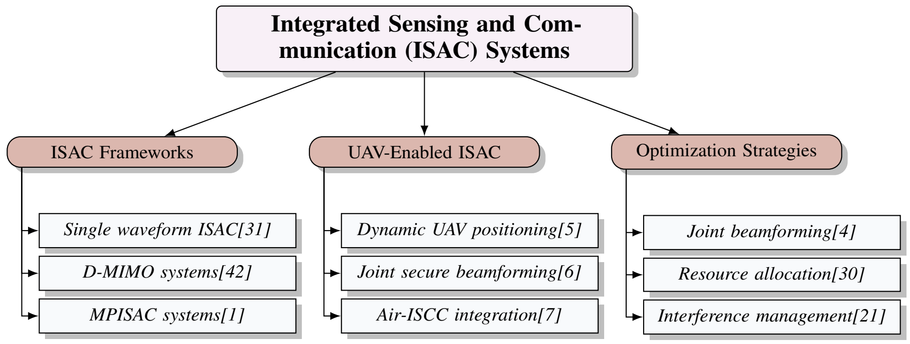

Figure 5: This figure illustrates the key frameworks and strategies in Integrated Sensing and Communication (ISAC) systems, highlighting ISAC frameworks, UAV-enabled ISAC, and optimization strategies.

D-MIMO systems have shown substantial improvements in communication and localization performance due to enhanced spatial resolution and resource allocation capabilities. These systems facilitate the integration of communication and sensing functionalities, optimizing spectral efficiency and enabling precise positioning in complex environments. The D-MIMO approach is particularly effective in scenarios demanding high spatial resolution and robust interference management, utilizing numerous distributed nodes to enhance both communication and sensing capabilities, thus improving overall service quality [20, 42].

Conversely, MPISAC frameworks leverage multi-view fusion to enhance detection accuracy and optimize functionality selection, balancing trade-offs between sensing and communication needs. This approach is particularly effective for applications requiring multi-perspective data integration, significantly enhancing detection accuracy and system robustness by utilizing data redundancy from multiple ISAC devices. By employing a multi-point ISAC system, this method addresses challenges such as fading and interference, improving sensing performance and resilience in dynamic environments [1, 21].

UAV-enabled ISAC systems represent a cutting-edge approach within sixth-generation (6G) wireless networks, utilizing UAVs as dynamic aerial platforms to optimize their positions for enhanced sensing and communication capabilities. This technique allows for simultaneous execution of communication and sensing tasks, addressing UAV size, weight, and power constraints while improving coverage and operational efficiency. Advanced algorithms for UAV trajectory optimization, motion control, and resource allocation can significantly enhance performance in joint communication and sensing scenarios, leading to improved service delivery in complex environments [70, 16, 30, 51]. These systems are particularly effective in low-altitude applications where adaptability and mobility are crucial for maintaining performance under varying environmental conditions.

Furthermore, joint beamforming and power allocation strategies in ISAC systems enhance both communication and sensing capabilities, improving overall system performance. These strategies are particularly beneficial in high-interference environments, enabling coordinated resource allocation that enhances system resilience and operational efficiency. By integrating advanced techniques for interference mitigation and optimizing resource distribution, ISAC systems can effectively manage various types of interference, including self-interference and multiuser interference. This coordinated approach not only enhances performance but also ensures that quality of service (QoS) requirements for distinct communication and sensing tasks are met, leading to more robust and efficient wireless systems [71, 32, 12].

The comparative analysis of ISAC techniques underscores the importance of selecting appropriate methodologies based on specific application requirements and environmental conditions. By integrating diverse methodologies, ISAC systems can optimize both communication and sensing capabilities, positioning themselves as foundational elements of next-generation wireless networks. This optimization is achieved through innovative frameworks, such as a radio access technology (RAT) selection process utilizing vision sensing to enhance performance, and advanced architectures like the mixture of experts (MoE) that improve accuracy and robustness in target detection. Additionally, ISAC systems exhibit superior flexibility in resource allocation and interference management, effectively

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supporting high-resolution sensing alongside high-data-rate communication, thereby addressing the complex demands of future wireless environments [29, 2, 12, 72].

6 Waveform Optimization Techniques

6.1 OFDM and Multicarrier Waveform Optimization

Orthogonal Frequency-Division Multiplexing (OFDM) and multicarrier techniques are pivotal for optimizing waveforms in Integrated Sensing and Communication (ISAC) systems, enhancing spectral efficiency and system performance. As illustrated in Figure 6, which highlights key techniques in OFDM and multicarrier waveform optimization for ISAC systems, these methods encompass OFDM techniques, advanced multicarrier designs, and dual-function waveforms, all of which are crucial for enhancing spectral efficiency and overall system performance. OFDM's resilience against multipath fading and high spectral efficiency make it ideal for ISAC, facilitating simultaneous communication and sensing via beam steering across subcarriers.

Integrating OFDM with advanced signal processing, such as collaborative precoding, refines signal transmission from adjacent ISAC base stations, minimizing interference while adhering to power constraints [73]. Advanced multicarrier designs leverage sophisticated signal processing and machine learning, enabling ISAC systems to adapt to dynamic environments and optimize resource utilization [74]. Stochastic geometry analysis offers insights into the trade-offs between radar sensing and communication functionalities [74]. Symbol-Level Precoding (SLP) enhances waveform design by minimizing range-Doppler sidelobe levels while maintaining power and communication quality constraints [75].

Dual-function waveforms adhering to Peak-to-Average Power Ratio (PAPR) constraints efficiently serve both communication and radar needs, optimizing dual functionalities [58]. The CAS-WDF method refines waveform performance by employing dual transmission schemes to enhance sensing while adhering to power budgets and separation theorem constraints [58].

The integration of Full-Duplex (FD) massive MIMO Base Stations exemplifies FD capabilities in ISAC systems, using hybrid A/D beamforming to transmit and sense concurrently, optimizing beamforming and power allocation [76, 56].

OFDM and multicarrier techniques in ISAC systems provide a comprehensive approach to waveform optimization, promoting enhanced spectral efficiency, reliable communication, and precise sensing. These techniques are crucial for advancing next-generation wireless networks, particularly in 6G, facilitating the integration of communication and sensing functionalities. By harnessing signal processing, optimization, and machine learning, these innovations enable new services and enhance overall network performance and adaptability [23, 21].

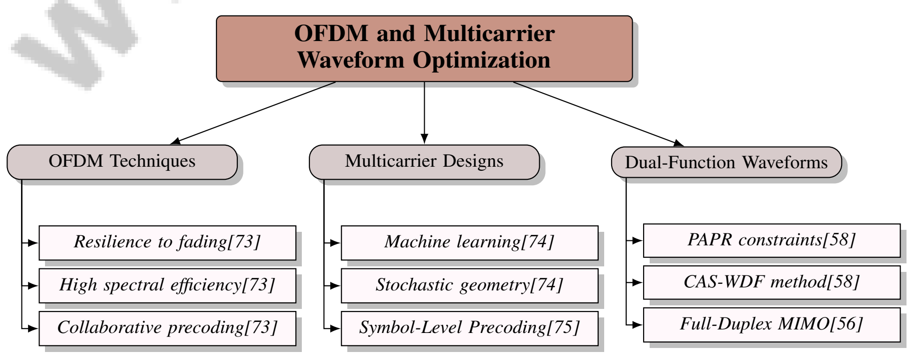

Figure 6: This figure illustrates the key techniques in OFDM and multicarrier waveform optimization for ISAC systems, highlighting OFDM techniques, multicarrier designs, and dual-function waveforms, which are crucial for enhancing spectral efficiency and system performance.

Method Name	Optimization Objectives	Resource Allocation Strategies	Interference Mitigation
SP-PA[71]	Mutual Information	Power Allocation	-
GAP-OPC[45]	Spectral Efficiency	Power Control	Interference Alignment
RAO-ISAC[77]	Energy Efficiency	Dynamic Spectrum Allocation	Interference Mitigation Techniques
ISAC-OFDM[78]	Mutual Information Maximization	Dynamic Spectrum Allocation	Interference Alignment
IMT-ISAC[12]	Mutual Information	Coordinated Resource Allocation	Interference Alignment
PBF[79]	Spectral Efficiency	Time-frequency Resource	Beam Alignment
JASCMO[57]	Mutual Information	Dynamic Programming	Beamforming

Table 2: Overview of various methods for dynamic resource allocation and power control in ISAC systems, detailing their optimization objectives, resource allocation strategies, and interference mitigation techniques. This table highlights the diversity of approaches in enhancing waveform performance by balancing communication and sensing functionalities.

6.2 Dynamic Resource Allocation and Power Control

Dynamic resource allocation and power control are essential for optimizing waveform performance in ISAC systems, balancing the trade-offs between communication and sensing functionalities to ensure efficient resource use and enhanced performance. Abouelmaati et al. propose optimal spectrum and power allocation in semi-ISAC systems, maximizing mutual information and energy efficiency while meeting Quality of Service (QoS) requirements [71]. Table 2 provides a comprehensive comparison of different methods employed for dynamic resource allocation and power control in Integrated Sensing and Communication (ISAC) systems, illustrating their respective optimization objectives and strategies for interference mitigation.

The GAP-OPC method dynamically selects Access Point (AP) operation modes based on long-term channel state information, maximizing spectral efficiency while ensuring sensing performance [45]. Xu et al. suggest segmenting the ISAC frame into communication and sensing phases to optimize resource allocation within these phases [77].

In OFDM-based ISAC systems, optimizing time-frequency resource allocation minimizes the Cramér-Rao Bound (CRB) for delay and Doppler estimation while maintaining spectral efficiency [78]. Interference Mitigation Techniques for ISAC (IMT-ISAC) include coordinated multipoint transmission, interference alignment, and highly-directional beamforming to enhance system performance [12].

Integrating accurate Angle of Arrival (AoA) and Angle of Departure (AoD) predictions enhances position and attitude tracking, improving spectral efficiency [79]. A trade-off objective function incorporating communication and sensing metrics facilitates dynamic resource allocation and power control, catering to varying operational requirements [57].

Recent advancements introduce a multi-granularity resource allocation framework, addressing limitations in existing methods, particularly in OFDM waveforms, maximizing sensing performance while mitigating high sidelobes and reduced accuracy in resource-limited environments [32, 80]. These strategies are pivotal for advancing next-generation wireless networks, driving innovations in the integration of communication and sensing functionalities.

6.3 Beamforming and Antenna Optimization

Beamforming and antenna optimization are critical for enhancing ISAC system performance, significantly improving both communication and sensing functionalities. As illustrated in Figure 7, key strategies in this domain include the deployment of sparse antenna arrays, methods for interference mitigation, and advanced techniques such as sensing-centric beamformers and the use of movable antennas. Strategic deployment of sparse antenna arrays and optimization of array shapes enhance system performance without substantial cost increases [81]. Designing the spatial configuration of antennas achieves superior spatial resolution and signal quality, essential for radar sensing and communication tasks.

Methods that spatially separate transmission and reception processes reduce self-interference, enhancing ISAC system reliability and efficiency [82]. This separation is achieved through coordinated beamforming techniques optimizing resource allocation and mitigating interference.

Integrating Reconfigurable Intelligent Surfaces (RIS) into ISAC systems enhances beamforming capabilities, providing additional degrees of freedom for signal manipulation. Utilizing a block coordinate descent (BCD) algorithm, along with Dinkelbach's transform and successive convex approximation (SCA) methods, addresses non-convex optimization challenges in RIS-enhanced cognitive ISAC systems [83].

Beamforming and antenna optimization techniques are pivotal in developing ISAC systems, enhancing spectral efficiency, signal quality, and overall performance. These techniques enable advanced designs such as sensing-centric and communications-centric beamformers, optimizing outage probability, ergodic communication rates, and sensing rates. Integrating movable antennas and jointly optimizing positions and beamforming mitigates self-interference, improving communication capacity and sensing mutual information. Multi-objective optimization frameworks allow ISAC systems to balance communication and sensing functionalities, ensuring robust performance even in challenging environments [84, 11, 57, 55, 85]. These techniques are crucial for advancing next-generation wireless networks, driving innovations in the integration of communication and sensing functionalities, and ensuring ISAC systems meet the demanding requirements of future wireless applications.

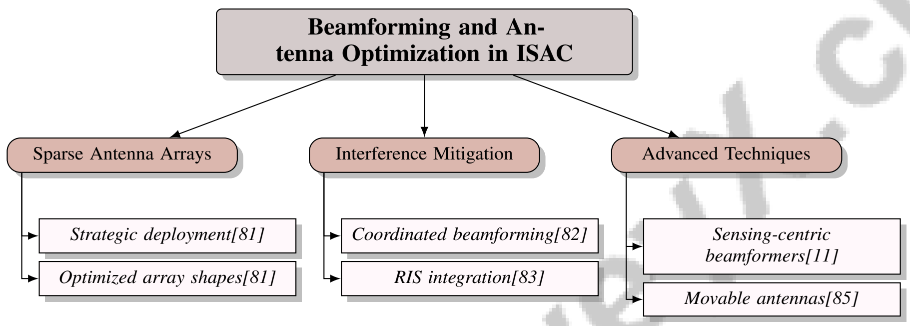

Figure 7: This figure illustrates the key strategies in beamforming and antenna optimization for ISAC systems, highlighting the deployment of sparse antenna arrays, methods for interference mitigation, and advanced techniques such as sensing-centric beamformers and the use of movable antennas.

7 Spectral Efficiency in ISAC Systems

Spectral efficiency is essential in Integrated Sensing and Communication (ISAC) systems, enabling the seamless integration of communication and sensing functions through the joint design of wireless transmissions. This optimization improves spectral and energy efficiencies, addressing challenges such as fading and interference, and achieves a favorable trade-off between communication and sensing rates, enhancing overall system performance compared to traditional frequency-division methods [1, 2]. This section underscores the importance of spectral efficiency in determining system performance and resource allocation strategies, laying the groundwork for exploring advanced algorithmic approaches that further enhance spectral efficiency in dual-function operations.

7.1 Importance of Spectral Efficiency in ISAC Systems

Spectral efficiency is critical to ISAC systems, optimizing communication and sensing functions by enabling simultaneous use of shared hardware. This approach enhances spectral and energy efficiencies, tackling challenges such as fading and interference, and improving performance through advanced resource allocation strategies and multi-point data fusion techniques [2, 71, 1, 86, 32]. Efficient spectrum utilization is crucial for high-performance ISAC applications, particularly in high-mobility and dense network environments. The development of advanced algorithms and frameworks for resource allocation and energy consumption minimization highlights the significance of spectral efficiency in meeting stringent communication and sensing requirements.

Spectral efficiency's impact on resource allocation facilitates effective communication and sensing task distribution, especially in high-dimensional non-convex optimization problems, where it aids in addressing complex resource allocation challenges [87]. Accurate channel state information (CSI) is vital in MaMIMO-UAV communications for optimizing spectral efficiency and managing delay spread, thus enhancing system performance [47].

Advanced power allocation strategies illustrate the importance of spectral efficiency. An OTFS-based method significantly enhances spectral efficiency and reliability in high-mobility scenarios by optimizing power distribution and minimizing interference [88]. This underscores the need for dynamic resource management to achieve optimal spectral efficiency and robust system performance.

Joint Beamforming and Power Allocation (JBPA) algorithms demonstrate superior performance in minimizing energy consumption while satisfying Ultra-Reliable Low-Latency Communication (URLLC) requirements, emphasizing spectral efficiency's role in balancing energy efficiency and communication reliability [89]. Full-Duplex (FD)-based ISAC optimization frameworks maximize downlink communication rates while accurately estimating the direction of arrival, range, and velocity of multiple radar targets [76].

Designing dual-functional waveforms that optimize spectral efficiency enhances system performance by minimizing sensing distortion while adhering to power constraints. This approach achieves a 25% performance gain for the dual-functional scheme over separated designs, highlighting the importance of waveform optimization [58].

Spectral efficiency is integral to advancing ISAC systems, driving innovations in resource allocation, power management, and waveform design. Its significance is increasingly recognized across various applications, playing a pivotal role in the evolution of next-generation wireless networks. As wireless networks progress towards 6G, integrating sensing data from infrastructure and user equipment will enhance resilience against channel-dependent challenges and facilitate innovative services, underscoring the critical need to optimize spectral efficiency in this transformative landscape [21, 71, 68, 25].

7.2 Advanced Algorithmic Approaches

Advanced algorithmic approaches are crucial for enhancing spectral efficiency within ISAC systems, addressing the complex challenges of dual communication and sensing functions. These approaches leverage advanced signal processing techniques, machine learning algorithms, and optimization frameworks to improve resource allocation, signal quality, and interference management. They address various types of interference—such as self-interference, mutual interference, crosstalk, clutter, and multiuser interference—by applying tailored optimization methods, thereby enhancing the resilience and energy efficiency of wireless networks across diverse applications, including communications-only, sensing-only, and integrated scenarios [21, 71, 12].

Joint beamforming and power allocation strategies exemplify advancements in maximizing spectral efficiency through dynamic resource distribution based on real-time channel conditions. These strategies are particularly effective in high-interference environments, significantly enhancing system resilience and efficiency [89]. The integration of Rate-Splitting Multiple Access (RSMA) techniques further illustrates the potential of advanced algorithmic approaches in reducing interference and improving both communication and sensing performance [50].

Machine learning techniques, including deep reinforcement learning and supervised learning, show promise in optimizing ISAC system performance by enabling dynamic adaptation to changing environmental conditions, thereby enhancing spectral efficiency and ensuring robust operation [74]. Learning-based approaches for resource allocation and interference management highlight the role of artificial intelligence in addressing the complexities of ISAC systems.

Hybrid beamforming designs, particularly those aided by Reconfigurable Intelligent Surfaces (RIS), enhance spectral efficiency by providing additional degrees of freedom for signal manipulation and propagation, optimizing communication and sensing performance while managing trade-offs between these dual functionalities [83].

Advanced algorithmic approaches are vital for optimizing spectral efficiency within ISAC systems. They enable enhanced resource allocation, improve signal quality through sophisticated beamforming and interference mitigation techniques, and ensure robust performance by addressing challenges such as channel estimation errors and multiuser interference. By effectively integrating communication and sensing functionalities, these algorithms facilitate dynamic adjustments in transmission rates and the efficient use of wireless resources, supporting high-resolution sensing and high-performance communication in next-generation networks [11, 90, 29, 91, 12]. Their role is pivotal for the future of wireless networks, driving innovations in the integration of communication and sensing functionalities to meet the demanding requirements of emerging applications.

8 Challenges and Future Directions

The integration of Integrated Sensing and Communication (ISAC) systems into advanced wireless technologies offers significant opportunities but also presents challenges. As connectivity becomes more pervasive, addressing the complexities of merging communication and sensing functionalities is crucial. This section explores the challenges and trade-offs in deploying ISAC systems, highlighting the hurdles to be overcome to realize their full potential in next-generation networks.

8.1 Challenges and Trade-offs

Incorporating technologies like Massive MIMO, ISAC, 6G, and UAVs into future wireless networks entails challenges crucial for optimizing performance. Balancing communication rates with sensing performance is a primary concern, as inefficient bandwidth use can impair both functions [31]. This balance is essential for seamless integration, further complicated by the need for adaptable air interfaces.

In UAV-enabled ISAC systems, optimizing UAV positioning and power allocation to enhance sensing while maintaining communication quality is challenging. UAV mobility adds complexity, requiring precise deployment and trajectory planning in dynamic environments [26]. Additionally, cooperative ISAC networks face trade-offs due to increased signaling overhead and resource consumption, impacting system efficiency and scalability [9].

Deploying Reconfigurable Intelligent Surfaces (RIS) effectively is challenging in cluttered environments, where their utility is limited by multiplicative path attenuation. Innovative solutions are needed to mitigate these limitations, especially in designing waveforms that balance communication and sensing requirements [58].

Security concerns, such as minimizing eavesdropping risks while maximizing sensing performance, must also be addressed [6]. The assumption of perfect CSI in some models may not hold in practice, leading to performance prediction inaccuracies. Optimization challenges in large-scale networks, particularly with dynamic target movements or extreme conditions, further complicate communication and sensing integration [28]. Strong echo interference from multiple communication users can degrade radar performance, highlighting the need for robust interference management [73].

The non-convex nature of optimization problems, especially those involving closely coupled integer variables, complicates joint optimization of UAV trajectory, user association, sensing time selection, and transmit beamforming [26]. Challenges in signal processing and managing grating lobes in sparse MIMO systems further hinder effective communication and sensing [10]. ISAC system performance may degrade under low channel quality or insufficient effective dual-functional radars (DFRs) [1].

Innovative solutions and optimization strategies leveraging advanced signal processing, machine learning, and multi-objective optimization are essential for next-generation networks, especially in smart cities and connected vehicles [21, 92, 69]. Overcoming these challenges is crucial for unlocking ISAC systems' full potential in future wireless communications.

8.2 Future Directions and Potential Developments

The advancement of ISAC systems will be shaped by research aimed at overcoming existing challenges and enhancing capabilities. Integrating adaptive algorithms for real-time adjustments, especially in antenna positions, is vital for optimizing resource allocation in dynamic networks [34].

In UAV-enabled ISAC systems, future research should address imperfect Doppler compensation and explore multi-UAV scenarios to enhance the ISAC framework [26]. Developing advanced techniques for multi-sensory integration and addressing current ISAC implementation limitations are essential for improving UAV communication and sensing capabilities [8].

Exploring adaptive beamforming techniques and employing IRS are critical for enhancing sparse MIMO systems' performance, offering improved spatial resolution and signal quality [10]. Ad-

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dressing scalability and synchronization challenges in D-MIMO systems is imperative for creating standardized solutions that integrate communication, localization, and sensing functionalities [42].

Future research should enhance the robustness of functionality selection modules and investigate MPISAC applications in complex multi-target scenarios [1]. This exploration will yield valuable insights into ISAC systems' potential benefits and trade-offs compared to traditional configurations.

Addressing synchronization, security, and resource allocation challenges in cooperative ISAC networks is crucial for advancing these systems [9]. Developing efficient algorithms for real-time optimization and extending methods to complex scenarios involving dynamic environments and various UAV types are vital research directions [5].

Future research should enhance security measures, improve sensing and computation performance, and explore practical applications in edge intelligence and vehicular networks [7]. Investigating adaptive techniques for dynamic environments and further optimization strategies will be essential for improving ISAC performance under varying conditions [6].

These future research directions emphasize the need for performance optimization, adaptability, and integrating advanced technologies in ISAC systems. Developing innovative frameworks for radio access technology selection, effective interference mitigation, and adaptive resource allocation will enhance communication and sensing capabilities. By leveraging techniques like vision-based user localization and advanced optimization algorithms, ISAC systems are positioned to serve as foundational components of future communication infrastructures, ensuring high data rates and reliable service in complex environments [29, 12].

8.3 Security and Privacy Concerns

Security and privacy in ISAC systems are critical, particularly in networked environments where sensing functionalities may create vulnerabilities. These vulnerabilities are amplified in cooperative ISAC networks, facing heightened threats like unauthorized access and data interception [93]. Ensuring the integrity and confidentiality of sensing data is paramount, especially when transmitting or processing sensitive information.

To mitigate these concerns, ISAC system architecture must incorporate robust data protection mechanisms, ensuring compliance with regulations such as GDPR, which mandates stringent data privacy and security measures. Implementing the SPCTM framework is critical for managing access to sensing data and ensuring user consent and transparency in data handling processes [94].

Developing secure transmission methods is essential for enhancing communication security in ISAC systems. Such methods reduce risks associated with eavesdropping and data breaches by optimizing transceiver beamforming and UAV trajectories to maximize secrecy rates while leveraging sensing capabilities to detect threats [8, 16, 17, 68, 39]. This involves employing advanced encryption techniques and authentication protocols to safeguard communication channels, ensuring only authorized entities can access sensitive information. Additionally, integrating IRS can enhance security by providing additional layers of signal manipulation and control, reducing the likelihood of signal interception.

Addressing security and privacy concerns in ISAC systems requires a comprehensive approach combining technological innovations with regulatory compliance and user-centric data management strategies. By implementing advanced ISAC techniques that unify sensing and communication functions while addressing security challenges, ISAC systems can significantly enhance security and privacy measures. This ensures the safe and reliable operation of next-generation wireless networks, particularly in 6G environments, where strategies like dual identity mapping and expert network architectures optimize performance and safeguard against threats such as eavesdropping and malicious attacks [8, 16, 72, 39].

9 Conclusion

This survey has explored the integration of cutting-edge technologies such as Massive MIMO, Integrated Sensing and Communication (ISAC), 6G, and UAVs within next-generation wireless communication systems. It highlights the transformative impact of these technologies in enhancing spectral efficiency, optimizing resource allocation, and boosting overall network performance. The integration of RIS technology within ISAC frameworks stands out for achieving communication performance on par with traditional systems while offering precise location sensing. The WMMSE-PDD algorithm emerges as a potent solution for addressing joint common rate allocation and hybrid beamforming design, showcasing improvements in energy efficiency and interference management. The survey underscores the urgent need for standardization in ISAC, advocating for integrated systems that enhance sensing capabilities crucial for the practical advancement of these technologies. A multi-granularity framework is proposed to optimize resource allocation across different layers and dimensions, thereby structuring the management of complexities inherent in future networks. Sparse MIMO is recognized as a cost-effective strategy for enhancing performance in 6G ISAC systems, with future research directions suggested to address prevailing challenges. The Cell-Free massive MIMO ISAC system's beamforming scheme reveals a performance trade-off between communication and radar sensing. Additionally, the lifted super-resolution method effectively addresses phase nonlinearity in near-field ISAC systems, improving accuracy in angle and distance estimation. Finally, proposed energy-efficient MIMO ISAC systems demonstrate significant reductions in energy consumption while meeting stringent communication and sensing demands, outperforming existing benchmarks.

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