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6G-ENABLED AI-BASED SENSING AND COMMUNICATION CONVERGENCE: A COMPREHENSIVE SURVEY

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Abstract
The sixth generation of wireless networks is seeking to achieve the vision of integrated sensing and communication (ISAC), where wireless systems not only transmit data but also sense the environment. This concept allows for high-resolution mapping of environments, autonomous navigation, and extended reality that is immersive. However, implementing ISAC in 6G networks faces major challenges such as spectrum coexistence, shared hardware, adaptive waveform design, and real-time adaptability in dynamic environments. ISAC-enabled AI and ML applications for intelligent resource allocation, robust channel estimation, adaptive beamforming, and ISAC security fortification make them critical for ISAC. This survey offers a thorough overview on the inclusive backbone technologies like THz communications along with massive multiple input multiple output (MIMO) systems and reconfigurable intelligent surfaces (RIS), as well as the current approaches to ISAC channel modeling such as stochastic, deterministic, and hybrid models. Unique focus is given to AI techniques and deep learning, reinforcement learning, privacy-preserving federated ML and the issues of security and the interventions. This survey looks into practical use cases, existing models, as well as gaps in the research and is intended to be the starting point toward the development of AI-driven ISAC for 6G networks.

I. INTRODUCTION

The goal of the next generation (6G) of wireless networks is to take a leap from what 5G offers. 6G aims to achieve contextual awareness as well as perception of the environment. This development of 6G wireless networks will integrate Integrated Sensing and Communication (ISAC). The previous generations of wireless networks were created for a single purpose communication, but 6G networks will be able to seamlessly combine sensing and communication. Ultra-reliable communication services with high speed are available with ISAC due to the ability to jointly use radio resources, hardware components, and waveforms for both communication and environment perception. ISAC enables high-precision environmental mapping, autonomous vehicle navigation, smart manufacturing, and immersive extended reality (XR). Advanced vehicular networks would be able to use ISAC to enhance object detection and localization. UAV systems would also benefit from ISAC for navigation as well as dynamic data relaying in mobile environments. The Internet of Everything (IoE) and the ever-increasing need for context-aware services are raising the need for both communicative and perceptive wireless systems. This is exactly how ISAC fulfills its purpose by low latency and high reliability in autonomous systems and Industry 5.0 applications. Advanced signal processing enables high-resolution sensing in difficult environments and also low-cost hardware and spectrum due to shared resources. In addition, the powerful combination of communications in the THz band, massive MIMO, and 6G's Reconfigurable Intelligent Surfaces (RIS) will allow for ultra-broadband communication and high-fidelity sensing at the same time. Promising as it may be, ISAC realization on 6G faces some challenges. ISAC systems need to attend to the interfacing issue between communication and sensing operations in the confined spectral region of mmWave and THz frequencies due to high propagation losses. ISAC channel modeling is difficult because of the need to incorporate target reflections for sensing and multipath propagation for communication. Environments change rapidly in mobility, clutter, interference, and other dynamics, which requires real-time adaptive processors to implement the necessary signal processing heuristics. The dual use of shared hardware and waveforms increases susceptibility to eavesdropping, interception, and spoofing which requires strong defenses to be put in place. Role of AI and ML in ISAC incorporating Artificial Intelligence (AI) and Machine Learning (ML) into ISAC systems has the capability to transform the design, optimization, and operation of 6G networks. Due to the dual-functional aspect of ISAC, in which sensing and communication processes co-share radio resources and hardware, AI methods are most appropriate to manage the intrinsic complexity and dynamic demands. Using AI for Joint Optimization of Sensing and Communication, conventional design methods tend to isolate sensing and communication as distinct blocks, resulting in poor performance in shared-spectrum scenarios. AI-based frameworks, especially multi-objective optimization models, can co-optimize waveform characteristics, beamforming vectors, and resource allocation policies to reconcile the competing demands of accurate sensing and communication throughput. RL agents, for example, can alter transmission power and beam orientation in real time, enhancing ISAC system adaptability in fast-varying scenarios. AI-Enabled Channel Modeling and Estimation ISAC systems are designed for complex propagation environments, which means that the channel propagation characteristics are influenced by communication multipath effects and target reflections for sensing. Deep learning-based approaches, including convolutional neural networks (CNN) and graph neural networks (GNN), have demonstrated the ability to learn channel features from high-dimensional representation data and thus provide a powerful and robust channel estimation technique, even with hardware impairments and NLoS conditions. AI for Adaptive Beamforming and Target Detection Massive MIMO and Reconfigurable Intelligent Surfaces (RIS) will play a crucial role in enabling ISAC with the 6G architecture. AI algorithms may enable the management of the substantial degrees of freedom in a massive MIMO or RIS system by coherently configuring the antenna array and RIS elements concurrently to intercept and steer the directed beams towards the communication users and sensing targets. Further, AI-based signal processing may also improve the target detection and localization accuracy in the presence of interfering signals. ISAC Privacy concerns arise from the fact that an ISAC framework uses both communication and environmental information. Federated learning (FL), a strategy used to build AI models on device data while keeping the raw data on devices, can help with both privacy concerns and communication overhead. This obviously has significant benefits in applications where raw data is considered sensitive (e.g., vehicular networks and health regulatory systems). An ISAC framework operates using shared waveforms and hardware, increasing the attack surface to eavesdropping, spoofing, and jamming activities. AI methods using techniques such as anomaly detection using autoencoders, and adversarial training, can be employed to identify and mitigate these security issues as they arise. In conclusion, AI and ML offer a large variety of technical capabilities that can allow the multi-dimensional optimization of autonomous ISAC frameworks, make them more robust to real-world uncertainties, and make them smarter and more adaptable as 6G networks develop over the next decade.

Although recent literature has made considerable progress in surveying ISAC-related issues, all have limitations: This recent review [1] gives a broad overview of ISAC enabling technologies, including sections on THz communications, massive MIMO, and RIS; it included a brief discussion on security and privacy, as well as the role of AI/ML in optimizing systems, broad characterizations of ISAC architectures in a high-level taxonomy, and organized open research questions that covered hardware, software and security issues. Although useful in breadth, the paper did not offer any deep dives into scenario-specific system models or quantitatively analyze sensing vs. communication trade-offs for a spectrum of application environments (e.g., vehicular, UAV, indoor, edge networks). It also did not have tables or figures comparing the scenarios' insights. In [2], the authors provide an extensive study of RIS in ISAC systems, indicating that RIS can change the behavior of the electromagnetic waves to create improved coverage (reduced path loss) and improved sensing resolution. The authors present theoretical models and case studies of RIS-assisted channel reconstruction, where the authors quantitatively demonstrate how RIS dramatically increases spectral efficiency and perception of the environment. The paper does not examine AI to develop an adaptive RIS configuration, nor does it examine RIS-assisted ISAC in a highly dynamic environment (e.g., urban vehicular networks). The study does not consider multi-scenario evaluations of RIS with the other 6G technologies, such as THz and massive MIMO. This survey fills that void and proposes AI/ML frameworks for real-time control of RIS, as well as providing comparisons across many application scenarios, which would be more useful for actual 6G implementations. The review [3] presents a broad overview of how artificial intelligence methods, and in particular deep learning and reinforcement learning, can help advance ISAC systems. The authors provide examples of AI's potential to address optimization problems which were traditionally insoluble, specifically joint beamforming and waveform design, dynamic resource allocation, and cross-domain interference management. They present two case studies to demonstrate how superior trade-offs can be achieved between sensing fidelity (resolution and accuracy), and communication performance (throughput and latency). However, while useful, this work serves predominantly as a high-level conceptual tutorial without any tangible or system-level scenario modeling, or benchmarks against real use cases around the authors research areas. The authors also note the absence of deployment challenges for AI in THz or RIS-assisted systems. In short, this paper moves the field forward by introducing detailed comparative analyses and system models with AI across multiple 6G environments (THz, RIS, edge intelligence), and with thorough performance metrics and tables.

The review [4] demonstrates the prospect of cooperative SLAM (simultaneous localization and mapping) via multiple agents (i.e., vehicles, UAVs, IoT devices) as a key enabler for ISAC. In [4] the proposed multi-domain SLAM framework, the proposed SLAM methodology takes heterogeneous sensor observation (radar, LiDAR, IMU) and references them to build a map of the dynamic environment, while simultaneously providing channel estimation for reliable connectivity using the maps. The authors demonstrate the important evidence that SLAM can integrate sensing and communication tasks and achieve highly capable localization accuracy with efficacy in vehicle networks and UAV swarms. While this work enriches the body of work using SLAM for ISAC, it is limited to localization and mapping, and does not explore how SLAM can be used in conjunction with AI-based beam forming, waveform adaptation, or RIS to aid support sensing and communication tasks in 1) real-time; 2) dynamic environments. This survey paper extends this to demonstrate architectures in which SLAM is fused with AI, and hardware enablers (e.g., RIS, massive MIMO), to achieve end-to-end adaptive ISAC system. [5] serves as a good start for focusing our ISAC waveform designs for future wireless systems. It groups a variety of the major waveform families, such as OFDM (orthogonal frequency-division multiplexing), FMCW (frequency-modulated continuous wave), and OTFS (orthogonal time-frequency space), and evaluates each family in terms of coexistence with communication and sensing. The discussion also covers the trade-offs of using waveform designs, such as spectral efficiency versus range resolution and Peak-to-Average Power Ratio (PAPR). The authors also made passing comments about the signal processing algorithms needed to decouple communication and sensing information from a common waveform. While it provides significant coverage of waveform categories, it does not relate these designs to system architectures that leverage the THz bands, massive MIMO, and RIS as essential enablers for 6G ISAC architectures in the future wireless ecosystem, nor is there any meaningful investigation of AI/ML-assisted adaptive waveform generation, specifically, integrating machine learning models into the design process of both the waveform and the system.

TABLE 1 THE ABBREVIATION LIST

Abbreviation	Definition
3GPP	3rd Generation Partnership Project
6G	Sixth Generation
AI	Artificial Intelligence
AN	Artificial Noise
AR	Augmented Reality
AV	Automated Vehicle
CNN	Convolutional Neural Network
CSI	Channel State Information
DL	Deep Learning
DP	Differential Privacy
DNN	Deep Neural Network
DQN	Deep Q-Network
DRL	Deep Reinforcement Learning
EM	Electromagnetic Waves
FL	Federated Learning
FOV	Field of View
FMCW	Frequency-Modulated Continuous Wave
GAN	Generative Adversarial Network
GDPR	General Data Protection Regulation
GNN	Graph Neural Network
GPS	Global Positioning System
HE	Homomorphic Encryption
HMI	Human-Machine-Interfaces
IDS	Intrusions Detection System
IoE	Internet of Everything
IoT	Internet of Thing
ITS	Intelligent Transportation System
ITU	International Telecommunication Union
ISAC	Integrated Sensing and Communication

KPI	Key Performance Indicator
LoS	Line-of-Sight
MARL	Multi-Agent Reinforcement Learning
mmWave	millimeter-Wave
MIMO	Multiple Input Multiple output
ML	Machine Learning
mMTC	Massive Machine-Type Communication
NDT	Non-Destructive Testing
NLoS	Non-Line-of-Sight
OFDM	Orthogonal Frequency-Division Multiplexing
OTFS	Orthogonal Time-Frequency Space
PAPR	Peak-to-Average Power Ratio
PLS	Physical Layer Security
QoS	Quality of Service
RaCom	Radar Communication
RCS	Radar Cross section
RF	Radio-Frequency
RIS	Reconfigurable Intelligent Surface
RL	Reinforcement Learning
RNN	Recurrent Neural Network
SAR	Synthetic Aperture Radar
SDR	Software Define Radio
SLAM	Simultaneous Localization and Mapping
SMPC	Secure Multi-Party Computation
SNR	Signal-to-Noise Ratio
THz	Terahertz
UAV	Unmanned Aerial Vehicle
URLLC	Ultra-Reliable Low Latency Communication
V2X	Vehicle-to-Everything
VLC	Visible Light Communication
VR	Virtual Reality

A. KEY CONTRIBUTION

To provide a broad perspective on the enabling and enhancing technologies and their relationships within ISAC, survey provide a wide-ranging review of the ISAC enabling technologies (e.g., THz communications, massive MIMO, Reconfigurable Intelligent Surfaces (RIS), and edge computing). More importantly, unlike previously published surveys, this review has a systematic look at how these technologies are intertwined and provide complementary services with applicable deployment scenarios (e.g., autonomous driving, smart health care, UAV swarms). This paper reviews the use of artificial intelligence (AI) and machine learning (ML) methods to optimize waveform design, beamforming and dynamic resource allocation applications using the subset of methods, including deep learning, reinforcement learning, and federated learning. This survey categorizes and evaluate AI integration with the elements of sensing and communication and offer a new AI empowered ISAC framework to be used in dynamic environments. This review presents, in a detailed manner, scenario-based tables and figures from both qualitative and quantitative dimensions in outdoor urban, from a vehicular perspective, aerial, and indoor scenarios. Each is evaluated (and compared) based on their system model, enabling technologies, and AI integration, enabling any reader to see trade-offs of one kind or another in sensing accuracy, communication throughput, and computation overhead. We identify crucial research challenges that include security/privacy, energy consumption, and hardware limitations for ISAC systems. Additionally, we identify future research directions including AI-enabled RIS control, environmental awareness waveform designing, edge intelligence for ultra-low latency ISAC applications and visual synthesis of ISAC system architecture. To assist the analysis, this review provides relevant figures and diagrams to describe the operational environment of ISAC, AI-enabled adaptive systems, and the multi-domain application of 6G enabling technologies. The described visuals presented serve as a vision- guide for researchers regarding their conceptualization of end-to-end ISAC systems.

B. ORGANIZATION OF PAPER

This paper is organized as follows. Section II will present enabling technologies for ISAC. Section III will discuss channel modeling approaches. Section IV will review AI/ML techniques for ISAC systems. Section V will cover security and privacy considerations. Section VI will present applications and use cases. Section VII will outline open research issues and directions for future work. Finally, Section VIII will offer concluding remarks.

II. ENABLING TECHNOLOGIES AND SPECTRAL BANDS

The development and adoption of several enabling technologies for Integrated Sensing and Communication (ISAC) in 6G is key to the success of integrated systems and creating and using spectrum in higher bands. In 5G [5], sensing was ancillary to communication, while sensing will play a prominent role in 6G [6] systems in which the modalities of sensing and communication will be co-designed and co-optimized. This involves new forms of physical layer solutions and others. In this section, we will describe these enabling technologies with the spectral bands they occupy.

A. TERAHERTZ(THZ) COMMUNICATION AND SENSING

The Terahertz (THz) band with frequencies ranging from 0.1 THz and 10 THz [7] is one of the enablers of 6G ISAC systems. THz provides ultra-wide bandwidths and extremely short wavelengths to enable those two capabilities simultaneously, while allowing unprecedented data rates for communication and sub-millimeter resolutions for sensing. The massive content of the THz spectrum can give hundreds of GHz of bandwidth in contiguous frequency bands, which is a huge increase from the MHz wide bands in Sub-6 GHz and even from the GHz wide mmWave bands in 5G. THz communication is capable of multi-terabit-per-second (Tbps) data rates, when looking to the future will support data rates for applications such as holographic telepresence, immersive VR/AR, and massive machine-type communications (mMTC). The large available bandwidth reduces the transmission time for massive data packets which is critical for ultra-reliable low latency communications (URLLC). Emerging modulation techniques, such as Orthogonal Time Frequency Space (OTFS) and Index Modulation (IM) which provide ways to take advantage of ultra-wide bandwidths available in THz spectrum with techniques to maintain robustness against THz channel impairment. THz systems [8] have unique advantages for sensing applications due to their extremely short wavelengths, providing the ability to sense aspects of the environment, even at very small scales. With THz signals, localization accuracy can reach millimeter or sub-millimeter levels, outperforming Sub-6 GHz or mmWave systems. There are applications in autonomous vehicles, drone swarms, and indoor navigation systems where centimeter-level GPS is not good enough. THz waves can penetrate many non-conductive materials and method sensitive to molecular vibrations. There are applications in non-destructive testing (NDT) to detect defects in composite materials or quality assurance in food or pharmaceutical products. Through examining reflected THz signals, fine grain human gestures can be recognized, allowing for natural human-machine interfaces (HMI) to support smart environments. There are several significant challenges in deploying THz for ISAC like free space path loss at THz frequencies is far greater than for mmWave or Sub-6 GHz bands, and is due to the inverse square law with wavelength. Absorptions by atmospheric gases (particularly water vapor) creates frequency bands separated by an absorption peak. THz circuits, high powered sources, low-noise detectors are also in their infancy. The narrow beams needed for high SNR make systems sensitive to user mobility, which leads to misalignment. There are some emerging solutions like Graphene and other 2D materials are supreme candidates for high-frequency transistors, tunable antennas, and plasmonic waveguides owing to their unique electronic properties. Arrays with thousands of antenna elements (UM-MIMO) can form highly directed beams to overcome THz energy propagation losses. Blend of analog and digital beamforming which offers flexibility with reduced complexity in the number of RF chains. Deep reinforcement learning (DRL) [32] is proposed to know how to best track and switch the beam in dynamically changing environments.

B. MASSIVE MIMO AND BEAMFORMING

Massive multiple input multiple output (mMIMO) combined with beamforming play a fundamental role in enabling 6G [35] Integrated Sensing and Communication (ISAC) because they provide both spatial multiplexing gains for ultra-reliable communications and highly directionality of sensing. Hence, they are great enablers for developing narrow beamforming characteristics: high resolution transmission and sensing. Massive MIMO uses hundreds (even thousands) of antenna elements to shape narrow, steerable beams. For communication the narrow beams direct the energy towards intended users which increases SNR while limiting interference and enables spatial multiplexing of multiple users. For sensing beamforming convert the antenna array into a synthetic aperture radar (SAR) system allowing sufficiently high resolution to survey the environment or detecting an object in space. Hybrid Beamforming combines analog or digital beamforming, allowing to balance between complexity and performance at mmWave and THz bands. For vehicular networks, narrow beams track moving vehicles for V2X communications and sensing the environment (detecting obstacles or pedestrians). For industry 4.0, narrow beams allow for machine-to-machine communication and high-precision robot localization simultaneous. For large bandwidth, the beam angle moves across frequencies. Mobile users require rapid tracking due to large doppler shifts in vehicular contexts. Rolling out RF-based chains and phase shifters for ultra-massive MIMO meaning hardware complexity. Few emerging solutions are deep learning to predict and select beams quickly. Holographic mMIMO experience the entire surface as an intelligent aperture, which can provide finer granularity of beam control. Enabling Multi-User ISAC in massive MIMO systems, spatial multiplexing takes advantage of being able to send multiple independent streams of data over the same time-frequency resource. For communication, the scaling in capacity with the number of antennas because of channel hardening and favorable propagation. For sensing, multiplexing beams illuminate parallel multi-target tracking at different locations in the environment. It is relevant to 6G ISAC urban scenarios where user density is high (for example, AR/VR users in stadiums) and allowing locational and multi-user communication simultaneously for emergency services. In mMIMO, there is a trade-off between maximizing gain through beamforming for communications and maximizing area for coverage with wide beamwidths for sensing. The trade-off for narrow beam is advantageous communication SNR but limited sensing FOV. The tradeoff for wider beam is reduced gain communication, improved sensing coverage. The solutions dynamically adapt beamwidth using AI and dedicated narrow beams for communications and dedicated wide beams for sensing.

C. RECONFIGURABLE INTELLIGENT SURFACE

Reconfigurable Intelligent Surfaces (RIS) [27] are engineered metasurfaces consisting of many passive or active reflecting elements that can manipulate incident electromagnetic (EM) waves. RIS can dynamically control the phase, amplitude, and polarization of the reflected signals, providing a means for environment-aware integration of sensing, communication, and localization (ISAC) systems. RIS behaves like a smart mirror manipulating EM waves to move around obstacles. RIS reflects signals around blockages to increase coverage and provide energy savings. RIS reflects additional virtual line-of-sight (LoS) paths to help illuminate targets that would remain invisible. In urban vehicular networks, RIS mounted to buildings provides a way to reflect signals around corners and maintain both the communication signal link and radar-based pedestrian detection. Dynamically changes reflection angles to direct energy to high priority users or sensing regions. Passive RIS made from almost lossless components (e.g., varactor diodes) having low power consumption and large aperture sizes but cannot amplify signals due to double fading. Active RIS contains amplifiers to amplify the reflected signals. It can compensate for double fading and allow for a longer sensing range but at the cost of increased energy consumption, heat dissipation and more complexity. Hybrid RIS combines passive and active components to deliver good energy efficiency and gain. RIS is uniquely position for ISAC task because it is programmable. Wide beams to sense large areas and narrow beams for huge data throughput. RIS allows for extended sensing without adding additional active sensors. RIS requires real time control of thousands of reflecting elements with changing channel states which is an uphill task. RL learn policies for configuring RIS [28] to maximize sensing and communication KPIs. GNN Model RIS as graph structures so as to configure at scale. While DNN given the channel state information (CSI) or user mobility patterns, model the optimal phase shifts. A federated learning system in which RIS units locally train a model, and then share only their weights, ensuring data privacy. Channel Estimation for RIS involves passive nature which is difficult to estimate with regard to RIS related channels. Integration with Legacy Systems means that RIS has to co-exist with non-RIS systems without interference.

D. EDGE INTELLIGENCE AND AI INTEGRATION

The convergence of edge intelligence and artificial intelligence (AI) within 6G networks represents a paradigm shift for enabling integrated sensing and communication (ISAC). As 6G aims to support applications requiring ultra-low latency, high reliability, and context-aware adaptability, centralized cloud-based solutions often fall short due to inherent backhaul constraints and propagation delays. As a result, edge intelligence will situate computation and decision-making more closely to the edge of the network at base stations, user devices, and even reconfigurable intelligent surfaces (RIS) to establish a more distributed, cooperative architecture. This convergence facilitates the ability of ISAC systems to engage in simultaneous tasks including, but not limited to, high-resolution environmental sensing, dynamic resource allocation, and adaptive waveform design in near real time.

Edge intelligence in ISAC allows for joint optimization of communication and sensing. As an illustration, AI models run at edge nodes in the network can dynamically adjust beamforming strategies for massive MIMO systems, schedule resources for time-sensitive applications, and refine sensing algorithms based on local environmental changes. Unlike traditional systems, which are based on pre-configured settings, edge-AI-enabled ISAC can autonomously adjust to travel patterns, interference levels, and obstacles in complex urban settings. This ability to adapt in real time is vital for new 6G use cases like self-driving cars, remote surgery, and immersive extended reality (XR) where sensing capability and reliable communication must work seamlessly.

In addition, AI-based learning paradigms such as federated learning and reinforcement learning (RL) have gained a lot of traction for ISAC at the edge. Federated learning allows for collaborative learning of models over distributed edge devices while not requiring raw data to be shared, preserving user privacy and lowering communication overhead. This is especially useful in cases where edge nodes process highly sensitive sensory data such as health monitoring systems or surveillance networks. Meanwhile, RL provides a framework for continuously adapting the network parameters to maximize long-term rewards in stochastic scenarios (i.e., uncertain future states). For example, RL agents onboard edge servers can learn how to jointly assign spectrum resources to sensing and communication based on user density and sensing accuracy requirements. State-of-the-art studies (e.g., X. Zhang et al. [1]) have shown how multi-agent RL can be utilized for decentralized beam management in RIS-assisted ISAC networks to reduce latency and improve spectral efficiency.

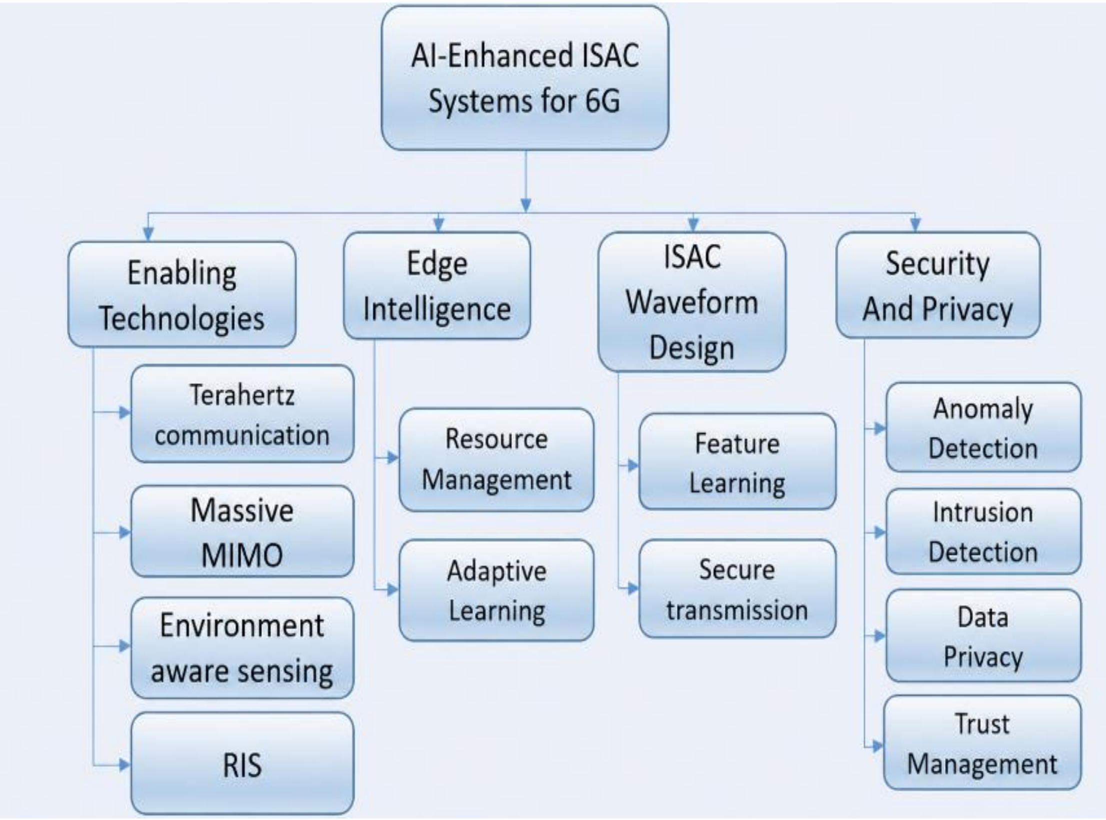


Fig. 1. Architectural Framework of AI-Enhanced 6G ISAC Systems

Edge intelligence is designed to facilitate one of the important needs of ISAC systems, support for heterogeneous and dynamic data streams. Sensing data are often characterized by high dimensionality, sparsity, and temporal variability while communication data requires specific quality of service (QoS) guarantees. Edge-based AI models can combine multi-modal data, e.g. radar, Lidar, and camera feeds, with the communication channel data, to generate a comprehensive situational awareness map that relates to the same identify temporal correlations in a dynamic sensed environment. Although there are promising advancements, several challenges remain in realizing edge intelligence for 6G ISAC. First, resource-intensive AI models need to be deployed geographic area. This cross-domain fusion and analysis of data is critical to ISAC applications such as cooperative vehicles and smart manufacturing. Edge-based deep neural networks (DNNs) have been proposed for a variety of inferencing tasks, including channel estimation tasks, inference from high-dimensional sensed data, and interference mitigation. For example, convolutional neural networks (CNNs) can classify objects using high-dimensional radar returns, and recurrent neural networks (RNNs)
on resource-constrained edge devices, which require innovation in lightweight model architectures and the incorporation of hardware accelerators. Techniques, such as model pruning, quantization, and knowledge distillation, are

being explored to optimize AI to reduce computational and memory footprints without compromising accuracy. Second, reliable AI inference in highly mobile and interference-prone environments requires strong training against adversarial conditions. Third, there is also a need for scalable orchestration frameworks that are capable of managing coordination of thousands of distributed edge nodes, while also assuring consistency and synchronization of AI models.

To respond to these challenges, emerging solutions are taking advantage of hierarchical edge-cloud architectures whereby complex training can take place in centralized clouds but lightweight inference can occur at the edge. Moreover, explainable AI (XAI) methods are being incorporated to improve trust and interpretability of AI decisions established in mission-critical ISAC systems, for example, if the head AI model within an edge AI system takes the decision to switch the communication-sensing trade-off in a vehicular network setting, understanding the rationale would be critical for safety assurance.

Incorporating edge intelligence and artificial intelligence into 6G ISAC systems is crucial to realizing the vision of a contextualize, ultra-reliable, and adaptive network fabric. By enabling distributed processing, real-time adaptability, and intelligent orchestration of joint communication and sensing functions, edge-AI fusion bridges the gap between theoretical ISAC frameworks and their practical deployment in real-world 6G applications.

E. SPECTRAL BANDS FOR 6G ISAC

Spectral bands are the foundation of 6G ISAC systems, enabling ultra-high data rate, low latency communication and accurate environmental sensing. The previous generations were primarily operating mainly in the sub-6GHz spectrum, while 6G ISAC systems will utilize a much wider range of spectral resource from sub-6GHz, millimeter wave (mmWave), THz, to optical bands. The move towards a more unified vision of an ISAC-enabled network is necessary because of the extreme demand of spectrum-hungry applications (holographic communications, ultra-high-resolution radar sensing, and intelligent transportation systems) in the future. ISAC systems can support the different objectives of communication and sensing when using spectral bands and not all bands will be used for both communication and sensing at the same time. At lower frequencies, especially sub-6 GHz, ISAC systems leverage strong propagation characteristics and the benefit of broad coverage area. This is useful to support large scale use cases like smart cities and rural networks. These bands offer highly reliable communication performance in a non-line-of-sight (NLoS) manner and allow for coarse-grain sensing problems such as big object detection scenarios or monitoring human presence. The downside is the small bandwidth, resulting in limitations to the data-rate and sensing resolution. The mmWave (30–300 GHz) and THz (0.1–10 THz) bands are capable of providing massive bandwidth that can support Tbps communication and achievable sensing resolutions smaller than a millimeter. One example of THz being used is that since THz has very short wavelengths, it is capable of providing localization with very high precision or provide insights to material characterization. THz is the perfect band to support fine-grain environmental characteristics such as hand gestures, vital signs, and identification of structural defects of materials. However, using the higher frequency bands for ISAC comes with even more significant challenges. The propagation loss in mmWave and THz bands is orders of magnitude higher than sub-6 GHz, which requires a dense network of base stations along with advanced beamforming to maintain connectivity. Furthermore, these higher bands suffer from tremendous molecular absorption and significant dependence on environmental blockages such as rain, fog, and foliage. These detrimental factors create a tradeoff between achievable sensing accuracy and communication reliability in changing environmental contexts. To help address these issues, new and developing solutions, such as Reconfigurable Intelligent Surfaces (RIS), and massive MIMO architectures are now targeting adaptive beam steering and reconfiguration of channels.

Another factor is sensing and communication propagation simultaneously within shared spectral resources. Historically, sensing systems (e.g., radar) and communication networks have operated in distinct frequency bands to avoid interference. However, ISAC systems aim to exploit spectrum sharing, which increases spectral efficiency and alleviates redundancy of hardware. Subsequently, this requires a level of sophistication in designing waveforms and handling interference. For example, OFDM-based waveforms can be used for ISAC applications because they offer flexibility in allocating subcarriers for different environments for either sensing or communication. Moreover, sophisticated AI algorithms deployed on edge devices facilitate real-time dynamic spectrum allocation that is sensitive to traffic demands and sensing needs. Additionally, optical waves, particularly visible light communication (VLC) and infrared (IR), are emerging as viable ISAC solutions for short-range applications. VLC systems, based on intensity modulation and photodetection, can both communicate and sense simultaneously. This feature is particularly relevant indoors (e.g., in smart homes or smart factories) when LED light networks can potentially provide both data communication and light for illuminative purposes. Spectrum policy will influence the design of ISAC systems as a function of the spectral band. Balancing the requirements of legacy systems and future ISAC applications in sub 6-GHz and mmWave bands will be essential to effective spectrum allocation policies. Work is also underway internationally to harmonize regulatory frameworks and operational guidelines for 6G ISAC usage. In summary, leveraging all of the available spectrum bands from sub-6 GHz to THz and optical frequencies is a crucial component in realizing the grand vision for 6G ISAC. Higher frequency bands will allow us to do things we would never have dreamed of, but with that comes limitations that will require hardware, algorithms, and regulations to work in conjunction with one another. The interaction of the spectral resources and enabling technologies like RIS, massive MIMO, and AI driven dynamic spectrum management are essential to enable future ISAC systems that enable scalability, adaptivity, and spectrum-efficiency.

III. CHANNEL MODELING FOR ISAC

Integrated Sensing and Communication (ISAC) frameworks in 6G networks necessitate a comprehensive understanding of the propagation environment due to their goals of simultaneous high-fidelity sensing and reliable data transmission. Thus, channel modeling [9] can be viewed as one of the central challenges to guarantee that ISAC operations occur adjacent to each other. Compared to typical channel models centered around communication, ISAC systems require a dual-purpose channel model that can precisely capture the details needed by the communication and sensing functions. In 4G and 5G systems, channel models were largely descriptive of statistical fading properties, and the large-scale elements only needed to guarantee more reliable data transmission. Similarly, ISAC systems introduce requirements not focused solely on enabling communication but also on spatial, temporal, and spectral representations in order to capture the level of detail needed for fine-grained environmental sense-making capabilities. For example, detecting minor environmental risks, such as movements of objects, changes in properties of materials, or deflected human gestures require detectors to largely fit into multi-static and mono-static sensing situations. These losses or changes also require some form of radar cross-section (RCS) characteristic for each target or the accounting of high-frequency interactions. For components of the model to take into account EM simulations with classical stochastic models, as this triangulates accounts of both a physical and stochastic picture of the wireless channel. In the millimeter-wave (mmWave) and terahertz (THz) frequency bands that are central to 6G ISAC, propagation is impacted much more substantially due to the environmental factors such as diffraction, scattering, molecular absorption, or reflections from surfaces. In particular, THz channels experience significant molecular absorption, ultimately leading to sparse multipath propagation and frequency-selective fading. As many of these link effects can be characterized via deterministic models (for example via ray tracing, to accurately specify the environment) and then possibly supplemented with some stochastic models, the physical aspects can be modeled. The deterministic models are primarily of a hybrid nature in order to provide the opportunity to combine ultra-high resolution sensing with high-speed communication. In addition to the importance of modeling aspects in hybrid situations, ISAC systems need to be designed such that they are capable to operate in highly dynamic environments wherein the channel state information (CSI) changes quickly based due to mobility of users and objects within the environment. The nature of temporal variations means that the appropriate modeling takes the form of time varying channel models, wherein both Doppler shifts and phase variations across the communications and sensing processes can be described and analyzed. Environment-aware channel models expand the modeling perspective as they can be exploited to implement data from real time environment sensing into the channel state estimation process for adaptive resource allocation schemes including beamforming. This process of adapting the CSI is especially useful in developing Reconfigurable Intelligent Surfaces (RIS), wherein the propagation environment is effectively modified or adapted to maximize the ISAC functionality or performance.

Additionally, interference effects must be incorporated into a joint radar-communication (RaCom) channel model, particularly clutter or other potential signal interactions such as mutual coupling between the communication and sensing signals. Inclusion of clutter becomes more complex at higher frequencies because of the high reflectivity of objects themselves, and higher densities of multipath effect typically found in urban environments. ISAC systems operating in these frequency band and dense urban environments have been designed to include clutter and other interference mechanisms, and in these regimes, the interference patterns from different signals must be established in the channel model to allow for waveform design, trajectory alignment and the clean separation of sensing from communication signals. The biggest challenge that remains with regard to ISAC channel models [10] is standardization of the model properties across frequency bands, use cases and deployment conditions. While ISAC models exist (e.g., 3GPP TR 38.901 channel model for 5G NR), and there have been some initial efforts in establishing models to assess dual functionality, it is that they do not account for the dual-functionality aspect of ISAC. The most recent models [11] that have been proposed include sensing-specific attributes (e.g., radar cross-section profiles, micro-Doppler effects) to join the two functions, while providing a baseline that recognizes the differences within the basic framework of ISAC. In conclusion, channel modeling for 6G ISAC will require a multidisciplinary approach that integrates classical wireless channel theory, electromagnetic propagation studies, and data-driven AI techniques. These models will be used to design and assess ISAC systems and pave the way for new forms of beamforming, resource allocation, and signal processing to achieve the promises of 6G. Future research will need to prioritize scalable, real-time channel modeling frameworks that can accommodate heterogeneous applications of ISAC from autonomous vehicles to holographic communications.

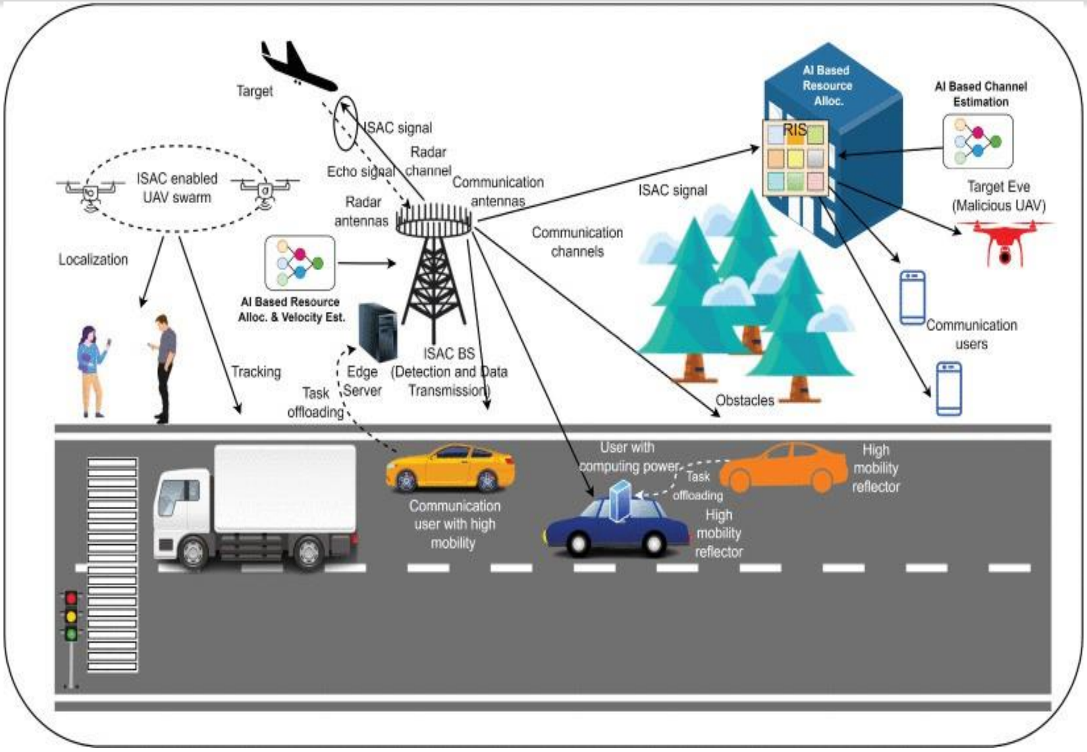
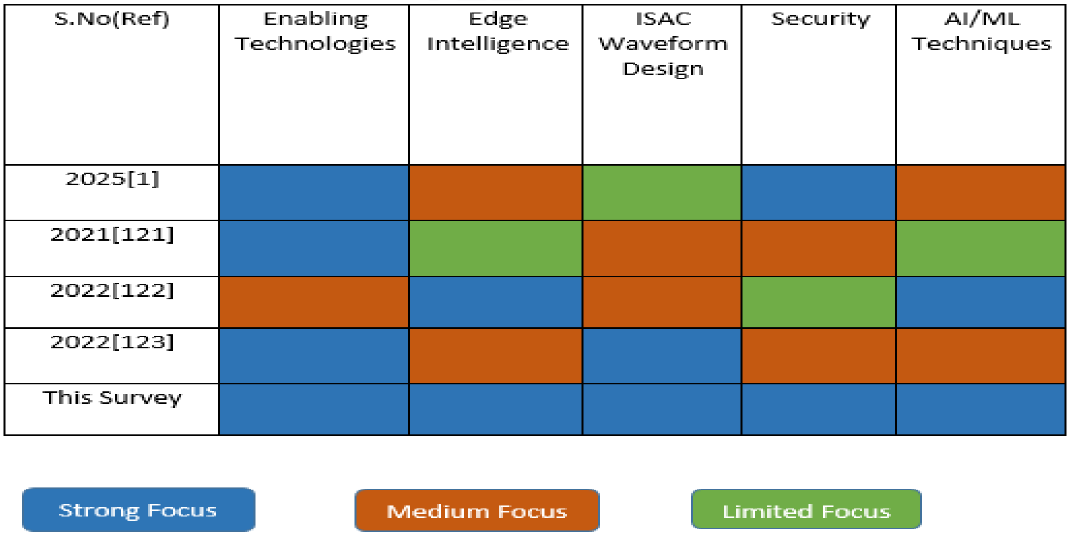


Fig. 2. Application Scenarios For 6G ISAC Systems. Reproduced from (S. Aldirmaz-Colak et al) [1].



S.No(Ref)	Enabling Technologies	Edge Intelligence	ISAC Waveform Design	Security	AI/ML Techniques
2025[1]	🟦	🟧	🟩	🟦	🟧
2021[121]	🟦	🟩	🟧	🟧	🟩
2022[122]	🟧	🟦	🟧	🟩	🟦
2022[123]	🟦	🟧	🟦	🟧	🟧
This Survey	🟦	🟦	🟦	🟦	🟦

🟦 Strong Focus 🟧 Medium Focus 🟩 Limited Focus

Fig. 3. Heatmap across multiple ISAC Scenarios

IV. AI/ML TECHNIQUES IN ISAC

Integrated Sensing and Communication (ISAC) systems are moving in the direction of 6G deployments. This will require higher degree of intelligence for real time decisions on spectrum sharing, integration of the two main functionalities of ISAC, communication and sensing, and potentially environment-aware communication with item agents as well as adapting to different environment conditions. This all requires cleaner and, in some cases, intelligent control mechanisms as we move beyond deterministic ways of modelling systems. AI and ML methodologies [12] have become foundational pillars for ISAC, including approaches such as Deep Learning (DL), Reinforcement Learning (RL), and Federated Learning (FL). These data-driven concepts and methodologies have changed the ways in which wireless systems are now learning and adapting. DL is providing a deeper interaction and bringing the gap closer between sensing and communication. Therefore, this section intends to provide a meaningful, collective review for the exploration of the three main paradigms of AI and ML for ISAC.

Deep Learning [13] is a powerful tool for modeling complicated non-linear mappings on large, multidimensional datasets. This ability makes DL a natural fit for ISAC, given how much data is sourced from both sensing and communication. Within ISAC systems, DL is currently being used to support channel estimation, beamforming optimization, radar image processing, and the fusion of modal source data. For instance, Convolutional Neural Networks (CNN) and Recurrent Neural Networks (RNN) have been applied to predicting wireless channels in highly mobile contexts. Recent work has demonstrated that these DL techniques outperform conventional estimation methods in dynamic environments characterized by time-variant multipath fading. These models leverage spatial-temporal correlations of the data in order to learn from previous instances to fill gaps of uncertainty to improve reliability and throughput of links in ISAC applications. In addition, autoencoder architectures and Generative Adversarial Networks (GANs) have demonstrated the ability to jointly optimize waveform [40] design for both communication and sensing domains in a compact application. These networks can reconstruct radar images from noisy and compressed signals in such a way that the communications component remains intact. In use cases such as vehicular ISAC applications, where rapid changes in the environment require responsive capabilities, DL models have been trained on LiDAR, radar, and RF data streams simultaneously to assist in real-time beam alignment and resource management. This approach shows significant potential for scalability, and is generalizable in cases where we have a great deal of data. However, the prospect of ISAC with DL has significant challenges. The high data annotation, computational cost, and risk of overfitting or adversarial attacks, are significant challenges to deal with. The increasing use of lightweight neural architectures (e.g., MobileNets and EfficientNets) and model compression methods (e.g., pruning and quantization) makes deployment on edge devices feasible. In addition, knowledge distillation enables larger DL models to support smaller, deployable models without performance degradation.

Reinforcement Learning (RL) is specifically designed for situations where an agent needs to learn optimal policies in uncertain and evolving environments. Some areas of application in ISAC are spectrum allocation, beamforming, power management, and real-time configuration of Reconfigurable Intelligent Surfaces (RIS). ISAC system behavior can be modeled as a Markov Decision Process (MDP) which allows for RL agents to learn how to optimize long-term cumulative rewards (for example, throughput, sensing accuracy, and energy efficiency) through trial and error. Deep Q-Networks (DQN), Policy Gradient Methods, and Actor-Critic structures are being widely used for fruitfully spectrum sharing, which means that there are limited resources allocated dynamically for both communication and sensing, and there is no environmental model. These algorithms have proved capable of recognizing superior context-reactive policies based on learning and thus outperforming static allocation regimes by learning, and adapting to interference, fading channels, and movement. In a multi-user ISAC, collaboration and cooperation between different nodes can be enabled by Multi-Agent Reinforcement Learning (MARL) allowing coordinated beam steering and power allocation. Another promising application is with RIS-assisted ISAC where Deep RL can dynamically tune phase shifts and reflection coefficients to achieve a good balance in link performance and capability on the sensing side. The downside of RL for ISAC is associated with convergence. Convergence time may be too slow in environments that change rapidly and in some cases mission critical. Research into Hierarchical RL, which encourages high-level agents to control the policy of their sub-agents, as well as meta-learning, which provides ways to learn based on prior knowledge, is progressing to mitigate latency issues.

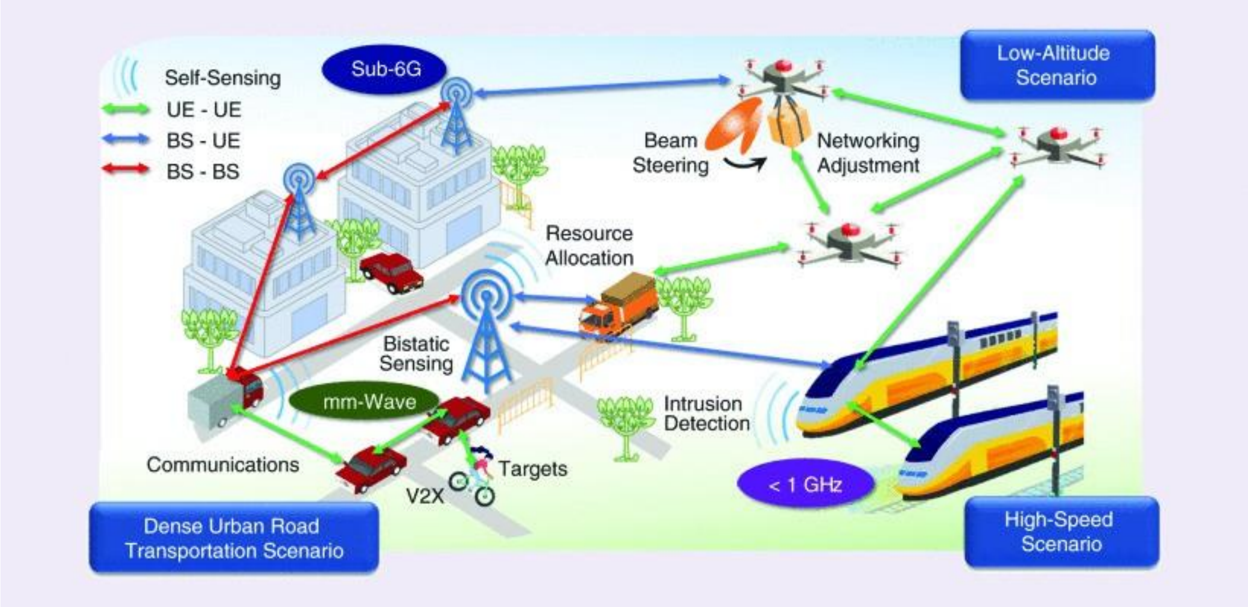


Fig. 4. 6G ISAC Channel Modeling. Reproduce from (Liu, Ting, Ke Guan, Danping He, P. Takis) [24]

Federated Learning (FL) [18] is a new direction for AI in ISAC that allows model training to take place collaboratively across devices in a distributed manner, without sharing any raw data. The benefits of decentralized learning are clear in ISAC use cases, where data is generated at the edge, such as flaming autonomous vehicles, UAV [31] swarms, and smart factories, and can contain sensitive user information or situation/contextual information. In FL, edge nodes engage in local training and only share model updates with the central aggregator, protecting sensitive information while aggregating intelligence for the model updates. In the ISAC space, FL is applied to collaborative channel modeling and radar scene understanding. Edge devices can collaboratively train models that predict behavior of the channel in real-time, while incorporating spatial diversity and mobility profiles, without sacrificing user privacy. FL can also be used for cooperative sensing for various applications involving, for example, vehicle-to-everything (V2X) communication that leverages multiple cars sensing radar, visual and LiDAR data in a 'model', that can utilize combined sensory data to build a shared model of the environment, ehancing communication and safety. Despite the positive contributions of FL, FL faces a variety of challenges. For one, the heterogeneous data distribution at the nodes as a result of different devices can reduce the convergence of the model and make for worse accuracy. Also, documents can have a lot diversity in their computational and energy capabilities determined by a variety factors of the device. Some avenues explored to combat these issues are to personalize FL in which models are personalized to every client and to do communication-efficient FL which reduces communication frequency and compress model minute model transmission. In order to protecting privacy, Differential Privacy and Secure Aggregation have been explored in order to keep FL in the ISAC arrangement promising for mission-critical applications.

The true potential of AI in ISAC is the overlap of deep learning (DL) [14], reinforcement learning (RL), and federated learning (FL). Deep learning models can develop embeddings and representations that can help reduce the exhaustive amounts of sensing and communication data, which could also be treated as input states for RL agents and thereby provide better learning speed and robustness. Federated reinforcement learning allows multiple ISAC agents to cooperatively learn sensing and communication policies while keeping data decentralized. Furthermore, privacy-preserving DL is designed to utilize FL to simultaneously coordinate de-identified, compliant training of significant DL models. The emergence of Explainable AI (XAI) in these systems is also gaining traction. As AI-enabled systems begin to be employed to support autonomous driving, smart healthcare, industrial automation, and other high-stakes applications, it will be important to ensure that the rationale for a system's communication or sensing decision is well understood. Emerging frameworks are also integrating interpretability into deep learning (DL) and reinforcement learning (RL) models so that there is a level of trust or understanding regarding the embedded intelligence. Ultimately, the goal of AI/ML is to enable ISAC systems to act with cognitive intelligence in a manner that is adaptive, trustworthy, autonomous, and safe in dynamic 6G systems. Embedding intelligence into the wireless network means that, through ISAC systems, we are not only enabling communication and sensing, but we are also enabling thinking and learning.

V. SECURITY AND PRIVACY IN ISAC

Integrated Sensing and Communication (ISAC) systems serving as the main technology for 6G networks, their unique dual-purpose nature encompasses unique access concerns and potentially significant security and privacy implications. ISAC systems will simultaneously involve sensitive sensing information along with high-bandwidth communication data. These two capabilities combined create an entirely new surface of vulnerable operations at the physical layer, network layer, and application layer. In this section we will analyze in detail the security concerns, privacy issues, and developments related to ISAC systems, and will discuss how new emerging technologies such as AI and ML can be leveraged to secure them in the future.

1)THREAT LANDSCAPE FOR ISAC SYSTEMS

ISAC will inherently expand the attack surface. The traditional wireless systems only face threats to communication like eavesdropping, jamming, and spoofing. With ISAC, it broadens the threats to include sensing, thereby revealing new vulnerabilities related to sensing, like jamming the radar, injection of false data, or spoofing of the sensing. Let us consider the case of autonomous vehicles operating with ISAC networks. An adversary might modify the reflected radar signals such that false objects are created, leading to the ability to hide real objects and put the safety of the vehicle (and passengers) at threat. In ISAC surveillance applications, an attacker could even interfere with the environmental sensing, and create misclassifications or deny the ability to sense (deny sensing) altogether. Moreover, ISAC systems will be particularly susceptible to multi-domain attacks. Given that communication and sensing both utilize common resources (spectrum, hardware, and waveforms), an attack or jamming in one domain will affect the other. An adversary leveraging the sensing pipeline could inject distortion in such a way as to undo joint waveform optimizations, if they can reduce the effectiveness of the communication, an attacker can make communication unreliable or ineffective by only injecting sensing artifact (which might confuse the communication).

2)PRIVACY CONCERNS IN ISAC

The privacy dimension in Integrated Sensing and Communication (ISAC) systems is much more complex and multifaceted than traditional communication networks. ISAC systems have a dual-purpose, where environmental sensing data and communication payloads are tightly coupled, and in most instances processed simultaneously. While integrated sensing and communication can lead to significant performance improvements and efficiency of spectrum utilization, it magnifies privacy risks due to new risks of data leakage, inference attacks, and unauthorized monitoring. Privacy in ISAC systems primarily revolves around the granularity of environmental sensing. ISAC systems are built on technologies including high-resolution radar, LIDAR, and millimeter-wave or THz bands which allow systems to extract detailed information about dynamic environments. The same capability that allows adversaries to exploit sensitive personal information. For example, adversaries can analyze reflected signals to know that people are present, recognize what those people may be doing, or reconstruct the layout of the private space. "Sensing eavesdropping" entered into a new class of privacy, with risks that cannot be based solely on a theoretical framework focused on communications. While the role of AI/ML in ISAC systems supports smart sensing and adaptive communications, it also introduces algorithmic privacy threats. Federated learning and distributed AI architecture are implemented to reduce exposure to centralized data; however, both still pose risks of model inversion attacks whereby an adversary can potentially reconstruct portions of private training data from model parameters, and membership inference attacks which could help attackers detect whether a particular user's data was part of the training period. Thus, these risks highlight the need for privacy-preserving machine learning (PPML) to protect sensitive user or environmental data. Moreover, the interaction occurring in shared resources between the sensing domains and communications impacts the privacy problem. Waveforms designed with joint sensing and communications necessarily reflect unique information content of both domains. Thus, capturing and intercepting these waveforms introduces new challenges of keeping user payloads, environmental information (e.g., context and location), and metadata private. Unlike conventional networks, where encryption at the network layer focuses primarily on user payloads, research on ISAC systems must take into consideration protecting metadata and unwanted side-channel leakage signals encoded into physical layer transmit/joined signaling messages. Privacy concerns also arise from distributed ISAC architectures that involve edge devices, autonomous vehicles, and IoT sensors. These systems commonly replace, often distributed, local sensing data across heterogeneous networks where security properties differ by network. If sensitive data from different communities is aggregated, then the risk of privacy violations grows with any dataset with sensitive data. In addition, legislation (EU General Data Protection Regulation or GDPR, etc.) articulates data minimization and user consent, and this practice of privacy is often lost in real-time ISAC system that can process in highly dynamic environments. To mitigate these challenges, many researchers are examining privacy-preserving technology for ISAC. Researchers have had some success employing Differential Privacy (DP) for sensing data that can be used to add statistical noise to the data in order to stop the reconstruction of the data at the individual level. Homomorphic Encryption (HE) and Secure Multiparty Computation (SMPC) can allow sensing and communications data to do the joint signal processing and learning task, but has a lot of computational cost that limits use in real-time ISAC. Another example of this is privacy-aware waveform design where an ISAC waveform is designed to reduce the understanding of the sensing functionality while maintaining communications integrity. The fusion of sensing and communication in 6G ISAC systems needs a new approach to privacy protections. This new approach must evolve beyond traditional cryptographic mitigation and include other advancements like: AI-assisted anomaly detection, federated and distributed machine learning strategies, and hardware trust mechanisms like secure enclaves. ISAC's transformative potential and user privacy protection from highly skilled adversaries cannot be achieved through traditional methods alone.

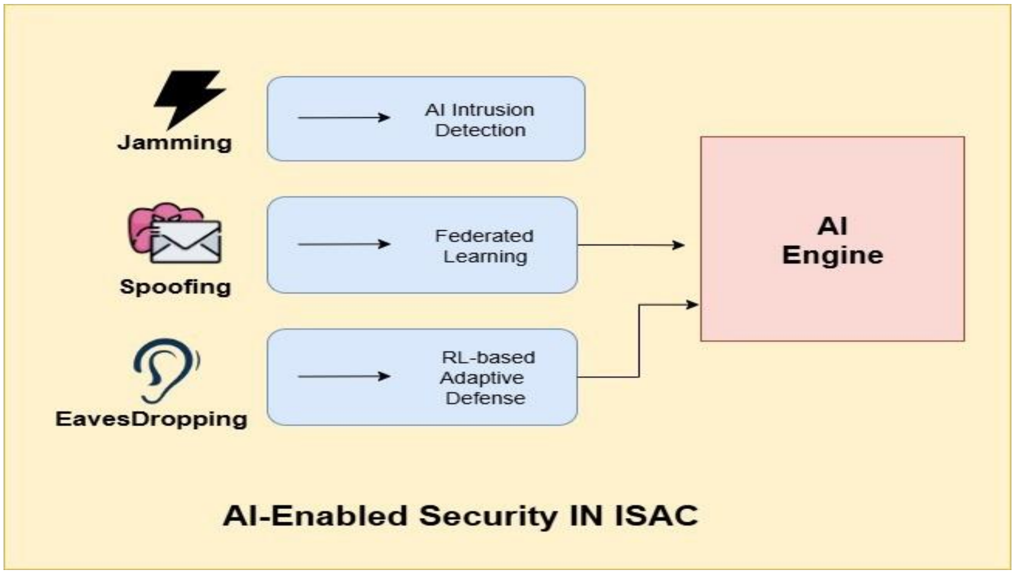


Fig. 5. AI-Enabled Security in ISAC

3) AI/ML-ENABLED SECURITY MECHANISMS

As Integrated Sensing and Communication (ISAC) systems will appear in many different forms connected together, in the 6G era, typical security methods will surely struggle to adapt to an ever-changing and multidimensional threat profile. The duality of ISAC systems leveraging the same signals for communication and environmental sensing, creates new security gaps that must be addressed with a shift to AI/ML-enabled security systems that are adaptive, intelligent, and proactive. Currently, ML algorithms are attached to ISAC applications to avoid or mitigate security threats as they occur. Traditional rule-based intrusions detection systems (IDS) can fail in an ISAC setting due to unpredictable nature of the signals used for joint communication-sensing operations that generate a multitude of dimensions. ML algorithms can utilize different ML models to learn from complicated non-linear associations from a large number of dimensions. For example, convolutional neural networks (CNN) and recurrent neural networks (RNN) learn features from ISAC signals in spectral, spatial and temporal domains to identify the subtle anomaly associated with threats (i.e. jamming, spoofing, eavesdropping). Thus, a ML model was able to learn how to distinguish a jamming signal from a legitimate signal in an ISAC application with high accuracy. Moreover, reinforcement learning (RL) has emerged as another realistic approach for adaptive security in ISAC networks. Unlike supervised ML models that depend on a static dataset, RL agents immerse themselves in the ISAC environment and learn optimal defense policies based on continuous interaction within it. For instance, RL-based algorithms can make real-time adjustments to adapt transmission parameters, transmission directions (beamforming), and even waveform design based on detected threats (e.g., jamming and spoofing) to render the adversary's attacks ineffectual. These agents may even implement proactive security functionalities like attack prevention in secure communication paths in vehicular ISAC settings or directing distributed sensing nodes to recognize and avoid compromised regions. The implementation of federated learning (FL) serves as another mechanism to ensure protection by addressing privacy limitations associated with collaborative training of AI models across non-centralized ISAC devices. In FL, the sensing and communication data does not leave the local device, only the model updates generated from data that never leaves the device, resulting in less risk of exposing sensitive centralized sensing data to adversaries. This not only mitigates risk associated with anonymous adversaries obtaining encrypted or unencrypted centralized data, it allows newly developed security patterns to be learned collaboratively across ISAC networks spanning across geographic spaces. However, the problem of FL does present the risk of poisoning attacks or having the adversary insert malicious model updates back into the local models. Researchers are actively trying to develop robust aggregation techniques or DP mechanisms that could be employed within the FL paradigm in better developing adaptability, specifically in security applications.

4) EMERGING PRIVACY-PRESERVING TECHNIQUES

ISAC technology simultaneously presents new challenges regarding privacy by enabling unprecedented scalability for the collection and processing of data, particularly user data. ISAC systems routinely sense substantial amounts of fine-grained details about the user's physical environment, user location, user activity, and areas of user location, while simultaneously acting on the potentially personal and sensitive amounts of communication data of the user. We have indicated that while dual functionality may further enhance 6G application, it will make ISAC systems more prone to privacy breach regarding the individual if significant protective measures are not put in place. In this regard, the emergence of privacy-preserving techniques [19] has become an important area of research in developing safe and ethical approaches to the use of ISAC technology. One viable answer to these problems is federated learning (FL), a form of distributed machine learning that facilitates collective training of a model based on data from distributed ISAC devices without transferring raw data from each device's local storage. In ISAC contexts, FL allows devices at the edge like vehicles in vehicular networks or Internet of Things (IoT) sensors in smart cities to collectively learn global models for aspects like anomaly detection, channel estimation, or waveform optimization without feedback related to sensitive sensing and communication data being sent. But FL introduces its own set of challenges. Shared gradients allow for model inversion attacks that reconstruct original data or poisoning attacks that corrupt global models through bad actor updates. To meet these challenges, and working with the idea of countering FL vulnerabilities, researchers are proposing the use of secure aggregation protocols together with robust optimization algorithms to help ensure resilience of FL in ISAC environments.

In addition to FL, differential privacy (DP) is an alternative approach to preserve user information. DP adds controlled randomness, or "noise," to the model parameters or the query outputs in such a way that, mathematically, the decision to include or exclude any one data point has no considerable change in the result. When the purpose of the ISAC system is data inference, DP can also be useful for preventing opponents from reasoning about an attribute that may be treated as private, like a user’s exact location or activity behavior from sensing data or metadata of interactions. For example, if a collection of devices were operating together to produce a location-based service indoors, DP can protect the high-fidelity position coordinates by not disclosing exactly where the user is located or usable results, and only describing a general region to the external service, so that the user's anonymity is not compromised. Another approach that shows promise is secure multi-party computation (SMPC), which is a method of allowing several ISAC nodes to perform collaborative, joint computations, and share their private data for those computations without disclosing the data whoever. SMPC agreements can be processed to support collaborative sensing systems, such as cooperative radar imaging, or distributed beamforming, where several devices can share environmental information, and provide other actors with observations without disclosing their private data. Yet, the computational and communication overhead of SMPC undoubtedly presents a major barrier to incorporating into use in real-time ISAC applications. Homomorphic encryption (HE) provides a potential cryptographic solution that allows computations to occur on encrypted information. For ISAC systems, HE would protect the data being used from sensors or conveyed through communication channels, due such that neither intermediate nodes nor cloud servers can access information as plaintext. Therefore, the recent advancements in lightweight HE schemes that are more suited for latency-sensitive ISAC tasks such as edge-assisted signal processing makes adopting HE tenable. To enhance the privacy protection in dynamic, heterogeneous 6G ISAC networks, there is also research on context-aware privacy that would depend on data sensitivity and the trustworthiness of surrounding devices. In public sensing contexts, context-aware privacy may implement robust privacy protection compared to a private home context where privacy measures may be significantly relaxed. We need to balance competing aspects of privacy guarantees, system performance, and limited capacity when implementing privacy-preserving techniques in ISAC. For example, privacy-preserving sensing modality will include the introduction of random noise or means of encrypting data which will lead to more computational delay and detract from sensing resolution and/or communication performance. Research is underway to develop privacy and utility trade-off frameworks for ISAC with adaptive algorithms which can dynamically balance system performance and privacy requirements. In conclusion, current privacy-preservation techniques, such as federated-learning, differential privacy, secure multi-party computation, and homomorphic privacy, are solid starting points for addressing ISAC-specific privacy requirements. Given the significance of ISAC in unifying all forms of communication into the network for the 6G vision, it will be imperative to design privacy preservation which becomes part of that architecture to enable user trust and facilitate legal and regulatory compliance. There is still work to do develop privacy-aware methods of privacy preservation that are light-weight, scalable, contextualized, and real-time for ISAC to be enabled by 6G.

VI. APPLICATIONS AND USE CASES

Through the coupling of integrated sensing and communication (ISAC) and 6G, we expect to radically reshape wireless network types by merging environmental awareness with data transmission reliability. This design provides numerous applications requiring seamless sensing, immediate communication and informed decision-making including various sectors such as tightly coupled autonomous mobility, precision health, industrial automation, etc. 6G ISAC will be the foundation of the next generation of smart systems.

1)WIRELESS COMMUNICATION

The advancement of wireless communication technologies from 1G to 5G has led to the emergence of higher data rates, reduced latency, and increased capacity. However, with the introduction of 6G, wireless communication can no longer simply be treated as a relay for the transfer of information; instead, it is being viewed as a method of allowing for simultaneous communication and sensing. The growth towards Integrated Sensing and Communication (ISAC) focuses on shared hardware and spectral resources (two-way access using a single radio signal) to achieve efficiency in spectral usage/sensing, efficiency, spectral awareness, etc. Wireless communication is necessary for ISAC solving as it provides the high-capacity, ultra-reliable, and low-latency links that can support distributed sensing and real-time decision-making. In the physical layer, the new bandwidth available at the mmWave and THz bands [51] [52] [56] opens up significant bandwidth as a resource to sustain data rates in excess of 1 Tbps and ultra-low latencies less than 1 ms. These characteristics are especially important in environments where sensor arrays are sensing the surroundings while simultaneously supporting a data transmission transmitter; applications in which this would be essential include autonomous vehicles and industrial automation. Massive MIMO (Multiple Input Multiple Output) can include sophisticated capabilities with high antenna arrays and exploit high spatial resolution for sensing and reliable beamforming for transmission purposes.

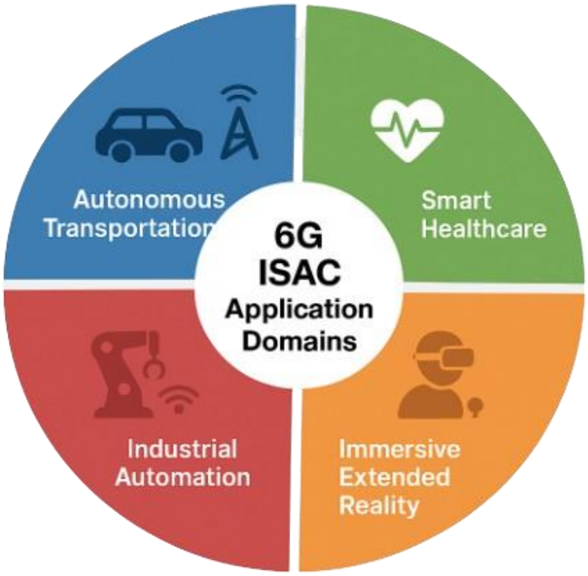


Fig. 6. ISAC Application Overview

In ISAC, the antenna array can support the transmission of transmitted signals while the algorithm captures the echoes from the environment and produce the environmental structure. Reconfigurable Intelligent Surfaces (RIS) are passive or actively controlled reflecting surfaces that can be integrated to adapt the wireless medium and therefore change the propagation environment dynamically. In urban environments where LoS signals are mostly absent, RIS can reflect and amplify the signal in the direction to which transmit a signal, this would be beneficial for reliability of communication and enhancement of the sensor coverage area. AI/ML will build algorithms pacing both ways to reconfigure RIS in real time to procure overall dual functionality from the signals from transmission to sensors under changing channel conditions. The incorporation of AI/ML models into the wireless communication stack offers even more transformative capabilities. Deep learning architectures, such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs), improve channel estimation, beam selection, and interference cancellation. More advanced techniques, specifically reinforcement learning (RL), enable the ISAC to dynamically balance resources between sensing and communication. In addition, federated learning may offer the potential to train AI models in a distributed fashion across devices while protecting user privacy. Federated learning clearly has value in use-cases involving high-sensitivity data, such as in healthcare or defense (which likely in case of the STRATOS use-case). With respect to network architecture, edge intelligence potentially allows for the distributed processing of sensing and communication data leading to substantial reductions in latency and backhaul traffic for ISAC use-cases. In an edge intelligence architecture, for example, Mobile Edge Computing (MEC) nodes will execute AI models processing raw sensory data locally leading to very rapidly interpreting the environment and autonomous decision-making without reliance on seeking further direction from data centres far away. Wireless communication in ISAC has its own challenges. First, sensing and communication will need to coexist and hence, effective waveform designs need to be used to avoid interference. For this, potential solutions are being sought in OFDM variants and new hybrid waveforms. Moreover, security concerns are multiplied as the wireless signals convey both critical sensing information as well as communication payload. The information will become vulnerable to eavesdropping, jamming, and spoofing attacks. Physical layer security mechanisms using artificial noise and beamforming-based security are essential for reducing this risk. In conclusion, wireless communication is foundationally what makes ISAC systems operate as a single entity with perceptual abilities, and the capacity to comprehend and interact with their surroundings accurately and in real-time. By combining state-of-the-art technology which includes massive MIMO, RIS, AI/ML, and edge computing, the 6G-ISAC framework can convert traditional cellular networks to cognitive and adaptable infrastructure to accommodate a huge variety of different applications from autonomous mobility to immersive XR.

2)AUTONOMOUS VEHICLES AND INTELLIGENT TRANSPORTATION SYSTEM(ITS)

Autonomous vehicles (AVs) and Intelligent Transportation Systems (ITS) [54] are some of the most revolutionary use cases of Integrated Sensing and Communication (ISAC) in a 6G environment. The movement towards the fully autonomous, safe and efficient transportation system [45] requires ultra-reliable low-latency communication and high-resolution environmental sensing. With ISAC, vehicles have the ability to simultaneously sense their environment while sharing necessary information with infrastructure and other vehicles (V2X) and discover a new level of situational awareness and decision making ability. The foundation of this operation is provided by 6G's ability to deliver ultra-low latency (0.1 ms) and extremely high reliability (99.9999) which is paramount for safety-critical AV operations. ISAC systems utilize shared radar and communications waveforms, such as Frequency Modulated Continuous Wave (FMCW) radar FM-derived signals in vehicular communications modules, which allow the RF front-end to do two jobs, sense obstacles and transmit/receive. In automated vehicles (AVs), high resolution sensing supports the key tasks of object detection, pedestrian tracking, road condition tracking, and vehicle localization. To achieve this within a connected ecosystem, 6G integrated sensing and communication (ISAC) systems at 100 GHz using massive MIMO (multiple-input multiple-output) arrays, and THz (terahertz) band communications offer localizations at centimeter resolution and gigabit communications concurrently. This integration uses both the communications and the sensing capabilities of the 6G ISAC system to mitigate issues such as non-line-of-sight (NLoS) detection within urban canyons and dense traffic environments that make object detection by traditional sensors (LiDAR, cameras) ineffective due to occlusions or adverse weather conditions. For Intelligent Transportation Systems (ITS), ISAC then provides a framework for AVs, roadside units (RSU), traffic signals, and cloud servers to integrate seamlessly into a highly coordinated and synchronized ecosystem. By installing reconfigurable Intelligent Surfaces (RIS) on urban infrastructure, the RIS can dynamically reconfigure each signal propagation path and maintain their communication and sensing in a very dynamic environment by multi-pathing the signal. For example, RIS can redirect THz signal communication around a large truck or building, maintaining communication links while preserving some sensing footprint without drawing additional radio frequency (RF) power.

3)HEALTHCARE AND REMOTE SENSING

The healthcare sector has the greatest potential to be enhanced with sensing and communication capabilities in 6G networks, considering that we are now in a transition to a period of remote diagnostics, telehealth, and smart healthcare infrastructures. Similarly, remote sensing use cases are expanding as new applications arise in arenas such as environmental monitoring and disaster management, including applications that leverage ISAC (Integrated Sensing- and Communication)-based systems to provide real-time situational awareness and management of high-resolution contexts of spatial and temporal resolution, and performance constraints. Taken together, the combination of these interactions in the health and remote sensing domains in the context of 6G ISAC systems is exciting to see how the grouping of technologies will build in capacity (in terms of massive bandwidth), ubiquitous connectivity, while realizing ultra-low latency. With the integration of sensing and communication, ISAC facilitates continuous and non-contact patient monitoring. An ISAC system can be designed utilizing radio frequency (RF) signals to sense vital signs notably heart(rate), respiratory rate and blood glucose values without direct contact with the patient. RF-based sensing is especially useful for vulnerable patient populations, e.g. seniors or individuals in critical care conditions, compared to additional wearables. For instance, millimeter-wave (mmWave) or Terahertz (THz) communication (e.g. high-resolution radar), can detect small chest movements associated with breathing or superficial microvascular absences under the skin. With machine learning (ML) and artificial intelligence (AI) to apply algorithms to the sensed data and basically build a data profile to incorporate anomaly detection, health outcome forecasting and alerts (e.g. in advance of an adverse health eventually) then the means to intervene would be faster. Additionally, ISAC-enabled telemedicine platforms offer an evolutionary change in remote healthcare delivery by supporting uninterrupted, high-quality audio-visual communications, even in bandwidth-limited and/or remote location situations. With massive MIMO and beamforming technology, the performance gains provided by ISAC enabled systems can be extended even further with improved signal reliability and decreased interference in an effort to support seamless video streams during critical conversations. The combination of sensing and communications is leveraged by the most sophisticated robotic-assisted surgeries, where the control of robotic instruments across distances is reliant on ultra-low latency (<200 µs). In remote sensing; an ISAC-enabled 6G system can be the basis for environmental monitoring, climate change assessment, and incident response as an example. Remote sensing with ISAC-enabled 6G systems provides quick and high-resolution radar and LIDAR systems that, through the integration of the 6G communications systems, can facilitate near real-time tracking of environmental conditions such as air pollution, soil moisture content, or deforestation rates, and high-fidelity waveforms can also be utilized for on-board processing of relevant data. For incident response, such as natural disasters (earthquakes, floods, and wildfires), ISAC-enabled drone and satellite systems are capable of providing both mapping of impacted areas as well as providing the data to emergency responders simultaneously. If necessary, in addition to traditional antennas, Reconfigurable Intelligent Surfaces (RIS) can improve signal propagation depending on the environmental conditions in remote or blocked areas without available infrastructure. Integration of AI/ML is important in both areas. Deep learning algorithms process large amounts of sensed data to obtain actionable insights, such as detecting early indicators of epidemics by characterizing population-level health metrics, or inferring potential flood risk based on excessive rainfall detected within satellite imagery. Federated learning (FL) [47] offers a unique approach for privacy-preserving data management in a healthcare context, providing a distributed approach to collaborative model training across hospitals or clinics, while not revealing sensitive patient data-even in places with privacy legislation, such as HIPAA or GDPR. Reinforcement learning (RL) can be used to optimize resource allocation in remote sensing networks even under stressful operational phases, where bandwidth and power are limited in environments like emergency operations. However, these advances are not without problems. In the healthcare context, it is important to consider individuals' privacy because RF based sensing systems may unintentionally display private information. Systems employing physical-layer security and differential privacy could been an important option to consider for preserving security of sensitive health data. In the context of remote sensing, the development of architectures that provide functionalities which process heterogeneous sensing modalities (e.g radar, LIDAR, infrared) and provide interaction with high-speed communication links face scheduling and interference problems which require design and implementation of advanced waveforms and signal processing algorithms. In conclusion, the healthcare and remote sensing in

6G-enabled ISAC systems with the support of AI/ML is a succession of a proactive, connected, and intelligence services. Healthcare and remote sensing in 6G-enabled ISAC systems provide greater quality of life, improved disaster recovery, and sustainable development with the security and privacy of data.

4)INDUSTRIAL AUTOMATION AND INDUSTRY 5.0

Shifting from Industry 4.0 to Industry 5.0 signifies a major shift to human-centric, resilient, and sustainable industrial ecosystems. The push to Industry 5.0 leverages 6G-enabled Integrated Sensing and Communication (ISAC) systems and the next level of Artificial Intelligence (AI)/Machine Learning (ML)-enabled capabilities [54] [55] [57]. Industry 4.0 was about streamlining processes, automation, cyber-physical systems, and connectivity. Industry 5.0 focuses on the collaboration between human and machine, personalized manufacturing, and reconfigurable production environments. ISAC is the foundation of this transition and will enable decision making in the moment, combined with ultra-reliable low-latency communications (URLLC) in complex factory environments. Industry 5.0 is fundamentally linked to smart factories, in which not only robotic systems, autonomous guided vehicles (AGVs), and collaborative robots (cobots) will co-exist with humans, with human co-design of the workspace. A complexity of interactions in the factory environment means that extreme precision in positioning, navigation, and environmental perception will be required. The goals of manufacturers are extreme precision, high speed, and resilience in their factory design plans. Similarly rise of smart microgrids also requires efficient energy and power management [58] [59] [60]. 6G ISAC systems will utilize massive MIMO, beamforming, and THz communications to achieve these goals. THz has sub-millimeter accuracy localization that will allow AGVs to operate safely (i.e., avoiding collisions) and efficiently and benefit something as advanced as a complex and dynamic factory layout. At the same time, Reconfigurable Intelligent Surfaces (RIS) combinations will create app-based adaptive radio environments to better utilize signal propagation and limit any interference from a studio full of machines and metal surfaces. AI/ML is disruptive in being able to sift through the immense amounts of sensed data collected from distributed devices and networks. Deep learning processes video feeds and radar data to recognize irregularities in machinery function, such as nip predicting equipment malfunctions before they occur (predictive maintenance). Reinforced learning (RL) algorithms further optimize task scheduling of robots and resource allocation over the network for latency and energy efficiency. Federated learning (FL) [46] allows factories to collaboratively build strong "AI" models without sharing their sensitive production data and protecting data privacy. Industrial settings also exhibit a high degree of variability and unpredictability. Edge intelligence, along with ISAC, allows for real-time adaptability that gives manufacturing systems the ability to dynamically react to unpredictable situations, such as sharp variances in product demand or unexpected supply chain delays. For example, with edge devices holding ISAC capabilities, a manufacturing operation can immediately detect a bottleneck at a certain point on the production line, and quickly propagate this critical information across the network to improve workflows. The importance of security and privacy is elevated with an increasing number of networks and connected devices in collaborative industrial environments populated by human resources in Industry 5.0. Privacy-preserving Artificial Intelligence and security mechanisms at the physical-layer are assisting in enhancing protection of sensitive operational data from cyberattacks and industrial espionage. The ISAC paradigm provides both environmental awareness and secured communication links within an all in one system, allowing a more secure communication and sensing environment than if these tasks were performed separately. Additionally, ISAC will enhance new industrial technologies as digital twin configurations where a digital twin of the physical factory can be continuously updated with real-time data from the connected machines. Digital twin technologies enable complex simulation and predictive analytic which will assist the factory manager in becoming pro-active in optimizing a process. All of these technologies rely upon high throughput and low latency communication coupled with high density accurate environmental sensing which are all two core capabilities of 6G ISAC systems. To conclude, 6G ISAC and AI/ML applications in industrial automation will be an important evolution toward emerging intelligent, collaborative, and secure manufacturing environments. These capabilities will enhance the productivity and efficiency factors and also support the Industry 5.0 concept of operating in sustainable and human centered workplaces of the future where humans and machines work collaboratively.

5)IMMERSIVE EXPERIENCE AND EXTENDED REALITY(XR)

The rise of Extended Reality (XR), Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) has dramatically affected how humans and machines share a media ecosystem. XR enhances this experience by creating rich digital environments that have immersive qualities where real and virtual elements stabilize and supersede that have strong narrative or high context characteristics as the user steps into another world. However, as XR technology matures and creates dependence on interconnectedness at ultra-high data rates, ultra-low latencies on the order of milliseconds, accurate localization and sufficient context awareness, and continues to push current 5G networks and conventional sensing systems to the limits during operation, it becomes a technology that is increasingly burdensome to deploy for industry in high application scenarios. The logical foundational technology to support next generation XR for entertainment, health, education and defense is Integrated Sensing and Communication (ISAC) application with observability and augmented capabilities that are enhanced with AI/ML strategies. Among the most significant accelerators for repositioning XR as a technological paradigm shift is the very fabric of ultra-reliable communications (URLCC), specifically the low jitter reliability, as this will occur as a perceivable improvement over previous X experiences where these parameters of like protocol were never possible without very negative consequences for different body positions leading to augmented motion sickness determined by excess motion-to-photon latency of frame rate to motion transfer. Operating in the sub-THz and THz spectral domains, 6G ISAC systems offer massive bandwidth to support delivery of ultra-high definition streaming of 8K, and even holographic video. This capability is essential for real-time rendering of high-fidelity virtual environments and overlays. Further, with Massive MIMO and beamforming capabilities, a 6G-enabled XR experience will also be able to maintain consistent high-quality connections in crowded and dynamic spaces like theme parks and virtual conferences or seminars. Sensing is essential for XR systems to accurately model and engage naturally with real-world environments. With ISAC's high-resolution radar and LIDAR features, we can create accurate 3D models of the environment and with millimeter accuracy recognize gestures or track the human body as it moves through these environments. For example, in AR-assisted surgery, ISAC allows surgeons to view patient-specific holographic anatomical models overlaid on their actual bodies building on high-precision localization and low-latency updates of user position. AI and ML techniques act as the intelligence layer for XR experiences, by merging multi-modal sensor data and optimizing network resources. Such deep learning models analyze user motion or other real time environmental data to continuously adapt scene rendering to improve realism and responsiveness. Reinforcement learning-based algorithms could dynamically optimize beamforming and resource allocation to continuously provide a smooth experience to a user who is mobile or surrounded by other users, even when the network is congested. And federated learning approaches provide the ability to disperse XR-related AI model training on edge devices while providing privacy to the user and minimizing latency as well as reliance on centralized data servers. Privacy and security are serious considerations in XR applications, especially in instances with personal data such as biometric data, user facial expressions, or recording private work and living spaces, as recorded via AR glasses. ISAC systems provide privacy-preserving AI methods and physical layer security approaches, in a way that immersive experiences (e.g. XR experiences) can be developed without affecting a user's trust. In collaborative XR, such as virtual classrooms, virtual workplaces, and multiplayer videogames, ISAC systems provide the ability of tracking many user participants and objects, which are mapped to a 3D space, and support the seamlessness between physical and virtual worlds, which is imperative for the early development of the Metaverse. In addition, by providing ultra-low latency communication between devices and servers, ISAC support for haptic feedback systems permit the user's tactile response to be in sync with the other elements of the experience. In defense applications, XR provided through ISAC has the capability to give soldiers real-time situational awareness overlays in enemy environments and augment multiple sources of data from sensors into AR representations inside their helmets. For industrial applications, XR offered enhanced remote equipment maintenance through ISAC's capability to insert operational and maintenance data and steps into the technician's view using augmented reality. In summary, the integrated potential of 6G ISAC technology and AI/ML tools will provide the foundational building blocks for next generation XR tools in human perception and interaction with the environment facilitating merging of the physical with the virtual, and systematically unleash the conceptual excitement of immersive experiences across all applications.

VII. OPEN CHALLENGES AND FUTURE DIRECTIONS

While 6G-enabled Integrated Sensing and Communication (ISAC) systems improved with Artificial Intelligence and Machine Learning (AI/ML) show enormous potential for revolutionizing wireless communications and sensing paradigms, the path to full-scale integration includes steep technical relationships. It is essential to solve one or more of these unresolved challenges to achieve the transformative applications discussed in the previous section, from immersed XR services to autonomous transportation and smart cities.

Spectrum Scarcity and Coexistence: Integrating technologies at sub-THz and THz spectrum presents some of the most demanding aspects of deployment with respect to the speed of technology integration. While these bands can accommodate a huge array of potential bandwidth and spectrum, the limitations of performance due to path loss, molecular absorption, and blockage is characterized by the band's propagation characteristics. Integration of multiple ISAC systems into high-density urban environments will enabled interference mitigation and prevention in both contexts of data communications and environment sensing. AI-based algorithms will provide dynamic spectrum allocations and sharing for improving spectral efficiency. New regulation will need to be also implemented in conjunction with new policies that develop and testing new approaches to regulating the ISAC spectrum as multi-tasking modality that will tolerate trade-offs of sensing and data communications capabilities.

Robust Channel Modeling and Environmental Dynamics: Accurate channel models for ISAC remain an open research area, especially thinking about the dynamic environments envisaged for 6G use cases in typical daily life circumstances. Common channel models fail to effectively represent the chores of sensing and communication and how they jointly determine channel behavior. For example, mobile scenarios with multiple reflecting surfaces and dynamic obstacles to consider will require suitable channel representations that will incorporate real-time physical environment awareness. Future research should explore environment-aware, physics-based and data-driven channel models that involve both stochastic and deterministic approaches. It is also important to note that we need to incorporate Reconfigurable Intelligent Surfaces (RIS) and their programmable reflection behaviors in channel modelling.

AI/ML Integration and Interpretability: AI and ML are at the heart of ISAC, however, there are challenges in terms of computational complexity, high energy consumption, and most importantly, lack of interpretability. Training large-scale deep neural networks for tasks like beamforming, waveform optimization and multi-user resource allocation can burden edge devices that have limited computational capabilities. In addition, there are trust issues with many AI models which are viewed as "black boxes," and so their use in safety-critical domains like healthcare and defense is problematic. Some future research directions and activities are lightweight explainable AI models that are based on human-interpretable decision-making processes and federated learning paradigms which facilitate collaborative training while maintaining privacy.

Privacy and Security Concerns: The environmental sensing and user data collection capabilities of ISAC systems can lead to privacy issues around unauthorized site tracking or eavesdropping and can also be susceptible to spoofing attacks [53]. Additionally, AI models raise specific issues as adversaries can use crafted inputs (maliciously or not) to produce false detections or degrade communication performance. New privacy-preserving techniques such as homomorphic encryption and differential privacy, as well as secure multi-party computation techniques offer potential solutions, but existing implementations would require adaptations to meet the latency and bandwidth requirements imposed by ISAC systems. Furthermore, we must build upon existing physical-layer security techniques to address risks and mitigations associated not only with ISAC/sensing but also from evolving RIS and denser potential massive MIMO scenarios.

Hardware Limitations and Energy Efficiency: For ISAC systems to be practically implemented, hardware must be able to operate effectively at high frequencies and should be power and energy efficient. It is still, however, very difficult to fabricate inexpensive and very low-power consuming transceivers, analog-to-digital converters, and antenna arrays for sub-THz bands. Even more defined when considering the support of AI processing at the edge for real-time adaption where power consumption is vital. There are novel hardware architectures that utilize nanotechnology, photonic elements, and energy scavenging methods to address these challenges, but they are still in early stages of usage.

Standardization and Interoperability: To achieve global interoperability of ISAC systems, the standardization process needs to progress at a rapid pace. The existing frameworks by 3GPP and ITU-R do not sufficiently cover the specific needs of ISAC systems. The need to establish interoperability standards for heterogeneous networks composed of UAVs, satellites, terrestrial infrastructure, and IoT devices is imperative. This will require cooperation between academia, industry, and regulatory authorities to establish performance specifications, testing requirements, and security specifications.

Future Research Directions: The future of innovation in intelligent connectivity within 6G will include multi-disciplinary processes that blend wireless communications with sensing technologies, AI/ML and hardware design. There are exciting research opportunities such as:

- Unified optimization frameworks to jointly optimize sensing and communication performance with real-time requirements.
- Quantum-enhanced sensing and communication using quantum entanglement, quantum MLA, and quantum communication.
- Bio-inspired architectures to create energy-efficient and adaptive ISAC systems that employ some characteristics of neural systems.
- Interaction with space-air-ground integration networks (SAGIN) to offer ubiquitous coverage in remote and underserved areas.

In conclusion, addressing the open challenges above is essential to achieve the next level for 6G ISAC systems. Intelligent connectivity will be realized through multi-dimensional, cross-domain collaboration, and innovations that push the boundaries of the technology stack at all levels. This will enable an implementation of intelligent connectivity that is AI-enhanced, environment-aware, and respects privacy and privacy will usher in the new era of intelligent connectivity.

VIII. CONCLUSION

The joint advancement of Integrated Sensing and Communication (ISAC) and Artificial Intelligence (AI) is catalyzing a significant transformation toward 6G wireless networks. We examined the technology enablers, spectral bands, channel modelling approaches, AI/ML methods, and security considerations in realising 6G-enabled ISAC systems. The combination and integration of Massive MIMO, Reconfigurable Intelligent Surfaces (RIS), and sub-THz/THz communication will create additional capabilities for ISAC by providing higher resolution, ultra-low latency and ubiquitous connectivity. This advancement will also bring many challenges to address, including spectrum coexistence, hardware constraints, an ever-changing environment, and various trade-offs between sensing and communication.

AI and ML are important tools for tackling these complexities and enabling more elaborate solutions to dynamic beamforming, intelligent waveform design, and privacy-preserving data processing. Nevertheless, AI presents challenges with model interpretability, computational efficiency, and distance from adversarial attacks, necessitating the development of explainable and resource-efficient learning architectures.

This study also highlights new security and privacy frameworks specifically for the ISAC environment which demonstrates the value of holistic approaches encompassing a full suite of physical layer defense to system level protection. Examples in autonomous vehicles, health care, industrial automation and immersive extend reality (XR) demonstrate the inevitable transformation potential of 6G-ISAC, and the transformation impact on smart societies of the future.

In summary, the anticipated presence of AI/ML-assisted ISAC in 6G networks will certainly face a lot of interdisciplinary research in different policy and technology areas. Future work must develop standards, new algorithms, hardware capabilities, and ethical considerations in ways that ISAC systems will be technically feasible and socially responsible. In order to achieve the vision of intelligent, secure, and sustainable 6G networks to support the next generation of applications and services, these open research challenges must be overcome.

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