



ISAC Revolution: Array Antennas Enabling Integrated Sensing and 6G Communications

Dr. M. Ramanan^{1*} **Dr. S. Mathumohan**² **Mr. K. Surendra Reddy**³ **Dr. I. Sofiya**⁴

¹Teaching Assistant, Department of Physical Sciences and IT, Agricultural Engineering College and Research Institute, Tamilnadu Agricultural University, Coimbatore – 641003, India.

²Professor, Computer Science and Engineering, Fatima Michael College of Engineering and Technology, Madurai, Tamilnadu – 625020, India.

³Assistant Professor, Department of Data Science, Malla Reddy (MR) Deemed to be University, Hyderabad, Telangana 500100, India.

⁴Assistant Professor, School of Computational Intelligence, Joy University, Vaddakkankulam, Tamil Nadu – 627116, India.

DOI: <https://doi.org/10.70333/ijeks-05-07-011>

*Corresponding Author: ramanan.m@tnau.ac.in

Article Info: - Received : 12 May 2026

Accepted : 25 June 2026

Published : 30 July 2026

Abstract

Integrated sensing and communication is emerging as a core idea for next-generation wireless networks, especially in the 6G era. This work explores how array antennas can serve as a central enabler of this shift by supporting both high-capacity communication and precise environmental sensing through the same radio hardware. Unlike traditional systems that separate radar and communication functions, ISAC aims to combine them into a unified framework that improves spectral efficiency, reduces hardware complexity, and enables intelligent services such as vehicle perception, smart infrastructure monitoring, and industrial automation. Array antennas play a critical role by offering beam steering, spatial filtering, and adaptive transmission capabilities that allow the network to focus energy where it is needed most. The paper also discusses key design challenges, including beam management, waveform compatibility, interference control, calibration, and near-field effects in dense 6G deployments. In addition, it highlights how advanced signal processing and machine learning can enhance joint sensing and communication performance. Overall, the study presents array antenna-based ISAC as a practical and transformative pathway toward flexible, efficient, and context-aware 6G networks.

Keywords: *Integrated Sensing and Communication, Array Antennas, 6G Wireless Networks, Beamforming, Massive MIMO, Joint Waveform Design, Smart Environments, Radio Sensing.*



© 2026. Dr. M. Ramanan et al., This is an open access article distributed under the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

1. Introduction

Integrated sensing and communication (ISAC) is becoming one of the most important concepts in the evolution of wireless systems because it combines two functions that were traditionally designed separately. Instead of using one network for data transmission and another for radar-style sensing, ISAC allows both tasks to operate together on shared spectrum, shared hardware, and shared signal resources. This approach is especially relevant for 6G, where networks are expected to do much more than connect devices [1].

They will also need to support perception, localization, environmental awareness, and intelligent decision-making in real time. Array antennas are central to this transformation because they provide spatial control over transmitted and received signals, making it possible to direct energy, suppress interference, and detect objects or users with high precision. As a result, ISAC is not only a technical upgrade but also a shift toward smarter, more efficient wireless infrastructure [2].

1.1 Background and motivation

The motivation for ISAC comes from the rapid growth of wireless applications that require both reliable communication and accurate sensing. In modern environments, systems are increasingly expected to know not only how to send information but also how to understand what is happening around them. For example, autonomous vehicles need communication links for coordination, but they also require sensing capabilities to detect obstacles, traffic patterns, and nearby motion [3].

Similarly, smart factories, healthcare systems, and intelligent cities need networks that can monitor their surroundings while still delivering low-latency data transfer. Traditional wireless architectures are inefficient in this respect because sensing and communication are handled by separate platforms, which increases cost, hardware complexity, and spectrum usage. ISAC addresses these limitations by merging the two functions into a single framework. This makes the system more compact, more energy efficient, and more suitable for future intelligent services. The growing demand for context-aware

connectivity is therefore the main force driving research in this area [4].

1.2 From 5G to 6G: the need for ISAC

The transition from 5G to 6G is not simply about faster data rates; it is about creating a network that can sense, reason, and respond to the physical world. While 5G introduced enhanced mobile broadband, massive machine-type communications, and ultra-reliable low-latency services, 6G is expected to extend these capabilities by adding environmental awareness and digital intelligence. This is where ISAC becomes essential [5].

Future 6G systems will support applications such as immersive extended reality, autonomous mobility, industrial robotics, and precision monitoring, all of which require the network to detect positions, movements, and object characteristics in addition to transmitting data. Using ISAC, the same radio signal can support communication and sensing simultaneously, which reduces redundancy and improves efficiency. It also helps networks operate in dense and dynamic scenarios where spectrum and hardware resources are limited. [6].

1.3 Role of array antennas in integrated sensing and communication

Array antennas are fundamental to ISAC because they offer the spatial flexibility needed to combine sensing and communication within one system. By using multiple antenna elements, the transmitter and receiver can steer beams in selected directions, focus energy on intended users, and improve the ability to detect targets or reflectors in the environment. This directional control is particularly valuable in 6G, where millimetre-wave and sub-terahertz frequencies require highly precise beam management due to increased path loss and limited coverage [7].

Array antennas also support adaptive beamforming, which allows the system to dynamically adjust its radiation pattern depending on whether the priority is data transfer, target detection, or both. In addition, arrays help suppress interference and improve spatial resolution, which are important for separating communication users from sensing targets in crowded environments. Their role is therefore not limited to signal transmission; they

function as the physical layer enabler that makes integrated sensing and communication practical, scalable, and efficient in future wireless networks [8].

2. Fundamentals of ISAC

Integrated sensing and communication, or ISAC, is a framework in which wireless systems perform data transmission and environmental sensing together instead of as separate functions. This idea is important because future networks need to do more than carry information; they also need to detect objects, estimate positions, monitor motion, and understand the surrounding environment [9].

ISAC makes this possible by using a common waveform, common antenna resources, and common signal-processing methods for both tasks. In practical terms, this means a network can support communication links while also acting like a sensing platform. The result is a more efficient use of spectrum, hardware, and energy. For 6G, this concept is especially valuable because it supports intelligent applications that require both connectivity and awareness in real time [10].

2.1 Concept of integrated sensing and communications

The core concept of ISAC is to merge sensing and communication into one coordinated wireless framework. In conventional systems, communication focuses on delivering bits reliably, while sensing focuses on detecting range, velocity, angle, or motion of targets. ISAC combines these two objectives so that the same transmitted signal can carry user data and simultaneously illuminate the environment for sensing purposes [11].

This dual function creates a more unified network architecture and reduces duplication of resources. It also opens the door to intelligent services such as autonomous driving, smart surveillance, industrial automation, and indoor localization. The main advantage is that the network becomes more versatile without requiring completely separate sensing equipment. However, achieving this integration requires careful waveform design, beam control, and receiver processing so that neither function significantly degrades the other [12].

2.2 Shared spectrum and shared hardware principles

A major principle behind ISAC is the use of shared spectrum and shared hardware. Instead of allocating one frequency band for communication and another for sensing, ISAC systems try to operate both functions in the same spectral space. This improves spectral efficiency and reduces regulatory and deployment complexity. Shared hardware means that the same antennas, radio-frequency chains, and processing units can support both tasks, which lowers cost and size while improving integration [13].

This principle is especially useful in compact 6G devices and dense network deployments, where space and power are limited. By reusing infrastructure, operators can build systems that are more economical and easier to scale. The challenge is to design hardware that can meet the demands of both high-data-rate transmission and accurate sensing without excessive interference or performance loss. Careful calibration and signal separation are therefore essential [14].

2.3 Sensing-communication trade-offs

Although ISAC offers many benefits, it also introduces trade-offs between sensing and communication performance. A signal optimized for high-rate data transmission may not always be ideal for precise sensing, and a waveform designed for accurate target detection may reduce communication efficiency. For example, improving beam focus for one user can limit the spatial coverage needed for sensing. Similarly, allocating more power to communication can weaken sensing sensitivity, while prioritizing sensing may reduce user throughput [15].

These trade-offs make system design more complex because both objectives must be balanced according to the application scenario. In some cases, communication may be the priority, while in others sensing accuracy may matter more. Effective ISAC systems therefore require adaptive optimization methods that can dynamically adjust waveform, power, and beam patterns. The goal is not to maximize one function alone, but to find the best joint performance for the intended use case [16].

2.4 Key performance metrics for ISAC systems

The performance of an ISAC system is measured using both communication and sensing metrics. On the communication side, important indicators include data rate, spectral efficiency, latency, reliability, and coverage. On the sensing side, key metrics include range accuracy, angle resolution, velocity estimation, detection probability, and false alarm rate. Since ISAC combines two functions, it is also important to evaluate how well the system balances them. Joint metrics often examine trade-off curves that show how sensing quality changes as communication performance improves, or vice versa [17].

Another useful measure is energy efficiency, since ISAC aims to reduce the total power required for dual-function operation. In practical deployments, robustness to interference, mobility, and environmental clutter is also important. These metrics help researchers and engineers compare different ISAC designs and determine whether a system is suitable for applications such as vehicular networks, smart infrastructure, or industrial monitoring [18].

3. Array Antenna Basics

Array antennas are a group of radiating elements arranged and fed in a controlled way so that their combined radiation pattern achieves a desired shape. In ISAC and 6G systems, arrays are essential because they help steer beams, improve coverage, increase gain, and support both sensing and communication from the same platform [19]. Their performance depends on element spacing, array geometry, excitation amplitudes, and phase differences across the elements. A properly designed array can concentrate energy in selected directions while reducing unwanted radiation in others, which is exactly what joint sensing and communication requires. The same principles also make it possible to estimate direction, track targets, and support high-frequency 6G links [20].

3.1 Antenna array configurations

Antenna arrays can be arranged in several configurations, including linear arrays, planar arrays, circular arrays, and conformal arrays. A

linear array places elements along one axis and is often used for simpler beam steering in a single plane. A planar array extends the concept to two dimensions, allowing control over both azimuth and elevation, which is very useful for 6G base stations and sensing platforms [21]. In general, the total array factor for an N -element array can be written as

$$AF(\theta) = \sum_{n=0}^{N-1} w_n e^{jn\psi} \quad (1)$$

where w_n is the excitation weight of the n -th element and ψ is the progressive phase term. For a uniform linear array with spacing d , the phase term is often

$$\psi = kdcos\theta + \beta \quad (2)$$

where $k = \frac{2\pi}{\lambda}$ and β is the applied phase shift [22]. This relationship shows how geometry and phase control determine the overall pattern. In ISAC, planar and massive MIMO arrays are especially valuable because they provide high spatial resolution and flexible beam shaping.

3.2 Beamforming principles

Beamforming is the process of controlling the relative amplitude and phase of antenna elements so that radiated energy is directed toward a desired angle. The main idea is to make waves from different elements add constructively in the intended direction and destructively elsewhere. For a steering vector $a(\theta)$ and weight vector w , the array response can be expressed as

$$y(\theta) = w^H a(\theta) \quad (3)$$

and the corresponding beam pattern is

$$P(\theta) = |w^H a(\theta)|^2 \quad (4)$$

If the goal is to steer the beam toward θ_0 , then the weights are often chosen to match the conjugate of the steering vector, such as $w = a(\theta_0)$

This creates a strong main lobe in the desired direction [23]. In practice, beamforming may be fixed, phase-only, time-delay-based, or adaptive depending on the system requirement.

For ISAC, beamforming must often support both user connectivity and target sensing at the same time, so the weights may be jointly optimized for communication quality and sensing accuracy.

3.3 Array gain, directivity, and sidelobe control

Array gain describes how much the antenna array increases signal strength in a chosen direction compared with a single element. Directivity measures how concentrated the radiation is in one direction relative to the average radiated power. A common expression for directivity is

$$D = \frac{4\pi U_{\max}}{P_{\text{rad}}} \quad (5)$$

where $U_{\max}$ is the maximum radiation intensity and P_{rad} is the total radiated power [24]. If antenna losses are included, the realized gain can be written as

$$G = \eta D$$

where η is the radiation efficiency [25].

Sidelobes are the smaller unwanted lobes outside the main beam, and they matter because they can cause interference, reduce sensing accuracy, and leak energy into undesired directions. One way to reduce sidelobes is amplitude tapering, where the outer elements are weighted less than the center elements. This usually reduces sidelobes but can also widen the main beam and slightly reduce directivity. In ISAC, sidelobe control is important because it improves both link reliability and target discrimination [26].

3.4 Wideband and multi-band array operation

Wideband and multi-band operation is important in 6G because different services may use different frequency ranges, including sub-6 GHz, millimetre-wave, and possibly sub-THz bands. A wideband array must maintain beam

stability across a large frequency range, but this is difficult because the beam angle can vary with frequency, a phenomenon known as beam squint [27]. For a phase-shift array, the steering angle may change as frequency changes, which can reduce performance at the band edges. Time-delay beamforming helps reduce this problem because it applies true delays instead of only phase shifts. The ideal delay for steering toward θ_0 is

$$\tau_n = \frac{nd \cos \theta_0}{c} \quad (6)$$

where c is the speed of light. For multi-band arrays, the design must also ensure that the same physical structure can work efficiently across separated frequency bands [28]. This is often achieved using broadband elements, reconfigurable feeds, or hybrid analogue-digital architectures. In ISAC, wideband and multi-band arrays are especially useful because they support high-resolution sensing as well as flexible high-capacity communications.

4. ISAC-Enabled Antenna Architectures

ISAC-enabled antenna architectures are designed to support sensing and communication through a single physical platform. These architectures go beyond conventional antenna designs by introducing flexibility in radiation pattern control, polarization, beam steering, and spatial resolution, which are all crucial for 6G systems [29]. The main idea is to exploit additional degrees of freedom so the antenna structure can serve multiple roles without requiring separate sensing and communication hardware. This is particularly useful in dense and dynamic environments where compactness, efficiency, and adaptability are essential. In ISAC, the antenna architecture is not just a front-end component; it becomes a core part of the system intelligence [30].

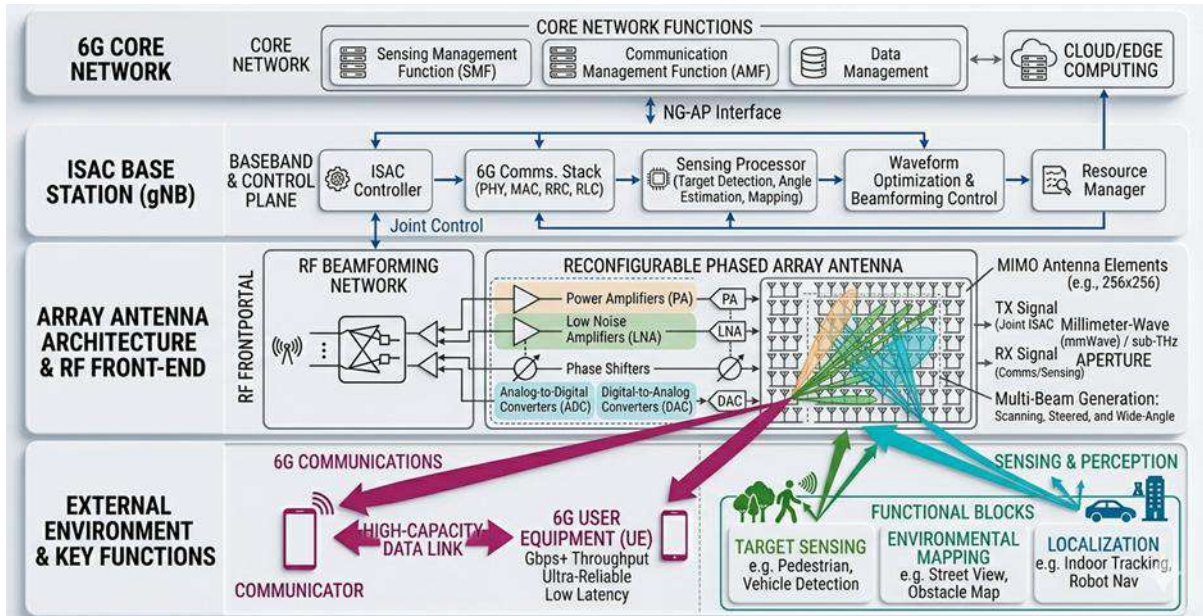


Figure 1. ISAC-Enabled Antenna Architectures

4.1 Dual-function antenna arrays

Dual-function antenna arrays are built to transmit communication signals while simultaneously supporting sensing tasks such as target detection, localization, and tracking. These arrays often use shared aperture designs so that the same physical elements contribute to both functions. A common way to model the transmitted signal is

$$x(t) = w_c s_c(t) + w_s s_s(t) \quad (7)$$

where $s_c(t)$ is the communication signal, $s_s(t)$ is the sensing signal, and w_c and w_s are the corresponding beamforming weights [31]. This allows one antenna system to serve two objectives at once. In practical ISAC platforms, the challenge is to ensure that the sensing waveform does not disturb communication quality and that the communication waveform still provides enough structure for accurate sensing. Recent research shows that dual-functional arrays can be designed with beam-scanning or quasi-uniform radiation properties to support both user coverage and sensing accuracy. Their appeal lies in compactness, spectrum reuse, and reduced hardware duplication [32].

4.2 MIMO and massive MIMO for ISAC

Multiple-input multiple-output, or MIMO, is one of the most powerful techniques for ISAC because it creates spatial diversity and enables fine control over transmitted and received

signals. In MIMO-based ISAC, different antennas can be used to form beams, suppress interference, and estimate direction or range with high precision. Massive MIMO extends this idea by using a very large number of elements, which increases spatial resolution and makes joint sensing and communication more effective in high-frequency 6G settings [33]. The received signal in a MIMO system is often represented as

$$y = Hx + n$$

where H is the channel matrix, x is the transmitted vector, and n is noise. For ISAC, the same spatial structure helps both channel estimation and target sensing. Massive MIMO is especially important because it provides narrow beams, strong array gain, and support for multi-user operation, all of which are valuable for next-generation integrated networks. It also enables joint optimization across many antennas, which improves robustness in complex environments [34].

4.3 Reconfigurable and adaptive arrays

Reconfigurable and adaptive arrays are designed to change their radiation behaviour depending on the environment or service requirement. These arrays can modify phase, amplitude, polarization, or even the effective geometry of the antenna elements. In ISAC, this adaptability is valuable because sensing and communication conditions may change rapidly, especially in mobile or cluttered scenes. Recent studies show that reconfigurable pixel antennas

and compound reconfigurable arrays can exploit electromagnetic-domain degrees of freedom to improve sensing rate, communication security, and overall system efficiency. An adaptive array may optimize its weight vector as

$$w^* = \arg \max_w \alpha R_c + (1 - \alpha) R_s \quad (8)$$

where R_c is communication performance, R_s is sensing performance, and α balances the two objectives. This kind of framework allows the antenna to respond dynamically to changing priorities. Such designs are highly promising for future 6G networks because they combine flexibility, compactness, and performance optimization [35].

4.4 Antenna-in-package and antenna-on-chip solutions

Antenna-in-package and antenna-on-chip solutions are important for miniaturized ISAC hardware, especially at millimeter-wave and sub-THz frequencies. Antenna-in-package integrates the antenna with the packaging layer, which reduces interconnect losses and improves compactness. Antenna-on-chip places the antenna directly on the semiconductor chip, enabling highly integrated transceiver designs for short-range and highly dense applications. These solutions are attractive for 6G because they support small form factors, low latency, and high-frequency operation [36].

However, they also face challenges such as thermal management, fabrication tolerance, mutual coupling, and efficiency loss. In ISAC, the integration must be carefully engineered so that both communication and sensing functions remain reliable. This is particularly challenging when the antenna must support wideband or multi-band operation in a compact module. Despite these issues, such integration strategies are widely viewed as key enablers for future wearable devices, embedded sensors, automotive units, and compact base stations [37].

5. Beamforming and Spatial Sensing

Beamforming and spatial sensing are central to ISAC because they allow the same antenna array to deliver communication signals and extract environmental information at the same time. The main idea is to shape the

radiation pattern so energy is sent where it is needed and received from the directions that matter most. In 6G systems, this is especially important because dense deployments, high frequencies, and mobility make fixed coverage patterns inefficient [38].

Beamforming improves link quality by increasing signal strength in desired directions, while spatial sensing uses the same array structure to detect angles, movements, and target locations. Together, these capabilities make the antenna array an active part of the sensing and communication process rather than a passive front-end component [39].

5.1 Spatial filtering for communication and sensing

Spatial filtering refers to the ability of an antenna array to emphasize signals from some directions while suppressing others. In communication, this helps the system focus energy on an intended user and reduce interference from neighbouring users or unwanted reflections. In sensing, spatial filtering helps isolate echoes from a particular object or region while rejecting clutter from the background. Mathematically, this is often represented through the beam response

$$P(\theta) = |w^H a(\theta)|^2 \quad (9)$$

where w is the beamforming vector and $a(\theta)$ is the steering vector for direction θ . A strong response at the desired angle and low response elsewhere indicates effective spatial filtering [40].

In ISAC, this property is especially useful because it allows one array to communicate with a user and sense the surrounding environment using different spatial views. Good spatial filtering improves both reliability and sensing clarity, particularly in crowded or reflective environments [41].

5.2 Direction-of-arrival estimation

Direction-of-arrival, or DoA, estimation is the process of determining the angle from which a received signal arrives at the antenna array. This is one of the most important sensing functions in ISAC because it supports localization, tracking, and object detection.

Arrays estimate DoA by comparing the phase differences across multiple elements, since signals reaching different antennas arrive with slightly different delays [42]. For a uniform linear array, the steering vector is often written as

$$\mathbf{a}(\theta) = [1, e^{jk d \sin \theta}, e^{j2k d \sin \theta}, \dots, e^{j(N-1)k d \sin \theta}]^T \quad (10)$$

where $k = \frac{2\pi}{\lambda}$. By matching the received signal against possible steering vectors, the system can identify the most likely arrival angle. Methods such as Bartlett, Capon, MUSIC, and ESPRIT are commonly used in array processing because they provide different trade-offs between complexity and accuracy. In ISAC, accurate DoA estimation is valuable not only for sensing targets but also for improving beam alignment in communication links [43].

5.3 Beam scanning and beam tracking

Beam scanning is the process of sweeping an antenna beam across multiple directions to search for a user, object, or target. It is often used when the system does not yet know the exact location of the receiver or sensing target. Beam tracking is the next step, where the beam is continually updated to follow a moving user or object. These functions are particularly important in 6G because high-frequency links have narrow beams and are sensitive to blockage and motion. A basic steering rule can be expressed as

$$\psi = k d \sin \theta_0 + \beta \quad (11)$$

where θ_0 is the desired steering direction [44].

By adjusting the phase shift β , the array can redirect its main lobe. In practice, scanning and tracking often use feedback from received signal quality, sensing observations, or motion prediction. For ISAC systems, beam scanning helps discover both communication users and sensing targets, while beam tracking keeps the link and sensing estimate stable over time. This dynamic capability is essential for vehicular networks, drones, and mobile robotics [45].

5.4 Joint transmit-receive beamforming

Joint transmit-receive beamforming is a coordinated strategy in which both the transmitter and receiver are designed together to optimize sensing and communication performance. Instead of treating transmission and reception as separate problems, the system chooses weights on both sides to improve signal quality, reduce interference, and enhance target detection. A common formulation is to optimize a weighted objective such as

$$\max_{\mathbf{w}_t, \mathbf{w}_r} \alpha R_c + (1 - \alpha) R_s \quad (12)$$

where R_c is communication performance, R_s is sensing performance, and α balances the two goals [46].

This approach is powerful because the transmit beam can be shaped to illuminate a target or user, while the receive beam can be shaped to extract the most useful echoes or data streams. In ISAC, joint beamforming is especially useful in multi-user and multi-target scenarios because it allows the network to manage several objectives at once. The main challenge is to find weights that satisfy both tasks without causing excessive complexity or delay [47].

6. Waveform and Signal Design

Waveform and signal design is a core part of ISAC because the transmitted signal must support both reliable communication and accurate sensing. In traditional systems, communication waveforms are optimized mainly for throughput and robustness, while radar waveforms are optimized for range, velocity, and target resolution. ISAC requires a compromise or a joint design that can serve both purposes effectively [48].

This makes waveform design one of the most technically important areas in 6G integrated systems. The chosen waveform affects spectrum efficiency, sensing accuracy, beam compatibility, interference behaviour, and hardware complexity. In practice, a good ISAC waveform should be flexible enough to carry data while still retaining enough structure for estimation and detection [49].

6.1 Joint communication and radar waveforms

Joint communication and radar waveforms are designed so that a single transmitted signal can carry information and also support sensing functions such as range and Doppler estimation. The key idea is to embed communication symbols into a radar-friendly structure, or to adapt radar pulses so they can transport digital data. A general transmitted signal may be written as

$$x(t) = \sum_n s_n p(t - nT) \quad (13)$$

where s_n is the symbol sequence and $p(t)$ is the pulse shape. For sensing, the waveform must preserve timing, bandwidth, and correlation properties, while for communication it must support modulation and decoding. The challenge is that radar usually prefers deterministic or highly structured signals, while communication prefers randomness and high spectral efficiency. Joint waveforms try to bridge this gap by balancing both requirements. In ISAC, such waveforms reduce redundancy because the same signal performs two functions at once. This makes them very attractive for compact and efficient 6G systems [50].

6.2 OFDM-based ISAC waveforms

Orthogonal frequency division multiplexing, or OFDM, is one of the most widely studied waveform families for ISAC because it is already used in modern communication systems and can also support sensing. In OFDM, the transmitted signal can be expressed as

$$x(t) = \sum_{k=0}^{K-1} X_k e^{j2\pi f_k t}, 0 \leq t < T \quad (14)$$

where X_k is the data symbol on subcarrier k . OFDM is attractive because it naturally provides frequency diversity, flexible resource allocation, and compatibility with existing wireless standards. For sensing, the phase and amplitude structure across subcarriers can be used to estimate range and velocity [51].

However, OFDM also has limitations, including high peak-to-average power ratio and sensitivity to Doppler spread. In fast-moving scenarios, these effects can reduce sensing and communication performance. Even so, OFDM

remains a strong candidate for ISAC because it offers a practical path toward joint functionality with minimal changes to existing architectures. Its flexibility makes it especially suitable for 6G systems with multi-service demands [52].

6.3 Pulse design and ambiguity control

Pulse design is critical in ISAC because the waveform must be able to resolve targets in range and velocity while still carrying communication information. A major concept here is the ambiguity function, which describes how well a waveform can distinguish between different delays and Doppler shifts. The ambiguity function is often written as

$$\chi(\tau, \nu) = \int x(t) x^*(t - \tau) e^{-j2\pi \nu t} dt \quad (15)$$

where τ is delay and ν is Doppler frequency. A good sensing waveform usually has a sharp main peak and low sidelobes, which helps reduce confusion between targets and suppress false detections [53].

In communication, pulse shape also affects inter-symbol interference, bandwidth occupancy, and receiver complexity. Therefore, pulse design in ISAC must control ambiguity while maintaining data quality. Techniques such as pulse compression, sidelobe shaping, and multi-carrier pulse construction are often used to improve performance. The goal is to create a waveform that is informative for sensing but still efficient for communication [54].

6.4 Resource allocation for sensing and communication

Resource allocation in ISAC refers to how power, bandwidth, time, and spatial resources are divided between sensing and communication tasks. Since both functions use the same hardware and spectrum, the system must decide how much should go to each objective at a given moment. This can be formulated as an optimization problem such as

$$\max_{p, b} \alpha R_c + (1 - \alpha) R_s$$

subject to total power and bandwidth constraints, where R_c is communication rate and R_s is sensing performance [55].

The parameter α determines the priority between the two. In some applications, like vehicle safety, sensing may be more important,

while in others, like video streaming, communication may dominate. Resource allocation can also be dynamic, allowing the system to adapt based on user mobility, channel quality, or sensing urgency. This flexibility is one of the main advantages of ISAC because it enables the network to respond intelligently to changing conditions. Effective allocation strategies are therefore essential for practical 6G deployment [56].

7. Channel Propagation and Environment Modelling

Channel propagation and environment modelling are essential in ISAC because sensing and communication both depend on how radio waves travel through space, reflect from objects, and interact with the surrounding environment. Unlike idealized textbook channels, real 6G deployments are affected by reflections, diffraction, scattering, blockage, and mobility, all of which influence both link quality and sensing accuracy [57].

In ISAC, the channel is not just a medium for data transfer it also contains information about the environment itself. This means that propagation models must capture both communication performance and sensing observables such as target position, motion, and reflectivity. Accurate modelling is therefore a foundation for array design, waveform selection, beam management, and system optimization [58].

7.1 Radio propagation for ISAC

Radio propagation in ISAC describes how transmitted signals move through the environment and return useful information about both users and objects. At a basic level, propagation determines path loss, delay spread, angle spread, and Doppler shift, all of which affect system performance. In free space, received power is often approximated by the Friis relation

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \quad (16)$$

where P_t is transmit power, G_t and G_r are antenna gains, λ is wavelength, and R is distance. In ISAC, propagation is more complex because

reflected paths are also valuable for sensing [59]. Each path may carry information about a target or scatterer, so the channel becomes both a communication link and a sensing source. This dual role makes propagation modeling particularly important for mmWave and sub-THz bands, where directionality and blockage dominate behavior. As a result, accurate propagation analysis helps the system predict where signals go and what they reveal [60].

7.2 Near-field and far-field effects

The near-field and far-field distinction is especially important for large antenna arrays in 6G. In the far field, wavefronts are approximately planar, and the steering vector depends mainly on angle. In the near field, however, the wavefront is spherical, so both angle and range influence the received phase. A common boundary for the far-field region is the Fraunhofer distance

$$R_F = \frac{2D^2}{\lambda}$$

where D is the largest array dimension. When the target or user is closer than this distance, near-field effects must be considered [61]. This matters in ISAC because large arrays and high frequencies can make many practical targets fall into the near-field region. Near-field operation can actually improve sensing because it provides additional spatial structure for range estimation, but it also complicates beamforming and channel estimation. Far-field models remain useful for simpler cases, but future 6G systems must increasingly account for near-field behaviour to support accurate localization and high-resolution sensing [62].

7.3 Multipath, blockage, and clutter modelling

Multipath occurs when radio signals reach the receiver through multiple reflected or scattered paths. In communication, multipath can cause fading and interference, but in ISAC it also provides valuable sensing information about the environment. Blockage happens when a direct path is obstructed by buildings, vehicles, people, or other objects, which is especially common at higher frequencies [63]. Clutter refers to unwanted reflections from surrounding surfaces that can mask the desired target echo. A simplified channel model may be written as

$$h(t) = \sum_{l=1}^L \alpha_l \delta(t - \tau_l) e^{j2\pi f_{D,l}t} \quad (17)$$

where α_l , τ_l , and $f_{D,l}$ are the gain, delay, and Doppler shift of the l -th path. This representation shows that the channel contains multiple delayed and shifted replicas of the transmitted signal. In ISAC, the challenge is to separate useful target returns from clutter and unwanted multipath. Good models must therefore represent geometry, material properties, mobility, and temporal variation. This is especially important in urban, vehicular, and indoor environments where reflections are rich and dynamic [64].

7.4 Channel sounding and measurement methods

Channel sounding is the process of probing the wireless channel to measure how signals propagate in a real environment. In ISAC, sounding is important because it helps estimate channel impulse response, delay spread, angular structure, Doppler behaviour, and target signatures. Measurement methods often use known pilot signals, wideband test waveforms, or specialized probing sequences that are sent through the channel and analysed at the receiver.

The measured response can be used to build empirical models and validate theoretical designs. In sensing-oriented setups, sounding may also reveal object motion, reflection strength, and spatial geometry. Practical measurement campaigns are usually performed with calibrated antennas, controlled motion platforms, and synchronized transceivers to ensure reliable results. These measurements are essential because simulation alone cannot capture all real-world effects such as material losses, non-line-of-sight propagation, and dynamic blockage. For ISAC, channel sounding provides the evidence needed to design realistic 6G systems that work in practical environments [65].

8. Conclusion

Integrated Sensing and Communication (ISAC) with array antennas represents a paradigm shift toward unified wireless infrastructures that simultaneously enable

high-precision sensing and high-rate communication, unlocking transformative applications in autonomous driving, smart cities, industrial automation, and contactless health monitoring. By leveraging scalable array designs, near-field channel models, AI-driven learning for beam management and channel prediction, and cooperative network architectures, ISAC lays the foundation for 6G-native, environment-aware networks that can adaptively optimize sensing and communication performance across diverse scenarios. Standardization efforts in 3GPP, ETSI, and ITU, along with emerging research on interoperability, protocol support, and joint optimization, are paving the way for practical, large-scale deployments, while open directions in scalable hardware, near-field sensing, and privacy-aware, federated sensing frameworks will continue to push the boundaries of what ISAC can achieve in future wireless systems.

References:

- [1] Chunawala, H., Ihsan, M., Praveen, R. V. S., Boob, N. S., Thethi, H. P., & Badhouthiya, A. (2027). [Agriculture Supply Chain Management System Using Blockchain](#). *Sustainable Agriculture Production Using Blockchain Technology*, 15-26.
- [2] Singh, C., Praveen, R. V. S., Vemuri, H. K., Peri, S. S. R. G., Shrivastava, A., & Husain, S. O. (2027). [Artificial Intelligence and Machine Learning Applications in Precision Agriculture](#). *Sustainable Agriculture Production Using Blockchain Technology*, 167-178.
- [3] Praveen, R., Simhadati, P., Kavitha, K., Majeeth, N. D. A., Sethumadhavan, R., & Chauhan, A. (2024, December). [Emotion Detection and Psychological Prediction Using Capsule Networks and Recurrent Neural Networks](#). In *2024 4th International Conference on Mobile Networks and Wireless Communications (ICMNWC)* (pp. 1-6). IEEE.
- [4] Eswari, S., Nadgaundi, S. K., Praveen, R. V. S., & Trakroo, K. (2025, November). [Hybrid Genetic Algorithm-Fuzzy Logic Framework for Optimized Seed Quality Assessment and Yield Enhancement](#). In *2025 5th International Conference on Ubiquitous Computing and Intelligent Information Systems (ICUIS)* (pp. 1074-1079). IEEE.
- [5] Radhakrishnan, P., Manoranjithem, V., Garapati, R. S., Singh, S., & Praveen, R. V. S. (2025, November). [Random Forest-XGBoost Hybrid Model for Early Detection of Breast Cancer in Medical Imaging Datasets](#). In *2025 IEEE 3rd*

- Global Conference on Wireless Computing and Networking (GCWCN) (pp. 1-6). IEEE.
- [6] Sundaramoorthy, P., Praveen, R. V. S., Puli, B., Tiwari, A., Kanimozhi, S., & Keerthana, N. V. (2025, October). Decentralized Anomaly Detection in IoT Networks Using Federated Learning Models. In 2025 International Conference on Cognitive, Green and Ubiquitous Computing (IC-CGU) (pp. 1-6). IEEE.
- [7] Vandana, C. P., Basha, S. A., Madijagan, M., Jadhav, S., Matheen, M. A., & Maguluri, L. P. (2024). IoT resource discovery based on multi faected attribute enriched CoAP: smart office seating discovery. *Wireless Personal Communications*, 1-18.
- [8] Shrivastava, A., Praveen, R. V. S., Husain, S. O., Sholapurapu, P. K., Kulshreshtha, K., & Dwivedi, S. P. (2025, September). Financial AI: Harnessing Machine Learning for Algorithmic Trading, Risk Assessment, and Fraud Detection. In 2025 IEEE International Conference on Advances in Computing Research On Science Engineering and Technology (ACROSET) (pp. 1-6). IEEE.
- [9] Vasanti, G., Rani, M., Gupta, P., Praveen, R. V. S., Kumar, A., & Ramasamy, D. (2025, September). Fuzzy-Logistic Regression Approach for Analysing Consumer Behaviour and Shopping Preferences in E-Commerce. In 2025 2nd Asia Pacific Conference on Innovation in Technology (APCIT) (pp. 1-6). IEEE.
- [10] Chittakula, R., Kalpanadevi, D., Praveen, R. V. S., Pragadeeswaran, S., & Amsa, M. (2025, September). An Adaptive AI Model for Intelligent Fraud Detection and Customer Engagement in Digital Banking. In 2025 IEEE 4th International Conference for Advancement in Technology (ICONAT) (pp. 1-6). IEEE.
- [11] Padmaja, A. R. L., Mani, M. S. R. M., Thangam, A., Praveen, R. V. S., Tikhe, K., & Sharma, M. S. (2025, September). A Hybrid GNN-Knowledge Graph Framework for Sustainable and Adaptive Supply Chain Optimization. In 2025 IEEE 4th International Conference for Advancement in Technology (ICONAT) (pp. 1-6). IEEE.
- [12] Sreelatha, B., Rajamohanam, R., Kalaiarasi, G., Praveen, R., Bugge, B. P., & John, T. J. (2025, September). A Novel Decision Tree and LSTM Powered Intelligent Agent System for Early Detection of Vegetable Plant Diseases. In 2025 6th International Conference on Electronics and Sustainable Communication Systems (ICESC) (pp. 1617-1622). IEEE.
- [13] Bhagat, S. K., Thamma, S. R., Devalampeta, B. R., Jangareddy, M. R., Kumar, R., & Pandey, S. D. (2025, May). Smart Parallel Algorithm for Optimized Load Balancing in Cloud Computing. In 2025 2nd International Conference on Research Methodologies in Knowledge Management, Artificial Intelligence and Telecommunication Engineering (RMKMATE) (pp. 1-6). IEEE.
- [14] Suganya, V., Vijayakumar, L., Annur, E. A., Praveen, R. V. S., Bharathi, A., & Amsa, M. (2025, September). A Hybrid LSTM-Fuzzy Inference Model for Uncertainty-Aware Stock Market Forecasting. In 2025 International Conference on Electronics and Computing, Communication Networking Automation Technologies (ICEC2NT) (pp. 1-6). IEEE.
- [15] Rachapally, O., Kopparthi, G. S., Praveen, R. V. S., Tiwary, R., Pandey, V., & Shete, N. (2025, September). A GRU-CNN Based Framework for Real Estate Price Prediction and Transaction Analysis. In 2025 International Conference on Computing and Communications (COMPUTINGCON) (pp. 1-6). IEEE.
- [16] Lora, S., Ramya, S., Priya, S., Praveen, R. V. S., Tharini, C., & Pathak, P. (2025, August). Hybrid CNN-RNN Model for Identifying and Classifying Literary Themes and Structures in English Novels. In 2025 IEEE 2nd International Conference on Information Technology, Electronics and Intelligent Communication Systems (ICITEICS) (pp. 1-6). IEEE.
- [17] Gurralla, R. R., Ravish, M., Shukla, R., Praveen, R. V. S., & Pandey, V. (2025, August). A Heterogeneous Graph Neural Network Combined with a Rule-Based System for Financial Fraud Detection and Prevention. In 2025 5th Asian Conference on Innovation in Technology (ASIANCON) (pp. 1-6). IEEE.
- [18] Jadhav, S., Durairaj, M., Reenadevi, R., Subbulakshmi, R., Gupta, V., & Ramesh, J. V. N. (2024). Spatiotemporal data fusion and deep learning for remote sensing-based sustainable urban planning. *International Journal of System Assurance Engineering and Management*, 1-9.
- [19] Nutalapati, P., Dhavale, S. M., Shrivastava, A., Praveen, R. V. S., Vemuri, H. K., & RiadHwsein, R. (2025, August). IoT and Machine Learning-Enhanced Energy Management in Enabled Smart Grids for Predictive Load Balancing. In 2025 World Skills Conference on Universal Data Analytics and Sciences (WorldSUAS) (pp. 1-6). IEEE.
- [20] Thayumanavan, K., Kumar, A., Praveen, R. V. S., Bhendale, M. A., & Agnihotri, K. (2025, August). Hybrid Transformer Based Framework for Enhanced Financial Market Analysis and Online Trading Forecasting. In 2025 2nd International

- Conference on Intelligent Algorithms for Computational Intelligence Systems (IACIS) (pp. 1-6). IEEE.
- [21] Patil, B. D., Praveen, R. V. S., Rambhatla, A. K., Trakroo, K., Singh, K., & Vishanth, R. (2025, August). Graph Neural Network Model for Intelligent Urban Traffic Flow Prediction and Smart City Mobility Management. In 2025 2nd International Conference on Intelligent Algorithms for Computational Intelligence Systems (IACIS) (pp. 1-6). IEEE.
- [22] Chandra, N. S., Rao, K. S., Praveen, R. V. S., Upadhye, N. A., & Kaliappan, S. (2025, August). Hybrid Auto-Encoder Framework for Water Pollution Prediction in Smart Cities. In 2025 2nd International Conference on Intelligent Algorithms for Computational Intelligence Systems (IACIS) (pp. 1-6). IEEE.
- [23] Victor, S., Kumar, K. R., Praveen, R. V. S., Aida, R., Kaur, H., & Bhadauria, G. S. (2025, August). GAN and RNN Based Hybrid Model for Consumer Behavior Analysis in E-Commerce. In 2025 2nd International Conference on Intelligent Algorithms for Computational Intelligence Systems (IACIS) (pp. 1-6). IEEE.
- [24] Thamma, S. R., Prajwala, N. B., Pushpa, N. B., & Patra, A. (2025). Neuroimaging: A Computational Lens on the Brain. In Visualization in Neuroanatomical Sciences (pp. 53-68). Cham: Springer Nature Switzerland.
- [25] Kumar, S., Shrivastava, A., Praveen, R. V. S., Subashini, A. M., Vemuri, H. K., & Alsalam, Z. (2025, August). Future of Human-AI Interaction: Bridging the Gap with LLMs and AR Integration. In 2025 World Skills Conference on Universal Data Analytics and Sciences (WorldSUAS) (pp. 1-6). IEEE.
- [26] Choudhari, P., Tatiya, M., Praveen, R. V. S., Kaur, H., Vemuri, H. K., & MuhsnHasan, M. (2025, August). Enhancing Energy Efficiency in IoT Networks Using Deep Learning-Based Predictive Maintenance. In 2025 World Skills Conference on Universal Data Analytics and Sciences (WorldSUAS) (pp. 1-6). IEEE.
- [27] Vijayakumar, L., Kannadasan, B., Hinge, P., Reddy, L. K. K., Praveen, R. V. S., & Kalidindi, N. (2025, September). Analysis and Prediction of Employee Turnover with Effective Feature Selection based on Lee-Carter and ANN Model. In 2025 2nd Asia Pacific Conference on Innovation in Technology (APCIT) (pp. 1-6). IEEE.
- [28] Dhanabal, S., Goswami, C., Praveen, R. V. S., & Vetriselvi, T. (2025). Shuffle-F-ZFNet: ShuffleNet Fuzzy Zeiler and Fergus network for data aggregation in WSN data communication. *Wireless Networks*, 31(6), 4111-4134.
- [29] Bhuvaneswari, E., Prasad, K. D. V., Ashraf, M., Jadhav, S., Rao, T. R. K., & Rani, T. S. (2025). A human-centered hybrid AI framework for optimizing emergency triage in resource-constrained settings. *Intelligence-Based Medicine*, 12, 100311.
- [30] Hundekari, S., Shrivastava, A., Mhsnhasan, M., Praveen, R. V. S., Labde, V. V., & Yadav, K. (2025). Link Prediction in Graph-Based Data: Techniques for Analyzing and Predicting Network Connections. In Graph Mining: Practical Uses and Instruments for Exploring Complex Networks (pp. 67-76). Cham: Springer Nature Switzerland.
- [31] Maharajan, K., Parasar, A., Khurana, P., Praveen, R. V. S., Sathiyathan, S., & Priti, C. (2025, July). Enhancing Business Education Through AI-Powered Teaching Innovations in Quantitative Subjects Using Neural Architecture Search with Self-Attention. In 2025 International Conference on Communication and Smart Devices (ICCoSD) (Vol. 1, pp. 1-6). IEEE.
- [32] Mishra, P., Kalburgikar, A., Praveen, R. V. S., Soujanya, K., Balamurugan, S., & Kalra, G. (2025, July). A Graph Neural Network-Based Hybrid AI Model for Detecting Fake Reviews and Fraudulent Sellers to Enhance Trust in E-Commerce. In 2025 3rd World Conference on Communication & Computing (WCONF) (pp. 1-7). IEEE.
- [33] Kani, R. M., Kumar, K. S., Gasimov, J. Y., Praveen, R. V. S., Daniel, D. J. D., & Kumari, K. S. (2025, July). Stock Price Trend Prediction in the Banking Sector for Market Analysis and Investment Decision-Making Using a Hybrid Random Forest-LSTM Model. In 2025 3rd World Conference on Communication & Computing (WCONF) (pp. 1-6). IEEE.
- [34] Tiwari, S. S., Kumar, S., Praveen, R. V. S., Kumar, G., Sekhar, S. C., & Bhokare, R. (2025, July). Automated Smart Attendance System for Higher Education using a Lightweight DNN Model-based Face Recognition. In 2025 8th International Conference on Computing Methodologies and Communication (ICCMC) (pp. 1513-1518). IEEE.
- [35] Magdum, V. B., Adivarekar, P. P., Praveen, R. V. S., Kovalenko, A. B., & Kumar, B. S. (2025, May). Advanced Global Safety with Precision Disaster Prediction and Early Warning Systems Using HPRADS Models. In 2025 Global Conference in

- Emerging Technology (GINOTECH) (pp. 1-6). IEEE.
- [36] Thamma, S. R., Devalampeta, B. R., Jangareddy, M. R., & Tanna, P. (2026). Confidential AI Prompt Sharing: A Block-chain Driven Framework for Secure Data Exchange. In *Emerging Perspectives and Applications of Computational Intelligence and Smart Systems* (pp. 363-368). CRC Press.
- [37] NR, A. R., Rajasri, T., Praveen, R., Kalla, D., Bendale, S. P., & Venu, N. (2025, April). CAC Training-A Unified Cybersecurity Training Program for Military Staff. In *2025 3rd International Conference on Communication, Security, and Artificial Intelligence (ICCSAI)* (Vol. 3, pp. 569-573). IEEE.
- [38] Jadhav, S., Aruna, C., Choudhary, V., Gamini, S., Kapila, D., & Reddy, C. P. (2025). Reprogramming the Tumor Ecosystem via Computational Intelligence-Guided Nanoplatfroms for Targeted Oncological Interventions. *Trends in Immunotherapy*, 210-226.
- [39] Supraja, N. S., Praveen, R. V. S., Vemuri, H. K., Jaiswal, V. K., & Sista, S. (2025). Leveraging AI and ML in Central Bank Strategies for Financial Stability. *Advances in Consumer Research*, 2(4).
- [40] Gudimella, A., Ram Gopal Peri, S. S. S., Praveen, R. V. S., Labde, V. V., Deshmukh, R., & Shrivastava, A. (2025). Green Finance and ESG Investing: Evaluating Impact on Corporate Valuation. *Advances in Consumer Research*, 2(3).
- [41] Sujitha, B. B., Rao, C. V., Thiyagarajan, C., Shakhov, D., & Praveen, R. V. S. (2025, June). Intelligent Energy Consumption Estimation in IoT-Enabled Smart Homes Using a Hybrid CNN-GRU Model. In *2025 Second International Conference on Cognitive Robotics and Intelligent Systems (ICC-ROBINS)* (pp. 140-145). IEEE.
- [42] Jose, N. N., Deshpande, R., Yalagi, P. C. K., Praveen, R. V. S., & Rohini, V. R. B. (2025, June). Mind Fusion: Utilizing the Mixstyle Neural Networks in Constructing Mental Health Diagnosis and Therapy for Individual Patient. In *2025 11th International Conference on Communication and Signal Processing (ICCSP)* (pp. 328-332). IEEE.
- [43] Poonguzhali, C., Neethika, A., Yalagi, P. C. K., Praveen, R. V. S., Isaac, S., & Srivel, R. (2025, June). Transforming Mental Health Care through Clinical Decision Support System Surface Technology. In *2025 11th International Conference on Communication and Signal Processing (ICCSP)* (pp. 474-479). IEEE.
- [44] Selvam, M., Srivani, M., Jose, N. N., Saravanabhava, P., Praveen, R. V. S., & Vijayalakshmi, P. (2025, April). Implementing a Resilient and Pairing-Free Aggregate Signature Scheme for Healthcare Internet of Things Networks. In *2025 3rd International Conference on Communication, Security, and Artificial Intelligence (ICCSAI)* (Vol. 3, pp. 428-433). IEEE.
- [45] Shahane, M. S., Rajasri, T., Praveen, R., SR, A. R., Bendale, S. P., & Venu, N. (2025, April). Optimizing the Placement of Virtual Network Functions for Energy Efficiency in a Wireless Mesh Network. In *2025 3rd International Conference on Communication, Security, and Artificial Intelligence (ICCSAI)* (Vol. 3, pp. 580-585). IEEE.
- [46] Alfurhood, B. S., Danthuluri, M. S. M., Jadhav, S., Mouleswararao, B., Kumar, N. P. S., & Taj, M. (2025). Real-time heavy metal detection in water using machine learning-augmented CNT sensors via truncated factorization nuclear norm-based SVD. *Microchemical Journal*, 115375.
- [47] Thamma, S. R., Devalampeta, B. R., & Jangareddy, M. R. (2025, January). Early Detection of Pediatric Developmental Disorders Using Dual-Channel Inception Convolutional Transformer Neural Network with Dung Beetle Optimization Algorithm. In *2025 International Conference on Next Generation Communication & Information Processing (INCIP)* (pp. 961-966). IEEE.
- [48] Nagarajan, S., Vijay, S., Karthi, S., Praveen, R. V. S., & Naresh, B. (2025, March). Enhancing IoT-Based Smart Farming Security with a Hybrid GRU Intrusion Detection System. In *2025 IEEE International Conference on Interdisciplinary Approaches in Technology and Management for Social Innovation (IATMSI)* (Vol. 3, pp. 1-6). IEEE.
- [49] Sagili, S. R., Shibi, B., Praveen, R. V. S., & Anjana, P. (2025). Sentiment Classification for Depression Detection: Integrating Capsule Networks with CNNs on Review Data. *2025 Emerging Technologies for Intelligent Systems (ETIS)*, 1-7.
- [50] Kukreti, S., Praveen, R. V. S., Bansal, S., Raju, H., Singh, N., & Begum, R. (2025, February). Object Detection in Real-Time Surveillance Using Deep Learning-Based YOLO Framework. In *2025 International Conference on Computational, Communication and Information Technology (ICCCIT)* (pp. 601-606). IEEE.
- [51] Sridharan, A., Praveen, R. V., Gupta, R. K., Kumar, P., SG, P. K., & Anusuya, M. (2025, January). Optimization of Ag-Loaded BifO₃/Cus Photocatalysts for Enhanced Antibiotic Degradation Using Random Forest and Genetic Algorithms. In *2025 Fifth International*

- Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies (ICAECT) (pp. 1-7). IEEE.
- [52] Malviya, M., Adhana, D. K., Praveen, R. V. S., Mishra, B. R., Madasu, P., & Haralayya, B. (2025). *Adaptation to Integration A Review on the Indian Accounting Standards (Ind AS) in Global Financial Reporting Convergence*.
- [53] Chaubey, N. K., Dahiya, R., Venkateswaran, R., RVS, P., Hemavathi, U., & Subramaniam, S. (2025). *Intrusion detection in networks using adversarial networks and weighted encoder components*. In *Advanced Cyber Security Techniques for Data, Blockchain, IoT, and Network Protection* (pp. 413-434). IGI Global Scientific Publishing.
- [54] Subburaj, T., Praveen, R. V. S., Devi, S. R., & Reddy, D. S. (2024, December). *Enhancing Electricity Theft Detection and Loss Prediction in Metro Cites Using Hybrid Machine Learning Model*. In *2024 Eighth International Conference on Parallel, Distributed and Grid Computing (PDGC)* (pp. 865-870). IEEE.
- [55] Shinkar, A. R., Joshi, D., Praveen, R. V. S., Rajesh, Y., & Singh, D. (2024, December). *Intelligent solar energy harvesting and management in IoT nodes using deep self-organizing maps*. In *2024 International Conference on Emerging Research in Computational Science (ICERCS)* (pp. 1-6). IEEE.
- [56] Mrudula, J., Praveen, R. V. S., Sowmya, V. J., Shinde, N. N., & Ganvir, P. S. (2024, December). *Advanced IoT and machine learning solutions for sustainable groundwater management using edge-based residual graph attention network model*. In *2024 International Conference on Emerging Research in Computational Science (ICERCS)* (pp. 1-6). IEEE.
- [57] Jadhav, S., Chakrapani, I. S., Sivasubramanian, S., RamKrishna, B. V., Mouleswararao, B., & Gangwar, S. (2025). *Designing Next-Generation Platforms with Machine Learning to Optimize Immune Cell Engineering for Enhanced Applications*. *Trends in Immunotherapy*, 226-244.
- [58] Khan, M. A., Kumaraguru, S., Praveen, R., Chinthamu, N., Sarkar, R., Deka, N., & Shrivastava, A. (2024). *Exploring the Role of Artificial Intelligence in Personalized Healthcare: From Predictive Diagnostics to Tailored Treatment Plans*. *Frontiers in Health Informatics*, 13(3).
- [59] Thamma, S. R., Gurumoorthi, E., Prakash, C. O., Muthusundar, S. K., Nidhya, M. S., & Maram, B. (2025, March). *Comparison of SVM and Random Forest for Detection of Malicious Node in Wireless Sensor Networks*. In *2025 International Conference on Machine Learning and Autonomous Systems (ICMLAS)* (pp. 1637-1643). IEEE.
- [60] Kemmannu, P. K., Praveen, R. V. S., & Banupriya, V. (2024, December). *Enhancing Sustainable Agriculture Through Smart Architecture: An Adaptive Neuro-Fuzzy Inference System with XGBoost Model*. In *2024 International Conference on Sustainable Communication Networks and Application (ICSCNA)* (pp. 724-730). IEEE.
- [61] Pulugu, D., Praveen, R. V. S., Moharana, R. L., Raju, M. N., Revathy, P., & Saravanan, K. (2024, December). *IoT-integrated leaf analysis for early plant disease detection in agriculture using hybrid ensemble models*. In *2024 4th International Conference on Mobile Networks and Wireless Communications (ICMNWC)* (pp. 1-6). IEEE.
- [62] Mohandas, R., Elavarasi, M., Praveen, R. V. S., Chittapragada, H., Nithiya, C., & Prabagar, S. (2024, December). *Advanced cyber-attack detection in iot networks using deep belief networks and gradient boosting mechanisms*. In *2024 4th International Conference on Mobile Networks and Wireless Communications (ICMNWC)* (pp. 1-7). IEEE.
- [63] Wange, N. J., Praveen, R. V. S., Babavali, S. F., Rao, P., Gamini, P., & Ramasamy, D. (2024, December). *Optimizing Thermal Comfort and Energy Efficiency in Smart Buildings using GANs and Reinforcement Learning Models*. In *2024 4th International Conference on Mobile Networks and Wireless Communications (ICMNWC)* (pp. 1-6). IEEE.
- [64] Subha, B., Nagarajan, S., Thangam, A., Srinivas, V. S., Praveen, R. V. S., & Bakshi, K. D. (2024, December). *Fuzzy Clustering and Autoencoder-Based Cybersecurity for EVs in a Blockchain-Enabled Smart Cloud Environment*. In *2024 4th International Conference on Mobile Networks and Wireless Communications (ICMNWC)* (pp. 1-7). IEEE.

- [65] Sreelatha, B., Sheela, D. V., Praveen, R. V. S., Maheswari, K., Saravanan, A., & Singh, K. (2024, December). [Smart Agriculture: IoT-Driven Soil Monitoring and Fertilizer Recommendation with CNN and Bidirectional GRU Models](#). In [2024 4th International Conference on Mobile Networks and Wireless Communications \(ICMNWC\)](#) (pp. 01-06). IEEE.

Cite this article as: Dr. M. Ramanan et al., (2026). ISAC Revolution: Array Antennas Enabling Integrated Sensing and 6G Communications. *International Journal of Emerging Knowledge Studies*. 5(7), pp. 1093–1108.
<https://doi.org/10.70333/ijeks-05-07-011>