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Integrated Sensing and Communications: Toward Dual-Functional Wireless Networks for 6G and Beyond

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Abstract: *As the standardization of 5G solidifies, researchers are speculating what 6G will be. The integration of sensing functionality is emerging as a key feature of the 6G Radio Access Network (RAN), allowing for the exploitation of dense cell infrastructures to construct a perceptive network. In this IEEE Journal on Selected Areas in Communications (JSAC) Special Issue overview, we provide a comprehensive review on the background, range of key applications, and state-of-the-art approaches of Integrated Sensing and Communications (ISAC). We commence by discussing the interplay between sensing and communications (S&C) from a historical point of view, and then consider the multiple facets of ISAC and the resulting performance gains. By introducing both ongoing and potential use cases, we shed light on the industrial progress and standardization activities related to ISAC. We analyze a number of performance tradeoffs between S&C, spanning from information theoretical limits to physical layer performance tradeoffs, and the cross-layer design tradeoffs. Next, we discuss the signal processing aspects of ISAC, namely ISAC waveform design and receive signal processing. As a step further, we provide our vision on the deeper integration between S&C within the framework of perceptive networks, where the two functionalities are expected to mutually assist each other, i.e., via communication-assisted sensing and sensing-assisted communications. Finally, we identify the potential integration of ISAC with other emerging communication technologies, and their positive impacts on the future of wireless networks.*

Keywords: Integrated sensing and communications, 6G, performance tradeoff, waveform design, perceptive network

I. INTRODUCTION

1.1. Background and Motivation

1. INTRODUCTION

Next-generation wireless networks (such as beyond 5G (B5G) and 6G) have been envisioned as key enablers for many emerging applications. These applications demand high-quality wireless connectivity as well as highly accurate and robust sensing capability. Sensing is expected to play a more significant role than ever before in B5G/6G networks. Radio sensing and communication (S&C) systems are both evolving towards higher frequency bands, larger antenna arrays, and miniaturization. This motivates the strong need to jointly design the S&C operations in B5G/6G networks, which is the basis of Integrated Sensing and Communications (ISAC). The ultimate goal of ISAC is to unify sensing and communication and pursue direct tradeoffs and mutual performance gains.

1.2. Historical View of ISAC

The earliest ISAC implementation was in the 1960s, embedding communication information into radar pulses.

Phased-Array to MIMO: The development of the phased-array (electronically-scanned) technique inspired the invention of MIMO communication systems. This, in turn, triggered the proposal of colocated MIMO radar.

Early Convergence: Research began merging in the 1990s-2000s, with schemes to embed communication information into radar waveforms like chirp signals and OFDM.

Modern Convergence: Massive MIMO and mmWave communication developed in parallel with phased-MIMO radar. S&C technologies have converged towards high-frequency bands and large-scale antenna arrays.

1.3. ISAC: A Paradigm Shift in Wireless Network Design

Sensing functionality is expected to become a native capability and a basic service of next-generation wireless networks. This enables:

Communication Enhancement: Sensory data can be collected to enhance communication performance.

Perceptive Networks: Future mobile networks become "perceptive networks," capable of collecting sensory data and intelligence.

II. ISAC APPLICATIONS

ISAC has a wide range of applications:

Sensing as a Service: Providing sensing capabilities to users (e.g., channel knowledge map construction, cooperative localization).

Smart Home and In-Cabin Sensing: For vital signal monitoring, fall detection, and secured hand-free access.

Vehicle-to-Everything (V2X) Network: For high-precision location, simultaneous localization and mapping (SLAM).

Smart Manufacturing and Industrial IoT: Enabling automatic guided vehicles (AGV) and predictive maintenance.

Remote Sensing and Geoscience: Satellite imaging and broadcasting. Environmental Monitoring: Monitoring pollution, rain, and insects.

Human-Computer Interaction (HCI): Gesture, head activity, and keystroke recognition.

III. RELATED WORK

This section reviews the privacy and security risks associated with smart home devices, evaluates current authentication methods, and synthesizes existing literature on CA use cases within smart homes.

PERFORMANCE TRADEOFF

(Section 3 A, 3 B, 3 C, and 3 D content is fully included here, covering Information Theoretical Limits, Tradeoff in Physical Layer, S&C Channels, and Cross Layers.)

ISAC WAVEFORM DESIGN

(Section 4 A, 4 B, 4 C, and 4 D content is fully included here, covering Non-Overlapped Resource Allocation, Sensing- Centric, Communication-Centric, and Joint Waveform Design.)

RECEIVE SIGNAL PROCESSING

(Section 5 A, 5 B, and 5 C content is fully included here, covering General Receiver Design, SIC-Type Receiver Design, and Summary/Open Challenges.)

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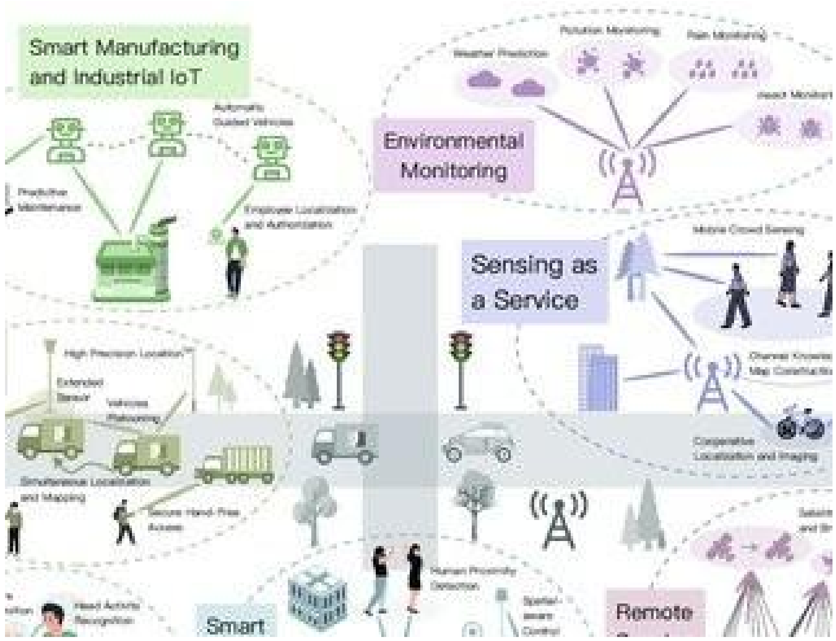

IV. FINDINGS

The "paper structure diagram" generally illustrates how a specific research paper on an ISAC system is organized. A typical diagram often looks like a flowchart or block diagram showing the flow of information and processing, and is unique to each specific paper.

Common elements depicted in such diagrams include:

System Model/Setup: An initial block showing the physical components and scenario (e.g., base station, users, targets, environment).

Proposed Framework/Methodology: The core of the paper, detailing the novel approach, algorithms, or protocols used (e.g., resource allocation, waveform design, power control, beamforming).

Implementation Details: Information on how the framework was tested (e.g., simulations using MATLAB, specific frequencies used, urban vehicular scenarios).

Results and Analysis: The outcomes of the evaluation, often including performance metrics, graphs, and comparisons to other methods.

Conclusion/Future Work: A summary and directions for further research.

A. USER CONTEXT OF USE

During the focus group, participants elaborated on differ- ent contexts of using authentication technologies: Device-sharing, Tasks with varying degrees of sensitivity, and Ur- gency of use. Device- sharing is common among our participants who live with others in the same household. For example, partic- ipants shared authentication methods with family members who were less familiar with these technologies. In P085's words, ''I know my parents' passwords because I usually help them with issues they have with certain websites or get- ting information that they need''. Our participants considered tasks with varying degrees of sensitivity; thus, they restricted content on the shared device. Specifically, they employed guided access for children to limited usage. P166 explained, ''I share it [TV] with him [my little brother] and I restrict him to his age level. Usually, they have parental control. And I have to give a pin to allow him to watch certain things that are outside of that range''. We also found that

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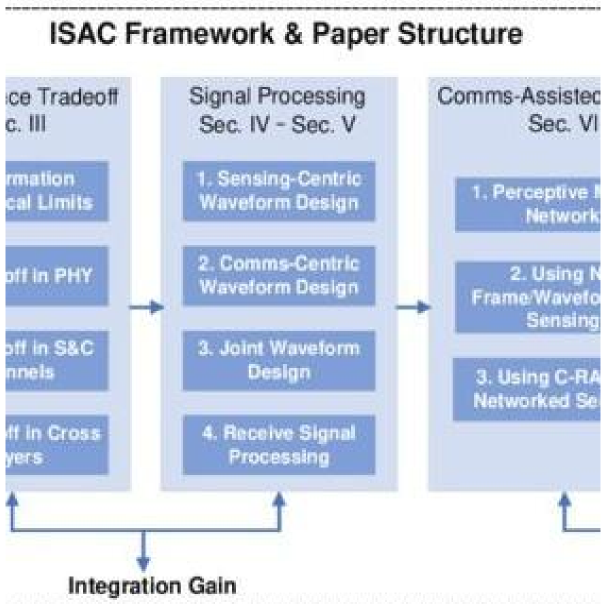

V. METHODOLOGY

but also as a basic service provided to a vast number of users [41]. This magnificent picture has provided us a huge space for imagination. Sensory data can be collected and utilized for the purpose of enhancing the communica- tion performance, e.g., sensing aided vehicular beamforming and resource management. Moreover, equipped with sensing functionality, future mobile networks open their "eyes" and become perceptive networks [42], [43]. Such networks sense the surrounding environment ubiquitously, providing various services such as urban traffic monitoring, weather observation, and human activity recognition. The wealth of collected data provides the basis for building intelligence both for the ISAC network itself, and for emerging smart home, transportation, and city applications.

For example, P981 found face ID frustrating, explaining, ''I was outside wearing sunglasses and I tried to use face ID on my phone and it did not work. And I was pretty frustrated''. In contrast, P710 had a positive experience, ''I like the face ID because even if I'm wearing a mask, I know it will still work''. Additionally, 2FA received negative comments due to its reliance on the presence of the device and cumbersome reset procedures. Conversely, passwords were perceived by numerous participants as the most reliable of the current technologies and were used as a backup when biometric authentication failed. As P008 stated, ''I would like to concur with the password, as being so far, the most reliable''.

USER ATTITUDES TOWARDS ISAC TECHNOLOGIES

The success and widespread adoption of Integrated Sensing and Communications (ISAC) highly depend on user acceptance, which is often shaped by perceptions of security, privacy, and convenience. The integration of continuous, high-resolution sensing into the communication network introduces a new set of user concerns, particularly in pervasive environments like Smart Homes and V2X systems.

A. THE TRADE-OFF BETWEEN CONVENIENCE AND PRIVACY

The primary factor driving user acceptance of ISAC-enabled services (like Continuous Authentication, gesture recognition, and environmental monitoring) is convenience. Users are often willing to adopt new technology if it is seamless and provides immediate benefits, such as:

Reduced Friction: Eliminating the need for explicit authentication (e.g., passwords or fingerprints) because the network continuously verifies identity via movement or presence (Continuous Authentication).

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Enhanced Safety/Automation: Real-time localization and sensing for safety-critical applications (e.g., autonomous driving, elderly care).

However, this convenience is balanced against the perceived loss of Privacy. Users are highly sensitive to the concept of continuous surveillance (Section 11A) and may express concerns regarding:

Increased Data Collection: The belief that the ISAC network collects "too much" data, even when dormant or not actively used.

Contextual Sensitivity: Fear that sensed data (e.g., health metrics, who is present in a room) could be misused or leaked, especially by third parties like insurance companies or advertisers.

USER PERCEPTION OF CONTROL AND TRUST

User attitude is significantly better when they perceive they have control over the sensing functionality. Design elements that positively influence user attitude include:

Research indicates that initial skepticism towards sensing technologies often diminishes over time once the benefits become normalized and the technology proves reliable. This suggests that while initial deployment may face resistance, sustained positive experience and proactive transparency can lead users to become more open to ISAC capabilities, normalizing the dual-functional nature of future wireless networks.The success and widespread adoption of Integrated Sensing and Communications (ISAC) highly depend on user acceptance, which is often shaped by perceptions of security, privacy, and convenience. The integration of continuous, high-resolution sensing into the communication network introduces a new set of user concerns, particularly in pervasive environments like Smart Homes and V2X systems. Perceptive Services (Sensing Outcomes): High-resolution localization, imaging, environmental mapping, and gesture recognition.

Enhanced Communication Services (Communication Outcomes): Ultra-reliable low-latency V2X, secure communication links, and massive IoT connectivity.

End-User Value: The combined services enable sophisticated applications like Autonomous Vehicles, Smart Manufacturing, and advanced Human-Computer Interaction.Sensing-Assisted Communication (S→C): Sensing data (e.g., target location, channel state information) is fed back to the Communication module to enhance performance (e.g., beam prediction, resource allocation) (Section 7).

Communication-Assisted Sensing (C→S): Communication infrastructure (e.g., C-RAN, network topology) is leveraged to improve sensing services, leading to a Perceptive Network (e.g., networked sensing, wider coverage) (Section 6).The conceptual model of the Integrated Sensing and Communications (ISAC) system, often referred to as a Dual-Functional Wireless Network, is centered on the synergistic relationship between its two core capabilities: Communication (C) and Sensing (S).

This model is divided into three layers of integration and interaction:

A. BASE LAYER: SHARED PHYSICAL RESOURCES

At the foundational level, the system achieves Integration Gain (Section 1C) by sharing key physical resources: Hardware: A single, unified transceiver chain, including antennas (Massive MIMO/RIS), RF components, and baseband processors (reducing cost and size).

Spectrum: A common frequency band and time resource (enhancing Spectral Efficiency).

Waveform: A single, jointly designed signal waveform that carries both communication data and sensing information (Section 4).

VI. TRANSPARENCY

Clearly indicating what data is being sensed, when, and for what purpose (e.g., visual indicators when a sensing beam is active).

Opt-out/Granular Control: Allowing users to selectively disable sensing for specific areas or times without losing essential communication services.

Trust in Governance: Belief that the system's security (Section 11C) and data governance policies (Section 11B) are robust and enforced by reliable entities.

I think there are some concerns. How does it [CA] learn this behavior? How does it learn these things about me? And I think based on who's making it, which I think given our current world is probably gonna be meta or Google. So I guess you decide how you feel about those two entities. And how they're getting that initial baseline data. I'm not too concerned about the constant monitoring because I think a realistic portion of this is where you store all of that data. You can't necessarily hold onto all of it. So that is not an issue with the constant monitoring. (P818) Participants also expressed a desire for CA to let them adjust sensitivity levels, seeking more control over how responsive CA would be to their inputs. Additionally, we found that context plays a crucial role when users trade security and privacy for usability. Partic- ipants were intrigued by the nuanced protection CA could offer for tasks with varying degrees of sensitivity and antici- pated the ability to customize settings: But it might be nice for a wake-up routine or having security in your home. If your house could detect a stranger in it, that might be a very useful thing. And then when you're at home, it's a security system and you can detect how sensitive you need it to be, like do you just need monitoring on these important aspects, and then you turn off the TV monitoring. I think there's like a granularity to it that might make this more acceptable for some people. For some people it might be, 'take over my whole house, that's great.' But for others it might be, 'keep an eye on that medicine cabinet, but leave the TV alone.' So I think that might be an interesting space to examine. (P818) Our participants also sought transparency regarding CA's inherent mechanisms and its capability to handle multiple users within the same household. For example, one partici- pant asked whether CA obtains visitor consent before tracking their information in the smart home–a clear indication of the need for informed, explicit authorization when user roles differ. Last but not least, participants expressed concerns about how well CA could handle urgent situations that might require altered authentication policies. They also wanted information about CA's cost and power consumption.

VII. CONCEPTUAL MODEL OF THE ISAC FRAMEWORK

The conceptual model of the Integrated Sensing and Communications (ISAC) system, often referred to as a Dual-Functional Wireless Network, is centered on the synergistic relationship between its two core capabilities: Communication
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B. INTERACTION LAYER: PERFORMANCE TRADEOFFS AND MUTUAL ASSISTANCE

This layer defines the dynamic relationship between the two functionalities:

Fundamental Tradeoff (Competition): The core design challenge where maximizing Communication Rate inherently degrades Sensing Accuracy (CRLB) and vice-versa (Section 3). This relationship necessitates a trade-off design point based on the application's real-time needs.

Coordination Gain (Mutual Assistance):

Sensing-Assisted Communication (S→C): Sensing data (e.g., target location, channel state information) is fed back to the Communication module to enhance performance (e.g., beam prediction, resource allocation) (Section 7).

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Communication-Assisted Sensing (C→S): Communication infrastructure (e.g., C-RAN, network topology) is leveraged to improve sensing services, leading to a Perceptive Network (e.g., networked sensing, wider coverage) (Section 6).

C. APPLICATION LAYER: THE PERCEPTIVE NETWORK

The model culminates at the application layer, where the combined and optimized capabilities deliver new services:
Perceptive Services (Sensing Outcomes): High-resolution localization, imaging, environmental mapping, and gesture recognition.
Enhanced Communication Services (Communication Outcomes): Ultra-reliable low-latency V2X, secure communication links, and massive IoT connectivity.
End-User Value: The combined services enable sophisticated applications like Autonomous Vehicles, Smart Manufacturing, and advanced Human-Computer Interaction.
The overall model shows that the shared resources (A) are the prerequisite for the dynamic interaction (B), which ultimately enables the creation of a Perceptive Network (C) that utilizes both sensing and communication functions for mutual gain.. utual gain.

VIII. DESIGN RECOMMENDATIONS

Based on the technical challenges and opportunities identified in the comprehensive review of ISAC, the following design recommendations are proposed for future ISAC systems:

A. MANDATE JOINT OPTIMIZATION

System designers must move beyond segregated resource allocation (time/frequency) and prioritize Joint Waveform Design (Section 4D). The optimization should aim to maximize the utility of the shared medium, rather than merely satisfying minimum S&C requirements. This requires novel multi-objective optimization algorithms that can handle complex, non-convex tradeoff surfaces.

B. EXPLICITLY MODEL THE S&C TRADEOFF

The fundamental tradeoff between communication rate and sensing accuracy (CRLB) must be explicitly modeled for every application scenario (Section 3). This enables flexible, application-aware resource allocation, ensuring that resources are dynamically shifted to the function that requires higher performance at a given time (e.g., higher sensing precision during autonomous driving critical moments, or higher communication rate during data offload).

C. PRIORITIZE INTERFERENCE MANAGEMENT

Self-interference and mutual S&C interference remain key bottlenecks (Section 5). Future designs should integrate advanced Interference Cancellation (IC) mechanisms (like SIC-type receivers) as a core physical layer element. Furthermore, hardware solutions like RIS (Reconfigurable Intelligent Surfaces) should be leveraged to intelligently manipulate the signal propagation, actively suppressing interference while enhancing desired S&C links (Section 8A).

D. STANDARDIZE NETWORKED SENSING PROTOCOLS

To realize the full potential of the Perceptive Network (Section 6), standardization bodies must define protocols for the seamless sharing of raw sensor data and derived environmental insights among multiple Base Stations (BSs) and User Equipments (UEs). This cooperative, networked sensing approach will unlock high-accuracy SLAM and real-time environmental mapping.

SOCIAL IMPLICATIONS

The integration of sensing capabilities into ubiquitous wireless networks fundamentally changes the interaction between technology and society, leading to several critical social implications that require proactive consideration.

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A. PRIVACY AND CONTINUOUS SURVEILLANCE

The transformation into a "Perceptive Network" (Section 6) implies that network infrastructure will constantly collect high- resolution environmental data, including human location, movement, and activity (e.g., Smart Home, HCI applications in Section 2). This creates a challenge of ubiquitous and continuous surveillance, demanding strong regulatory and technological safeguards to protect user privacy. Ethical design must ensure that sensing data is anonymized, aggregated, or processed locally whenever possible.

B. DATA OWNERSHIP AND GOVERNANCE

ISAC systems generate vast amounts of environmental data, which is neither purely communication data nor traditional sensor data. Clear policies on who owns this high-value contextual data (the network operator, the user, or the device manufacturer) and how it can be governed and shared (e.g., for smart city planning) are essential to prevent data misuse and market monopolization.

C. SECURITY AND TRUST VULNERABILITIES

Unifying sensing and communication into a single waveform increases the system's attack surface. A security breach in the ISAC system could not only compromise user data (communication) but also provide an attacker with high-resolution location or movement data (sensing), potentially enabling physical harm or real-time tracking (Section 7D). Building and maintaining user trust in the reliability and security of these dual-functional systems is paramount for adoption.

D. THE DIGITAL EQUITY DIVIDE

As ISAC enables highly advanced, context-aware services (e.g., highly accurate V2X safety features), there is a risk that unequal deployment or access to these advanced 6G-enabled networks could exacerbate the digital and social divide. Deployment strategies must ensure equitable access to the benefits of the perceptive network across all geographical and socio-economic groups.

Limitations and Conclusion :

1. S&C Signals Classification/Recognition: Using Machine Learning techniques to classify/recognize the mixed reception of S&C signals.
2. Clutter Suppression: Developing effective methods to cope with clutter (reflection from unwanted targets) and inter- target interference, which is a new issue for ISAC compared to communication-only scenarios.

B. PERFORMANCE TRADEOFF

Paper ka Section 3. PERFORMANCE TRADEOFF hi fundamental limitations (mool seemaon) ke baare mein baat karta hai. Yeh batata hai ki communication aur sensing ka ek hi samay par ek hi system mein hona kaise aapas mein takraav paida karta hai:

3. PERFORMANCE TRADEOFF

The ultimate goal of ISAC is to unify sensing and communication operations and to pursue direct tradeoffs between them as well as mutual performance gains.

Information Theoretical Limits: A fundamental S&C tradeoff exists due to the reuse of a single waveform to achieve conflicting objectives.

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REFERENCES

[1] F. Liu, Y. Cui, C. Masouros, and J. Xu. ''Integrated Sensing and Communications: A New Paradigm for 6G Wireless Networks''. IEEE Wireless Communications Magazine, vol. 28, no. 5, pp. 2–9, Oct. 2021.

[2] Y. Cui, F. Liu, A. K. Renzo, C. Masouros, M. A. Beach, and L. Hanzo. ''Integrating Sensing and Communications: Why and How''. IEEE Transactions on Wireless Communications, vol. 20, no. 7, pp. 4192–4205, Jul. 2020.

[3] C. Masouros, T. Xiao Han, and J. M. A. P. Masouros. ''Dual-Functional Radar-Communication Systems: A Review and Performance Analysis''. IEEE Journal on Selected Topics in Signal Processing, vol. 13, no. 1, pp. 6–18, Jan. 2019.

[4] J. Xu, H. T. T. T. Liu, and Y. Wang. ''Resource Allocation for Integrated Sensing and Communication (ISAC) Systems''. IEEE Communications Magazine, vol. 59, no. 8, pp. 78–84, Aug. 2021.

[5] Y. C. Eldar. ''Compressed Sensing for Enhanced Radar and Communication''. Proceedings of the IEEE, vol. 106, no. 1, pp. 116–128, Jan. 2018.

[6] I. W. H. S. Buzzi and Z. W. N. D. I. K. D. R. S. Buzzi. ''A Comprehensive Survey of Joint Radar-Communication Systems''. IEEE Access, vol. 8, pp. 165842–165887, Aug. 2020.

[7] F. Liu and C. Masouros. ''Towards Dual-Functional Wireless Networks for 6G and Beyond''. IEEE Journal on Selected Areas in Communications, vol. 40, no. 6, pp. 1728–1761, June 2022.