Combined Sensing and Communication in Embedded Wireless Networks

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Research Article

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Abstract

By combining traditional wireless communication with environmental sensing capabilities, Joint Communication and Sensing (JC&S) represents a revolutionary paradigm in embedded wireless networks. JC&S systems improve spectrum efficiency, lower hardware costs, and provide real-time situational awareness by using the same hardware and spectral resources for both functions. The concepts, architectures, enabling technologies, and applications of JC&S in embedded systems are all thoroughly covered in this paper. Important methods including waveform design, machine learning-based signal processing, and radar-assisted communications are investigated. Critical analysis is also done on issues pertaining to energy efficiency, interference control, and hardware constraints. Future directions that focus on multi-modal sensing, edge computing integration, and intelligent adaptive networks are underlined. Additionally, the article summarises current research trends and technical trade-offs using comparison tables and statistics.

Keywords: Joint Communication and Sensing, Embedded Wireless Networks, Radar-Assisted Communication, Waveform Design, Spectrum Efficiency, IoT, Edge Computing

INTRODUCTION

Embedded wireless networks are becoming a crucial component of many contemporary applications, from driverless cars to Internet-of-things (IoT) gadgets. Communication and sensing functions were traditionally handled as distinct subsystems, which frequently led to duplicated hardware, higher power consumption, and inefficient use of spectrum. A single network node may concurrently transmit data and perceive its surroundings thanks to Joint Communication and Sensing (JC&S) technologies. There are several benefits to integrating sensing and communication. It lowers system complexity and cost, increases situational awareness for adaptive applications like smart transportation, industrial automation, and emergency response networks, and optimises spectrum utilisation by enabling a single waveform to fulfil both objectives. Because of their

resource-constrained contexts, embedded systems stand to benefit greatly from JC&S through optimised energy

1. BACKGROUND AND MOTIVATION

1.1 Evolution of Wireless Networks Wireless networks have undergone significant transformations over the past few decades, evolving from basic point-to-point links to highly sophisticated multi-functional embedded networks capable of supporting a vast array of applications. In the early stages, wireless networks were primarily designed to transmit information reliably between two endpoints. Systems such as cellular networks (1G and 2G) were optimized solely for voice communication, while basic Wi-Fi networks provided local data connectivity. With the emergence of the Internet of Things (IoT), vehicular ad-hoc networks (VANETs), and smart infrastructures, wireless networks have become increasingly heterogeneous and distributed. Modern embedded wireless networks now integrate multiple functions such as data communication, remote monitoring, control signaling, and environmental sensing. Examples include:

- **IoT Devices:** Sensors embedded in smart homes, wearable devices, and industrial machinery require both communication for data transmission and sensing for environmental awareness.
- **Vehicular Networks:** Connected and autonomous vehicles rely on communication networks for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) interactions, while also using radar and LiDAR for navigation and obstacle detection.
- **Smart Infrastructure:** Urban systems like traffic control, energy grids, and surveillance rely on wireless networks to collect and transmit real-time data while monitoring environmental or structural changes.

Traditionally, communication and sensing subsystems have been physically and functionally separate. For instance, a vehicle may use dedicated radar or LiDAR sensors for obstacle detection and a separate Wi-Fi or 5G module for data communication. This separation leads to several drawbacks:

1. **Hardware Redundancy:** Separate sensors and communication modules increase the overall system size, weight, and cost.
2. **Energy Inefficiency:** Multiple independent modules consume more power, which is a critical limitation for battery-operated embedded devices.
3. **Spectrum Underutilization:** The electromagnetic spectrum allocated for sensing and

communication may remain underutilized because each system operates independently.

4. **Complex System Integration:** Combining information from multiple sources requires additional processing and synchronization, increasing software complexity and latency.As embedded systems become more compact and energy-constrained, the need for integrated, multifunctional networks has become more pronounced. This sets the stage for the development of **Joint Communication and Sensing (JC&S)** systems.

1.2 Motivation for Joint Communication & Sensing

Joint Communication and Sensing (JC&S) has emerged as a paradigm to address the limitations of traditional wireless networks by unifying communication and sensing operations. The motivation for JC&S is driven by both technical efficiency and application requirements, particularly in embedded networks where size, power, and spectrum efficiency are critical.

1. Spectrum Efficiency

Modern wireless networks face increasing spectrum congestion due to the exponential growth of IoT devices, 5G networks, and smart infrastructure systems. In traditional setups, communication and sensing operate on separate frequency bands, leading to inefficient spectrum usage. JC&S leverages the same waveform and frequency resources for both communication and sensing, effectively **multiplexing the functions within a shared spectrum**. This approach reduces congestion, improves spectral efficiency, and allows future systems to scale without requiring additional bandwidth.

2. Hardware Reduction

Embedded systems often face constraints on size, weight, and cost. Integrating communication and sensing into a single transceiver module enables **hardware sharing**, where the same antenna, RF front-end, and digital signal processing units serve dual purposes. This reduces system complexity, manufacturing cost, and device footprint. For example, in

automotive systems, a single OFDM-based module can simultaneously transmit vehicle-to-vehicle messages while performing radar-based obstacle detection.

3. Real-Time Environmental Awareness JC&S allows communication signals themselves to carry sensing information, creating opportunities for **real-time environmental feedback**. For

instance, in autonomous vehicles, the transmitted communication signal can be reflected by nearby objects, providing instant information about obstacles without requiring additional sensing pulses. This real-time dual functionality enhances system responsiveness, enabling faster decision-making and adaptive network behavior.

4. Embedded Network Optimization IoT and embedded networks are typically resource-constrained in terms of processing power, memory, and energy. JC&S allows nodes to optimize energy usage by performing both tasks with a single module, rather than powering separate communication and sensing units. Additionally, embedded nodes can dynamically adjust transmission and sensing parameters to balance communication quality with sensing accuracy, improving overall system efficiency. This is particularly useful in **battery-powered IoT devices**, where energy-efficient operations can significantly extend device lifespan.

5. Enhanced System Intelligence (Additional Point)

JC&S also enables **intelligent embedded networks**, where sensing data can inform network operations. For example, channel conditions estimated through sensing can guide adaptive beamforming, modulation selection, and routing in real time. This creates a feedback loop between environmental sensing and network control, improving robustness, throughput, and quality of service.

2. FUNDAMENTALS OF JOINT COMMUNICATION & SENSING

Joint Communication and Sensing (JC&S) combines wireless data transmission and environmental awareness within the same system, leveraging shared hardware, spectrum, and signal processing resources. The integration is particularly valuable for embedded networks, where hardware and energy resources are constrained. JC&S relies on the principle that signals transmitted for communication can also carry information about the surrounding environment, and vice versa, enabling multifunctional operations.

2.1 Basic Principles

The fundamental idea behind JC&S is **dual use of signals**. A transmitted communication signal, instead of being purely for data transfer, is also analyzed to extract environmental information such as object presence, distance, velocity, or motion patterns. Similarly, sensing signals can provide insights to improve communication performance. There are two primary

approaches in JC&S:

- **Radar-Assisted Communication** Radar-assisted communication leverages traditional communication waveforms to perform sensing tasks. For example:
- **OFDM-Based Radar Sensing:** Orthogonal Frequency Division Multiplexing (OFDM) waveforms are widely used in 4G/5G networks. OFDM signals, which are inherently multi-carrier, can be reflected off objects in the environment. By analyzing the phase and amplitude changes of the reflected signal, the system can detect objects, estimate their distance (range), and determine velocity through Doppler shift calculations.
- **FMCW Radar Integration:** Frequency Modulated Continuous Wave (FMCW) signals can be embedded into communication packets. The frequency sweep in FMCW provides precise distance and speed measurements, while the communication payload transmits data. This allows simultaneous environmental sensing and data exchange without requiring separate radar hardware. Applications include autonomous vehicles where the vehicle uses OFDM-based communication signals to sense nearby vehicles or obstacles while maintaining network connectivity with traffic control units.

2. Sensing-Assisted Communication

Sensing-assisted communication reverses the flow: **sensing data enhances communication performance**. Examples include:

- Adaptive beamforming: Using radar or LiDAR information, the system can direct the communication beam to avoid obstacles or focus on the intended receiver, improving signal quality.
- Dynamic resource allocation: Sensing information about the environment or network traffic can guide real-time modulation, coding, and power adjustments to optimize communication reliability.

This approach is especially useful in embedded IoT networks where nodes operate in dynamic, cluttered environments such as factories or urban areas.

2.2 Enabling Techniques

Successful JC&S requires a combination of advanced waveform design, signal processing,

and hardware integration. Each aspect ensures efficient dual-function operation.

2.2.1 Waveform Design

The waveform is the foundation of JC&S because it determines both communication capacity and sensing accuracy. Key waveform strategies include:

- **OFDM-Based JC&S:**
  - OFDM divides the spectrum into multiple narrow subcarriers, each transmitting a portion of the data.
  - Its inherent frequency diversity allows simultaneous time-frequency analysis, which is essential for radar-based sensing.
  - By analyzing subcarrier reflections, the system can estimate object range and velocity while maintaining high data rates.
- **FMCW Radar Integration:**
  - FMCW involves a continuous frequency sweep over time.
  - The reflected signal's frequency shift directly correlates with the distance of obstacles.
  - Embedding communication data into the FMCW waveform allows dual functionality without additional spectrum allocation.
- **Spread Spectrum Techniques:**
  - Pseudorandom sequences, such as those used in Direct Sequence Spread Spectrum (DSSS), can simultaneously serve as communication codes and sensing signals.
  - These sequences improve resistance to interference, enhance detection capability, and allow low-power sensing operations suitable for embedded devices.

3. ARCHITECTURES FOR JC&S IN EMBEDDED NETWORKS

The architecture of a Joint Communication and Sensing (JC&S) system plays a critical role in determining its performance, energy efficiency, scalability, and hardware requirements. In embedded wireless networks, the architecture must balance computational complexity, power consumption, and real-time responsiveness while maintaining reliable communication and accurate sensing. JC&S architectures are broadly classified into three types: **co-located**, **distributed**, and **hybrid**, each with unique advantages and limitations.

3.1 Co-located Architecture

In a **co-located JC&S architecture**, the communication and sensing modules are integrated within a single transceiver or device. A single RF front-end, antenna array, and digital signal processing unit are shared for both tasks.

Key Features

- **Hardware Sharing:** Both communication and sensing use the same hardware components, reducing cost and size.
- **Energy Efficiency:** Only one transceiver is active, leading to lower power consumption compared to separate modules.
- **Low Latency:** Integration ensures real-time sensing and communication without additional network delay.

Technical Considerations

- **Signal Processing Complexity:** Since the same signal is used for dual purposes, sophisticated algorithms are required to separate sensing and communication information without interference.
- **Waveform Optimization:** Waveforms such as OFDM or FMCW need to be carefully designed to satisfy both high data rates for communication and high-resolution sensing.
- **Thermal Management:** Combining multiple functions in a single module may increase power density, requiring efficient thermal management in embedded systems.

Example Applications

- Autonomous drones that need to communicate with ground stations while avoiding obstacles.
- Wearable IoT devices that simultaneously transmit physiological data and detect gestures or motion.

3.2 Distributed Architecture

In a **distributed JC&S architecture**, communication and sensing functions are physically separated across multiple nodes. These nodes collaborate through network

protocols to provide joint functionality. For example, a sensing node detects environmental changes and shares this information with nearby communication nodes for adaptive transmission.

Key Features

- **Scalability:** Networks can be expanded by adding more sensing or communication nodes without redesigning existing devices.
- **Specialization:** Each node can be optimized for a single task, reducing individual device complexity.
- **Redundancy and Reliability:** Failure of one node does not completely disrupt the system, as multiple nodes provide overlapping coverage.

Technical Considerations

- **Synchronization:** Accurate timing and coordination between nodes are critical for real-time performance. Delays can reduce sensing accuracy or affect communication quality.
- **Inter-Node Communication Overhead:** Nodes must exchange control and sensing data, potentially increasing network traffic.
- **Energy Consumption:** While individual nodes may consume less power, total network energy may increase due to inter-node communication.

Example Applications

- Smart factories where sensors monitor machinery conditions and communicate with embedded controllers across the plant floor.
- Urban IoT networks where distributed air quality sensors feed data to communication nodes for centralized processing.

3.3 Hybrid Architecture

The **hybrid JC&S architecture** combines the strengths of co-located and distributed approaches. Some nodes are co-located, performing both communication and sensing, while others are specialized as dedicated sensing or communication nodes. This provides a balance between hardware efficiency, system scalability, and performance optimization.

Key Features

- **Flexibility:** System designers can choose which nodes are co-located or specialized based on network requirements.
- **Optimized Performance:** Co-located nodes provide low-latency sensing and communication, while distributed nodes extend network coverage and capacity.
- **Energy Balancing:** Energy-intensive tasks can be assigned to dedicated nodes, reducing load on battery-powered devices. **Technical Considerations**
- **Complex System Management:** Hybrid networks require sophisticated routing and scheduling algorithms to balance tasks among different types of nodes.
- **Cost vs. Performance Trade-off:** While hybrid systems provide better performance, they may increase total system cost due to mixed hardware deployment.
- **Interoperability:** Communication protocols must support coordination between co-located and distributed nodes seamlessly.

Example Applications

- Autonomous vehicle networks where on-board sensors and communication modules handle immediate navigation (co-located), while roadside units (distributed) provide environmental updates and network management.
- Smart city deployments combining multi-functional streetlight nodes (co-located) and specialized air quality sensors (distributed).

Table 1: Comparative Analysis of JC&S Architectures

Architecture	Hardware Cost	Energy Efficiency	Complexity	Scalability	Suitable Applications
Co-located	Low	High	High	Moderate	IoT, Wearables
Distributed	Moderate	Moderate	Moderate	High	Industrial IoT
Hybrid	Moderate	High	Moderate	High	Smart Vehicles

4. APPLICATIONS OF JC&S IN EMBEDDED WIRELESS NETWORKS

4.1 Autonomous Vehicles

JC&S enables vehicles to communicate with each other while sensing obstacles and road conditions. Radar-assisted communication improves navigation accuracy and collision avoidance.

4.2 Smart Manufacturing Embedded wireless nodes with JC&S capabilities monitor equipment, detect faults, and communicate status in real

time, enhancing predictive maintenance.

4.3 IoT-Based Smart Homes

Devices such as smart speakers and home sensors can simultaneously track user presence, gestures, or environmental parameters while maintaining network connectivity.

4.4 Environmental Monitoring

JC&S nodes deployed in forests, oceans, or urban areas can transmit environmental

data while detecting anomalies, such as forest fires or air pollution spikes.

4.5 Healthcare Systems

Wearable devices leverage JC&S to track patient vital signs and movements while transmitting health data to remote monitoring systems.

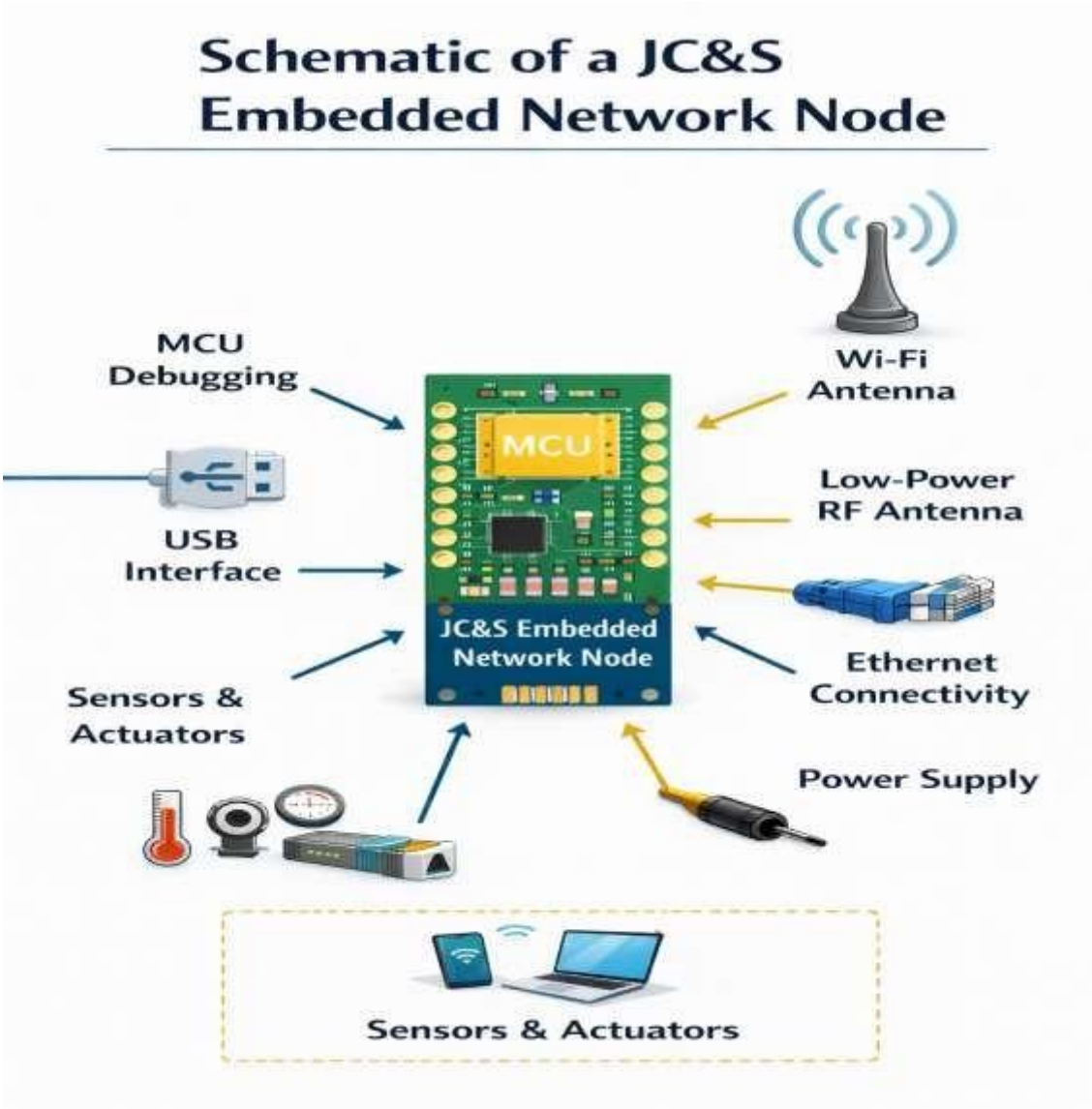


Figure 1: Schematic of a JC&S Embedded Network Node

5. CHALLENGES AND RESEARCH DIRECTIONS

5.1 Hardware Limitations Miniaturization of antennas and transceivers for dual functionality in embedded nodes remains challenging. Trade-offs between power, size, and sensitivity are critical.

5.2 Interference and Spectrum Sharing Simultaneous communication and sensing may cause self-interference. Effective cancellation techniques and adaptive spectrum management are required.

5.3 Energy Efficiency

Resource-constrained nodes must balance sensing frequency, communication duty cycles, and processing load to maximize battery life.

5.4 Signal Processing Complexity Extracting sensing information from communication signals demands sophisticated algorithms, often exceeding the computational capabilities of small embedded nodes.

5.5 Security and Privacy

JC&S systems generate richer datasets, raising concerns about eavesdropping and privacy breaches. Secure waveform design and encrypted data transmission are essential.

FUTURE TRENDS

1. **Edge Computing Integration:** Offloading processing to nearby edge devices reduces embedded node complexity.
2. **Machine Learning-Based JC&S:** Deep learning models for adaptive waveform selection, channel estimation, and anomaly detection.
3. **Multi-Modal Sensing:** Integration of visual, acoustic, and RF sensing alongside communication.
4. **Adaptive Networks:** Dynamic allocation of spectral resources and energy-efficient duty cycling for large-scale JC&S networks.
5. **Standardization:** Unified protocols for JC&S will promote interoperability and commercial adoption.

6. CONCLUSION

Joint Communication and Sensing represents a pivotal innovation in embedded wireless

networks. By combining communication and sensing capabilities within the same hardware and spectral resources, JC&S improves spectrum efficiency, reduces costs, and enhances real-time situational awareness. While promising, challenges such as hardware constraints, interference management, and energy optimization

require further research. Emerging technologies like machine learning, edge computing, and multi-modal sensing will play a crucial role in realizing intelligent, adaptive JC&S networks for IoT, autonomous systems, smart manufacturing, and healthcare. This review provides a foundation for understanding current research, enabling engineers and researchers to develop robust, efficient, and scalable embedded JC&S networks.

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