1. Fundamental Limits of MIMO-OFDM Sensing

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Abstract: *This chapter explores the fundamental performance limits of MIMO-OFDM-based sensing in ISAC systems. We begin by analyzing the information-theoretic bounds on the accuracy of position and velocity estimation in far-field and near-field propagation scenarios. In the latter cases, it is crucial to consider the spherical nature of wavefronts, particularly when dealing with extremely large aperture arrays (ELAA). Next, we examine cooperative ISAC setups, deriving lower bounds on position and velocity estimation errors when multiple sensing nodes collaborate. Based on these insights and case studies, we discuss how these fundamental limits can inform design principles for network topology and resource allocation (including power, bandwidth, and time) for future sensing-enabled radio systems.*

1.1 Introduction

Understanding the fundamental performance limits of cooperative ISAC is crucial for benchmarking estimation algorithms and informing system-level design decisions, including resource allocation, base station (BS) deployment, and cooperation strategies. As ISAC evolves into a core component of future wireless networks, quantifying these limits becomes essential to prevent inefficiencies and performance degradation.

This chapter investigates the fundamental limits of sensing using multiple-input multiple-output (MIMO)–OFDM waveforms that are traditionally employed for communication. The MIMO–OFDM signal model tailored for sensing is introduced. Different operating regimes are then considered, with particular emphasis on whether the target lies in the far-field (FF) or near-field (NF) region of the adopted antenna arrays. Indeed, as array apertures grow and carrier frequencies increase, both trends being central to future 6G systems, NF effects can no longer be neglected.

The fundamental limits of parameter sensing are derived using the Cramér–Rao lower bound (CRLB). Under FF assumptions, we present the CRLB for range estimation, leveraging the spectral diversity of OFDM signals, for angle of arrival (AoA) estimation, enabled by spatial observations across the antenna array, and for radial velocity estimation, exploiting the temporal domain. The analysis is then extended to NF conditions, where CRLBs for range, AoA, and radial velocity are revisited. In addition, in the NF

2. Information-theoretic Aspects of ISAC

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Abstract: *This chapter reviews the information-theoretic foundations of Integrated Sensing and Communications (ISAC). We begin with monostatic ISAC under discrete memoryless models, where a single transmitted input simultaneously drives a communication channel and a sensing channel. For this setting, we establish the optimal rate distortion cost tradeoff region for an arbitrary additive sensing distortion (or error) metric. We then examine the special role of log-loss distortion and the resulting* sensing mutual information*, which yields a universal lower bound on all metrics via rate–distortion theory. The analysis is specialized next to vector Gaussian MIMO ISAC channels, where we characterize the fundamental capacity–CRB region. This reveals the two canonical and structural ISAC tradeoffs: the* subspace tradeoff *and the* random–deterministic tradeoff*, which respectively govern the geometric and statistical characteristics of the optimal ISAC input distributions. It is also shown that in the quasi-static regime where a single fading state spans the whole duration of a codeword, then the random-deterministic tradeoff disappears and Gaussian inputs are sensing and communication optimal. In this case, the tradeoff problem reduces to a transmit covariance design problem. We then move to monostatic ISAC with implicit feedback, modeling the case of sensing-aided communications, and we cover the memoryless and the case of in-block-memory. Finally, we present the bistatic ISAC model, where the sensing receiver knows the communication codebook but not the transmitted codeword. This setting leads to a fundamentally different capacity–distortion region, for which recent work establishes multiletter expressions, single-letter inner and outer bounds, and exact solutions in degraded cases. We conclude by highlighting open information-theoretic problems defining the frontier of ISAC research.*

2.1 Introduction

Integrated Sensing and Communications (ISAC) has emerged as a central paradigm in next-generation (6G) wireless systems. Its defining feature is the use of a *single* physical-layer signal for two distinct purposes: (i) reliable information transmission, and (ii) estimation of an unknown state, parameter, or environment. This duality introduces a fundamental *performance tradeoff* between communication rate and sensing accuracy.

Historically, the study of ISAC has unfolded along two axes: (i) signal-processing–centric designs, particularly in MIMO and OFDM radar–communication coexistence, and (ii) information-theoretic formulations, where ISAC is modeled using state-dependent channels, implicit feedback, and multi-objective optimization.

This chapter surveys the information-theoretic foundations of ISAC, emphasizing:

- capacity–distortion-cost tradeoff for monostatic ISAC,

3. Towards Seamless Networked Integrated Sensing and Communication

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Abstract: *The convergence of sensing and communication functionalities in next-generation wireless networks is driving a paradigm shift towards network-centric ISAC. This chapter explores the potential of cooperative ISAC architectures in 6G networks, where sensing tasks are no longer performed by isolated nodes but by distributed, interconnected devices. We first introduce the key enabling technologies and architectures that support networked ISAC. We then focus on cooperative sensing strategies, highlighting how inter-node coordination can enhance detection, localization, and tracking performance. Particular attention is devoted to resource allocation techniques, in which spectrum, time, and power are dynamically shared between communication and sensing functions based on application-specific priorities. Finally, we address AI-based methods for target classification and tracking in the networked ISAC context, discussing how target recognition can drive target-specific resource allocation and tracking strategies, ultimately boosting overall sensing performance.*

3.1 Introduction

The integration of sensing capabilities into future cellular networks has evolved beyond single-node operation, revealing a growing need for network-level cooperation to achieve robust situational awareness in complex environments. While early approaches to ISAC focused on monostatic sensing at individual BSs, practical scenarios such as urban mobility, vulnerable road user (VRU) protection, and autonomous driving demand a broader sensing coverage and improved resilience to blockages, multipath, and interference [1]. This shift calls for a transition towards distributed and networked sensing, where multiple infrastructure nodes operate collaboratively—sharing observations, synchronizing operations, and jointly reconstructing the environment.

The large-scale deployment of BSs in fifth-generation (5G) and beyond has created a pervasive sensor fabric capable of cooperative perception [2, 3]. In such settings, even monostatic nodes can be leveraged in a coordinated manner, enabling improved detection through spatial diversity and heterogeneous observations. Cooperative monostatic sensing addresses limitations inherent to isolated perception, such as sensitivity to non-line-of-sight (NLOS) conditions and reliance on a single viewpoint. However, effective cooperation introduces new challenges, ranging from data fusion and inter-BS synchronization to the design of scalable strategies that balance sensing accuracy against signalling and computational overhead [4]. Advancing from cooperation among monostatic nodes, bistatic

4. Radio-Based Imaging in Next-Generation ISAC Systems

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Abstract: *Integrated sensing and communication (ISAC) is a paradigm shift expected for the next generation of wireless systems (6G), where traditional communication systems are equipped with the capability of sensing the surroundings, enabling a plethora of possible applications. As of today, the research on ISAC systems from the sensing perspective is mostly devoted to localization, namely the estimation of meaningful parameters that describe the state of target objects, such as their position and velocity, at the maximum possible accuracy. Alternatively, radio imaging aims at generating a detailed map of the environment, enabling the detection and classification of targets, prior to their localization. The main figure of merit for imaging is resolution, namely the capability of distinguishing close targets. This chapter begins by outlining the fundamentals of radio imaging, from diffraction theory to main insights. Then, we outline the signal model and typical processing methods for multistatic integrated distributed communication and imaging (D-ICAI) systems, where the goal is the integration radio imaging in communication systems. Finally, we introduce the issues arising from synchronization and calibration of D-ICAI networks, discussing possible signal processing techniques. We end up by summarizing future challenges for such systems.*

4.1 Introduction

The convergence of communication and radio sensing functionalities is one of the expected pillars of the next generation of wireless systems (6G). The new paradigm of integrated sensing and communication (ISAC) aims at fusing the natural function of wireless networks of transmitting information with the capability of gathering information on the surroundings, all over the same radio resources—time, frequency and space, using a single waveform—and hardware equipment [1]. The vast majority of literature on ISAC systems deals with waveform design to maximize sensing performance under communication constraints (communication-centric ISAC), or, conversely, maximize communication under sensing constraints (sensing-centric ISAC). In the broad meaning of sensing, literature measures sensing performance with the accuracy on *target localization*, i.e., the exploitation of the reflected and the scattered of a communication signal in the environment (the usual multipath), to estimate the position, velocity and possibly orientation (in general, the *state*) of a desired set of targets [2]. As any estimation problem, the accuracy is represented by the mean squared error (MSE) for the selected parameters of interest and by suitable statistical bounds, e.g., the Cramér-Rao lower bound (CRLB). The waveform design is carried out over the spatial domain, designing the beampattern

5. Distributed Intelligence for ISAC Across the Computing Continuum

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Abstract: *As ISAC technologies generate vast volumes of sensing and contextual data collected in distributed locations, the computing continuum emerges as a critical enabler for processing this information efficiently and responsively. However, this shift brings new challenges related to latency, privacy, security, and resource orchestration. This chapter explores how distributed intelligence can support the design of scalable and adaptive ISAC systems across heterogeneous computing environments. Cooperative sensing and distributed signal processing enhance data acquisition and reconstruction, while federated and distributed learning enable collaborative knowledge extraction under communication and privacy constraints. By integrating these elements, the chapter outlines a modular ISAC architecture capable of adapting to changing network conditions and diverse performance requirements. This approach aims to guide the design of ISAC systems that are not only high-performing and efficient, but also context-aware, resilient, and capable of learning and evolving within dynamic operational ecosystems.*

5.1 Introduction

ISAC leverages the communication infrastructure to produce sensing measurements (e.g., reflections from device-free targets, channel features) alongside data connectivity. The real value of ISAC does not lie in keeping these measurements local, as in more classical stand-alone radars or isolated sensors, but in sharing and combining these measurements across many nodes to construct a collective view of the monitored environment. Consequently, sensing is inherently a *distributed service*: measurements are generated locally by heterogeneous *sensing entities (SEs)* (e.g., next generation Node Bs (gNBs), UEs, or other receivers) and are then processed partly where they originate and partly elsewhere in the network. Where and how this processing occurs strongly affects end-to-end latency, bandwidth usage, accuracy, and robustness.

In this view, architecture is a key aspect of ISAC systems. The 3GPP technical report (TR) 23.700-14 (Release 20, at the draft stage at this moment of writing) sketches a neutral, location-agnostic baseline that defines roles and data flows for ISAC without expliciting deployment sites. At its core are minimal abstractions: sensing entities (SEs) produce *sensing data* (raw or pre-processed signal measurements), and the *sensing result* (the exposed outcome, i.e. objects, positions, events, maps) delivered to applications through standard exposure functions. The document anticipates distributed/localized deployments, alternative data paths from SEs to processing functions, and dynamic parameter configuration so that sensing can adapt in real time. These choices enable scaling and coordination while keeping data access authorized and auditable.

6. Security and Privacy for ISAC

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Abstract: *This chapter explores the security and privacy dimensions of ISAC systems, including regulatory and legal considerations. As ISAC technologies involve the collection, processing, and potential sharing of environmental and user-related data, they raise important questions about compliance with data protection frameworks such as the general data protection regulation (GDPR). The chapter begins by outlining these concerns, highlighting key principles and their implications for ISAC system design. We then introduce relevant threat models that capture both conventional and ISAC-specific attacks, helping to frame the system's vulnerability landscape across physical and communication layers. Attention is given to the detection of physical-layer attacks, such as spoofing and jamming, which can undermine both sensing accuracy and communication reliability. We also discuss countermeasures ranging from system-level protections to cooperative defense strategies. Throughout, the chapter emphasizes the need for a holistic approach to security and privacy, one that integrates technical resilience with regulatory compliance and privacy-by-design principles.*

6.1 Introduction

While ISAC promises significant gains in spectrum efficiency, situational awareness, and the development of novel applications, it also raises unprecedented concerns in terms of security and privacy. Unlike traditional communication systems, ISAC nodes simultaneously exchange information and collect fine-grained physical data about their surroundings, which expands the attack surface and introduces new risks for users and infrastructures.

The potential threats to ISAC can be broadly grouped into three categories. First, communication-related threats such as jamming, spoofing, and eavesdropping, which are inherited from conventional wireless systems. These threats have been extensively studied in the communications literature and fall outside the scope of this chapter, since our interest lies in aspects that are unique to ISAC. Second, sensing-related threats, where adversaries manipulate or exploit radar-like measurements to inject ghost targets, hide real ones, or infer sensitive information about users or environments. Third, cross-domain threats, in which errors or attacks in one domain (communication or sensing) propagate to the other, creating coupled vulnerabilities that are distinctive to ISAC.

7. OFDM Radar Onboard Moving Platform for GMTI

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Abstract: *Typical scenarios for Integrated Sensing and Communication (ISAC) involve networks of moving nodes, such as UAVs, aircraft, or vehicles, that transmit waveforms enabling both inter-node communication and radar-based surveillance. In this context, Orthogonal Frequency-Division Multiplexing (OFDM) waveforms offer a unified solution for supporting wireless communication alongside ground moving target indication (GMTI), i.e., the detection of targets moving on or above the surface across wide monitored areas, a key capability for autonomous navigation, standoff sensing, and situational awareness. Platform motion causes Doppler spreading of clutter echoes from stationary objects, complicating the detection of slow-moving targets. Effective clutter mitigation requires the use of multiple receiving channels and space-time processing (STAP) to exploit spatial and Doppler diversity and suppress clutter while preserving target echoes. However, while classical radar systems exploit trains of coherent pulses and constant-envelope waveforms to apply mature STAP techniques, the use of OFDM complicates this approach: its time-varying, information-bearing structure breaks the assumptions underlying conventional STAP methods. The scenario further complicates under bistatic configurations or when operating with low-gain antennas and limited onboard processing, conditions typical of low-cost platforms. This chapter investigates the joint effects of platform motion and waveform variability on radar GMTI performance, proposing tailored strategies for OFDM-based ISAC systems. The analysis is supported by theoretical insights, simulations, and experimental data collected in vehicular scenarios.*

7.1 Introduction

Integrated Sensing and Communication (ISAC) technology finds a particularly fruitful and challenging exploitation in applications that inherently involve mobile platforms, such as autonomous driving, unmanned aerial vehicle (UAV)-based surveillance, and vehicular networks [1, 2, 3, 4]. In these scenarios, from a sensing perspective, a key requirement is the ability to detect moving targets against a background of strong ground clutter. However, the relative motion between the ISAC platform and the surrounding environment induces a Doppler spread on the returns from the stationary scene. This effect causes the clutter echoes to occupy a wide portion of the Doppler spectrum, which can easily mask slow-moving targets of interest. Therefore, a robust Ground Moving Target Indication (GMTI) capability is a critical requirement to enable the primary sensing tasks in such dynamic environments.

8. MIMO-OFDM Transceiver for ISAC: Design and Performance Measures

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Abstract: *The Integrated Sensing And Communications (ISAC) paradigm has been inspired by the need for efficiently exploiting the physical resources, thus accommodating a plurality of services which would have otherwise required dedicated infrastructure. On the other hand, MIMO-OFDM has been establishing itself as the leading transmission format for wireless communications, thus bringing up the problem of defining suitable Dual Function Radar Communication (DFRC) structures to undertake sensing and communications. This contribution outlines some guidelines to jointly design the transmit waveform and the radar and communication receivers: a major advantage of the MIMO structure of the transceiver is that it allows forming space-time filters controlling the transmit and receive beampatterns on subsets of the available subcarriers mandated to perform ISAC. The transceiver structure results from the solution of a general optimization problem, wherein a radar-oriented figure of merit is maximized under a constraint on the communication error probability. We offer a formulation subsuming a number of significant figures of merit, whether detection-oriented or estimation-oriented or both, obviously accounting for the inherently multi-target nature of the controlled scene.*

8.1 Introduction

Integrated Sensing and Communications (ISAC) has been the focus of vibrating interest for over a decade now as an enabling paradigm to foster efficient spectrum exploitation and reduced environmental impact, while seconding the society evolution towards fully pervasive, multi-task wireless networks [1]. The underlying vision is one wherein sensing capabilities become a basic service of next-generation networks, capable of opening their own eyes on the surrounding reality, thus bringing the range of offered services to an unprecedented depth through the concept of a *perceptive network* [2, 3, 4].

A crucial ingredient for this evolution is the use of Multiple-Input Multiple-Output (MIMO) technology and its development from a simple multi-antenna structure equipping the transceivers of fourth-Generation (4G) networks, to the *massive* form prevailing in 5G up to the Extremely Large Scale (XL-MIMO), sparse MIMO, modular MIMO technologies foreseeable for 6G networks [5], capable of lifting the number of available Degrees of Freedom (DoF's) to the level required by the network intended pervasiveness.

These DoF's have been so far exploited with different criteria, typically determined by the architecture of the Radar-Communication ensemble. Coexistence between distinct

9. V2X-ISAC: Merging Perception and Communication in Vehicular Networks

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Abstract: *How could vehicular networks evolve if vehicles could perceive and communicate simultaneously using a single technology? Integrated sensing and communication (ISAC) is one of the most promising frontiers for future vehicular networks, where sensing — including radar-like perception and localization of radio-equipped road users — and communication merge to enable safer, smarter, and more cooperative mobility. By unifying these two functions, ISAC enhances situational awareness, reduces latency in shared decision-making, and optimizes radio spectrum usage, responding to the growing needs of an increasingly automated and intelligent ecosystem. This chapter introduces the fundamental principles of ISAC in vehicular scenarios illustrating how sensing, localization, and communication functions can coexist within the vehicle-to-everything (V2X) technology, ranging from spectrum sharing to joint signal design, presenting the limitations and potential of V2X-ISAC architectures. Moreover, the chapter offers an overview of the challenges of ISAC integration in vehicular networks, such as interference management, synchronization, scalability, and adaptation to dynamic road environments. It also includes numerical examples that highlight both the potential and critical issues of ISAC, which are now under active investigation by standardization bodies.*

9.1 Introduction

Vehicular systems are evolving from mere communication endpoints into distributed cyber-physical agents that must *perceive* their surroundings and *coordinate* actions under strict latency and reliability constraints. In this context, ISAC unifies the two traditionally separated functions - environment sensing (including radar-like perception and localization) and data exchange - on a common waveform, hardware, and spectrum perspective. Beyond architectural elegance, this integration is motivated by safety and scalability: a shared ISAC substrate reduces processing and signalling overheads, shortens decision loops, and enables cooperative functions such as collective perception, coordinated manoeuvring, and traffic-state estimation at scale.

Over the years, various wireless technologies offered varying levels of localization and sensing accuracy to suit different usage scenarios. Advancements in wireless communication networks, including expanded bandwidth, massive arrays, and high carrier frequency,