Bharat6G Alliance



Bharat 6G Alliance Whitepaper

INTEGRATED SENSING AND COMMUNICATION (ISAC) FOR 6G: TECHNOLOGIES, ARCHITECTURES, APPLICATIONS, AND FUTURE DIRECTIONS



October 2026 | Version 1.0

Bharat 6G Alliance Whitepaper

Integrated Sensing and Communication (ISAC) for 6G: Technologies, Architectures, Applications, and Future Directions

October 2026

Table of Contents

Foreword 7
Executive Summary 8
Abbreviations 9
Section 1 – Introduction 12
1.1. The Genesis of ISAC: An Evolutionary Perspective on Communication and Sensing 12
1.2. Vision of 6G ISAC 14
1.3. Evolution and Future Roadmap of ISAC in 3GPP 14
1.4. Scope of this White Paper 15
Section 2 – Fundamentals of ISAC 17
2.1 Fundamentals of Communication and Sensing: 17
2.2 Communication–Sensing: Trade-offs and Benefits 17
2.3 Key Performance Indicators 18
Section 3: Air-Interface Design of ISAC 19
3.1. KPI Definition and Optimization 19
3.2. Frame Structure Design for ISAC 19
3.3 Waveform Design and Signal Processing Architecture 20
3.4 Waveform Candidates for ISAC 22
Section 4: RF Front-End and Antenna Technologies 23
4.1. RF Front-End Architectures 23
4.2. Full-Duplex Antenna for ISAC 24
4.3 Beamforming and Precoding 24
Section 5 – Taxonomy of ISAC Systems 25
5.1 ISAC Deployment Paradigms 25
5.2 ISAC Operating Modes 26
5.3 Realization Framework for ISAC 26
Section 6: Network Architectures and System Orchestration 29
6.1 O-RAN Based ISAC Network Architecture 29
6.2 AI-native Architecture 30
6.3 Network Virtualization and Slicing for ISAC 31
Section 7: Sensing–Communication Mutual Assistance in ISAC 31
7.1 Communication-Assisted Sensing 31
7.2. Sensing-Assisted Communications 32
Section 8: AI-Native ISAC 35

8.1 AI Across the ISAC Processing and Control Loop 35
8.2 Trustworthy and Deployable AI-Native ISAC 36
8.3 Toward Closed-Loop AI-Native ISAC 37
Section 9: Standardization 37
9.1 ISAC Standardization Activities 37
9.1.1 ITU IMT-2030 37
9.1.2 3rd Generation Partnership Project (3GPP) 38
9.1.3 TSDSI 40
9.1.4 O-RAN Alliance 41
9.1.5 IEEE 41
9.2 Global Research Programs and National Initiatives 42
Section 10: Security and Privacy 44
10.1 Multi-Domain Threat Landscape 44
10.1.1 Cyber-physical domain 44
10.1.2 Physical-layer domain 44
10.1.3 Protocol and control-plane domain. 44
10.1.4 Cross-domain propagation 45
10.2 Sensing as a Security Enabler 45
10.3 Joint Design of Security, Sensing, and Communication 46
10.4 A Defence-in-Depth Architecture 46
Section 11: Performance Evaluation and Benchmarking 47
11.1 Principles of ISAC Performance Evaluation 47
11.2 Communication Performance Metrics 47
11.3 Sensing Performance Metrics 47
11.4 Joint Communication-Sensing Performance 48
11.5 System-Level and Implementation Metrics 49
Section 12: Experimental Platforms: ISAC Prototyping Platforms 49
12.1 SDR Platforms 50
12.2. FPGA Platforms 50
12.3 RFSoC Platforms 50
Section 13: Applications 51
13.1 Intelligent Mobility and Transportation 51
13.2 Smart Industry and Connected Living 52
13.3 Mission-Critical and Immersive Applications 53
Section 14: Economics and Commercialization 54

14.1 From Connectivity to Network-Generated Value 54
14.2 Operator Investment Perspective 55
14.3 Cost Structure and the Operator Business Case 55
14.4 Commercial Attractiveness Across Use Cases 55
14.5 Route to Market 56
14.6 Commercial Outlook 57
Section 15: Open Research Challenges 58
15.1 Fundamental Research Challenges 58
15.2. Emerging ISAC Technologies 59
15.3. System-Level Challenges and Future Outlook 61
Section 16: ISAC in India: Development, Standardization, and Future Opportunities 62
16.1 Priority Areas for India 63
Section 17: Future Vision Towards 2035 65
Acknowledgement: 66
References: 67

Foreword

The Bharat 6G Alliance (B6GA) prepares white papers to give its members, the Government and industry a common, factual basis for planning 6G work in India. This paper, prepared under the B6GA Technology Working Group, deals with Integrated Sensing and Communication (ISAC): the use of the same spectrum, radio hardware and signals for both communication and sensing.

ISAC is one of the six usage scenarios in the ITU-R IMT-2030 framework and is now being studied in 3GPP for 6G. India has a large 5G network, a growing set of ISAC projects funded by the Department of Telecommunications (DoT) and several sectors with clear sensing needs. Choosing where to focus is therefore as important as following the technology itself.

The paper was written by researchers from academia, industry and standards bodies. We hope it will help policymakers, operators, equipment makers, start-ups and research groups as they set their priorities for ISAC in India.

Executive Summary

ISAC allows a mobile network to sense its surroundings, for example to detect, locate and track objects, using the same spectrum, sites and signals that it uses for communication. This paper reviews the technology, its standardization status, applications and economics, and sets out where India should concentrate its effort.

Key messages

1. ISAC is moving from research into standards, but most of it is not yet specified. 3GPP Release 19 produced the ISAC service requirements (TS 22.137) and an agreed channel model for sensing evaluation. Release 20 is studying the 6G ISAC radio aspects, such as sensing reference signals, measurements and waveform enhancements with cyclic-prefix OFDM (CP-OFDM) as the baseline, together with the sensing architecture. Normative 6G ISAC specifications are expected only from Release 21. Table-2 gives the status of each topic covered in this paper.

2. Early deployments are likely to reuse existing sites and spectrum. ISAC will first appear as an added function of 5G-Advanced and 6G networks rather than as a separate sensing network. The business case is strongest where an operator can sell processed sensing information, such as presence, location or movement, to an enterprise or a public agency (Section 14).

3. Several technical problems remain open. These include self-interference in full-duplex operation, synchronization between distributed nodes, the loss of communication capacity when resources are given to sensing, privacy of sensing data, and the lack of shared datasets and test methods (Sections 10, 11 and 15).

4. India has a strong starting point but limited resources. 5G is available in almost every district, about 5.6 lakh 5G base stations are in service, nine projects funded through DoT's Telecom Technology Development Fund (TTDF) are working on ISAC and TSDSI has active study items. The base is broad, so a few areas need to be chosen for focused support.

Recommendations

R1. Give priority to four areas where India has an advantage (Section 16.1): reconfigurable intelligent surface (RIS)-assisted ISAC; disaster and environmental sensing; sensing along rail, highway and unmanned aerial vehicle (UAV) corridors; and India-specific channel measurements and evaluation for standards.

R2. Link TTDF-funded ISAC projects to the open items in the 3GPP Release 20 study and to TSDSI work, so that their results turn into standards contributions while the 6G specifications are still open.

R3. Set up shared ISAC test sites and datasets, building on existing 5G testbeds where possible, with common evaluation methods based on the 3GPP and TSDSI channel models.

R4. Start early discussion with DoT and TRAI on the regulatory questions ISAC raises, including authorization of sensing services and the handling of sensing data.

R5. Treat areas where India has no clear advantage today, such as THz, maritime and underwater sensing, as research topics to be reviewed later rather than as targets for large programmes.

Abbreviations

The abbreviations used in this paper are listed below.

Abbreviation	Definition
3GPP	3rd Generation Partnership Project
6GR	6G Radio
ADC	Analog-to-Digital Converter
AFDM	Affine Frequency Division Multiplexing
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AI/ML	Artificial Intelligence/Machine Learning
AoA	Angle of Arrival
AoD	Angle of Departure
AP	Access Point
API	Application Programming Interface
B6GA	Bharat 6G Alliance
BS	Base Station
CAPEX	Capital Expenditure
CAS	Communication-Assisted Sensing
CBF	Coordinated Beamforming
CoMP	Coordinated Multi-Point
CP-OFDM	Cyclic-Prefix Orthogonal Frequency Division Multiplexing
CPE	Customer Premises Equipment
CPU	Central Processing Unit
CRB	Cramér–Rao Bound
CSI	Channel State Information
DAC	Digital-to-Analog Converter
DARPA	Defense Advanced Research Projects Agency
DFT-s-OFDM	Discrete Fourier Transform-spread OFDM
DL	Downlink
DL-PRS	Downlink Positioning Reference Signal
DMRS	Demodulation Reference Signal
DOA	Direction of Arrival
DoT	Department of Telecommunications
EKF	Extended Kalman Filter
ELAA	Extremely Large Aperture Array
eMBB	Enhanced Mobile Broadband
ETSI	European Telecommunications Standards Institute
FD	Full-Duplex
FDM	Frequency-Division Multiplexing
FFT	Fast Fourier Transform

Abbreviation	Definition
FL	Federated Learning
FMCW	Frequency-Modulated Continuous Wave
FPGA	Field-Programmable Gate Array
FR1/FR2/FR3	Frequency Range 1/2/3
FSO	Free-Space Optical
FWA	Fixed Wireless Access
GASM	Generalized Adaptive Spreading Modulation
GFDM	Generalized Frequency Division Multiplexing
gNB	Next-Generation NodeB (5G base station)
GNSS	Global Navigation Satellite System
GSMA	GSM Association
HAPS	High-Altitude Platform Station
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
IoT	Internet of Things
IP	Intellectual Property
ISAC	Integrated Sensing and Communication
ISG	Industry Specification Group
ISLR	Integrated Sidelobe Ratio
ITS	Intelligent Transportation Systems
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
JCAS	Joint Communication and Sensing
JCR	Joint Communication and Radar
JRC	Joint Radar and Communication
KPI	Key Performance Indicator
LAE	Low-Altitude Economy
LiDAR	Light Detection and Ranging
LiFi	Light Fidelity
LNA	Low-Noise Amplifier
LTE	Long Term Evolution
MAC	Medium Access Control
MEC	Multi-access Edge Computing
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
mMTC	Massive Machine-Type Communication
mmWave	Millimeter Wave
NaaS	Network as a Sensor
NICT	National Institute of Information and Communications Technology

Abbreviation	Definition
NIST	National Institute of Standards and Technology
NLoS	Non-Line of Sight
NR	New Radio
NSF	National Science Foundation
NTN	Non-Terrestrial Network
O-CU/O-DU/O-RU	O-RAN Central Unit/Distributed Unit/Radio Unit
O-RAN	Open Radio Access Network
OCDM	Orthogonal Chirp Division Multiplexing
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operating Expenditure
OTFS	Orthogonal Time Frequency Space
OTSM	Orthogonal Time Sequency Multiplexing
PA	Power Amplifier
PAPR	Peak-to-Average Power Ratio
PDSCH	Physical Downlink Shared Channel
PHY	Physical Layer
PMCW	Phase-Modulated Continuous Wave
PSLR	Peak-to-Sidelobe Ratio
QoS	Quality of Service
RAN	Radio Access Network
RCS	Radar Cross Section
RF	Radio Frequency
RFFE	Radio Frequency Front-End
RFSoC	Radio Frequency System-on-Chip
RIC	RAN Intelligent Controller
RIS	Reconfigurable Intelligent Surface
RIT	Radio Interface Technology
RMSE	Root-Mean-Square Error
ROC	Receiver Operating Characteristic
RRU	Remote Radio Unit
RS	Reference Signal
RSS	Received Signal Strength
RSU	Roadside Unit
SA1/SA2	3GPP Service and System Aspects Working Groups 1 and 2
SAC	Sensing-Assisted Communication
SDR	Software-Defined Radio
SI	Self-Interference; Study Item (TSDSI)
SIC	Self-Interference Cancellation
SINR	Signal-to-Interference-plus-Noise Ratio

Abbreviation	Definition
SMO	Service Management and Orchestration
SNR	Signal-to-Noise Ratio
SNS JU	Smart Networks and Services Joint Undertaking
ST	Sensing Target
TCO	Total Cost of Ownership
TDD	Time-Division Duplexing
TDM	Time-Division Multiplexing
THz	Terahertz
ToF	Time of Flight
TR	Technical Report
TRAI	Telecom Regulatory Authority of India
TRP	Transmission and Reception Point
TS	Technical Specification
TSDSI	Telecommunications Standards Development Society, India
TSG	Technical Specification Group
TTDF	Telecom Technology Development Fund
UAV	Unmanned Aerial Vehicle
UE	User Equipment
UHD	USRP Hardware Driver
UL	Uplink
UMa/SMa	Urban Macro/Suburban Macro
URLLC	Ultra-Reliable Low-Latency Communication
UWB	Ultra-Wideband
V2X	Vehicle-to-Everything
VLC	Visible Light Communication
WLAN	Wireless Local Area Network
WP 5D	ITU-R Working Party 5D
XAI	Explainable Artificial Intelligence
XR	Extended Reality

Section 1 – Introduction

1.1. The Genesis of ISAC: An Evolutionary Perspective on Communication and Sensing

ISAC results from decades of progress in wireless communications, radar, signal processing, antenna systems, and semiconductor technology. As seen in Fig. 1.1, communication and radar systems initially evolved as distinct disciplines. Communication systems focused on reliable data transfer, high data rates, coverage, and spectrum efficiency, whereas radar systems focused on detection, localization, tracking, and environmental sensing. Although both rely on electromagnetic-wave propagation, they traditionally employed different designs, waveforms, signal-processing techniques, and performance indicators [1], [2].

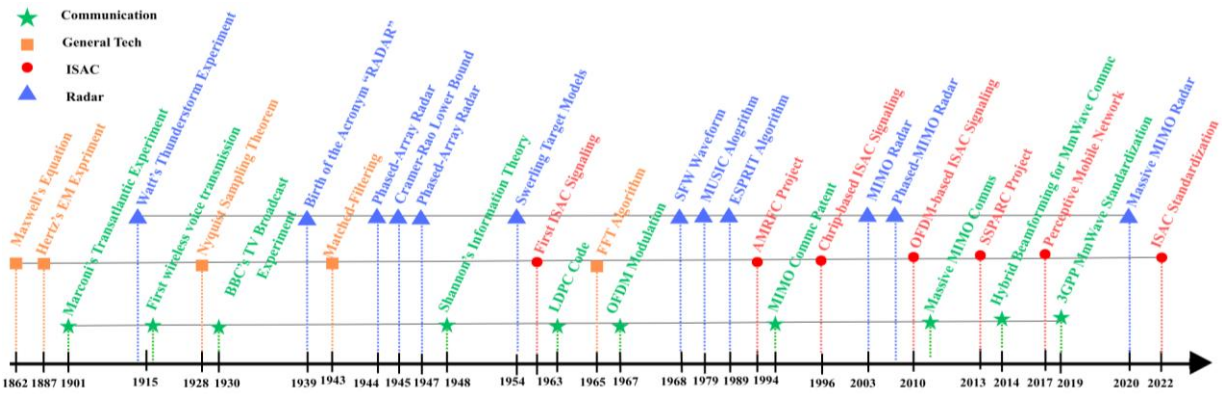


Fig. 1.1: Evolution of ISAC across communication, radar, and standardization.

Radar evolved from early detection systems to phased arrays, pulse-Doppler processing, direction-of-arrival estimation, and multiple-input multiple-output (MIMO) radar, while wireless communications progressed through digital modulation, coding, cellular networks, orthogonal frequency division multiplexing (OFDM), MIMO, and broadband systems. Technologies such as OFDM, MIMO, mmWave, massive MIMO, and adaptive beamforming offered a shared platform for communication and sensing [1], [3].

As shown in Fig. 1.2, the evolution progressed through integrated signaling and chirp/spread-spectrum approaches, radar-embedded communications, OFDM-based JRC, and perceptive mobile networks. The evolution has moved from coexistence and interference minimization toward cooperation and closer functional integration. With the advent of 5G-Advanced and the shift toward 6G, ISAC has broadened its scope from waveform and hardware integration to encompass use cases, channel models, sensing methodologies, topologies, and network interfaces.

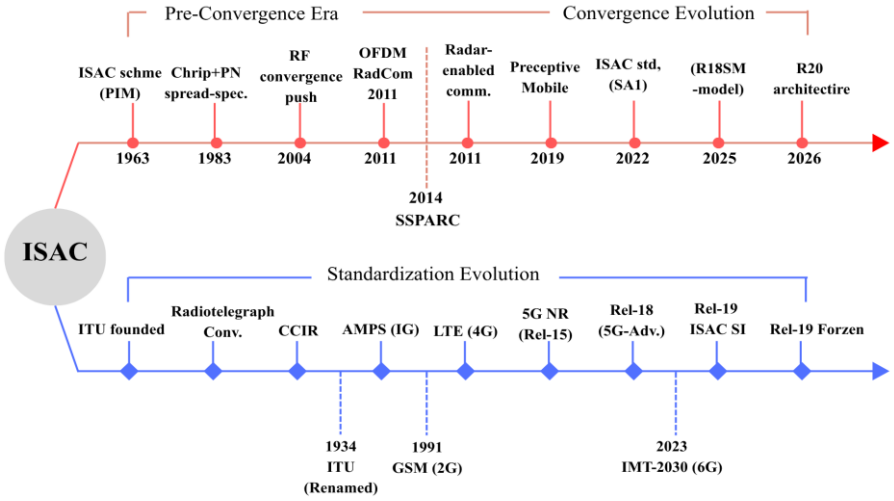


Fig. 1.2 Parallel evolution of ISAC technologies and mobile communication standards.

IMT-2030 and forthcoming Release-19 and Release-20 initiatives further support the systematic integration of sensing within cellular networks [4], [5]. Consequently, ISAC should be regarded as the culmination of a series of technological advancements rather than a singular innovation [6-10]. The upper timeline delineates significant advancements in ISAC, encompassing radar-enhanced communication, intelligent mobile networks, standardization efforts, and nascent 6G frameworks, while the lower timeline charts the evolution of telecommunication standards leading to 5G-Advanced and 6G. A primary catalyst for this convergence is the growing congestion of the RF spectrum.

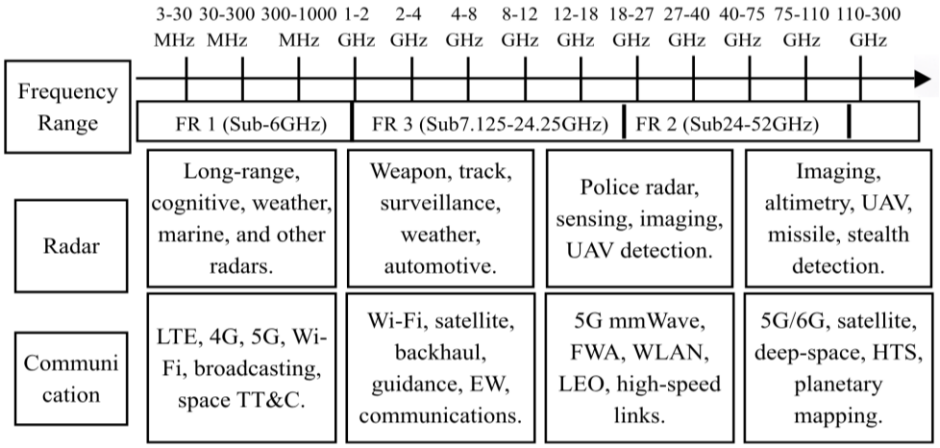


Figure 1.3. Frequency-spectrum coexistence of radar sensing and wireless communication systems.

The escalating need for wireless bandwidth has diminished the spectral separation between the two, especially in sub-6-GHz bands where communication and radar services are increasingly integrated. As networks move into upper-mid-band/FR3 and mmWave frequencies, as shown in Fig. 1.3, wider bandwidths enable both high-data-rate transmission and enhanced-resolution sensing. Nevertheless, operating in neighboring or overlapping bands leads to reciprocal interference and spectrum competition, prompting the need for spectrum sharing and collaborative system design. ISAC goes beyond coexistence by jointly managing spectrum, waveforms, RF equipment, antenna assets, and signal processing. For IMT-2030/6G, spectrum sharing and aggregation are a crucial basis for integrated sensing, especially as networks transition from sub-6 GHz to upper-mid-band and mmWave frequencies.

1.2. Vision of 6G ISAC

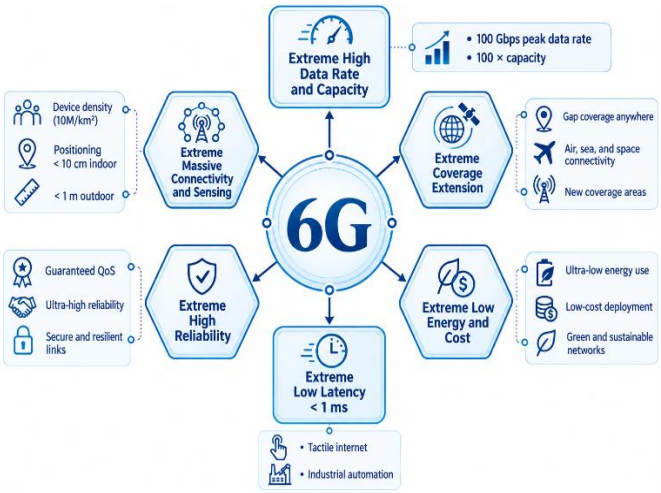


Figure 1.4. Convergence of communication, sensing, and intelligence in the 6G service landscape

The ITU-R IMT-2030 framework (Fig. 1.4) establishes the global 6G vision around communication, sensing, positioning, intelligence, and pervasive connectivity across six usage scenarios: Immersive Communication, Hyper-Reliable and Low-Latency Communication, Massive Communication, Ubiquitous Connectivity, AI and Communication and ISAC. Embedding sensing in base stations, access points, and potentially user devices can enable object recognition, positioning, imaging, environmental mapping, activity monitoring, and network enhancement without dedicated sensing infrastructure. The Bharat 6G Vision complements this approach by emphasizing affordability, sustainability, and intellectual property.

1.3. Evolution and Future Roadmap of ISAC in 3GPP

ISAC is progressing through a structured 3GPP evolution: earlier releases established the radio, positioning, and architectural foundations, while recent and upcoming releases introduce dedicated sensing capabilities. Release 15 defined the NR baseline, including scalable numerology and mmWave operation, thereby providing the bandwidth and spatial aperture required for high-resolution sensing. Releases 16 and 17 further introduced

positioning enhancements, sidelink, and non-terrestrial networking, which provide measurement procedures, reference signals, and deployment options that can be reused for sensing.

Release 18 did not formally standardize ISAC, but it introduced important physical-layer enablers, including studies on sub-band non-overlapping full-duplex operation and enhanced positioning. These developments support the feasibility of future monostatic and bistatic cellular sensing but do not yet define dedicated sensing configurations or KPIs. Release 19 subsequently established important service-level and architectural foundations through SA1 activities, including sensing use cases, terminology, sensing transmitter and receiver roles, authorization, privacy, charging, operator control, and initial sensing channel-modeling activities. Release 20 and beyond represent the transition toward dedicated RAN-level ISAC specifications, with work focusing on sensing channel models, physical-layer evaluation, sensing reference signals, waveform coexistence, feedback mechanisms, and terrestrial and non-terrestrial deployment scenarios.

Near-term 3GPP efforts are expected to emphasize NR-compatible sensing, reference-signal design, feedback, synchronization, interference management, and sensing KPIs. Longer-term research directions include unified terrestrial/NTN sensing models, AI-native resource management, cooperative multi-node sensing, beyond-OFDM waveforms, cell-free distributed sensing, integrated communication-sensing-localization, and standardized ISAC service classes aligned with IMT-2030.

Table-1: The predicted evolution in future 3GPP releases.

3GPP	**Year**	**ISAC Focus**
Rel-20	2025–2027	Study work on radio aspects and system architecture for sensing, including RAN1 TR 38.765 and SA2 TR 23.700-14.
Rel-21	2027–2030	First 6G radio and system specifications, in which sensing is expected to move from an overlay on an LTE-derived design input to waveform and architecture decisions

1.4. Scope of this White Paper

This paper covers ISAC from fundamentals to deployment. Sections 2 to 8 describe the technology: fundamentals and KPIs, air-interface and waveform design, RF front-end and antennas, system taxonomy, network architecture, the ways in which communication and sensing assist each other, and the role of AI. Section 9 reviews standardization in ITU-R, 3GPP, TSDSI, O-RAN and IEEE. Sections 10 to 12 cover security and privacy, performance evaluation and prototyping platforms. Sections 13 and 14 discuss applications and the commercial case. Section 15 lists open research problems, Section 16 describes India's activities and priority areas, and Section 17 gives an outlook to 2035.

The topics in this paper are at very different stages of maturity. To keep agreed specifications apart from research proposals, each topic is placed in one of three categories. **Standardized** means published in a specification or an agreed technical report. **Under study** means that a standards body (3GPP, ITU-R, TSDSI or IEEE) is studying it, with no normative outcome yet. **Research** means that it appears in the literature or in trials but is not part of any standardization work so far. Table-2 gives the status of the main topics, and Sections 3 to 8 and 15 each begin with a short status note.

Table-2: Maturity status of the ISAC topics covered in this paper.

Topic	Status (as of October 2026)	Section
ISAC service requirements and use cases (3GPP TS 22.137, TR 22.837, Release 19)	Standardized	9.1.2, 15.2
ISAC channel model for sensing evaluation (3GPP TR 38.901, Release 19)	Standardized (agreed TR)	9.1.2.1
WLAN sensing (IEEE 802.11bf)	Standardized	9.1.5
IMT-2030 framework with ISAC as a usage scenario (Recommendation ITU-R M.2160)	Standardized; requirement and evaluation Reports in progress	9.1.1
6G ISAC radio: sensing modes, sensing reference signals, measurements, CP-OFDM enhancements (3GPP Release 20, RAN1)	Under study	9.1.2.2
Sensing architecture and network functions (3GPP Release 20, SA2 TR 23.700-14)	Under study	1.3
Joint communication and sensing (JCAS) feasibility and ISAC channel model (TSDSI TR 6069, SI 128)	Under study (TSDSI reports)	9.1.3
Native ISAC waveforms (OTFS, OCDM, GASM) and experimental frame structures	Research	3
Full-duplex ISAC transceivers and self-interference cancellation	Research	4
O-RAN-based ISAC, ISAC slicing, AI-native and semantic ISAC	Research	6, 8
RIS-assisted, cell-free, optical, satellite and quantum ISAC	Research	5, 15.2

Section 2 – Fundamentals of ISAC

2.1 Fundamentals of Communication and Sensing:

Today's intelligent wireless systems mainly have two capabilities: wireless communication and wireless sensing. Communication focuses on reliable information transmission [1], [2], while sensing enables networks to perceive the environment by executing tasks such as target detection, localization, tracking, and parameter estimation. Sensing systems focus more on detection accuracy, spatial resolution, and environmental awareness, whereas communication systems focus more on throughput, latency, reliability, and spectrum efficiency [1-3].

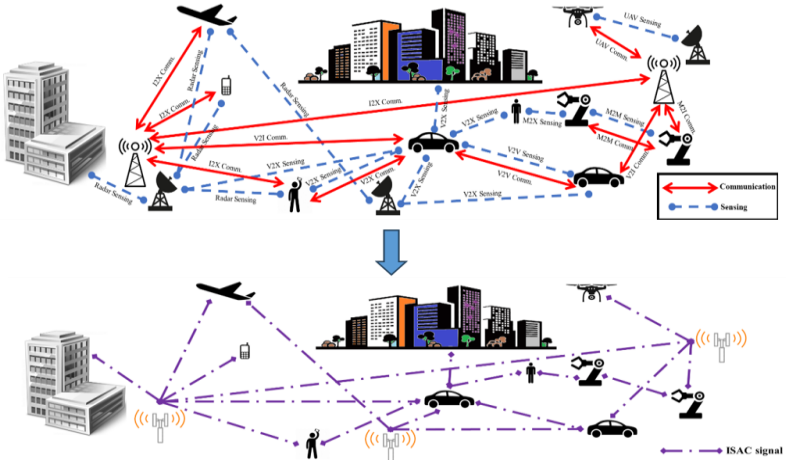


Fig. 2.1. Comparison of traditional scenarios, where communication and radar have separate infrastructure requirements (above part), with ISAC-enabled joint sensing and communication

Figure 2.1 compares conventional communication-and-sensing operation with an ISAC-enabled architecture. Communication and sensing use separate links and largely separate infrastructures, which may require additional hardware. This increases hardware duplication, spectrum usage, energy consumption, deployment cost, and coordination complexity. Communication and sensing are integrated through a common ISAC signal, allowing the same spectrum, antenna array, RF front-end, waveform, beamforming resources, and processing platform to support both data transmission and environmental sensing. This reduces duplicated hardware and infrastructure while improving spectrum and energy efficiency.

2.2 Communication–Sensing: Trade-offs and Benefits

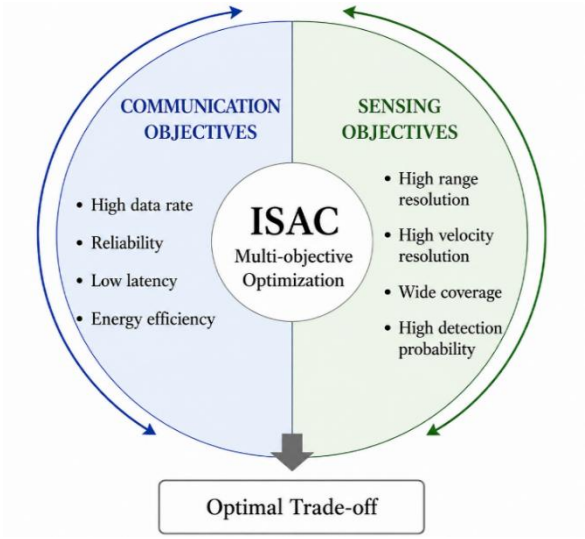


Fig. 2.2. Communication–sensing trade-offs, illustrating the joint resource optimization.

ISAC integrates communication and sensing within a common framework, enabling joint optimization of spectrum, hardware, waveforms, and signal processing [11]. However, achieving both functions involves trade-offs between sensing accuracy in detection, localization, and velocity estimation and communication requirements such as high data rates, low latency, and spectral efficiency. These trade-offs mainly affect bandwidth allocation, waveform selection, transmit power, beamforming, and observation time. For instance, wider bandwidth can improve sensing resolution and communication throughput. Similarly, longer observation times improve sensing accuracy but can increase communication latency. However, jointly designing sensing and communication offers clear benefits. ISAC may reduce duplicated hardware, spectrum use, and site infrastructure when communication and sensing functions can share resources effectively. As shown in Fig. 2.2, ISAC jointly optimizes communication and sensing functions to achieve an application- and scenario-dependent balance among communication rate and reliability, sensing accuracy and resolution, latency, energy efficiency, coverage, hardware complexity, and regulatory constraints.

2.3 Key Performance Indicators

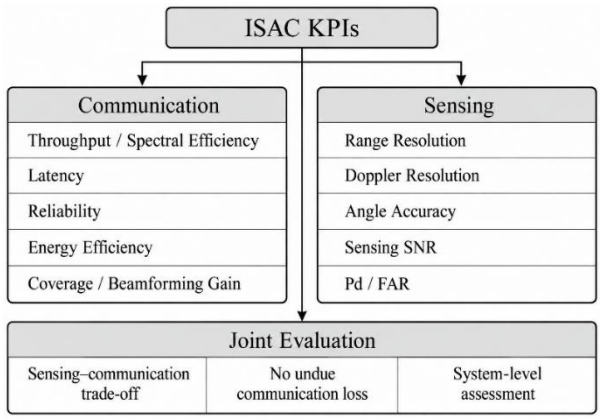


Fig. 2.3. Hierarchical categorization of KPIs for ISAC evaluation.

The performance of an ISAC system should be evaluated using communication, sensing, and joint ISAC KPIs, as shown in Fig. 2.3, because conventional communication metrics alone cannot capture the dual use of radio resources. The selected KPIs align with metrics widely used in ISAC research and emerging 3GPP studies [8], [9]. The evaluation captures the sensing–communication trade-off, including sensing-induced communication degradation and overall system performance. RIS-assisted propagation and Coordinated Beamforming may further influence sensing geometry and observation quality. These metrics enable identification of operating points that satisfy both communication and sensing requirements and support systematic evaluation of resource allocation, beamforming, RIS configuration, and other ISAC strategies.

Section 3: Air-Interface Design of ISAC

Status: *Under study and Research. 3GPP has agreed to use the 6G CP-OFDM waveform and frame structure as the starting point for 6G ISAC (Section 9.1.2.2). The frame structure and alternative waveforms described in this section are research proposals.*

This section describes the ISAC air-interface architecture, developed through four key stages: KPI definition and joint communication–sensing optimization, flexible frame design, waveform and signal-processing design, and compatibility with existing 5G NR infrastructure. Together, these enable efficient resource sharing, balanced sensing–communication performance, and a smooth evolution toward 6G deployment [9], [11-12].

3.1. KPI Definition and Optimization

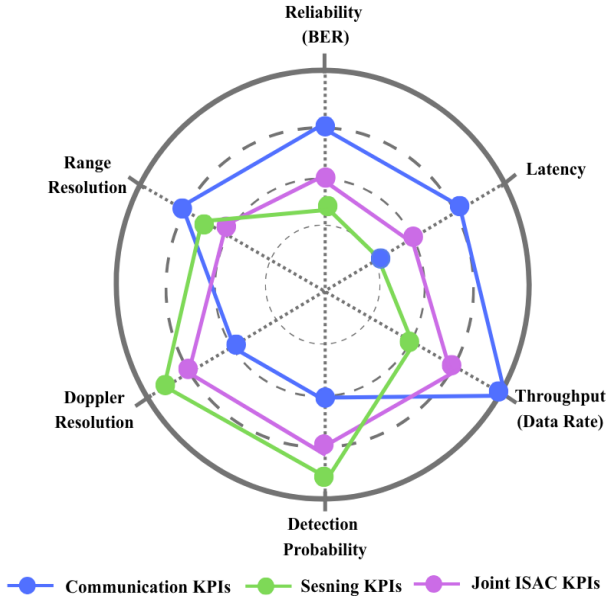


Fig. 3.1: Comparative performance profile of communication, sensing, and joint ISAC KPIs

Many KPI targets documented in the literature and discussed in standardization forums are ambitious, forward-looking goals that often assume mature algorithms, optimized hardware, and ideal deployment conditions [13]. Joint communication and sensing capabilities provide a shared platform for connectivity and environmental perception, but they also pose a fundamental challenge: the two functions have different performance priorities. As shown in the Fig. 3.1, communication-centric operation offers better throughput, latency, and reliability, whereas sensing-centric operation offers better detection and resolution (range and Doppler). The joint ISAC profile lies between these two extremes, balancing communication quality of service and sensing accuracy. This trade-off is inherent to ISAC design: allocating more bandwidth, power, or waveform resources to improve sensing resolution or detection performance may constrain communication throughput or increase latency, and vice versa. Thus, the aim is not necessarily to optimize all KPIs simultaneously. Therefore, adaptive ISAC architectures are expected to dynamically allocate communication and sensing resources based on channel conditions, sensing requirements, network load, and application priorities.

3.2. Frame Structure Design for ISAC

The proposed sensing extension is integrated into the existing 5G NR downlink frame without altering its fundamental structure. Frame duration, numerology, synchronization signals, broadcast channels, control region, and PDSCH scheduling remain unchanged. We consider two sensing-integration cases that mainly differ in whether PDSCH-DMRS resources are reused for sensing or fully preserved for communication-channel estimation. In the second case, the original DMRS allocation at $l = 2$and $l = 12$is retained, while additional sensing resource elements are introduced at $l = 3$and $l = 13$. Thus, sensing does not replace or interfere with the existing DMRS, preserving communication-channel estimation and clearly separating sensing and communication resources. This case offers better communication compatibility by maintaining the complete DMRS pattern, at the cost of additional resource elements that could otherwise carry PDSCH data. The two cases therefore enable direct comparison between resource-efficient DMRS reuse and sensing integration with complete DMRS preservation.

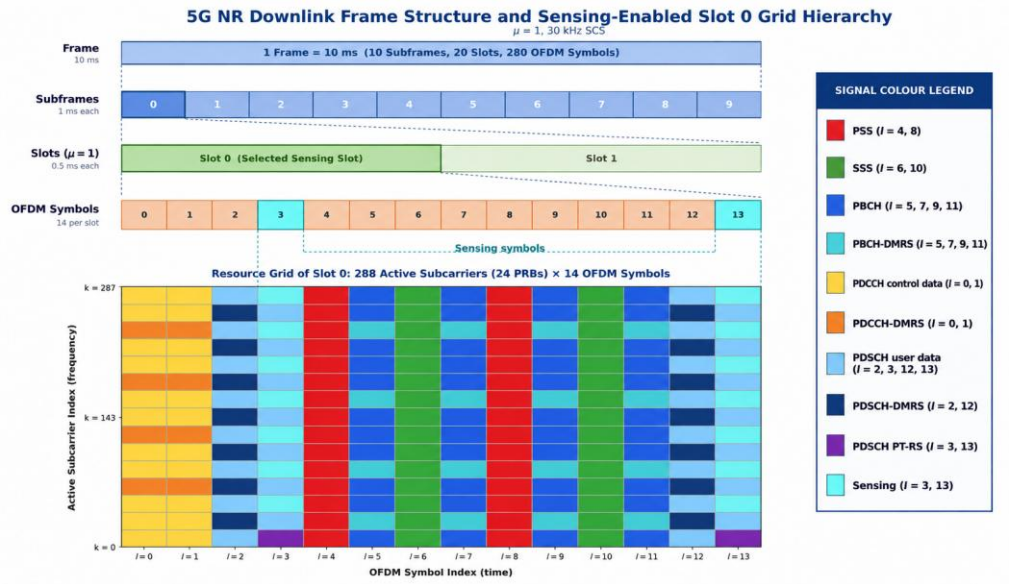


Fig. 3.2. NR-inspired experimental ISAC frame structure.

Fig. 3.2 shows the NR-inspired experimental ISAC periodic TDD frame structure, which preserves the fundamental 5G NR hierarchy to ensure seamless coexistence without disrupting backward compatibility or degrading communication performance. The 10 ms radio frame comprises 10 subframes, 20 slots, and 14 OFDM symbols per slot with 30 kHz subcarrier spacing (μ=1) [14]. In addition, it offers dedicated resources for sensing, making it suitable as a research-oriented framework for future 6G ISAC systems. Each slot has a fixed periodic symbol structure, including Synchronization (SS), Broadcast (PB), Control (CT), Downlink (DL), ISAC Reference Signal (RS), Guard Period (GP), Uplink (UL), and Sensing (SN) symbols. The same symbol pattern is repeated in all 20 slots of the radio frame, enabling deterministic resource allocation for easier synchronization, scheduling, sensing operation, and hardware implementation. The frame is mapped onto a common time-frequency resource grid, where the horizontal axis represents the OFDM symbols and the vertical axis the active subcarriers [10], [15]. The frame structure thus provides a flexible basis for evaluating waveform design, communication protocols, sensing algorithms, and AI-assisted resource management in future 6G ISAC systems.

3.3 Waveform Design and Signal Processing Architecture

Waveform engineering enables ISAC to use a common transceiver, shared spectrum, and integrated signal processing for reliable data transmission and accurate sensing. The evolution from radar-communication cohabitation, where both systems interfere, to cooperation through coordinated resource allocation, and finally to co-design with a shared waveform and architecture, motivates advanced waveform engineering. Waveform engineering should therefore provide an application-aware trade-off by jointly optimizing waveform structure, power, spectrum, spatial resources, and signal processing to improve spectral and energy efficiency, reduce mutual interference, and enable hardware sharing [2], [3].

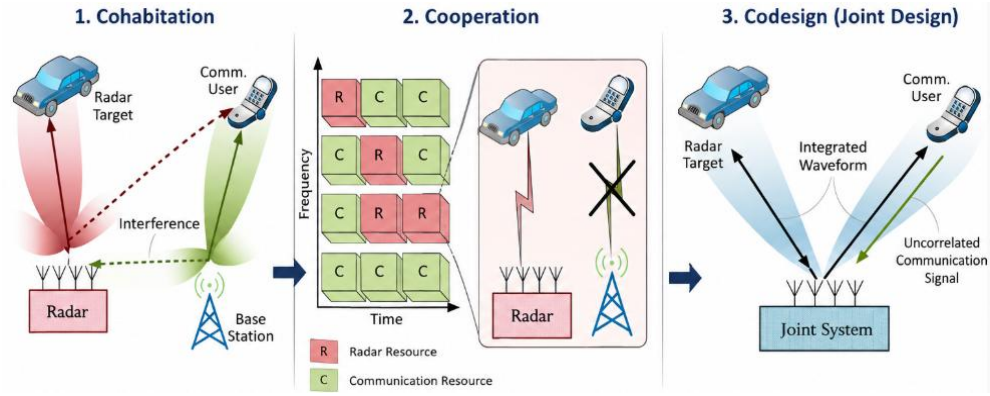


Fig. 3.3 Evolution paradigms of radar-communication integration: (1) Cohabitation, (2) Cooperation, and (3) Codesign, with an ISAC framework and unified hardware and integrated waveforms.

Fig. 3.3 shows the evolution of radar-communication spectrum integration through three stages: Cohabitation, Cooperation, and Codesign. In Cohabitation, radar and communication BSs use separate hardware and operate simultaneously on adjacent or overlapping channels, causing mutual interference that degrades radar detection and communication reliability. In Cooperation, both platforms coordinate shared resources by allocating specific time-frequency resource blocks to radar or communication, reducing interference but limiting spectral utilization and retaining separate hardware. Codesign uses a unified system platform in which antennas and hardware chains support an integrated Waveform for both radar target tracking and high-rate communication. An uncorrelated communication signal can also be dynamically multiplexed into the main waveform to improve throughput while maintaining spatial sensing accuracy [10].

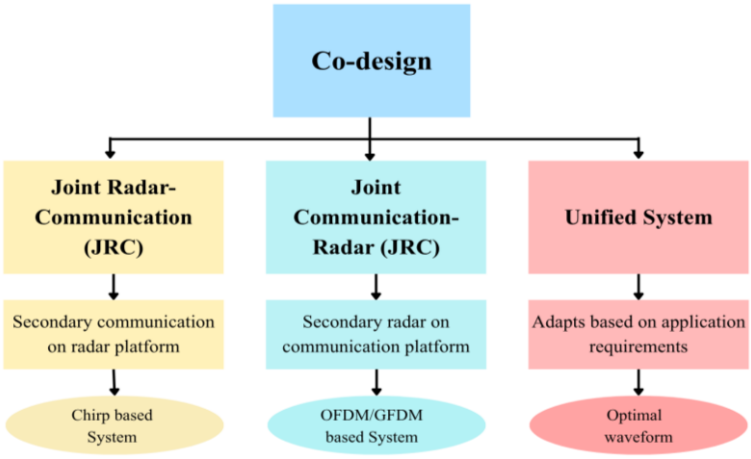


Fig. 3.4 Classification of codesign methodologies for ISAC systems based on operational priority

Fig. 3.4 classifies co-design frameworks into three approaches based on operational priority and waveform. JRC uses a radar-based platform, with sensing as the primary function and communication as a secondary function, typically using chirp-based waveforms or radar pulse modulation. JCR reverses this priority by adding radar sensing to a communication architecture and using structured multi-carrier waveforms such as OFDM or generalized frequency division multiplexing (GFDM) to extract sensing information from reflected communication signals. The unified system gives no priority to either function and dynamically adapts system parameters to application requirements. It enables an optimal waveform that jointly targets tracking precision and information throughput [3], [10].

3.4 Waveform Candidates for ISAC

Communication waveforms such as OFDM are designed for rate and reliability, while radar waveforms such as frequency-modulated continuous wave (FMCW) are designed for range and Doppler accuracy; neither fully meets both sets of requirements. OFDM remains the practical baseline because of its simple FFT-based implementation and its use in 5G NR, although its subcarrier orthogonality suffers under high Doppler. DFT-spread OFDM (DFT-s-OFDM) lowers the peak-to-average power ratio (PAPR), and GFDM improves spectral containment. Orthogonal time frequency space (OTFS) and orthogonal chirp division multiplexing (OCDM) spread each symbol across the delay–Doppler or chirp domain and cope better with high mobility, at the cost of more complex processing [16]. Adaptive designs such as Generalized Adaptive Spreading Modulation (GASM), a chirp-precoded extension of OFDM, allow the time–frequency spreading to be tuned to the channel and to the sensing and communication requirements [17]. These waveforms are research proposals. In 3GPP, the 6G CP-OFDM waveform is the starting point for the ISAC study, and other options are being considered only as enhancements to it (Section 9.1.2.2).

Section 4: RF Front-End and Antenna Technologies

Status: *Research. Full-duplex ISAC transceivers are not specified in 3GPP. The sub-band full-duplex work in Release 18 addresses communication only.*

After the physical-layer design, developing an efficient RF front-end and antenna architecture is essential for practical ISAC implementation. The RF front-end integrates key components such as power amplifiers (PAs), low-noise amplifiers (LNAs), and antenna systems to support simultaneous transmission and reception, while effective self-interference cancellation (SIC) is required to protect weak sensing echoes from strong Tx leakage. At mmWave frequencies, severe propagation loss further necessitates large-scale antenna arrays to provide sufficient beamforming gain and highly directional transmission and reception. The baseband functions operate jointly with the RF front-end to enable integrated communication and sensing within a common transceiver architecture.

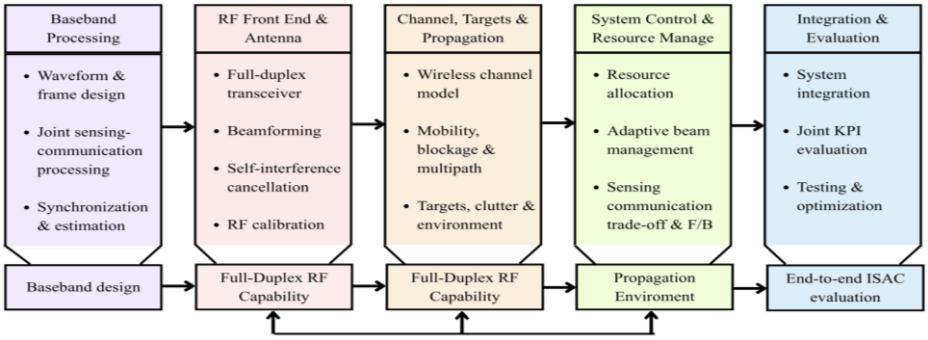


Figure 4.1: End-to-end ISAC system architecture highlighting RF and FD antenna technologies

As illustrated in Fig. 4.1, the RF architecture incorporates full-duplex (FD) operation, beamforming, beam steering, SIC, and RF hardware design to support efficient transmission and reception. These capabilities must operate effectively under mmWave propagation conditions, including mobility, blockage, and target-induced reflections. Together with adaptive beam management and resource allocation, the RF front-end provides the essential hardware foundation for reliable end-to-end ISAC system integration and performance [18-22].

4.1. RF Front-End Architectures

A typical ISAC RFFE comprises phased-array antennas, beamforming networks, PAs, LNAs, mixers, local oscillators (LOs), filters, ADCs/DACs, and SIC modules. These components jointly support waveform transmission, beam steering, frequency conversion, and signal reception with high dynamic range and low latency [19].

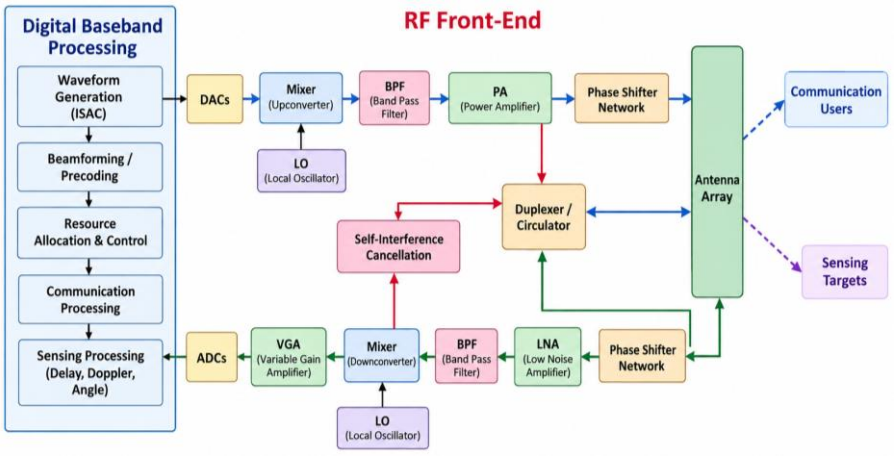


Fig. 4.2 Block diagram of FD ISAC transceiver and SIC cancellation.

As shown in Fig. 4.2, the FD ISAC transceiver integrates digital baseband processing, RF front-end components, antenna arrays, and SIC to support communication users and sensing targets simultaneously. RF front-end architectures can be broadly classified into fully digital, fully analog, and hybrid analog-digital implementations. Fully digital architectures offer the highest beamforming flexibility and communication-sensing performance but require a dedicated RF chain for each antenna element, resulting in high hardware cost and power consumption. Fully analog architectures provide a cost- and energy-efficient alternative; however, they offer limited beamforming flexibility and are less suitable for simultaneous multi-beam communication and sensing. In contrast, hybrid analog-digital architectures balance performance, hardware complexity, and power consumption, making them the preferred choice for large-scale 6G ISAC deployments employing Massive MIMO [23], [18].

4.2. Full-Duplex Antenna for ISAC

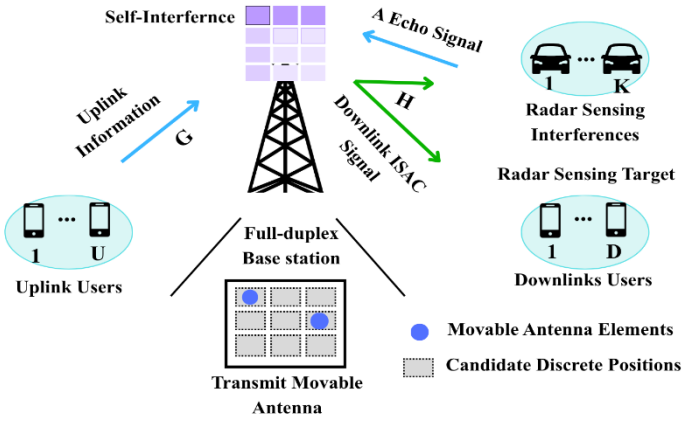


Figure 4.3. Multi-stage SIC in an FD ISAC transceiver.

FD is a key enabling technology for ISAC, allowing simultaneous transmission and reception over the same frequency band using shared hardware. Unlike half-duplex systems, which separate transmission and reception in time or frequency, FD operation supports continuous sensing without interrupting wireless communication. As Fig. 4.3 shows, advanced SIC in the RF, analog, and digital domains enables concurrent communication and sensing, making FD transceivers well suited for 6G applications [19-21]. The primary challenge in FD ISAC is SI, where the strong transmitted signal leaks into the receiver and masks weak target echoes or incoming communication signals. Without effective suppression, SI can saturate the receiver front-end and significantly degrade both communication and sensing performance.

4.3 Beamforming and Precoding

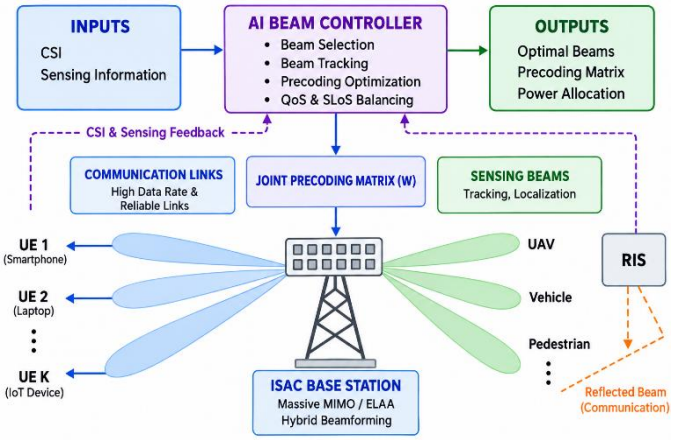


Fig 4.4. AI-assisted joint beamforming and precoding architecture for native 6G ISAC.

Through beamforming and precoding, ISAC systems can steer wireless signals to users while also illuminating the surrounding environment, enabling simultaneous communication and sensing. ISAC differs from conventional communication systems in that it jointly optimizes communication and sensing performance to achieve reliable data transmission, wide coverage, accurate localization, and efficient target detection. Future 6G ISAC networks will use massive MIMO, hybrid beamforming, and extremely large aperture arrays (ELAA) to create highly directional beams in the mmWave and sub-THz bands, improving signal quality, reducing interference, and enhancing sensing accuracy. As shown in Fig. 4.4, the joint design of beamforming, precoding, and intelligent resource management is a key component for efficient 6G ISAC systems [4], [22], [24].

Section 5 – Taxonomy of ISAC Systems

5.1 ISAC Deployment Paradigms

This section describes the different ISAC deployment scenarios such as monostatic, bistatic, and multistatic.

5.1.1 Monostatic ISAC

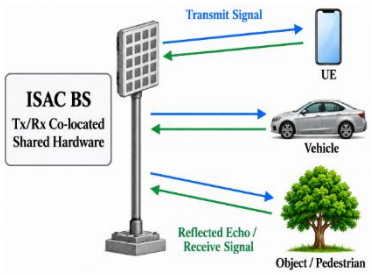


Figure 5.1 Architecture of a Monostatic ISAC System

In monostatic ISAC, the transmitter and receiver are co-located, i.e., at the same node, such as a BS, roadside unit, or access point. A common waveform is used for both wireless communication and environmental sensing. The same node receives the reflected echoes. A common time and phase reference enables coherent processing to accurately estimate target range and angle using a single hardware platform and a unified resource allocation framework. As shown in Fig. 5.1, the monostatic ISAC system co-locates transmission and reception. Monostatic ISAC can provide high sensing accuracy and simple synchronization. However, simultaneous transmission and reception in the same frequency band can induce SI, requiring efficient SIC, high transmit-receive isolation, and an FD transceiver [22, 24].

5.1.2 Bistatic ISAC

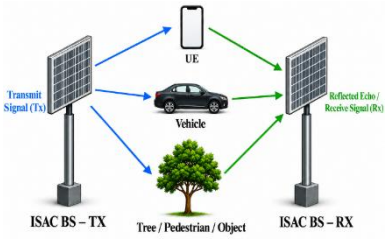


Figure 5.2 Architecture of a Bistatic ISAC System.

Bistatic ISAC uses spatially separated transmitter and receiver nodes. The transmitter transmits the communication waveform, and a spatially separated receiver receives the echoes reflected from the target, providing complementary spatial information and reducing SI. This distributed geometry can improve localization accuracy, sensing coverage, and target detection, especially in non-line-of-sight environments, but requires tight clock synchronization and CSI exchange [22, 24]. As shown in Fig. 5.2, the bistatic ISAC system employs spatially separated transmitting and receiving BSs for joint communication and sensing. The transmitter BS serves the UE and illuminates surrounding targets, while the receiver BS captures the reflected echo signals for target sensing.

5.1.3 Multistatic ISAC

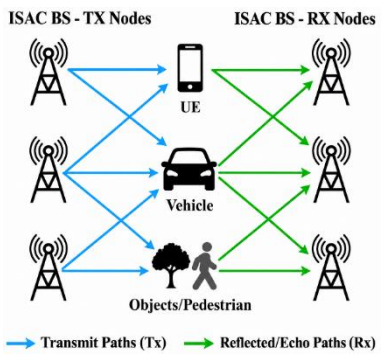


Figure 5.3 Architecture of a Multistatic ISAC System.

Multistatic ISAC extends monostatic and bistatic sensing by using multiple coordinated transmitters and receivers (e.g., BSs, APs, and RSUs) to perform joint communication and sensing. The distributed architecture provides wider sensing coverage, better localization accuracy through spatial diversity, greater robustness to blockage, and cooperative target detection and tracking. Multistatic ISAC may employ coordinated beamforming (CBF), Coordinated Multi-Point (CoMP), or centralized/distributed sensing fusion depending on the required level of cooperation. This enables coordinated multistatic sensing with improved estimation performance [24]. As shown in Fig. 5.3, the multistatic ISAC system employs multiple spatially separated Tx and Rx nodes to jointly support communication and sensing.

5.2 ISAC Operating Modes

In this section, we describe active and passive ISAC sensing modes. Active ISAC uses dedicated communication-sensing waveforms, whereas passive ISAC exploits ambient RF signals.

5.2.1 Active ISAC

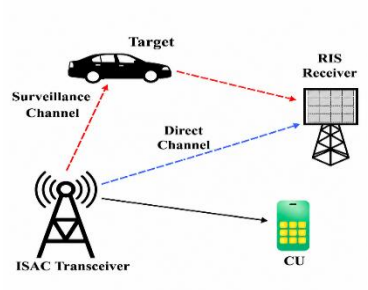


Fig. 5.4 Active ISAC System.

In active ISAC, active RF transceivers realize sensing and communication by generating, transmitting, and receiving wireless signals. Active ISAC provides high sensing accuracy and flexible waveform design. However, it requires dedicated RF chains, consumes more power, and has higher hardware complexity. As shown in Fig. 5.4, the ISAC transceiver simultaneously performs active target sensing and provides communication services to multiple communication users. It receives reflected sensing from the target, enabling target detection while supporting multi-user communication.

5.2.2 Passive ISAC

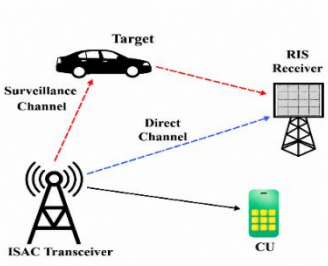


Fig. 5.5 Passive ISAC System.

Passive ISAC enhances sensing performance using passive electromagnetic structures such as RIS, which cannot generate RF signals but modify the propagation environment by introducing programmable phase shifts to incident waves. Because passive RIS elements reflect incident signals without amplification, multiplicative fading can fundamentally constrain their performance. As shown in Fig. 5.5, the ISAC transceiver simultaneously provides communication services to the user and illuminates the target through the surveillance channel.

5.3 Realization Framework for ISAC

In this section, we describe infrastructure-based, UE-assisted, cooperative, distributed, and network-wide architectures.

5.3.1 Infrastructure-based ISAC

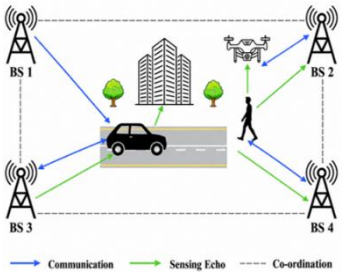


Fig. 5.6 Infrastructure-based ISAC.

Infrastructure-based ISAC supports coordinated communication and sensing across distributed network infrastructures such as BSs, APs, and air-ground-space platforms. It provides seamless multi-cell sensing, continuous target tracking, and large-area environmental perception by exchanging sensing information and network resources via backhaul and edge/cloud platforms. Compared to a single-node architecture, it provides wider sensing coverage and higher robustness to blockage and mobility, as shown in Fig. 5.6 [25].

5.3.2 UE-assisted ISAC

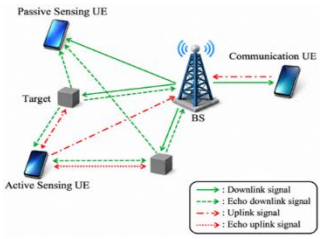


Fig. 5.7. UE-assisted ISAC

UE-assisted ISAC extends infrastructure-centric sensing by enabling UEs to actively participate in environmental sensing. In this architecture, the BS transmits the ISAC waveform, and UEs perform local sensing and report measurements [26]. This architecture exploits the spatial diversity of distributed UEs to enhance sensing coverage, localization accuracy, target tracking, and robustness for NLoS environments. Although UE-assisted ISAC enhances cooperative sensing, it requires accurate BS-UE synchronization and privacy-aware data sharing, as shown in Fig. 5.7.

5.3.3 Distributed and Cooperative ISAC

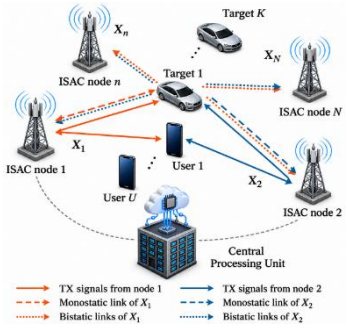


Figure 5.8 Architecture of Distributed ISAC System.

Distributed ISAC consists of multiple geographically separated BSs, APs, or remote radio units (RRUs) cooperating through a CPU or cloud controller for joint communication and sensing as shown in Fig. 5.8. It combines distributed MIMO sensing with CoMP communication to improve communication coverage and sensing accuracy [27]. It achieves high-accuracy target localization by fusing multiple node measurements such as AoA, ToF, and Doppler. In practice, distributed ISAC often relies on noncoherent cooperation due to synchronization constraints, where signal design jointly optimizes system performance subject to user SINR constraints [16].

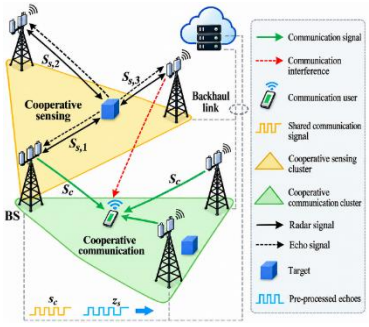


Figure 5.9 Architecture of cooperative ISAC System.

Within distributed ISAC, cooperative ISAC enables multiple geographically distributed BSs or APs to jointly perform communication and sensing by sharing information in a coordinated manner. It combines CoMP transmission and multistatic sensing to improve sensing coverage, localization accuracy, spatial diversity, communication reliability, and inter-cell interference mitigation. Multiple nodes cooperatively process reflected signals to estimate target range, velocity, angle, and position, and dynamically form communication and sensing clusters based on network conditions and backhaul constraints. As shown in Fig. 5.9, cooperative information sharing and multi-node data fusion significantly improve communication reliability and localization performance.

5.3.4 Network-wide ISAC

Network-wide ISAC extends sensing capabilities across the entire 6G ecosystem by integrating terrestrial networks, unmanned aerial vehicles (UAVs), satellites, high-altitude platform stations (HAPS), RIS, IoT devices, and cloud-edge computing platforms. The signal received by user k is given by

$$y^{(c)}{}_k(t) = \sum_{m=1}^{M} h_{m,k}(t)x_k(t) + n_k(t)$$

Where $x_k(t)$ denotes the waveform transmitted by node k, $h_{m,k}(t)$ represents the communication channel, $n_k(t)$ and denotes additive noise. Each node estimates

$$\widehat{\theta_m} = \{\widehat{R_m}, \widehat{V_m}, \widehat{\phi_m}, \widehat{C_m}\}$$

Where $\widehat{R_m}$: range estimate, $\widehat{V_m}$: velocity estimate, $\widehat{\phi_m}$: direction estimate, $\widehat{C_m}$: object classification.

Section 6: Network Architectures and System Orchestration

Status: *Research. No ISAC-specific network architecture has been agreed. SA2 is studying the sensing architecture in Release 20 (Table-2); the O-RAN and AI-native architectures in this section are research proposals.*

Following the taxonomy and classification of ISAC systems presented in Section 5, it is important to consider how the convergence of communication and sensing can be realized through practical network architectures and orchestration mechanisms. ISAC requires coordinating communication, sensing, computing, and intelligence across the RAN, edge, and cloud, supported by technologies such as massive MIMO, beamforming, mmWave communications, AI, and edge computing. This integration enables the shared use of radio and computing resources while supporting ISAC's diverse QoS requirements. In this context, Section 6 examines O-RAN-based architectures, AI-native architectures, and network virtualization and slicing to understand their role in supporting intelligent, context-aware, and automated ISAC services in future 6G networks.

6.1 O-RAN Based ISAC Network Architecture

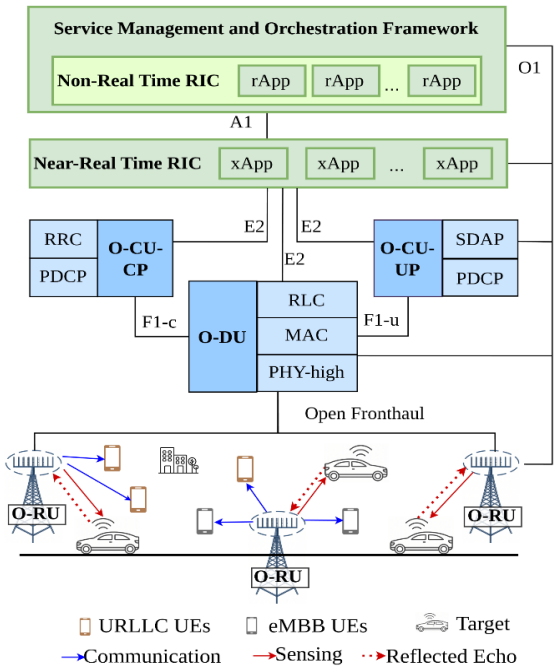


Figure 6.1 Architecture of the O-RAN-based ISAC Network.

Achieving ISAC in 6G requires a unified network architecture that seamlessly integrates communication, sensing, computing, and AI functions while coordinating shared resources to meet diverse service requirements. These functions are distributed and coordinated across the RAN, transport network, core, edge, and cloud. The RAN supports joint communication and sensing functions, including waveform transmission, channel estimation, localization, and target detection, while the transport network provides fronthaul, midhaul, and backhaul connectivity for exchanging communication and sensing data. The cloud-native core provides network and service functions, while edge and cloud platforms support distributed processing for AI inference, cooperative perception, data fusion, and large-scale analytics. An AI-native orchestration layer coordinates radio, sensing, computing, and network resources across these domains to adapt to diverse service requirements [28]. O-RAN provides a suitable architectural framework for this integration through its disaggregated, open, and programmable RAN architecture. It separates RAN functions across the Radio Units (O-RUs), Distributed Units (O-DUs), and Centralized Units (O-CUs) and provides standardized interfaces for their interconnection and control. The Near-Real-Time RAN Intelligent Controller (Near-RT-RIC), Non-Real-Time RIC (Non-RT-RIC), and Service Management and Orchestration (SMO) provide mechanisms for intelligent control, optimization, and orchestration of these functions [28].

The Fig.6.1 illustrates an O-RAN-based ISAC architecture, in which a disaggregated, intelligent RAN jointly supports communication and sensing functionalities. At the radio layer, O-RUs simultaneously provide wireless connectivity to URLLC/eMBB users and illuminate surrounding targets, with reflected echoes used for sensing,

localization, and environmental awareness. Intelligent control, resource management, and orchestration are provided through the Near-RT RIC, Non-RT RIC, and SMO framework. The Near-RT RIC uses xApps and the E2 interface for near-real-time optimization of radio and sensing resources, while the non-RT RIC employs rApps and AI/ML-driven policies for longer-timescale network optimization through the A1 interface. The O1 interface supports management, configuration, and monitoring of network functions. These interfaces and control functions provide mechanisms for optimizing communication and sensing resources, including interference and spectrum management, mobility, waveform parameters, and cooperative sensing across multiple radio nodes.

6.2 AI-native Architecture

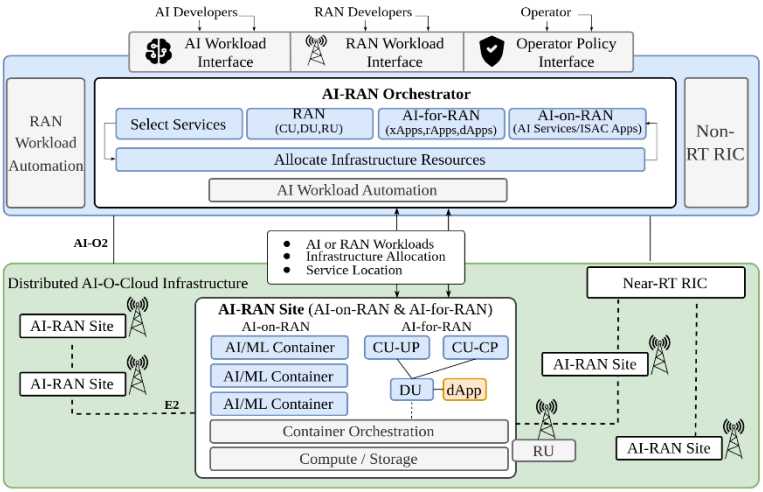


Figure 6.2 Architecture of the AI-native ISAC Network.

AI is expected to be a core part of the architecture of future 6G ISAC networks rather than just a performance optimization tool. AI capabilities will be integrated across the communication and sensing pipeline, enabling autonomous decision-making across the RAN, edge, core, and cloud. AI can continuously learn from network traffic, sensing data, and operating conditions to optimize beamforming, waveform selection, resource allocation, localization, mobility management, and cooperative sensing. This distributed intelligence across edge and cloud platforms further enables predictive optimization, anomaly detection, and self-organizing network operation.

Fig. 6.2 shows an AI-native RAN architecture for ISAC, where AI is embedded directly into the communication and sensing processing chain. At the transmitter, semantic encoding and adaptive source–channel rate allocation operate jointly with ISAC beamforming and waveform design, subject to power, bandwidth, and antenna constraints. The same transmitted waveform supports communication while also generating sensing echoes from the surrounding environment. At the receiver, semantic decoding and sensing estimation extract task-relevant communication information together with sensing parameters such as position, velocity, and target characteristics, while real-time AI inference supports low-latency PHY/MAC operation.

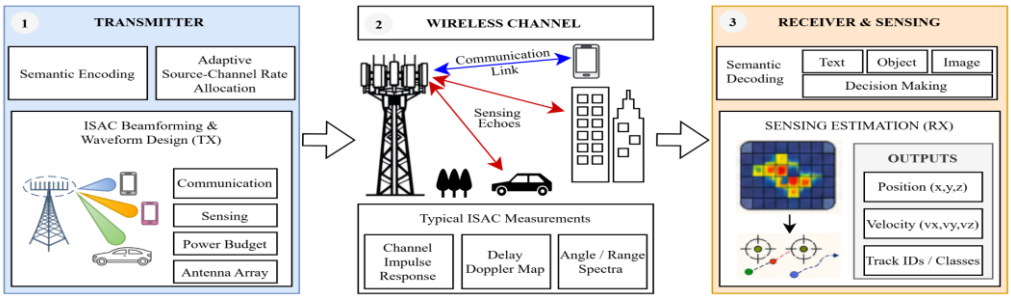


Fig. 6.3. AI-native RAN architecture for integrated communication and sensing with real-time AI processing.

Together, these architectural enablers provide the foundation for intelligent ISAC networks, in which orchestration, communication, sensing, and AI processing are jointly distributed across the RAN, edge, and cloud and integrated within the end-to-end reference architecture shown in Fig. 6.3.

6.3 Network Virtualization and Slicing for ISAC

Network virtualization abstracts shared physical communication, sensing, computing, and networking infrastructure into logical resources that can be independently configured for different ISAC services. This enables network slicing, which provides a practical mechanism for creating service-specific logical ISAC networks over shared physical infrastructure. Unlike traditional network slices that primarily consider communication, ISAC slices jointly allocate radio, sensing, computing, and networking resources based on application-specific QoS requirements. Through the SMO, Non-RT RIC, Near-RT RIC, and edge/multi-access edge computing (MEC), radio, sensing, computing, and network resources are dynamically orchestrated to meet slice-specific KPIs. This enables isolated and adaptive operation of heterogeneous ISAC services over a common infrastructure while supporting efficient utilization of shared resources [29-30].

Section 7: Sensing–Communication Mutual Assistance in ISAC

Status: *Mixed. Reuse of communication reference signals for sensing is one of the options under study in 3GPP Release 20. The other techniques in this section, including sensing-assisted beam management, are research topics.*

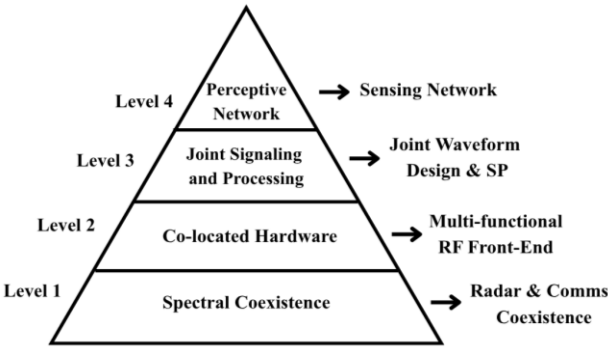


Fig. 7.1. Communication–sensing functional integration, from spectral coexistence to networked

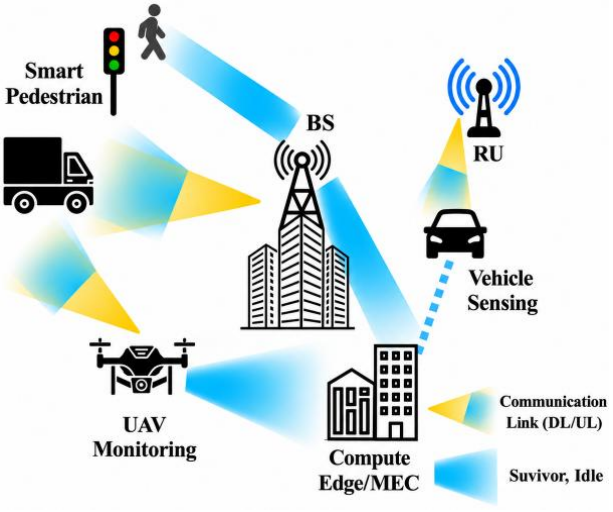


Fig. 7.2. Architecture of Communication–Assisted Sensing.

The evolution of ISAC reflects the integration of communication and sensing functionalities, ranging from spectrum sharing to coordinated networked sensing. As illustrated in Fig. 7.1, this progression is categorized into four functional levels: spectral coexistence, co-located hardware, joint signaling and processing, and networked sensing, with each level representing a deeper degree of integration between communication and sensing [1], [4].

7.1 Communication-Assisted Sensing

One of the main operational modes of ISAC is Communication-Assisted Sensing (CAS), which uses existing communication signals and network infrastructure to sense the environment rather than relying on dedicated radar hardware or separate sensing spectrum. Communication signals such as pilot symbols, synchronization signals, CSI, beamformed transmissions, and positioning reference signals can be reused to estimate environmental information while simultaneously supporting normal communication, as shown in the Fig. 7.2 [3], [4].

CAS has become a major focus of global 6G research and standardization activities, including ITU IMT-2030, 3GPP Releases 19 and 20, ETSI ISG ISAC, Hexa-X, Hexa-X-II, Next G Alliance, and the 6G Flagship Program. Massive MIMO, mmWave and sub-THz communications, dense RANs, and AI-native architectures make it possible to reuse communication signals for radar-like sensing, although how much additional infrastructure this needs is still being studied [3], [6], [7].

7.1.1 CSI-based Sensing

The development of 6G networks extends beyond conventional communication by incorporating CSI-based sensing, which exploits existing communication signals, hardware, spectrum, and pilot transmissions to infer changes in the surrounding environment without affecting normal data services. Variations in CSI due to human movement, object movement, or physiological activity can be analyzed to detect, recognize, and estimate environmental events [31]. CSI sensing, first studied in Wi-Fi systems, is now considered an important component of 6G ISAC. In practice, raw CSI measurements are usually contaminated by noise; therefore, pre-processing techniques such as filtering, phase calibration, static-path removal, outlier rejection, and subcarrier selection are applied before sensing or AI-based inference [31].

7.1.2 Beamformed Sensing

Beamformed sensing steers communication beams toward specific regions and processes reflected signals to estimate the target's location, direction, velocity, and movement. Massive MIMO and directional beamforming are the key technologies for future mmWave and sub-THz communication systems. Narrow, steerable beams increase communication network capacity and provide high spatial resolution that can be exploited for environmental sensing [4], [32]. AI-assisted beamforming enhances this capability by dynamically steering beams to moving users or targets, enabling simultaneous communication and sensing with minimal interference. These features make beamformed sensing a promising technology for intelligent transportation, industrial automation, UAV networks, and smart city applications [4].

7.1.3 Pilot-assisted Sensing

Wireless systems often transmit pilot signals for synchronization, channel estimation, and equalization. CAS uses existing pilot signals to sense the surrounding environment, without dedicated sensing waveforms or additional spectrum. Reflections from nearby objects alter the temporal and spectral characteristics of pilot signals, providing information on target distance, velocity, direction, and environmental variations. This means pilots are sent periodically during normal communication, enabling continuous sensing without interfering with data transmission. Future 6G networks are expected to jointly optimize pilot signal design for communication and sensing, trading off channel estimation accuracy, sensing performance, signaling overhead, and energy efficiency [3], [4]. In addition, AI-based pilot optimization is also expected to improve the sensing performance in dynamic wireless environments.

7.1.4 Device-free Sensing

CAS is one of the most promising applications of device-free sensing. Unlike traditional localization systems that rely on smartphones, wearables, or dedicated tags, it detects human presence, activities, and environmental changes by analyzing how wireless signals interact with people and objects. Changes in CSI, received signal strength (RSS), Doppler signatures, and multipath propagation due to human movement can be exploited to identify occupancy, gestures, respiration, heartbeat, falls, crowd density, and activity patterns without requiring the user to carry a device [33]. These capabilities can support healthcare, elderly care, smart homes, industrial safety, security, and public infrastructure monitoring.

7.2. Sensing-Assisted Communications

Sensing-assisted communication (SAC) follows the opposite paradigm to communication-assisted sensing. SAC leverages sensing information to enhance communication performance, rather than using communication

signals for sensing. Measurements such as user location, mobility, target movement, and channel conditions are constantly fed back to the network, enabling better-informed communication decisions. As shown in Fig. 7.3, SAC operates in a closed-loop process: the environment is sensed, its state is estimated, predictions are made, and the network adapts its communication strategy accordingly. This sensing-communication feedback loop enables the network to adapt intelligently to dynamic wireless conditions for applications such as beam selection, beam tracking, mobility prediction, handover management, and scheduling [4].

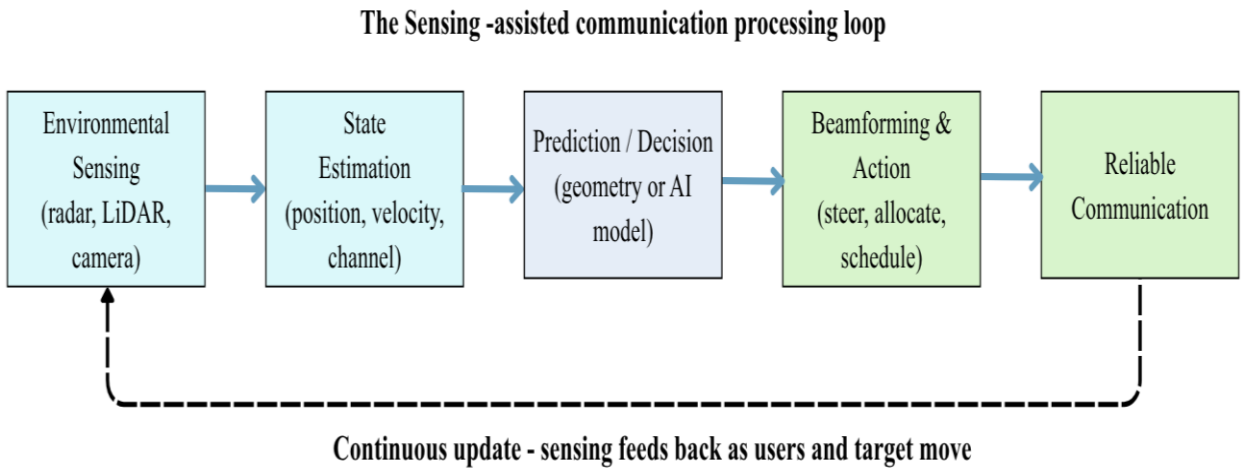


Figure 7.3. The common SAC processing loop shared by all Section 7 functions.

7.2.1 Beam Prediction

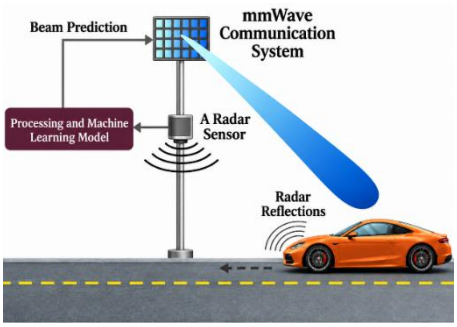


Fig. 7.4. Architecture of Beam Prediction.

Future 6G mmWave and THz networks require highly directional beams, making efficient beam alignment critical. Sensing-assisted beam prediction uses information such as position, velocity, trajectory, range, and angle to predict suitable transmit–receive beam pairs, reducing beam-sweeping overhead and improving mobility support, as shown in Fig. 7.4 [34]. Approaches include geometry-based, machine/deep-learning, radar-assisted, and sensor-fusion methods, with applications in XR, autonomous vehicles, UAVs, and intelligent transportation systems [34].

7.2.2 Beam Tracking

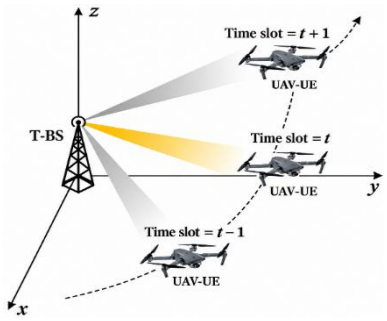


Fig. 7.5. Architecture of Beam Tracking.

Sensing-assisted beam tracking continuously updates beam directions using sensing information such as range, velocity, and angle, together with communication measurements including RSS, CSI, and AoA. By tracking user or target motion and adapting beams in real time, it reduces repeated beam-search operations and improves connectivity in high-mobility scenarios, as shown in Fig. 7.5 [34]. EKF, Bayesian filtering, AI-based, and sensor-fusion methods can further enhance tracking accuracy, reduce feedback overhead, and improve spectral efficiency for vehicles, UAVs, and high-speed rail systems.

Section 8: AI-Native ISAC

Status: *Research. 3GPP has specified AI/ML for some NR air-interface functions, such as beam management and positioning, but not for ISAC. The functions described in this section are research proposals.*

AI is expected to become a native component of future ISAC systems, embedding learning, inference, and decision-making across radio, sensing, edge, and network-control functions. ISAC provides contextual information about users, channels, mobility, and the environment, while AI converts these observations into predictions and control actions for waveform adaptation, beam management, sensing, resource allocation, and network optimization [35]. AI-native ISAC can be viewed through two complementary roles: AI4ISAC, where AI enhances communication, sensing, localization, beamforming, and resource management, and ISAC for AI, where ISAC infrastructure provides data, context, connectivity, and physical-world awareness to distributed AI systems. Realizing this closed sensing–communication–learning loop requires robust data pipelines, model lifecycle management, distributed inference, edge–cloud coordination, uncertainty handling, security, and standardized AI/ML procedures [35-36].

8.1 AI Across the ISAC Processing and Control Loop

8.1.1 Perception and Sensing Intelligence

AI's first job is to convert radio observations into useful representations of the physical environment. AI can assist in clutter suppression, target detection, object classification, multipath interpretation, localization, trajectory prediction, and multimodal fusion. In a distributed ISAC system, measurements from multiple nodes can be fused to create a more complete picture of the environment than a single link can provide. The main output of this layer is therefore not necessarily a raw sensing estimate, but rather a network state representation: a structured description of users, targets, obstacles, mobility, uncertainty, propagation conditions, and other environmental information relevant to subsequent communication or control decisions. This representation directly relates sensing to network intelligence.

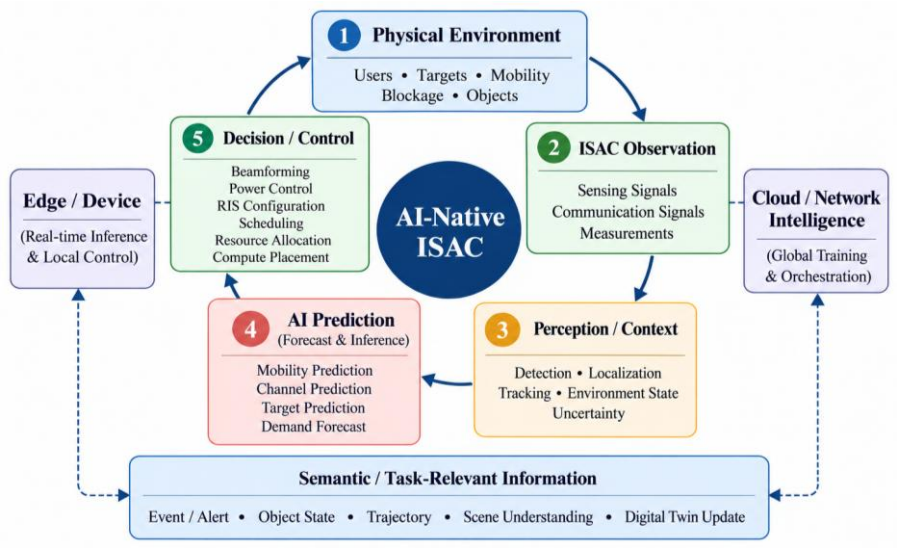


Fig. 8.1. Closed perception–decision loop in AI-native ISAC, integrating environmental sensing, context extraction, AI-driven prediction, network control, and edge–cloud intelligence.

As shown in Fig. 8.1, AI-native ISAC establishes a closed perception–decision loop that integrates environmental sensing, context extraction, AI-based prediction, and intelligent network control.

8.1.2 Communication and Resource Intelligence

AI can use the perceived network state to jointly configure communication and sensing resources. Relevant decisions include beamforming, power allocation, user association, bandwidth allocation, waveform selection, sensing scheduling, RIS control, interference management, mobility handling, and compute placement. AI-native ISAC is unique because these decisions do not optimize communication and sensing separately. Maximizing communication SINR can reduce target illumination, while a sensing-optimal waveform can consume resources needed for data transmission. Thus, AI addresses a multi-objective problem that considers communication quality, sensing quality, latency, energy consumption, and computational cost at once. This motivates a shift from signal-centric to task-aware sensing-communication-learning co-design [32].

8.1.3 Digital Twins and Predictive Network Operation

Digital twins offer a natural interface between sensing and AI-native network control. An ISAC network can continuously improve a digital representation of the physical and radio environment by measuring position, mobility, blockage, channel conditions, objects, and infrastructure state [36]. AI models can then use this representation to predict future network conditions and evaluate potential control actions before applying them to the physical system. A mobility model can predict beam handovers, a traffic model can predict congestion, and an environment model can predict where future blockage is likely. This resulting architecture moves the network from reactive optimization to predictive orchestration. This capability is especially relevant for autonomous transportation, robotics, industrial automation, and physical AI, where the communication network is increasingly part of a closed perception-decision-action loop [36].

8.2 Trustworthy and Deployable AI-Native ISAC

Using AI for radio and sensing control introduces new requirements that go beyond model accuracy alone. A model may achieve high average performance and still be unsuitable for deployment if it is unstable under distribution shift, vulnerable to manipulated observations, computationally excessive, or unable to indicate when its prediction is unreliable.

8.2.1 Explainability and Uncertainty

Explainable Artificial Intelligence (XAI) can help engineers understand which observations contributed to the model output and debug, audit, and interpret complex AI pipelines. This is especially helpful for safety-critical AI functions such as object detection, localization, autonomous mobility, and industrial control. Explanation does not replace verification, so AI-native ISAC also needs measures of uncertainty and confidence. A network must differentiate between a high-confidence sensing estimate and an observation outside the conditions represented in the training data. Low-confidence predictions can then trigger fallback mechanisms such as additional sensing, multi-node validation, conservative beam selection, or conventional model-based processing. This results in a more useful concept of trustworthy network intelligence [37]. The AI system should output not only a decision but also enough evidence for the network to decide whether to act on it.

8.2.2 Robustness, Security, and Privacy

AI introduces an attack surface beyond conventional communication and sensing threats. Training data can be poisoned, inference inputs can be adversarially manipulated, backdoors can be inserted into models, and model outputs or updates can leak sensitive information. In ISAC the risk is higher because an attacker can manipulate the physical observations themselves, for example through spoofed echoes, false CSI or malicious RIS settings [37]. Defences need to combine model-level measures with physical and cross-layer checks (Section 10). Privacy also matters because sensing observations may disclose information about location, behavior, occupancy, or physiological characteristics. Although edge processing and FL can reduce the need to centralize

raw observations, privacy guarantees depend on the entire data and model lifecycle, not just the learning architecture [37].

8.2.3 Model Lifecycle and Standardization

The AI-native radio system should be deployable and support orchestration of AI models throughout their service life. This problem already shows up in 3GPP work on AI/ML for the NR air interface. TR 38.843 covers not only individual AI use cases but also issues including dataset construction, training and validation, model lifecycle management, model transfer, signaling, capability indication, configuration, measurement, and feedback [37]. ISAC further complicates lifecycle management, since radio environments and sensing data can vary widely by deployment location. AI-native functions could use equipment from different vendors and models trained by different organizations. Future standards will need to decide what aspects of the AI interface to standardize, such as measurements, inputs and outputs, model identifiers, performance requirements, or lifecycle procedures, without over-standardizing the internal architecture of each model.

8.3 Toward Closed-Loop AI-Native ISAC

The move to AI-native ISAC is likely to be gradual. AI will first assist individual functions such as channel estimation, target detection and beam prediction. It will then share information between the sensing and communication functions, and later be spread across devices, edge and cloud as part of a single loop of perception, prediction and control. This adds a third design objective to the usual communication and sensing metrics: how useful the sensing and communication resources are to the learning task itself [38]. Not every function needs AI. Where model-based processing is well understood and reliable it should be kept, and learning should be used where analytical models fall short [38].

Section 9: Standardization

Standardizing ISAC is crucial to enable interoperability, scalability, spectrum harmonization, security, and multi-vendor compatibility. The roadmap of this technology corresponds to the ITU IMT-2030 vision, where 3GPP is developing the radio access and core network specifications, and ETSI, IEEE, the O-RAN Alliance, and initiatives like Hexa-X and Hexa-X-II are developing AI-native architectures, Open RAN, and other key technologies for future 6G ISAC networks [8], [35, 39-41].

9.1 ISAC Standardization Activities

9.1.1 ITU IMT-2030

Sensing has been recognized as a core feature of a mobile communication standard, with ISAC being identified as one of the intrinsic functionalities of IMT-2030 by the International Telecommunication Union – Radiocommunication Sector (ITU-R). While IMT-2020 was focused on eMBB, URLLC and mMTC, IMT-2030 expands this vision to include integrated sensing, AI, digital twins, ubiquitous connectivity and sustainability [7], [35]. The IMT-2030 framework specifies the vision, major performance requirements, evaluation methodology, and roadmap for future 6G technologies.

Within the ITU, the Radiocommunication Sector (ITU-R), and specifically Working Party 5D (WP 5D) of Study Group 5, defines the global framework, requirements, and evaluation methodology for "IMT-2030," the ITU's designation for 6G. ITU-R formally recognized ISAC as one of six core usage scenarios of IMT-2030 in Recommendation ITU-R M.2160 (November 2023) [35], and has since

progressively built out the technical performance requirements, test environments, and channel models needed to evaluate ISAC-capable candidate technologies.

9.1.1.1 Timeline of ITU-R Work Relevant to ISAC

- February 2020 — WP 5D begins work on a Report on future technology trends for IMT towards 2030 and beyond.
- December 2022 — Report ITU-R M.2516, "Future technology trends for the terrestrial component of IMT towards 2030 and beyond," is published, identifying ISAC among the emerging technology trends (alongside AI, sub-THz transmission, and reconfigurable intelligent surfaces).
- June 2023 — WP 5D agrees the draft new Recommendation on the "IMT-2030 Framework," formally including ISAC as one of six usage scenarios.
- November 2023 — The Radiocommunication Assembly 2023 (RA-23) approves Recommendation ITU-R M.2160, "Framework and overall objectives of the future development of IMT for 2030 and beyond," together with revised Resolutions ITU-R 56 and 65 confirming the "IMT-2030" name for 6G.
- May 2024 — Report ITU-R M.2541, "Technical feasibility of IMT in bands above 100 GHz," is approved by ITU-R Study Group 5, complementing Report M.2376 and providing propagation/channel data relevant to high-frequency ISAC operation.
- October 2024 — WP 5D (meeting #47) agrees on the Circular Letter inviting candidate radio interface technologies (RIT) for IMT-2030, to be submitted in the 2027–2029 timeframe.
- February 2026 — WP 5D completes the draft new Report on "Minimum requirements related to technical performance for IMT-2030 radio interface(s)" (IMT-2030 Technical Performance Requirements), defining 20 minimum technical performance requirements, including Sensing.
- June 2026 — WP 5D completes the draft new Report "Guidelines for evaluation of radio interface technologies for IMT-2030," introducing dedicated ISAC test environments (Indoor Factory-ISAC and Urban Macro-ISAC) and ISAC-specific channel models.

9.1.2 3rd Generation Partnership Project (3GPP)

Standardized ISAC channel models are an important milestone in Release 19, providing a common framework for evaluating wireless environments comprising communication users, sensing targets, environmental objects, and dynamic scatterers. These models allow for consistent evaluation of ISAC algorithms, waveform design, beamforming techniques, localization methods, and overall system performance in both academic and industrial settings. Release 19 also includes AI/ML for the NR air interface, MIMO enhancements and positioning work, which later ISAC studies can build on [36], [39].

Release 20 contains the 3GPP 6G study, and ISAC is one of the topics studied for 6G Radio in RAN1 and for the 6G system architecture in SA2. Release 20 also carries 5G-Advanced work on NR ISAC, whose measurement definitions are used as a reference in the 6G study. The release also aligns 3GPP activities with the ITU IMT-2030 roadmap to ensure that future 6G technologies will evolve in line with internationally agreed performance requirements.

The current 3GPP roadmap aims for Release 21 to bring the core of the 6G radio interface, network architecture, protocol stack, AI-native network functions, integrated sensing and advanced positioning services. For ISAC, Release 21 may define, depending on the outcome of the Release 20 study, key elements such as sensing

procedures, signaling protocols, sensing reference signals, performance metrics, interoperability requirements, and interfaces that enable communication and sensing in a common network framework.

9.1.2.1 3GPP Release 19

3GPP Release 19 initiated an ISAC channel modeling study item to address limitations in existing standardized communication channel models for supporting sensing performance evaluation. Accordingly, at RAN #102 in December 2023, the 3GPP Radio Access Network (RAN) Technical Specification Group (TSG) approved the study item "Study on Channel Modeling for ISAC for NR" [42], marking the start of developing standardized ISAC channel models.

This study item aims to develop channel models that support the evaluation of representative ISAC deployment scenarios and use cases. The work is structured into two main aspects: ISAC deployment scenarios and calibration, and ISAC channel modeling. The study spanned RAN1 #116 in February 2024 to RAN1 #121 in May 2025. Fig. 9.1 provides an overview of the study timeline and highlights key agreements and conclusions reached during the discussions. The major agreements achieved during the study are listed below.

- At RAN1 #116, it was agreed to use the sensing targets (STs) of UAVs, indoor humans, outdoor humans, automotive vehicles (at least for outdoor scenarios), automated guided vehicles (e.g., in indoor factories), and road/railway hazard objects specified in [33] as the baseline sensing targets for the ISAC channel modeling study.
- By RAN1 #119, the evaluation parameters associated with the agreed representative sensing targets (STs) had been successively finalized.
- At RAN1 #116, it was agreed that the ISAC channel model should be based on a common framework composed of the following two components:
  - Target channel component
  - Background channel component
- At RAN1 #118bis, the Radar Cross Section (RCS) characteristics for the sensing target and scattering point (STSP) were defined.
- At RAN1 #120bis (April 2025), it was agreed to adopt a 3-Reference-Point (RP) based modeling method as part of the ISAC channel modeling framework.

RAN1 progress on ISAC channel modelling, meeting by meeting. Red flags mark agreement milestones.

RAN1 / Research	#116 Feb. 2024	#116bis Apr. 2024	#117 May 2024	#118 Aug. 2024	#118bis Oct. 2024	#119 Nov. 2024	#120 Feb. 2025	#120bis Apr. 2025	#121 May 2025
Deployment scenario and calibration	Prioritized STs (UAV, human, vehicle, AGV, etc.) and scenarios, key definitions.	The evaluation parameter template for sensing scenarios is initially determined.	Evaluation parameter table for UAV is initially determined.	Evaluation parameter table for UAV is updated.	Evaluation tables for vehicle, human, AGV, object creating hazards are determined.	Evaluation tables for UAV, vehicle, human, AGV, object creating hazards are updated.	Simulation assumptions for large-scale calibration for UAV is agreed.	Calibration of UAV, vehicle, human, AGV, EO-type2, spatial consistency.	
Channel framework	$H_{ISAC} = H_{target} + H_{background}$					Power normalization between target and background channels is not performed.	Discussion on raising TRs for TPR-TRPUe/ UT/TRP-UT channels.	Discussion on raising TRs for the other propagation channels (total in 9 cases).	Power normalization can be applied (placeholders), Existing TRs for BSU UT.
Physical object model		ST is modeled as 1 or multiple SRs, random or deterministic RCs.		RCS = A * B as WA, the impact of ST is modeled as VRCs - CPM_{VRC}.	RCS = A * B vs. A * B + A * B * B2 of an SPST; A * B * B2 for monostatic UAV.	Monostatic RCS of human (with model 1 and 2) and vehicle (with 1 rc multiple SRs), CPM_{VRC}.	A * B * B2 for bistatic RCS, monostatic RCS values for UAV and human model-1.	Bistatic RCS model (WA), monostatic RCS values for UAV and AGV, XPR values of STs.	The last WA is confirmed. Bistatic RCS of UAV, human, vehicle, AGV. XPR of AGV.
Target channel		Concatenation / non-concatenation modelling.	Direct path (LoS + LoS) and indirect path (three propagation).	The target channel is agreed as a concatenation.	The detailed concatenation methods are approved, channel XPR CPM_{target}	Full convolution or 1-by-1 coupling for NLoS + NLoS rays.	The power scaling factor $L_{Tx-ST,rx-ST}$ is agreed, path dropping after concatenation.		Power threshold for path dropping after concatenation is -40/-52 dB.
Background channel				Existing TRs serve as a start point, discussion on monostatic modelling.	The power threshold for removing clusters is revised to X < -25 dB.		Drop N RRs following certain distribution to model monostatic channel (WA).	$N_p > 3$ RRs from Gamma distribution for one Tx, the values of TRP / UT sensing.	The values of UT-AV sensing. Absolute delay model is agreed.
Spatial consistency			Spatial consistency is discussed.		At least UAV scenario.		Reuse existing TR. Model between UT / ST to X / Y, X-Y-1 and X2-Y2.		Can be enabled for multiple SRs of an ST.
EO		Preliminary discussion on four modelling methods.	Considered in spatial consistency and target channels.	Existing TRs serve as a start point for EO-type 2.		EO type-1 is modeled in the same way as an ST, type-2 is modeled only specular reflection.	The polarization matrix of EO type-2 link.		EO type-2 model of specular reflection, can be modelled in NLOS.
Doppler						Doppler equation including macro- and micro-Doppler.			The placeholder in the CIR is kept in the draft CR.
Blockage						If not considered, a path interacted with several STs is not modelled.			The existing TR can be reused for T-ST, ST-Rx, background channels.

Fig. 9.1: Timeline and Progress of 3GPP ISAC Channel Standardization [43]

9.1.2.2 3GPP Release 20

RAN1 started the 6G ISAC study for 6G Radio (6GR) at RAN1 #124bis under three headings: evaluation, integration with communication, and waveform and frame structure. The outcomes so far are study-phase agreements. They define what will be studied and how it will be evaluated; none of them is yet a specification. The main points agreed from RAN1 #124bis to RAN1 #126 are summarized below.

- **Evaluation:** baseline cases cover UAVs, humans, vehicles and automated guided vehicles (AGVs) in the urban macro (UMa), suburban macro (SMa), indoor hotspot, urban grid, highway and indoor factory scenarios, at 4 GHz, about 7 GHz and 30 GHz. Six sensing modes are considered: transmission and reception point (TRP) and UE monostatic, and TRP–TRP, UE–UE, TRP–UE and UE–TRP bistatic. Metrics include velocity accuracy, missed detection probability and false alarm probability, with further assumptions for data fusion across multiple sensing nodes.
- **Integration with communication:** three options for the sensing reference signal (reuse of the communication RS, an enhanced RS and a dedicated RS), single-port and multi-port sensing RS resources, TRP-side and UE-side measurement definitions, time- and frequency-division multiplexing (TDM/FDM) of sensing and communication, phase continuity of the sensing RS, and the need for beam, power-control and interference-related enhancements.
- **Waveform and frame structure:** the 6GR CP-OFDM waveform and frame structure are the starting point, and CP-OFDM is the benchmark. Enhancements under study aim to improve PAPR, ambiguity-function sidelobes, resilience to interference and resource efficiency, mainly through Zadoff–Chu and Gold sequence variants and chirp-like reference signals, evaluated using the peak and integrated sidelobe ratios (PSLR, ISLR) and main-lobe width.

9.1.3 TSDSI

The Telecommunications Standards Development Society, India (TSDSI) has been actively promoting research, standardization, and ecosystem development for Integrated Sensing and Communication (ISAC) as a key technology for 6G. TSDSI views ISAC as an important enabler for India's future telecom networks, supporting applications in transportation, public safety, industry, agriculture, smart cities, and environmental monitoring. Technical Study and Standardization Work of TSDSI for ISAC are listed below:

9.1.3.1 Joint Communication & Sensing in 5G Networks & Beyond

The report [44] studies the feasibility of Joint Communication and Sensing (JCAS) using existing 5G NR infrastructure and legacy NR reference signals, aiming to enable sensing capabilities with minimal architectural and specification changes. The central idea is to reuse the communication network, particularly gNBs, RAN, Core, and Cloud infrastructure for sensing. This can provide environmental information such as object location, range, velocity, direction, and movement, while sharing spectrum, hardware, signal-processing resources, and network infrastructure between communication and sensing.

Key findings and recommendations of the report are listed below:

- The report identifies DL-PRS as the strongest baseline for sensing, primarily because of its wide bandwidth capability and flexible time-frequency resource allocation.
- The report notes that the referenced 3GPP feasibility study identified 32 JCAS use cases. For the Indian context considered by the report, the study prioritizes:

    - Sensing unexpected intrusion in blind spots on a road
    - Sensing traffic movement
- The report emphasizes network-based sensing, where the cellular network itself acts as a sensing infrastructure.
- The report identifies six principal sensing KPIs: Accuracy, Resolution, False Alarm Rate, Coverage, Availability, and Refresh Rate.
- The sensing accuracy and resolution of FR2 & FR3 would be superior to FR1 due to its larger bandwidth and larger antenna array size; hence, this study shall broadly consider 6 – 56 GHz range spectrum-based deployments for JCAS application.

9.1.3.2 Study of the Channel Model for Integrated Sensing and Communication Networks

The report [45] studies how existing 3GPP channel models, principally TR 38.901, need to be extended to support Integrated Sensing and Communication (ISAC), a capability envisioned for 6G in which the mobile network itself acts as a sensor, detecting objects that are not actively transmitting.

Key findings and recommendations of the report are listed below:

- This report focuses on the study of communication channels and ISAC channel models, with particular emphasis on the potential FR1 and FR3 frequency ranges. In particular, the FR3 mid-band spectrum spanning 7–15 GHz is expected to play a key role in enabling 6G technologies.
- Calibration methodology for ISAC channel discussed for providing significantly lower computational complexity and improved flexibility for Monte Carlo simulations.
- In this study, the deterministic background channel is formulated by explicitly modeling the background as the superposition of direct, ground-reflected, building-reflected, and environmental scattering components using ray-tracing principles.

9.1.4 O-RAN Alliance

The O-RAN Alliance is spearheading the development of open, intelligent, and interoperable RANs through standardized interfaces, virtualization, cloud-native architectures, and AI-driven network control. These principles provide a strong foundation for future ISAC deployments, where communication and sensing functions must work together in heterogeneous, multi-vendor networks [46]. A major enabler for ISAC within the O-RAN framework is the RAN Intelligent Controller (RIC), which, together with service management frameworks and programmable interfaces, enables AI-driven optimization and flexible integration of sensing functions into the RAN. This framework can enable dynamic coordination of communication and sensing resources, reduce dependence on proprietary vendor solutions, and enable faster evolution of ISAC capabilities. Open interfaces in O-RAN also foster innovation from third-party vendors and enable deployment of distributed AI services, edge computing platforms, and sensing applications on the RAN.

9.1.5 IEEE

In parallel with ISAC studies in 3GPP for cellular and future 6G systems, the IEEE 802.11 Working Group has initiated the IEEE 802.11bf WLAN Sensing project to support sensing capabilities within WLAN networks.

This work is of significant interest because Wi-Fi infrastructure is widely deployed across residential, enterprise, industrial, transportation, and public environments. By leveraging existing WLAN deployments, IEEE 802.11bf aims to enable sensing applications such as occupancy detection, motion

sensing, localization, gesture recognition, and environmental awareness with minimal additional infrastructure.

Rather than specifying an independent sensing system, IEEE 802.11bf concentrates on standardizing the mechanisms for acquiring, exchanging, and processing sensing-related information within WLAN networks. This approach enables sensing functionality to integrate with existing communication systems, extending the capabilities of Wi-Fi networks beyond traditional data communications [47],[48].

9.2 Global Research Programs and National Initiatives

Global research and national initiatives indicate that ISAC has emerged as a strategic technology for 6G, with major countries investing in joint communication–sensing research, testbeds, AI-native architectures, spectrum studies, and pre-standardization activities [7], [8]. In the United States, the Next G Alliance, NSF, NIST, DARPA, universities, and industry are advancing ISAC in areas such as waveform design, sensing-data architectures, spectrum coexistence, distributed sensing, and AI-enabled radio systems. China, through the IMT-2030 (6G) Promotion Group and major academic and industrial programs, is pursuing large-scale work on integrated waveform design, massive-MIMO sensing, localization, cooperative sensing, mmWave/THz technologies, and experimental validation. India, under the Bharat 6G Mission and Bharat 6G Alliance, is developing indigenous ISAC capabilities through FR3 testbeds, joint waveform and beamforming research, localization, AI-assisted sensing, spectrum-efficient architectures, and contributions to international standards. In Japan, Beyond 5G/6G initiatives led by organizations such as NICT and supported by academia and industry are examining ISAC for intelligent mobility, distributed sensing, edge intelligence, and high-accuracy positioning. South Korea is integrating ISAC into its national 6G R&D roadmap, emphasizing AI-native sensing, massive MIMO, mmWave and sub-THz systems, autonomous mobility, digital twins, and early 6G demonstrations. Germany is addressing ISAC through national 6G research hubs, focusing on industrial sensing, automotive applications, JRC design, localization, security, and resilient infrastructure. Finland, building on its 6G Flagship program, has contributed strongly to ISAC-related work in localization, environmental sensing, distributed intelligence, high-frequency radio, and sustainable wireless systems [7], [14]. Spain and Italy contribute extensively through European SNS JU and Horizon Europe projects, particularly in smart mobility, industrial automation, vehicular sensing, localization, and edge intelligence. At the regional level, the European Union, through the Smart Networks and Services Joint Undertaking and projects such as Hexa-X and Hexa-X-II, is promoting a common European 6G framework in which communication, sensing, AI, computing, and localization are jointly developed. In the Asia-Pacific and Middle East regions, Singapore is exploring ISAC for smart cities, autonomous systems, dense urban sensing, mmWave technologies, and digital twins, while Australia is active in radio localization, autonomous sensing, spectrum sharing, and resilient communications. Canada is pursuing ISAC within broader 5G-Advanced and 6G research, including intelligent transportation, localization, distributed sensing, and AI-based radio processing. The United Arab Emirates and Saudi Arabia are incorporating ISAC into emerging 6G and smart-city strategies, with particular relevance to autonomous mobility, infrastructure monitoring, AI-enabled networks, industrial digitalization, and large-scale future urban environments. Based on global research and national initiatives, ISAC is a strategic technology for 6G, with major countries investing in joint communication-sensing research, testbeds, AI-native architectures, spectrum studies, and pre-standardization activities. Overall, a coordinated international effort is shaping ISAC standardization. Together, different international organizations are moving ISAC from a research concept to a standardized, interoperable, and commercially deployable technology for future 6G networks [7], [8], [35].

Section 10: Security and Privacy

The section is organized around two principles. First, sensing is a double-edged sword: the ability that increases the attack surface can also provide physical evidence for security. Second, security should be coupling-aware: the physical layer, sensing, protocol, AI, and governance mechanisms should reinforce each other rather than serve as independent add-ons.

10.1 Multi-Domain Threat Landscape

ISAC threats fall into three interrelated system-level domains, i.e., cyber-physical, physical-layer, and protocol [1], a taxonomy especially useful in safety-critical systems like transportation, robotics, and industrial automation, where attacks often cross domains before their consequences become visible.

10.1.1 Cyber-physical domain

The cyber-physical domain links sensing (cameras, radar, lidar, cooperative/infrastructure sensing) to control actions like steering or braking; compromised BSs/RSUs or spoofed/jammed signals can inject false environmental data, causing phantom obstacles or unsafe actions even though the attack occurs at the waveform level [46, 49]. Because communication performance also depends on sensing (beam alignment, blockage prediction, link selection), corrupting sensing can degrade reliability and latency without ever touching the encrypted payload, making ISAC's perception-communication-control coupling tighter than in conventional systems [46].

10.1.2 Physical-layer domain

The physical-layer domain includes generating, propagating, receiving, and estimating the common sensing-communication waveform. It introduces several threats that become more significant when communication and sensing share signals and hardware [46, 49].

- **Waveform and signal exploitation:** Adversaries can passively infer location and motion from predictable pilots, synchronization signals, and reflections without decrypting any payload [46], and malicious targets near dual-functional beams can eavesdrop on embedded communication data. Actively, attackers can replay or manipulate echoes to spoof ghost/hidden targets, jam or contaminate pilots to jointly corrupt channel estimation and sensing accuracy, and manipulate RIS states to bias sensing geometry or redirect energy [8].
- **Learning-assisted physical-layer attacks:** Where AI/ML drives beam prediction, waveform selection, sensing fusion, or target classification, adversaries can use data poisoning or adversarial perturbations to shift the attack surface from the raw waveform to the underlying model and data pipeline itself.

10.1.3 Protocol and control-plane domain.

This domain governs identity, authentication, key management, mobility, and secure transport of sensing data. Its core challenge: lower-layer sensing can mislead higher-layer security assumptions—payload encryption doesn't stop location leakage from the waveform, and falsified sensing results can trigger corrupted handovers, route changes, or trust updates ("control-plane poisoning") even though the protocol itself behaves correctly [46]. ISAC also strains cryptographic design, as frequent mobility and tight sensing deadlines make key establishment and (especially post-quantum) verification a significant latency/compute cost—a system-design burden, not an attack, and should be visually distinguished from adversarial threat paths.

10.1.4 Cross-domain propagation

The critical insight is the coupling between domains, not the individual attack list: a false echo can bias a physical-layer estimate, corrupt perception, and trigger an unsafe cyber-physical action; a compromised RSU can falsify sensing, skew a protocol decision, and degrade beam selection; a poisoned AI model can produce implausible estimates that control and communication functions then trust. ISAC security therefore requires validating cross-layer evidence consistency, not just each layer in isolation [46, 49]. Figure 10.1 maps these risks across the three domains and shows how vulnerabilities propagate into system-level failures, based on the taxonomy in [46].

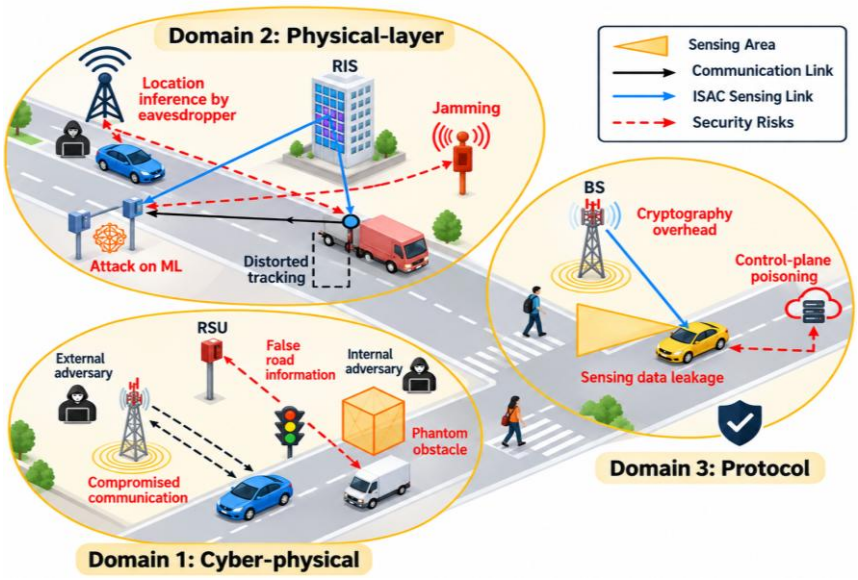


Fig. 10.1. Multi-domain security threat landscape for vehicular ISAC.

10.2 Sensing as a Security Enabler

The sensing capability of ISAC can bolster security only when the adversary or its effect is physically observable—a fully passive receiver with no detectable echo or protocol footprint remains invisible regardless of the network's sensing support. Under this observability condition, the defensive opportunities summarized in Figure 10.2 are substantial.

- **Sensing-enhanced secure transmission:** When an eavesdropper or target is physically observable, sensing enables estimation of its position/channel for secure precoding robust to estimation uncertainty [46]; secure beamforming then shapes the beam pattern (via artificial noise, jamming, joint precoding) to limit leakage, while covert communication—measured by a warden's actual detection performance rather than assumed invisibility—can hide behind the sensing waveform itself [46]. RIS adds further spatial degrees of freedom to this secrecy-sensing trade-off, though its benefits depend on accurate channel knowledge and control, and should never be assumed to guarantee secrecy or key entropy without a specific analyzed protocol.
- **Verification and trust mechanisms:** Physical-layer authentication uses CSI, angle, timing, or RF fingerprints—cross-checked against independently sensed device position—as supplementary evidence in an authentication chain, not a replacement for cryptographic identity [49]. Separately, trustworthy learning techniques (adversarial training, robust estimation, provenance tracking, multi-sensor consistency checks) can reduce the impact of malicious inputs, offering bounded or empirical robustness guarantees; XAI aids diagnosis and auditability but doesn't itself ensure security.

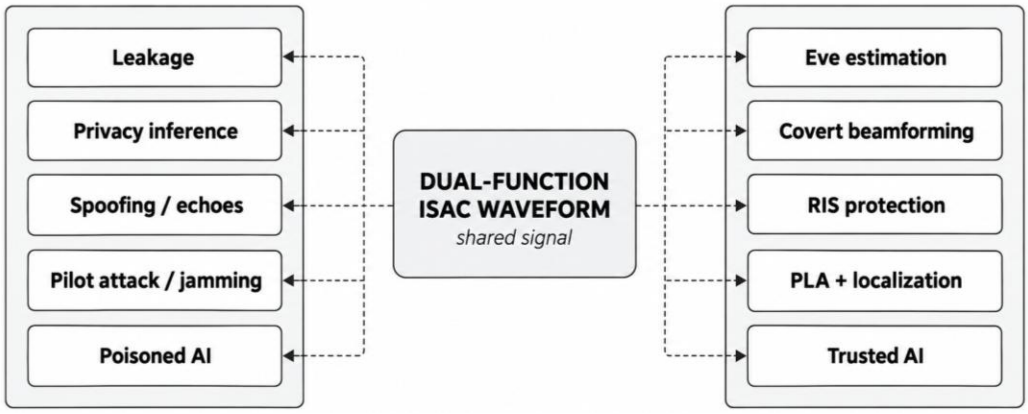


Fig. 10.2. Dual-function ISAC waveforms balance security and sensing.

Fig. 10.2 shows the sensing role in ISAC security. The common ISAC waveform not only creates attack surfaces (e.g., communication leakage, privacy inference, sensing deception, jamming, and attacks on learning) but also provides defense mechanisms (e.g., sensing-assisted eavesdropper estimation, secure/covert beamforming, RIS-assisted protection, sensing-consistent authentication/localization, and anomaly-aware learning). The main design challenge is balancing security, sensing quality, and communication performance [46, 49].

10.3 Joint Design of Security, Sensing, and Communication

Security, sensing, and communication compete for shared resources (e.g., artificial noise, nulling, and longer training intervals all trade off against sensing or communication performance), making the goal a Pareto trade-off across matched metrics—secrecy rate/outage for security, CRBs/detection probability for sensing, and rate/latency/reliability for communication—rather than a single optimum [4]. Physical-layer security co-designed with ISAC waveforms offers spatial selectivity and low-latency evidence, but should complement, not replace, cryptography, which provides endpoint confidentiality, integrity, and authentication [46, 49].

10.4 A Defence-in-Depth Architecture

No single mechanism can secure the entire ISAC attack surface. A defense-in-depth approach therefore combines multiple layers, allowing one control to compensate for weaknesses in another.

- **Physical Layer:** Secure waveforms, beamforming, artificial noise, and channel-based key generation help reduce eavesdropping and interference. Authentication remains necessary to prevent active attacks [46].
- **Sensing and Localization Layer:** Spoofing detection, consistency checks, geometric validation, and multi-node verification help protect sensing integrity.
- **AI and Learning Layer:** Adversarial training, robust aggregation, and explainable AI improve model reliability. Federated learning alone does not guarantee privacy, and secure aggregation or differential privacy may be needed [46].
- **Network and Edge Layer:** Zero-trust principles support continuous authentication and authorization across devices, edge servers, and cloud platforms.
- **Governance Layer:** Policies should control sensing authorization, data use, retention, and incident management.

Section 11: Performance Evaluation and Benchmarking

In ISAC, both functions share spectrum, transmit power, antennas, waveforms, beamforming, processing resources, and often the same radio observations; therefore, assess performance jointly.

11.1 Principles of ISAC Performance Evaluation

Assess ISAC performance across three dimensions: communication, sensing, and joint/system-level performance. Communication metrics evaluate data-transfer efficiency, sensing metrics measure detection, estimation, localization, and tracking, while joint metrics characterize coexistence and shared-resource utilization. Because improving sensing can degrade communication, and vice versa, ISAC performance is better represented by achievable trade-off regions than by a single metric. Accordingly, compare communication-centric and sensing-centric designs with jointly optimized, Pareto-efficient operating points. Fair evaluation requires consistent assumptions for bandwidth, transmit power, antenna aperture, observation time, hardware resources, channel conditions, and deployment scenarios.

11.2 Communication Performance Metrics

Communication KPIs keep their usual meaning in ISAC: throughput and spectral efficiency, latency, reliability (bit and packet error rates), energy efficiency and coverage. What changes is how they are reported. Each KPI should be stated with the sensing configuration active, including the share of time, frequency, power and beam resources given to sensing, so that the cost of sensing to communication is visible and results with full communication resources are not compared directly with ISAC results. Throughput should be reported with the bandwidth, modulation and coding, traffic model and sensing set-up. Latency should state where it is measured, since sensing processing, beam updates and edge computing add delay. Energy efficiency should state the power model, including baseband, edge processing and RIS control where relevant. Coverage should be defined against a stated rate, reliability or latency criterion, and for RIS-assisted ISAC the RIS geometry and configuration should be given.

11.3 Sensing Performance Metrics

Sensing evaluation should distinguish between resolution, accuracy, detection, localization, and tracking, as they represent different sensing capabilities. Resolution is the ability to discriminate close targets or parameters; accuracy is the estimation error; and tracking is state estimation over time [2].

- **Range Resolution and Accuracy:** The range resolution is mostly governed by the effective sensing bandwidth, and the range accuracy is a function of the SNR, waveform design, synchronization, multipath, calibration, estimator design, and model mismatch. Accuracy is presented independently using RMSE (absolute error), percentile error, or theoretical boundaries.
- **Doppler and Velocity Performance:** Doppler resolution is primarily a function of the coherent observation duration. Velocity estimation depends on carrier frequency, waveform, target dynamics, SNR, and interference. Express velocity accuracy individually as RMSE, percentile error, or trajectory-based state error.
- **Angle Resolution and Accuracy:** The performance of a direction of arrival (DOA) estimator depends on the antenna aperture, wavelength, array design, beamwidth, signal-to-noise ratio (SNR), calibration, and estimation method. Angle accuracy is defined as AoA/AoD estimation error, and resolution is the minimal resolvable angular separation. RIS-assisted gains also depend on RIS placement, aperture, configuration, geometry, and path availability.

- **Sensing SNR and SINR:** Sensing SNR evaluates the ratio of beneficial target signals to receiver noise, whereas enabling sensing further incorporates clutter, communication interference, self-interference, and extra reflections. The provided values must be accompanied by assumptions about the target, geometry, propagation, and interference [31].
- **Detection and False Alarms:** The likelihood of detection P_D ought to be shown alongside the probability of false alarm (P_{FA}), ideally at a designated (P_{FA}) or using ROC curves. Assessment must delineate intended RCS/scattering, SNR, clutter, observations, detector classification, and cutoff methodology.
- **Localization Accuracy:** Localization efficacy can be defined by two-dimensional or three-dimensional positional inaccuracies, root mean square error, percentile discrepancies, or theoretical limits. Outcomes must delineate node and target geometry, path accessibility, synchronization, and statistical reporting parameters, especially for RIS-supported and multi-node configurations.
- **Tracking Accuracy:** Assessment of tracking must be conducted across sample trajectories by analyzing position and velocity discrepancies, track continuity, frequency of track loss, correctness of associations, and time for reacquisition
- **Sensing Coverage:** Sensing coverage must encompass the area that meets established sensing-quality criteria, including a minimum detection probability at a designated false-alarm rate and constrained errors in localization, range, angle, or tracking. This concept encompasses obstruction, target RCS, beam orientation, RIS configuration, clutter, and interference.

11.4 Joint Communication-Sensing Performance

ISAC should be assessed based on the concurrent execution of communication and sensing within a shared resource allocation. Consequently, the primary result is a set of viable collaborative operating points rather than a single communication or sensing KPI [46].

- **Communication-Sensing Trade-off:** Communication-centric topologies may optimize throughput or dependability, whereas sensing-centric setups optimize detection or estimation accuracy. Emphasize this trade-off through joint evaluation by varying power, bandwidth, beamforming, sensing time, RIS configuration, or scheduling. Select the appropriate operating point based on application-specific communication and sensing needs.
- **Communication Degradation Due to Sensing:** The communication performance should be compared to a communication-only baseline with the same number of resources. Assess degradation in throughput, spectral efficiency, coverage, energy efficiency, or delay. This directly assesses the communication cost of enabling sensing.
- **Sensing Gain Due to Integration:** Sensing improvements should be compared to a well-defined baseline, e.g. direct-path, non-RIS, non-optimized waveform reuse, or dedicated sensing. Gains can include improved detection, lower estimation error, better localization, longer coverage, or greater blockage robustness. For a fair comparison, the assumed resources must be the same.
- **QoS and Sensing-QoS Feasibility:** A joint evaluation should find the operational regions where the communication needs (e.g., rate, reliability, latency) and the sensing requirements (e.g., detection probability, false-alarm rate, localization and tracking precision) can be satisfied simultaneously [4].
- **Joint Coverage:** The joint coverage is described as the spatial area where both the communication and the sensing service demands are fulfilled. It is especially helpful for evaluating beamforming, RIS placement, BS density, and distributed sensing systems by quantifying the spatial overlap of communication and sensing capabilities.

11.5 System-Level and Implementation Metrics

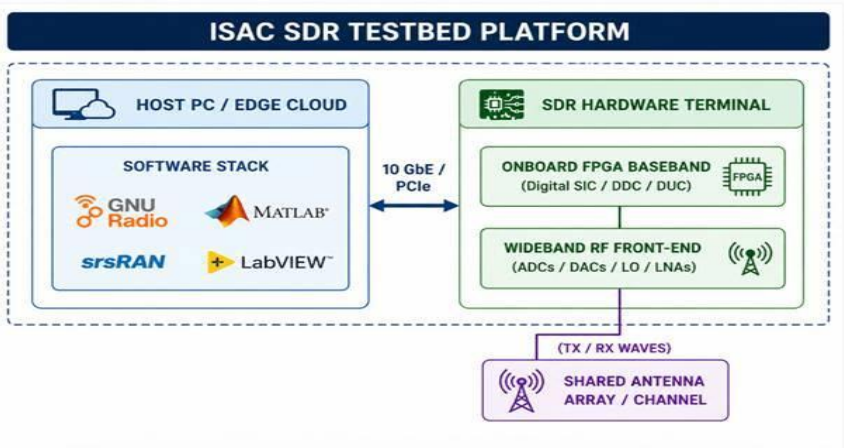
Not all metrics pertinent to ISAC execution should be depicted as universal ISAC KPIs. Certain metrics have significance solely when specific architectural decisions, including distributed sensing, RIS, edge computing, AI processing, or simultaneous transmit-receive operations, are implemented. These metrics are more appropriately regarded as system-level or architecture-specific indicators.

- **Resource Utilization:** ISAC encompasses various categories of resources, including spectrum, transmission power, time-frequency assets, antennas and spatial dimensions, processing capability, memory, transport connections, and beam or RIS control signaling. Resource utilization must measure the extent of the available resources needed to meet the collective service objective.
- **Processing and Computational Latency:** When sensing input is processed at the edge or through an AI model, the processing latency contributes to the effective sensing-decision cycle. Relevant latency may include sensing collection, transportation, inference, decision-making, reconfiguration, and actuation.
- **Synchronization Accuracy:** Coherent sensing and distributed ISAC may exhibit sensitivity to discrepancies in timing, carrier frequency, and phase among nodes. Convey synchronization quality using application-relevant metrics, including residual timing offset, carrier-frequency offset, phase inaccuracy, or inter-node clock offset.
- **Self-Interference Suppression:** Residual SI is crucial for systems that broadcast and receive concurrently, especially in monostatic or full duplex implementations where transmitter leakage may obscure faint sensor echoes. Document the achieved cancellation alongside transmission power, receiver dynamic range, bandwidth, and the cancellation stage. It should not be treated as a general ISAC KPI because it depends on the architecture.
- **RIS Control and Reconfiguration:** RIS-assisted ISAC is accompanied by additional implementation issues, including reconfiguration delay, control-signaling overhead, phase quantization, reflection efficiency, channel-estimation overhead, update rate, and calibration accuracy. These parameters determine the feasibility of theoretical beamforming and sensing gains in practice and should be incorporated into system-level RIS evaluations.
- **Scalability and Coordination Overhead:** Distributed ISAC can increase coverage, geometry, and robustness via coordination across numerous base stations, APs, RSUs, sensors, or RIS panels. This coordination also requires synchronization, information sharing, and processing. Thus, assess scalability in terms of the number of supported users or sensing targets, as well as the related signaling overhead, processing load, latency, and fronthaul or backhaul demand.

Section 12: Experimental Platforms: ISAC Prototyping Platforms

This section discusses the hardware platforms used for prototyping and experimental validation of ISAC technologies.

12.1 SDR Platforms



Software-defined radio (SDR) platforms are widely used for ISAC prototyping and validation because they let users implement and reconfigure communication and sensing functions in software without hardware redesign. They support real-time evaluation of dual-function waveforms, emerging schemes such as OTFS and AFDM, and the impact of practical RF impairments across different propagation environments [50-51].

Frameworks such as GNU Radio, srsRAN, OpenAirInterface, MATLAB/Simulink, and UHD further enable flexible ISAC experimentation, protocol modification, CSI extraction, and radar/communication signal processing. For distributed bistatic and multistatic testbeds, accurate time, frequency, and phase synchronization across SDR nodes is essential to achieve reliable communication and precise sensing performance [50-51].

12.2. FPGA Platforms

In ISAC systems, FPGAs accelerate computationally intensive operations such as waveform generation, matched filtering, range–Doppler FFT processing, beamforming, channel estimation, SIC, and physical-layer (PHY) signal processing. Their deterministic latency, high throughput, and energy-efficient architecture make them an attractive platform for real-time communication and environmental sensing [50-51]. Modern FPGA platforms, such as the Xilinx Zynq RFSoC, integrate ARM processors and programmable logic into a single chip, allowing communication and radar sensing to run on the same hardware platform. This tight integration enables communication and sensing algorithms to run in real time and provides the flexibility to prototype, evaluate, and optimize new ISAC techniques without redesigning dedicated hardware.

12.3 RFSoC Platforms

Radio Frequency System-on-Chip (RFSoC) has been proposed as a promising hardware platform for real-time ISAC systems. Compared to traditional SDR platforms that need separate FPGA boards and external RF components, the RFSoC integrates FPGA programmable logic, embedded ARM processors, high-speed ADCs, DACs, on-chip memory, and high-speed transceivers into a single device. This high degree of integration reduces hardware complexity, processing latency, and synchronization errors, improves energy efficiency, and provides the computational capability needed for simultaneous communication and sensing. The RFSoC combines processing, data conversion, and RF interfaces into one chip and enables real-time ISAC functionalities, including waveform generation, beamforming, channel estimation, target detection, and signal processing.

Section 13: Applications

ISAC can enable intelligent applications in transportation, healthcare, manufacturing, public safety, smart cities, and industrial automation [33, 52-55].

13.1 Intelligent Mobility and Transportation

13.1.1 Smart Transportation

ISAC combines V2X communication and automotive sensing on a unified platform. As shown in Fig. 13.1, RSUs can simultaneously transmit data and sense vehicle position and motion using reflected 6G signals, improving situational awareness and reducing blind spots and onboard processing load [52]. ISAC integration with LiDARs, cameras, and GNSS enables safer autonomous driving, effective traffic management, and reliable ITS operation.



Figure 13.1 ISAC Performance Requirements in Smart Transportation [6].

13.1.2 UAVs and Airspace

ISAC enables UAVs to perform joint communication, sensing, target tracking, and navigation over a common wireless platform, as shown in Fig. 13.2. This supports flight safety, situational awareness, trajectory planning, cooperative networking, and autonomous operation. In addition, ISAC-enabled UAVs can support surveillance, disaster response, logistics, agriculture, infrastructure inspection, environmental monitoring, and future 6G applications [33, 52-55].



Fig. 13.2 Low-Altitude Economy (LAE) requirements for UAV operations, illustrating communication, sensing, and management functions [3]

The future UAV networks will enable the Low Altitude Economy (LAE) through integrated communication, location, sensing and intelligent airspace management. Combined with AI-driven navigation, beamforming, edge computing, and mmWave/THz connectivity, ISAC may enhance flight safety, resource efficiency, and autonomous operation, making UAVs an integral part of future 6G networks.

13.1.3 Non-Terrestrial Networks (NTN)

NTNs with ISAC support, e.g., satellites, HAPs, and airborne platforms, expand communication and sensing coverage beyond the terrestrial domain. They can enable environmental monitoring, maritime surveillance, precision agriculture, disaster management, border security, and remote-area connectivity [45]. Integrating terrestrial and non-terrestrial ISAC aims to enable seamless 6G connectivity with broad sensing coverage over land, sea, and air.

13.1.4 Maritime and Underwater ISAC

ISAC can improve maritime and undersea networks by combining communication and environmental sensing on a shared platform. [5] It facilitates vessel tracking, harbor surveillance, underwater navigation, infrastructure inspection, fisheries management, environmental monitoring, oceanographic sensing and disaster warning. Future maritime ISAC systems may include acoustic, optical, RF, and satellite links to improve connectivity, situational awareness, safety, and operating efficiency.

13.2 Smart Industry and Connected Living

13.2.1 Smart Manufacturing

ISAC is a key enabler of Industry 5.0, combining wireless communication with environmental sensing in a single industrial network. It offers real-time monitoring of machines, robotics, production lines, and material movement without a separate sensing infrastructure. Typical applications include equipment health monitoring, defect detection, worker safety, inventory tracking, digital-twin synchronization, and predictive maintenance. ISAC, combined with AI, may increase productivity, quality, and resource efficiency while reducing downtime and maintenance costs.

13.2.2 Healthcare

ISAC provides continuous health monitoring and reliable communication for smart hospitals and home-care systems. Wireless sensing can provide contactless monitoring of respiration, heartbeat, movement, posture, occupancy, and falls, thus minimizing the reliance on wearable equipment [8]. Together with AI, ISAC can improve remote monitoring, aged care, rehabilitation, anomaly detection, and personalized healthcare while improving patient safety and quality of care [45].

13.2.3 Smart Cities

ISAC supports smart cities by turning communication networks into distributed sensing platforms to monitor traffic, pedestrians, infrastructure, environmental conditions, and public safety. Applications include adaptive traffic control, smart parking, crowd surveillance, structural health assessment, emergency response, waste management, and urban digital twins. AI and cloud computing with ISAC enable efficient, sustainable, and resilient urban services.

13.2.4 Agriculture

ISAC provides stable connectivity and continuous environmental sensing for sensors, machines, drones, and farm systems, supporting precision agriculture. Applications include crop and livestock monitoring, autonomous farming, irrigation control, soil assessment, greenhouse automation, and precision spraying. ISAC

paired with AI may optimize water and fertilizer use, disease detection, and harvesting to increase yield while reducing cost and environmental impact.

13.2.5 Environmental Monitoring

ISAC enables large-scale environmental monitoring by combining sensing and reliable connectivity on terrestrial, aerial, satellite, and underwater platforms. Its applications range from air quality, water resources, forests, glaciers, coastal areas, and wildlife monitoring to flood, wildfire, landslip, earthquake, and pollution detection. AI enables ISAC to provide early warning, climate modeling, ecosystem management, and faster disaster response.

13.3 Mission-Critical and Immersive Applications

13.3.1 Defense and Public Safety

ISAC strengthens national security and disaster response by combining trusted communications with real-time environmental sensing. Applications include surveillance, target detection and localization, perimeter security, search and rescue, disaster response, border security, infrastructure protection, and autonomous reconnaissance. ISAC, together with AI and network-wide sensing, enhances situational awareness, response time, and operational reliability in hostile or communication-limited environments [45].

13.3.2 Extended Reality (XR)

ISAC enables rigorous XR applications by combining high-speed connectivity, minimal latency, and accurate user detection [56]. Prospective XR applications may necessitate data transfer speeds above 10 Gbps, end-to-end latency under 5 ms, positioning accuracy within sub-centimeter precision, and orientation accuracy within sub-degree accuracy. As illustrated in Fig. 13.3, ISAC-capable 6G access points can concurrently provide immersive content while monitoring user position, speed, and orientation, facilitating low-latency engagement, precise localization, and immediate environmental awareness.

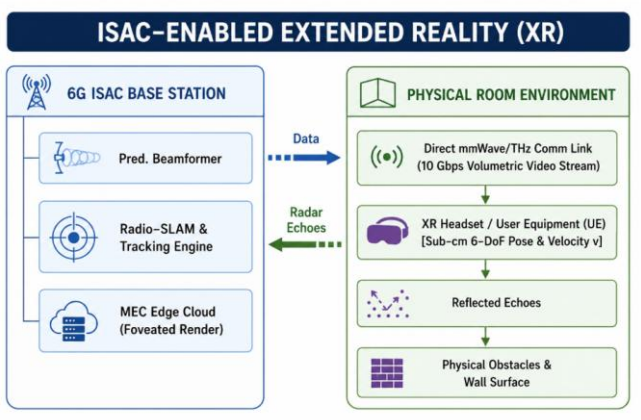


Figure 13.3: Conceptual architecture of an ISAC-enabled 6G wireless network supporting immersive XR [7]

ISAC turns wireless networks into intelligent platforms that can transmit, perceive, and analyze their surroundings simultaneously. It facilitates applications in transportation, manufacturing, healthcare, agriculture, environmental surveillance, maritime operations, security, and immersive services. By integrating AI, edge computing, and digital twins, ISAC is expected to harmonize communication, sensing, and intelligent decision-making in future adaptive, context-aware 6G networks [45].

Section 14: Economics and Commercialization

The business case for ISAC extends beyond its technical benefits of spectrum reuse, shared radio hardware, and environmental sensing. For operators, ISAC must generate new revenue, reduce service costs, avoid dedicated sensing infrastructure, or improve network-asset utilization sufficiently to justify additional capital and operating expenditure. This requirement is particularly important given the scale of existing telecom investment: mobile operators globally invest about USD 109 billion annually in connectivity infrastructure, while Europe alone faces a substantial projected investment gap toward 2035 [1], [4], [14], [40].

India presents a similarly important case for infrastructure reuse. According to the GSMA, Indian operators have invested more than ₹4 lakh crore in 5G rollout, reinforcing the need for future ISAC capabilities to leverage existing 5G/5G-Advanced infrastructure rather than require extensive parallel deployments. Consequently, ISAC's commercial viability in India will depend strongly on reusing deployed spectrum, massive-MIMO systems, network sites, edge/cloud platforms, and 5G infrastructure while creating measurable value across enterprise, industrial, transportation, public-safety, and other emerging 6G applications.

14.1 From Connectivity to Network-Generated Value

Historically, mobile-network revenues have been tied to connectivity through subscriptions, traffic, roaming, enterprise access, fixed-wireless services, and private networks. ISAC adds another value layer, as the network can produce information about the physical environment, rather than just transporting information generated elsewhere. Telefónica describes this transformation as the mobile network becoming more than just a connectivity platform, but an infrastructure that can sense its physical environment. A key feature is that the sensed objects do not necessarily need to be connected to the network [4]. Vodafone has shown a similar concept using cellular infrastructure to estimate characteristics such as location, speed, and direction of connected and unconnected objects, with potential applications in environments such as airports, ports, and campuses [5].

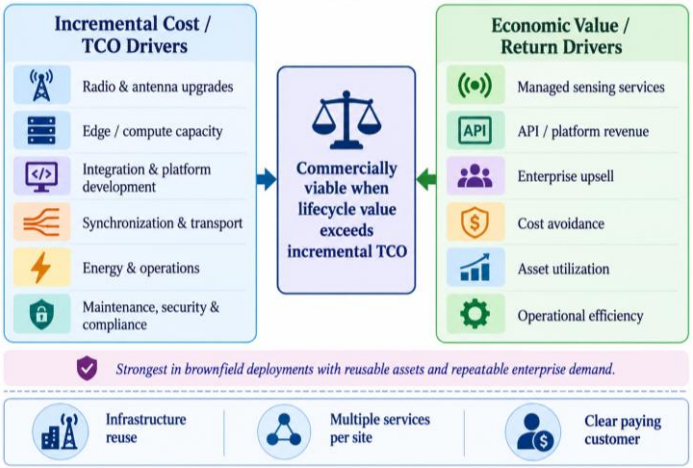


Fig. 14.1. ISAC commercial value chain from existing network assets to sensing-enabled services, customer outcomes, and economic value.

Fig. 14.1 highlights an important economic difference. It covers the whole chain from infrastructure reuse to sensing enablement, data processing, service delivery, and the final enterprise outcome. The figure also distinguishes the main cost and benefit mechanisms between incremental CAPEX and OPEX, and between new revenue sources and avoided costs. ISAC could be one such capability, especially if sensing outputs could be made available as processed information rather than unconstrained raw measurements [54].

14.2 Operator Investment Perspective

The economics of network migration will be a major factor in ISAC commercialization. Industry perspectives on 6G emphasize evolutionary deployment, software-driven innovation, energy efficiency, backward compatibility, cloud-native architectures, and sustainable migration from existing networks [3], [6]. For ISAC, solutions that reuse current massive-MIMO arrays, baseband platforms, network sites, and edge infrastructure are therefore more attractive than approaches requiring extensive hardware replacement, site densification, dedicated sensing receivers, or major transport upgrades.

Recent operator activities reflect this emphasis on infrastructure reuse. Vodafone, Telefónica, Deutsche Telekom, and T-Mobile have explored ISAC as an extension of existing communication infrastructure, including network sensing, API exposure, integrated positioning, distributed computing, and physical AI [4], [5], [33]. However, most activities remain at the research, demonstration, trial, or pre-standardization stage. Commercial adoption will depend on whether ISAC can be delivered as a scalable, economically repeatable service that improves deployment efficiency while integrating communication and sensing capabilities [44].

14.3 Cost Structure and the Operator Business Case

For an operator, economic relevance is not the full cost of a future 6G network but the incremental TCO (Total Cost of Ownership) needed to introduce and operate sensing capability. The magnitude of this incremental cost depends very much on the deployment architecture. At one end of the spectrum, sensing can be added primarily through software, baseband processing, existing antennas, and available edge-compute capacity. In contrast, a demanding multistatic or high-resolution deployment may need additional receivers, new sites, phase-coherent synchronization, high-capacity transport, edge accelerators, and substantial integration work. The two architectures might have similar technical functionality but very different commercial prospects. Capital expenditure can come from radio and antenna upgrades, compute capacity expansion, synchronization infrastructure, site modifications, transport upgrades, edge platforms, and enterprise integration. Existing massive-MIMO arrays could support some sensing functions, but more demanding applications will require larger apertures, more bandwidth, better calibration, better receiver dynamic range, or simultaneous transmit-and-receive operation. Sensing may add energy consumption, computational load, data transport, storage, calibration needs, software maintenance, security monitoring, service assurance, and customer support costs. The economic benefit of infrastructure convergence can thus be undermined when sensing requires continuous transmission or processing-intensive sensing during periods when the service offers little value. These benefits must be weighed against revenue generation and cost avoidance. New income sources include managed sensing services, enterprise contracts, API exposure, analytics, or bundled services. Cost avoidance is relevant where network sensing replaces or supplements redundant radar, camera, LiDAR, localization, or industrial-sensor infrastructure [47].

14.4 Commercial Attractiveness Across Use Cases

The commercial attractiveness of ISAC will vary a lot depending on the application. A commercially attractive deployment will have sufficient customer value, a clear payer, high infrastructure reuse, manageable incremental costs, and acceptable regulatory and integration risks [47]. Fig. 14.2 places representative applications against these factors.

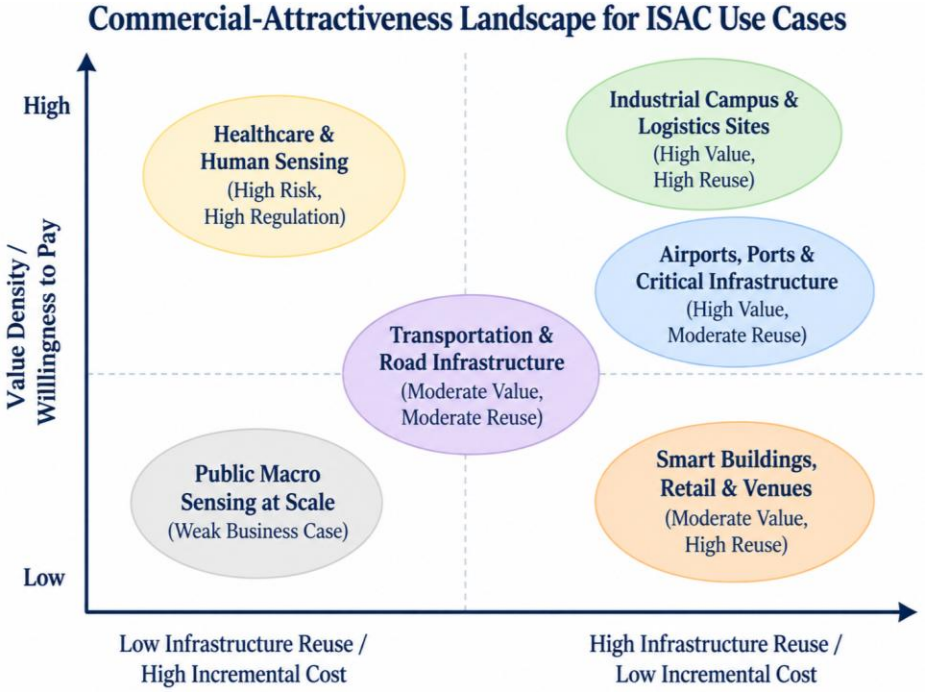


Fig. 14.2. Commercial attractiveness of representative ISAC applications as a function of infrastructure reuse, incremental deployment cost, and value density.

Controlled enterprise environments such as industrial campuses, warehouses, logistics centers, mines, factories, airports, and critical infrastructure are among the potential early ISAC deployment scenarios. A shared private-network infrastructure can simultaneously support connectivity, localization, asset tracking, safety monitoring, machine observation, automation, perimeter surveillance, drone detection, and situational awareness, thereby strengthening the overall business case [40].

Transportation infrastructure also offers significant potential for traffic monitoring, cooperative localization, vulnerable-road-user detection, abnormal-event detection, and digital-twin updates, although commercialization depends strongly on identifying a clear paying stakeholder. Smart buildings, retail environments, and venues offer opportunities for infrastructure reuse but face competition from cameras, Wi-Fi sensing, Bluetooth, UWB, and dedicated radar. Human and physiological sensing may support high-value healthcare and assisted-living applications, but stricter requirements for regulation, validation, consent, privacy, liability, and accuracy may delay large-scale adoption.

14.5 Route to Market

ISAC commercialization will likely adopt multiple business models, depending on how sensing is delivered and monetized. Potential approaches include bundling sensing with connectivity, offering managed sensing services, exposing sensing capabilities through network APIs, and integrating ISAC into vertical-specific solutions. In enterprise and private-network environments, sensing may be included within broader connectivity contracts, while managed services can be priced by coverage, assets, duration, or service-level requirements.

Network APIs provide another pathway by exposing processed sensing information, such as presence, position, trajectory, occupancy, or event notifications, rather than raw measurements, thereby reducing transport overhead and simplifying privacy and access control. Outcome-based models may offer greater commercial value by linking ISAC to operational benefits such as improved safety, asset visibility, reduced downtime, intrusion detection, and traffic optimization. Operators must therefore balance their role between capability

provider, managed-service provider, and full vertical-solution integrator, with success depending on ecosystem partnerships, domain expertise, service assurance, and demonstrated business value [5], [8], [10], [47].

14.5.1 Connected Intelligence: Convergence of ISAC, AI and Precise Positioning

The broader potential of ISAC emerges through its integration with AI, precise positioning, edge computing, and distributed intelligence. In this framework, wireless networks evolve from connectivity platforms into intelligent infrastructures that can perceive, localize, interpret, and respond to the physical environment. ISAC provides information about objects, motion, and surrounding conditions; positioning adds spatial context; and AI transforms these observations into predictions and decisions. This creates a continuous perception–intelligence–action loop:

Sense → Localize → Understand → Predict → Decide → Communicate/Act → Sense

Network-wide and cooperative sensing can further combine observations from infrastructure nodes, user devices, and other sensing platforms to form a shared environmental representation. AI can fuse sensing, positioning, mobility, and contextual information and communicate task-relevant intelligence—such as object location, class, velocity, trajectory, and confidence—rather than transferring all raw sensing data. Edge computing supports this process by enabling low-latency inference and real-time decision-making close to the point of sensing and action.

This convergence significantly expands the scope of 6G applications, including cooperative transportation, UAV and airspace management, industrial automation, digital twins, healthcare, smart environments, precision agriculture, public safety, environmental monitoring, and immersive XR. It also provides a foundation for physical AI, where autonomous vehicles, robots, drones, and other intelligent systems continuously interact with their surroundings. In this architecture, ISAC provides distributed perception, positioning establishes spatial relationships, AI enables interpretation and prediction, and communication coordinates distributed intelligence across the network.

14.6 Commercial Outlook

ISAC is a potential commercial opportunity, but the value is more subtle than simply adding a new sensing revenue stream to the mobile-network business. Radio sites, spectrum, antenna arrays, transport networks, edge platforms and operational systems are expensive assets. Sensing enables those assets to support additional enterprise services, reduce dependence on separate sensing infrastructure, or improve the operator's own network operations, thereby increasing their economic productivity. The most fragile cases are those in which sensing involves significant new infrastructure but addresses some diffuse application for which no clear payer can be identified. While technically impressive, such deployments may face difficulty competing for operator capital. The key commercial questions are therefore simple: what existing infrastructure can be reused, what incremental expenditure is required, who gets the value in the customer base, what alternative cost can be avoided, can the service be repeated without significant customization, and is the lifecycle return good enough compared to other network investments. ISAC should be understood as an emerging network capability and value platform, not a guaranteed standalone revenue category. Its move from research to sustainable deployment will depend on operators and their partners' ability to convert sensing capability into repeatable, economically meaningful outcomes [47].

Section 15: Open Research Challenges

Status: *Research. The topics in this section are not part of any agreed 3GPP specification, except where Section 15.2 refers to the Release 19 service requirements in TS 22.137.*

This section outlines key ISAC challenges and summarizes emerging ISAC technologies.

15.1 Fundamental Research Challenges

Despite substantial advances in waveform design, several challenges remain before ISAC can be practically deployed at scale in 6G networks. The major open research directions are summarized below.

- **Joint Communication–Sensing Design:** Communication and sensing share spectrum, power, bandwidth, time, and spatial resources while targeting different performance objectives. Future research should establish unified KPIs and develop adaptive mechanisms that balance communication throughput, reliability, and latency with sensing accuracy, resolution, detection, and localization performance.
- **Frame Structure and Waveform Design:** Flexible ISAC frame structures are required to efficiently allocate communication symbols, sensing symbols, and reference signals while maintaining compatibility with existing NR frameworks. Moreover, existing waveforms, including OFDM, OTFS, OTSM, AFDM, PMCW, and FMCW, provide different trade-offs. Future research should focus on adaptive, low-PAPR, multi-band, and AI-assisted waveform designs with robust synchronization and channel estimation.
- **Full-Duplex, Antenna, and Hardware Design:** Full-duplex ISAC requires effective self-interference cancellation to detect weak sensing echoes in the presence of strong transmit leakage. Phase noise, nonlinearities, antenna coupling, limited ADC resolution, and oscillator instability further degrade system performance. High-isolation antennas, compact massive-MIMO architectures, hybrid beamforming, efficient RF front ends, and robust mmWave/THz hardware therefore remain important research directions.
- **Network-Level Coordination and Resource Allocation:** Future ISAC networks may distribute communication and sensing functions across radio nodes, O-RAN, edge/MEC platforms, core networks, and cloud infrastructure. Efficient orchestration, synchronization, cooperative sensing, interference management, and network slicing are consequently required. Dynamic allocation of spectrum, power, time, beams, and computing resources must jointly satisfy communication and sensing requirements under changing network conditions.

Beamforming, RIS, and Joint Optimization: Communication beams must simultaneously provide reliable connectivity and accurate environmental sensing. RIS introduces additional opportunities for coverage enhancement, blockage mitigation, and sensing-assisted beam steering, but creates challenges in channel estimation, real-time configuration, and joint active-passive optimization. Multi-objective and cross-layer optimization will therefore be essential for jointly controlling beamforming, power, scheduling, spectrum, RIS configuration, and computing resources.

- **AI-Native and Semantic ISAC:** AI-native ISAC can support beam management, resource allocation, channel estimation, target recognition, mobility prediction, and network automation. However, real-time operation requires lightweight, reliable, explainable, robust, and energy-efficient AI under strict latency and computational constraints. Semantic ISAC is another promising direction, where task-relevant information such as object identity, behavior, and environmental context can be transmitted instead of raw sensing data, potentially reducing communication overhead and latency.
- **Emerging ISAC Architectures and Technologies:** Cell-free ISAC can exploit distributed access points for cooperative communication and sensing, although scalable synchronization, distributed beamforming,

fronthaul optimization, and sensing-data fusion remain challenging. RIS-assisted ISAC, satellite/NTN ISAC, and UAV-enabled ISAC can further extend sensing coverage and connectivity. Their practical realization requires efficient coordination, and integration with terrestrial 6G infrastructure.

- **Security, Standardization, and Benchmarking:** ISAC introduces additional security and privacy concerns because sensing data may reveal information about users, objects, locations, and environments. Sensing-aware authentication, privacy-preserving processing, secure protocols, and trustworthy AI are therefore necessary. Large-scale deployment also requires standardized KPIs, interfaces, reference signals, data formats, channel models, benchmark datasets, and common evaluation methodologies to ensure interoperability and reproducibility.

15.2. Emerging ISAC Technologies

- **Cell-free ISAC:** Cell-free massive MIMO architectures have the potential to significantly improve both communication coverage and sensing performance by breaking the fixed boundaries of conventional cellular networks. A cell-free ISAC system comprises many distributed APs that serve users and sense the environment concurrently. This cooperative operation can improve localization accuracy, reduce interference, improve coverage, and increase overall network reliability [57]. However, these benefits come with practical challenges. Future work needs to address issues such as scalable synchronization among distributed APs, efficient distributed beamforming, fronthaul optimization, cooperative sensing protocols, and reliable fusion of sensing information collected from multiple network nodes. Thus, developing low-complexity, scalable cell-free ISAC architectures will be an important step toward realizing large-scale 6G wireless networks.
- **RIS-assisted ISAC:** RIS provides a promising approach to actively manipulate the wireless propagation environment for improved communication and sensing performance. RIS can improve localization accuracy, extend coverage, overcome blockage, and enable adaptive beam steering by intelligently controlling electromagnetic-wave reflection without active RF transmission. However, several challenges remain for the wide application of RIS in practical ISAC systems. These include accurate channel estimation, real-time RIS element configuration, hardware imperfections, passive beam control, energy efficiency, and scalable optimization algorithms. Future work will focus on AI-based RIS control and cooperative deployment of RISs and integrated active-passive sensing frameworks to fully exploit the potential of RIS in 6G ISAC networks.
- **Optical ISAC:** Optical wireless technologies, such as VLC, LiFi, and FSO communication, offer extremely high bandwidth and are naturally immune to electromagnetic interference. These features make them attractive for future ISAC systems, especially in environments that require high-speed communication and precise sensing. By combining optical communication with sensing, these technologies can support applications such as high-accuracy indoor positioning, gesture recognition, industrial automation, and autonomous robotics. However, practical deployment remains limited by challenges including line-of-sight requirements, signal blockage, ambient light interference, weather effects in outdoor environments, synchronization, and user mobility. To overcome these limitations, future research is expected to focus on hybrid radio-optical ISAC systems, where optical and RF technologies complement each other. Such hybrid architectures can combine the high data rates of optical communication with the broad coverage and robustness of radio systems, making them a promising solution for next-generation heterogeneous wireless networks.
- **Satellite and NTN ISAC:** ISAC integration into satellite communications and NTNs offers opportunities for communications and sensing beyond the coverage of terrestrial networks. Future satellite-enabled ISAC systems can support a wide range of applications, including global environmental monitoring, maritime surveillance, disaster management, precision agriculture, and remote sensing. They can also provide reliable connectivity to remote and underserved regions.

Despite these benefits, some technical challenges remain. These include long signal propagation delays, Doppler compensation, satellite mobility, efficient resource allocation, inter-satellite coordination, and smooth integration with terrestrial 6G networks. Addressing these problems will require new communication protocols, intelligent network management, and sophisticated signal-processing techniques [44]. NTN-enabled ISAC is an important research direction for future 6G and beyond wireless networks, where efficient space-air-ground integrated network architectures need to be designed to provide seamless global communication and sensing services.

- **UAV-enabled ISAC:** UAVs are a versatile platform for joint communication and sensing, and are appropriate for applications such as rapid deployment and wide-area coverage. UAV-enabled ISAC can support emergency communications, disaster recovery, smart agriculture, traffic monitoring, surveillance, and temporary wireless networks in locations with unavailable or damaged conventional infrastructure. Despite these advantages, several challenges must be addressed before wide deployment of UAV-based ISAC. UAV mobility creates rapidly changing wireless channels and network topologies, while onboard energy limitations, payload constraints, trajectory planning, and other factors further complicate the design. Reliable communication and accurate sensing under such dynamic conditions remain active research topics. Future work will most likely focus on cooperative UAV swarms, AI-assisted flight control, energy-efficient trajectory optimization, distributed sensing, and autonomous coordination among aerial network nodes. These advances will help unlock the full capabilities of UAV-enabled ISAC in future 6G wireless networks.
- **CPE-based ISAC:** Customer Premises Equipment (CPE) devices are typically fixed, mains-powered, and capable of supporting larger antenna arrays than handheld terminals. These characteristics enable enhanced sensing capabilities that are difficult to achieve with battery-constrained smartphones or sparsely deployed base stations. Consequently, CPE-based sensing has emerged as a promising ISAC deployment approach. Reflecting this potential, several use cases in 3GPP Release-19 Study Report TR 22.837 [33], which establishes the foundational ISAC use cases and service requirements for 5G systems, are explicitly centered on CPE deployments. Some such test cases are listed below:
  - Use case of intruder detection in a smart home
  - Use case of intruder detection in the surroundings of a smart home
  - Use case on contactless sleep monitoring service
  - In a similar manner, TS 22.137 [54], the normative outcome of the Release-19 ISAC study, listed several service scenarios that are particularly suited to CPE-based sensing, such as presence detection, intrusion detection and activity monitoring in homes and enterprise premises.
  - Recent market projections indicate that India is expected to emerge as the world's largest 5G Fixed Wireless Access (FWA) market by 2030, accounting for approximately 37 million subscriptions and nearly 40% of the global FWA subscriber base [58]. Therefore, this research area is important from an Indian perspective.
- **Quantum-inspired Sensing:** Emerging quantum technologies can lead to significant improvements to sensing capabilities that may benefit future wireless networks. Quantum-enabled sensing can leverage quantum coherence, entanglement, and advanced quantum signal processing to achieve accuracy in detecting, localizing, timing, and monitoring targets and environmental conditions that is currently unreachable [59]. Practical quantum wireless systems are still in their infancy but are a promising long-term research direction for ISAC. Current research focuses on quantum radar, quantum-enhanced localization, quantum machine learning, secure quantum sensing, and hybrid classical–quantum optimization algorithms. As these technologies mature, they could pave new avenues for highly accurate, secure, and intelligent communication and sensing systems beyond 6G.

15.3. System-Level Challenges and Future Outlook

- **Green ISAC:** Energy efficiency and environmental sustainability are becoming important design objectives for future wireless networks. Because ISAC performs communication and sensing simultaneously, it may face higher computational complexity and power consumption without efficient resource management. Thus, developing energy-efficient ISAC systems that enable large-scale 6G deployments with a low environmental footprint will be vital.
  Future work should include energy-aware waveform design, intelligent sleep scheduling, renewable energy integration, carbon-aware network optimization, low-power hardware architectures, and lifecycle sustainability assessment. It will also be important to develop standardized energy-efficiency metrics and carbon footprint assessment frameworks to measure and guide the sustainable deployment of ISAC infrastructure. Green ISAC will foster the development of wireless networks that are smart, trustworthy, and environmentally friendly, blending high performance with energy-efficient operation.
- **Benchmark Datasets:** The rapid development of AI-based ISAC has revealed a need for standardized benchmark datasets to facilitate development, evaluation, and comparison of novel algorithms. Most existing communication datasets lack synchronized sensing information, while radar datasets generally lack communication data for integrated sensing and communication research. This makes it difficult to compare different ISAC techniques fairly and to reproduce published results. Future research should aim at creating publicly available multimodal datasets that integrate communication signals, sensing measurements, mobility information, channel characteristics, and environmental context. Equally important is developing standardized evaluation methodologies and open-source simulation platforms to support consistent performance assessment and accelerate innovation across the ISAC research community. Such resources will be critical to improving reproducibility, fostering collaboration, and enabling the development of robust and reliable ISAC technologies for future 6G networks [33].
- **Real-Time AI for ISAC:** For future ISAC systems, in highly dynamic wireless environments, real-time AI will be essential. Applications such as autonomous vehicles, industrial automation, XR, and intelligent transportation systems require communication and sensing decisions in milliseconds, leaving little tolerance for processing delays. To meet these requirements, future artificial intelligence algorithms should predict channels, track beams, identify targets, distribute resources, mitigate interference, and optimize networks in real time, even under strict latency, computation, and energy constraints. To achieve this performance level, we need progress in lightweight edge AI, distributed inference, online learning, hardware acceleration, and XAI techniques that enable fast, reliable real-time decisions. Therefore, a key research direction for enabling practical, large-scale ISAC deployment in future 6G wireless networks is developing efficient, trustworthy real-time AI frameworks [4], [40].

Section 16: ISAC in India: Development, Standardization, and Future Opportunities

India is developing a rapidly expanding ISAC research ecosystem as part of its broader transition toward 6G. The Department of Telecommunications (DoT) supports much of this activity through the Telecom Technology Development Fund (TTDF), which funds projects spanning both foundational ISAC research and application-oriented demonstrations. The current portfolio reflects a coordinated effort to build indigenous capabilities across the ISAC technology stack, including physical-layer and air-interface design, waveform engineering, channel modeling, reconfigurable intelligent surfaces (RIS), full-duplex antenna systems, AI-assisted resource management, security, testbed development, and sensing applications. The following subsection summarizes the major DoT-supported projects and their respective research areas.

S. No	Proposal ID	Broad areas under ISAC
1	TTDF/6G/66	RIS-assisted ISAC system, RIS design and development
2	TTDF/6G/86	RIS architecture design for THz using ML algorithms, SDR-based Demonstration
3	TTDF/6G/202	RIS-assisted ISAC testbed for deployment across 3GPP TR 22.837 use cases, with advanced methods to utilize sensing signals for accurate communication channel estimation
4	TTDF/6G/203	RIS-assisted ISAC framework combining intelligent pilot design and deep learning-based joint channel estimation
5	TTDF/6G/309	Enable joint sensing and communication at the 6G edge networks and with a Deep Reinforcement Learning model to adapt sensing and communication dynamically.
6	TTDF/6G/349	Using the ISAC signal for Landslide Detection and Prevention (LandSense)
7	TTDF/6G/358	Waveform Design for Joint Radar and Communication
8	TTDF/6G/402	Physical layer design, air-interface design, channel modeling, testbed development
9	TTDF/6G/507	Development of active massive MIMO (mMIMO) based base station by utilizing state-of-the-art full-duplex multi-polarization antennas

India offers a strong environment for adopting ISAC because of its large-scale telecom infrastructure, diverse geography, rapidly expanding digital economy, and growing needs for intelligent transportation, industrial automation, agriculture, public safety, healthcare, and environmental monitoring. India already has an extensive foundation on which ISAC can evolve: as of June 2026, 5G was available in 99.9% of districts, with approximately 5.63 lakh 5G base stations deployed nationwide. Industry investment is also substantial; GSMA reported that Indian operators had invested more than ₹4 lakh crore in 5G rollout by May 2026. This extensive infrastructure creates an opportunity for ISAC to reuse existing spectrum, base stations, massive-MIMO antennas, edge platforms, and network sites for both connectivity and sensing, potentially reducing the need for separate sensing infrastructure.

- **Why ISAC Is Well Suited to India:** India combines very high population density in major cities with geographically dispersed rural, mountainous, coastal, and remote regions. Consequently, future networks must provide connectivity while also supporting localization, environmental awareness, infrastructure monitoring, and automated decision-making. ISAC is particularly attractive because the same wireless infrastructure can potentially perform multiple functions—communication, sensing, positioning, tracking, and environmental monitoring. This infrastructure-sharing model is relevant to India, where scalable and cost-efficient deployment will be important as networks evolve from 5G toward 6G. The DoT's spectrum roadmap similarly emphasizes efficient spectrum use, indigenous R&D, transformation of key vertical sectors, and preparation for future 6G networks.
- **Requirements for India:** Several Indian sectors have sensing requirements that could benefit from network-integrated solutions. Transportation systems require improved traffic perception, vehicle and vulnerable-road-user detection, localization, and cooperative mobility. Manufacturing and logistics require asset tracking, machine monitoring, worker safety, predictive maintenance, and automation. Agriculture can benefit from environmental and crop monitoring, while healthcare may use contactless monitoring and localization. Disaster-prone regions create additional requirements for environmental and structural sensing.
- **High-Impact Application Areas:** The most relevant Indian applications include smart manufacturing and Industry 4.0, intelligent transportation and railways, connected and autonomous mobility, UAV monitoring and low-altitude airspace management, smart ports and logistics, precision agriculture, environmental and disaster monitoring, critical-infrastructure protection, smart buildings, healthcare, public safety, and digital twins. The Government of India is already promoting advanced 5G applications in telemedicine, precision agriculture, smart manufacturing, and education, providing a natural pathway for more advanced sensing-enabled services as 6G develops.
- **Expected Transformation with ISAC:** ISAC could gradually change the role of Indian wireless networks from systems that primarily connect devices to infrastructures that can also perceive, localize, understand, and respond to their surroundings. Base stations could contribute to traffic and infrastructure awareness; private networks could connect and monitor factories simultaneously; communication infrastructure could provide positioning and sensing information to UAVs, vehicles, and robots; and edge AI could convert distributed sensing observations into real-time decisions. This represents a transition from connected devices to connected intelligence, where communication, sensing, positioning, AI, and edge computing operate as an integrated system.

India's opportunity is therefore twofold. Domestically, ISAC could improve the efficiency, safety, automation, and resilience of sectors such as transportation, manufacturing, agriculture, healthcare, and critical infrastructure. Strategically, India's ongoing DoT/TTDF research in RIS, waveforms, air interfaces, AI, security, testbeds, and sensing applications provides an opportunity to develop indigenous intellectual property, products, and standards contributions rather than relying solely on imported 6G technologies. In this sense, ISAC can be not only an enabling technology for India's future 6G infrastructure, but also an industrial and innovation opportunity spanning telecom operators, equipment manufacturers, semiconductor companies, system integrators, startups, research institutions, and vertical industries.

16.1 Priority Areas for India

This section and Section 13 list many possible applications. With limited funding and research capacity, India should concentrate on a small number of areas where it already has a lead, where its needs are not well covered by work elsewhere, or where Indian results can feed directly into standards. Four areas meet these tests.

RIS-assisted ISAC. Four of the nine DoT/TTDF ISAC projects listed above (TTDF/6G/66, 86, 202 and 203) work on RIS, covering RIS design, RIS for THz, testbeds and pilot design. This is the largest concentration of

Indian ISAC work and the most likely source of indigenous IP. The projects would gain from a common test plan and joint reporting of results.

Disaster and environmental sensing. Landslides, floods and cyclones affect large parts of the country, and 5G already reaches 99.9% of districts. Using this network to detect ground movement, water levels or obstructions meets a need that is specific to India and that few other regions are working on. The LandSense project (TTDF/6G/349) is a starting point; pilots in a few hilly and coastal districts would show what accuracy can be achieved in practice.

Rail, highway and UAV corridors. Railways, national highways and the growing use of drones need detection of objects, vehicles and UAVs along long routes. UAVs, vehicles, humans and road or rail hazards are already the baseline sensing targets in the 3GPP Release 19 and Release 20 studies, so Indian trials in these settings can feed results straight into 3GPP evaluation.

India-specific channel measurements and evaluation. Standards outcomes depend on the channel models and evaluation assumptions used to compare proposals. TSDSI has already studied ISAC channel models (Section 9.1.3.2). Measurement campaigns in dense Indian cities, rural areas and along rail and road corridors would give Indian companies and institutes a stronger basis for contributions to 3GPP and ITU-R, at modest cost.

Other areas, such as THz sensing, maritime and underwater ISAC, and XR, are worth following, but India does not have a clear advantage in them today. In the near term they are better treated as research topics than as targets for large programmes.

Section 17: Future Vision Towards 2035

ISAC is expected to play a central role in wireless evolution beyond 6G by tightly integrating communication, sensing, AI, and computing. Toward 2035, wireless networks may evolve from connectivity-oriented infrastructures into intelligent, autonomous, and context-aware systems capable of perceiving their surroundings, interpreting environmental conditions, and adapting network operations with limited human intervention.

- **Network as a Sensor:** Future wireless infrastructure may evolve toward a Network-as-a-Sensor paradigm, in which base stations, access points, UAVs, satellites, and intelligent reflecting surfaces jointly perform distributed communication and sensing. Cooperative measurements from geographically distributed nodes can improve localization, target detection, activity recognition, and environmental mapping. However, realizing NaaS requires scalable cooperative sensing, distributed data fusion, accurate synchronization, network-wide coordination, and privacy-preserving sensing mechanisms.
- **AI-Native and Autonomous Networks:** AI is expected to become a native component of future ISAC networks rather than an external optimization tool. Foundation models, large language models, graph neural networks, and federated learning may support waveform adaptation, resource allocation, channel estimation, target recognition, interference management, mobility prediction, and context-aware network control. Combined with edge computing and sensing intelligence, these capabilities can enable self-configuring, self-optimizing, self-healing, and self-protecting networks. Key challenges include trustworthy, explainable AI; lightweight edge intelligence; distributed decision-making; multi-agent learning; privacy preservation; energy efficiency; and interoperable AI-native architectures.
- **Digital Twins and Human-Centric Sensing:** Network-wide sensing combined with AI and edge/cloud computing can enable real-time digital twins of physical environments, including cities, transportation systems, factories, healthcare facilities, and ecosystems. Such digital replicas can support predictive maintenance, traffic management, industrial automation, infrastructure monitoring, and disaster response. At the same time, human-centric ISAC can enable contactless monitoring of respiration, heartbeat, posture, gestures, occupancy, falls, and human activities through wireless signals [60]. These capabilities can support healthcare, elderly care, rehabilitation, smart homes, XR, and workplace safety. Major challenges include real-time synchronization, secure data handling, and trustworthy sensing.
- **Sustainable and Human-Centric ISAC:** Sustainability is expected to become a fundamental design objective for beyond-6G ISAC. Joint communication and sensing must therefore be optimized not only for performance but also for energy consumption, computational complexity, and infrastructure cost. Adaptive waveforms, intelligent resource allocation, sensing scheduling, low-power hardware, renewable-energy-powered infrastructure, and intelligent sleep modes can reduce energy requirements. Future systems should additionally incorporate carbon-aware operation, equipment lifecycle assessment, recycling, and standardized sustainability metrics to evaluate the trade-offs among communication performance, sensing capability, and environmental impact.
- **Evolution Toward Beyond-6G Networks:** The evolution of ISAC is expected to progress gradually from enabling technologies toward autonomous sensing ecosystems. During 2025–2028, research is expected to focus primarily on waveforms, channel models, RF hardware, AI-assisted sensing, and standardization. During 2028–2031, greater emphasis may shift toward AI-native ISAC, distributed sensing, semantic communication, edge intelligence, and digital twins. By 2031–2035, these developments may enable cognitive and autonomous networks integrating terrestrial, aerial, maritime, and space-based communication and sensing infrastructures.

Acknowledgement:

The authors gratefully acknowledge the Bharat 6G Alliance (B6GA) for providing the opportunity and platform to contribute to this white paper on ISAC. We sincerely appreciate the Alliance's encouragement, guidance, and support in facilitating this effort. This white paper, entitled "Integrated Sensing and Communication (ISAC) for 6G: Technologies, Architectures, Applications, and Future Directions," aims to present a comprehensive perspective on the evolving ISAC ecosystem and its significance for future 6G networks. The authors also acknowledge the valuable contributions of the broader research, 5G labs, industry, and standardization communities whose ongoing work has helped shape the technical foundations and future outlook presented in this document.

Chair and Editor: Dr. Sonali Garg (Vice-Chair, Technology Group, B6GA), HFCL Limited, New Delhi

Lead Author: Dr. Atul Kumar (Member in Technology Working Group, B6GA), Department of Electronics Engineering, IIT (BHU), Varanasi

Contributing Members:

- Dr. Muralikrishnan Srinivasan, Department of Electronics Engineering IIT(BHU), Varanasi
- Dr. Prem Singh, International Institute of Information Technology Bangalore, Bengaluru
- Dr. Ekant Sharma, Department of Electronics and Communication, IIT Roorkee, India
- Dr. Subrata Maiti, Electronics and Communication Engineering, NIT Rourkela, India
- Dr. Shrishail M. Hiremath, Electronics and Communication Engineering, NIT Rourkela, India
- Dr. Gunasekaran Raja, Department of Computer Technology, Anna University, MIT Campus, Chennai
- Dr. Astha Sharma, Assistant Director (Technology), Bharat 6G Alliance
- Dr.G.Ananthi, Thiagarajar College of Engineering, Madurai
- Dr. Himanshu Mishra, Department of Electronics Engineering, IIT Dhanbad
- Dr. Prabhat Kumar Sharma, Visvesvaraya National Institute of Technology, Nagpur
- Dr. Alok Kumar Sinha, HFCL
- Dr. Sandeep Sharma, Tech Mahindra

Moreover, the authors would like to express their sincere appreciation to the Postdoctoral researchers (Dr. Priya Pandey, Dr. Rakesh Ranjan, Dr. Sudhakar Rai and Dr. Shivani Singh), Ph.D. scholars (Ms. Amratya Khattri, Malay Chakraborty, C. Sai Meghana), M.Tech scholars (Anurag Sharma, J. Satya Lakshmi, M. Kesav, and J. Kranthi Kiran Kumar) who contributed to the preparation of this white paper. Their valuable assistance in technical writing, literature review, content development, and figure preparation significantly supported the quality and completeness of this work. The authors gratefully acknowledge their dedicated efforts and scholarly contributions throughout the development of the white paper.

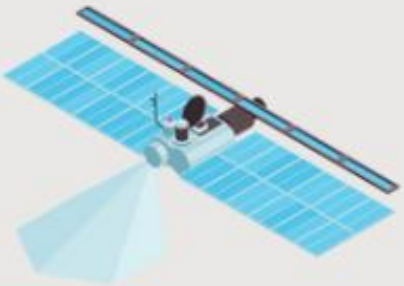
References:

[1] F. Liu et al., "Seventy Years of Radar and Communications: The road from separation to integration," in IEEE Signal Processing Magazine, vol. 40, no. 5, pp. 106-121, July 2023, doi: 10.1109/MSP.2023.3272881.
[2] F. Liu, C. Masouros, A. P. Petropulu, H. Griffiths and L. Hanzo, "Joint Radar and Communication Design: Applications, State-of-the-Art, and the Road Ahead," in IEEE Transactions on Communications, vol. 68, no. 6, pp. 3834-3862, June 2020, doi: 10.1109/TCOMM.2020.2973976.
[3] J. A. Zhang et al., "An Overview of Signal Processing Techniques for Joint Communication and Radar Sensing," in IEEE Journal of Selected Topics in Signal Processing, vol. 15, no. 6, pp. 1295-1315, Nov. 2021, doi: 10.1109/JSTSP.2021.3113120.
[4] F. Liu et al., "Integrated Sensing and Communications: Toward Dual-Functional Wireless Networks for 6G and Beyond," in IEEE Journal on Selected Areas in Communications, vol. 40, no. 6, pp. 1728-1767, June 2022, doi: 10.1109/JSAC.2022.3156632.
[5] A. Zhang, M. L. Rahman, X. Huang, Y. J. Guo, S. Chen and R. W. Heath, "Perceptive Mobile Networks: Cellular Networks With Radio Vision via Joint Communication and Radar Sensing," in IEEE Vehicular Technology Magazine, vol. 16, no. 2, pp. 20-30, June 2021, doi: 10.1109/MVT.2020.3037430.
[6] S. P. Chepuri, N. Shlezinger, F. Liu, G. C. Alexandropoulos, S. Buzzi and Y. C. Eldar, "Integrated Sensing and Communications With Reconfigurable Intelligent Surfaces: From signal modeling to processing," in IEEE Signal Processing Magazine, vol. 40, no. 6, pp. 41-62, Sept. 2023, doi: 10.1109/MSP.2023.3279986.
[7] E. Hossain and A. Vera-Rivera, "6G Cellular Networks: Mapping the Landscape for the IMT-2030 Framework," in IEEE Transactions on Technology and Society, vol. 6, no. 4, pp. 377-392, Dec. 2025, doi: 10.1109/TTS.2025.3611364.
[8] A. Kaushik et al., "Integrated Sensing and Communications for IoT: Synergies with Key 6G Technology Enablers," in IEEE Internet of Things Magazine, vol. 7, no. 5, pp. 136-143, September 2024, doi: 10.1109/IOTM.001.2400052.
[9] Hassanien, Aboulnasr, et al. "Dual-function radar-communications: Information embedding using sidelobe control and waveform diversity." IEEE Transactions on Signal Processing 64.8 (2016): 2168-2181.
[10] Rahman, Md Lushanur, et al. "Framework for a perceptive mobile network using joint communication and radar sensing." IEEE Transactions on Aerospace and Electronic Systems 56.3 (2020): 1926-1941.
[11] A. Kaushik et al., "Toward Integrated Sensing and Communications for 6G: Key Enabling Technologies, Standardization, and Challenges," in IEEE Communications Standards Magazine, vol. 8, no. 2, pp. 52-59, June 2024, doi: 10.1109/MCOMSTD.0007.2300043.
[12] Zheng, Jian, et al. "Inner-frame time division multiplexing waveform design of integrated sensing and communication in 5G NR system." Sensors 23.15 (2023): 6855.
[13] Niu, Yangyang, et al. "Interference management for integrated sensing and communication systems: A survey." IEEE Internet of Things Journal 12.7 (2025): 8110-8134.
[14] Shi, Shengnan, et al. "Distributed 5G NR-based integrated sensing and communication systems: Frame structure and performance analysis." 2022 30th European Signal Processing Conference (EUSIPCO). IEEE, 2022.
[15] Wei, Zhiqing, et al. "Integrated sensing and communication signals toward 5G-A and 6G: A survey." IEEE Internet of Things Journal 10.13 (2023): 11068-11092.
[16] Han, Kawon, Kaitao Meng, and Christos Masouros. "MIMO-OFDM signaling design for noncoherent distributed ISAC systems." IEEE Transactions on Wireless Communications 25 (2026): 7792-7808.
[17] D. Singh et al., "Generalized Adaptive Spreading Modulation: A Novel Waveform for Integrated Sensing and Communication Oriented Vehicular Applications," in IEEE Internet of Things Journal, vol. 11, no. 18, pp. 29486-29493, 15 Sept. 2024, doi: 10.1109/JIOT.2024.3431200.
[18] Islam, Md Atiqul, George C. Alexandropoulos, and Besma Smida. "Integrated sensing and communication with millimeter wave full duplex hybrid beamforming." ICC 2022-IEEE International Conference on Communications. IEEE, 2022.
[19] Liu, Ziang, et al. "Joint transmit and receive beamforming design in full-duplex integrated sensing and communications." IEEE Journal on Selected Areas in Communications 41.9 (2023): 2907-2919.
[20] Zhang, Jun, Xianghao Yu, and Khaled B. Letaief. "Hybrid beamforming for 5G and beyond millimeter-wave systems: A holistic view." IEEE Open Journal of the Communications Society 1 (2020): 77-91.
[21] Guo, Yuan, et al. "Joint beamforming for RIS aided full-duplex integrated sensing and uplink communication." ICC 2023-IEEE International Conference on Communications. IEEE, 2023.
[22] Wu, Kai, et al. "Sensing in bistatic ISAC systems with clock asynchronism: A signal processing perspective." IEEE Signal Processing Magazine 41.5 (2024): 31-43.
[23] Sen, Padmanava, et al. "RF front-ends for ISAC—design challenges and potential solutions." Integrated Sensing and Communications. Singapore: Springer Nature Singapore, 2023. 507-535.

[24] Babu, Nithin, et al. "Precoding for multi-cell ISAC: From coordinated beamforming to coordinated multipoint and bi-static sensing." IEEE Transactions on Wireless Communications 23.10 (2024): 14637-14651.
[25] Demirhan, Umut, and Ahmed Alkhateeb. "Integrated sensing and communication for 6G: Ten key machine learning roles." IEEE Communications Magazine 61.5 (2023): 113-119.
[26] Guo, Xianzhen, et al. "User equipment assisted localization for 6G integrated sensing and communication." IEEE Transactions on Communications 73.11 (2025): 12593-12607.
[27] Thomä, Reiner, et al. "Distributed multisensor ISAC." npj Wireless Technology 2.1 (2026): 22.
[28] Hamidi-Sepehr, Fatemeh, et al. "RAN architecture and implementation requirements for ISAC." Integrated Sensing and Communications for Future Wireless Networks. Academic Press, 2025. 325-346.
[29] Hossain, Mohammad Arif, et al. "AI-assisted E2E network slicing for integrated sensing and communication in 6G networks." IEEE Internet of Things Journal 11.6 (2024): 10627-10634.
[30] Guan, Yingying, et al. "Slicing-aware aerial networks for integrated sensing and communication: 3D placement and adaptive allocation of resources." IEEE Vehicular Technology Magazine 19.2 (2024): 79-88.
[31] Al-Qaness, Mohammed AA, et al. "Channel state information from pure communication to sense and track human motion: A survey." Sensors 19.15 (2019): 3329.
[32] Khan, Wali Ullah, et al. "Advancing integrated sensing and communications with RL/DRL in 6G networks: a survey." Artificial Intelligence Review (2026).
[33] 3GPP, TR 22.837 V19.2.1, "Feasibility Study on Integrated Sensing and Communication (ISAC)," Feb. 2024. [Online]. Available: https://www.3gpp.org/.
[34] Demirhan, Umut, and Ahmed Alkhateeb. "Radar aided 6G beam prediction: Deep learning algorithms and real-world demonstration." 2022 IEEE Wireless Communications and Networking Conference (WCNC). IEEE, 2022.
[35] ITU-R, Framework and Overall Objectives of the Future Development of IMT for 2030 and Beyond, Recommendation ITU-R M.2160-0, Nov. 2023.
[36] 3GPP, Study on Artificial Intelligence (AI)/Machine Learning (ML) for NR Air Interface, 3GPP TR 38.843, Release 18.
[37] Vassilev, Apostol, et al. "Adversarial machine learning: A taxonomy and terminology of attacks and mitigations." (2024).
[38] M. Al-Quraan, L. Mohjazi, L. Bariah, A. Centeno, A. Zoha, K. Arshad, K. Assaleh, S. Muhaidat, M. Debbah, and M. A. Imran, "Edge-Native Intelligence for 6G Communications Driven by Federated Learning: A Survey of Trends and Challenges," IEEE Transactions on Emerging Topics in Computational Intelligence, vol. 7, no. 3, pp. 957–979, June 2023, doi: 10.1109/TETCI.2023.3251404.
[39] 3GPP TR 38.901, "Study on channel model for frequencies from 0.5 to 100 GHz," Release 19 (incorporating the outcome of the Rel-19 study on channel modelling for ISAC for NR).
[40] 3GPP, 3GPP 6G Standardization Roadmap/Timeline, specifying Release 20 as the 6G study phase and Release 21 as the normative 6G phase.
[41] ETSI, Industry Specification Group on Integrated Sensing and Communications (ISG ISAC), ETSI, including its published reports on ISAC use cases, channel modelling/evaluation, system and RAN architectures, and security/privacy/trustworthiness.
[42] 3GPP TSG RAN Meeting #102, RP-234069, "New SID: Study on channel modelling for Integrated Sensing And Communication (ISAC) for NR," Dec. 2023. [Online]. Available: https://www.3gpp.org/.
[43] Y. Liu, Y. Zhang, et al., "A comprehensive survey of 3GPP Release 19 ISAC channel modeling: From empirical features to unified methodology and standardized simulator," arXiv preprint arXiv:2512.03506, 2025.
[44] TSDSI TR 6069 V1.0.0, "Joint Communication & Sensing in 5G Networks & Beyond," September 2026.
[45] TSDSI SI 128 V1.0.0, "Study of the Channel Model for Integrated Sensing and Communication Networks."
[46] Wani, Mohamad, et al. "Open RAN: A concise overview." IEEE Open Journal of the Communications Society 6 (2025): 13-28.
[47] "IEEE Standard for Information Technology -- Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks -- Specific Requirements - Part 11: Wireless MAC and PHY Specifications - Amendment 4: Enhancements for Wireless LAN Sensing," in IEEE Std 802.11bf-2025, pp. 1-228, 26 Sept. 2025, doi: 10.1109/IEEESTD.2025.11184214.
[48] IEEE 802.11 Working Group, IEEE 802.11bf Task Group—WLAN Sensing, documentation and project material. https://www.ieee802.org/11/Reports/tgbf_update.htm
[49] Pennanen, Harri, et al. "6G: The intelligent network of everything." IEEE Access 13 (2025): 1319-1421.
[50] Wei, Zhongxiang, et al. "Toward multi-functional 6G wireless networks: Integrating sensing, communication, and security." IEEE Communications Magazine 60.4 (2022): 65-71.
[51] Elnashar, Ayman, Marwan Bin Shakar, and Sami Muhaidat. "Integrated Sensing and Communication in 6G: A Comprehensive Survey of Use Cases, Enabling Technologies, Standardization Roadmap, and Monetization Frameworks." IEEE Open Journal of the Communications Society (2026), early access.
[52] Xie, Ning, Zhuoyuan Li, and Haijun Tan. "A survey of physical-layer authentication in wireless communications." IEEE Communications Surveys & Tutorials 23.1 (2021): 282-310.

[53] Engelhardt, Maximilian, et al. "Accelerating innovation in 6G research: Real-time capable SDR system architecture for rapid prototyping." IEEE Access 12 (2024): 118718-118732.
[54] 3GPP TS 22.137, "Service requirements for Integrated Sensing and Communication." https://www.3gpp.org/DynaReport/22137.htm
[55] Omdia, 5G FWA Go-to-Market Strategies – 2025, October 2025.
[56] Bhat, Nabeel Nisar, et al. "Integrated Sensing and Communications for Real-time Avatar Control in XR over 5G." 2026 7th International Conference on Communications, Signal Processing, and their Applications (ICCSPA). IEEE, 2026.
[57] Mao, Weihao, et al. "Communication-sensing region for cell-free massive MIMO ISAC systems." IEEE Transactions on Wireless Communications 23.9 (2024): 12396-12411.
[58] Simon, Jean Paul. "The global internet market(s): a reconstruction of the views of the industry." Digital Policy, Regulation and Governance 22.2 (2020): 109-133.
[59] Degen, Christian L., Friedemann Reinhard, and Paola Cappellaro. "Quantum sensing." Reviews of Modern Physics 89.3 (2017): 035002.
[60] Zhang, J. Andrew, et al. "Enabling joint communication and radar sensing in mobile networks—A survey." IEEE Communications Surveys & Tutorials 24.1 (2022): 306-345.

Bharat6G Alliance



Bharat 6G Alliance
2nd Floor, C DoT Campus,
Mandi Road, Mehrauli,
New Delhi- 110030 (INDIA)

info@bharat6galliance.com

www.bharat6galliance.com

