Joint Resource Allocation and Power Efficiency Optimization for O-RAN based ISAC

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***Abstract*— This study explores the integration of Open Radio Access Network (O-RAN) and Integrated Sensing and Communication (ISAC) systems, providing a flexible framework for diverse vendors to combine their technological expertise and develop innovative solutions. The research analyzes the application of game theory to derive optimal strategies in cooperative and competitive vendor scenarios, demonstrating how achieving Nash equilibrium fosters a stable ecosystem. Furthermore, this paper delves into optimization challenges within ISAC-based O-RAN systems and presents solutions formulated through mathematical models. Real-world applications, such as autonomous vehicle networks and smart cities, are highlighted, underscoring the transformative potential of O-RAN-based ISAC systems in next-generation networks.**

Keywords*— *O-RAN, Integrated Sensing and Communication (ISAC), Resource Allocation, Interference Minimization

I. Introduction

The evolution of wireless communication technologies has transformed modern connectivity, particularly with the advent of 5G and ongoing research into 6G. These advancements demand ultra-reliable, low-latency systems capable of integrating diverse functionalities to support emerging applications. Integrated Sensing and Communication (ISAC) has emerged as a critical technology in this domain, offering the ability to simultaneously sense the environment and transmit data. These dual capabilities are essential for applications such as autonomous vehicles, smart cities, industrial automation, and healthcare.

A. *The Role of ISAC in Next-Generation Systems*

ISAC unifies sensing and communication functionalities within a single framework, leveraging shared resources to maximize efficiency and minimize hardware and spectrum costs. For instance, in autonomous vehicles, ISAC enables obstacle detection and velocity estimation while facilitating data exchange between vehicles and infrastructure. Similarly, in smart cities, ISAC allows IoT devices to monitor environmental parameters in real time, driving more informed decision-making.

The benefits of ISAC are well-documented in the literature. Liu et al. [1] presented a unified framework for ISAC, highlighting its potential in resource-constrained environments such as autonomous systems. Their findings emphasized ISAC's ability to enhance operational efficiency while reducing deployment complexity. Similarly, Zhang et al. [2] explored resource allocation strategies tailored to ISAC applications, demonstrating their effectiveness in balancing sensing and communication requirements. These foundational studies underscore the importance of ISAC in addressing next-generation network demands.

B. *Open Radio Access Network (O-RAN) for ISAC*

While ISAC addresses functional integration, Open Radio Access Network (O-RAN) offers a complementary architectural solution. O-RAN introduces open, interoperable interfaces that decouple hardware and software components, enabling collaboration among diverse vendors. This approach contrasts with traditional RAN systems, which rely on proprietary integrations that limit flexibility and scalability. O-RAN fosters innovation, reduces deployment costs, and accelerates the adoption of advanced technologies such as ISAC.

The integration of O-RAN with ISAC amplifies the strengths of both frameworks. O-RAN's open architecture facilitates the seamless deployment of ISAC capabilities, creating a unified system that dynamically allocates resources based on real-time requirements. For example, in smart cities, O-RAN and ISAC together enable adaptive traffic management systems that use sensing data to optimize signal timings while maintaining reliable communication with autonomous vehicles.

Zhang et al. [3] highlighted the transformative potential of O-RAN in enabling dynamic resource allocation and enhancing network scalability. Their work demonstrated how O-RAN can support diverse applications, including ISAC-driven scenarios. By integrating these two frameworks, researchers have the opportunity to address critical challenges such as interference management, energy efficiency, and resource optimization.

Despite the evident benefits of ISAC and O-RAN integration, significant challenges remain. Effective resource allocation, energy-efficient operations, and interference mitigation are key areas requiring further exploration. This paper suggests mathematical optimization models and game theory-based approaches to solve these challenges. By applying these techniques, the study demonstrates how O-RAN-based ISAC systems can achieve superior performance in real-world scenarios such as autonomous vehicle networks and smart cities.

II. Optimization Challenges and Proposed Solutions in ISAC-based O-RAN Systems

This paper analyzed and proposed four problems with objective functions to optimize.

A. *Resource Allocation*

Optimal allocation of frequency and time resources between sensing and communication is essential to maximize overall system performance in an ISAC environment [4]. The formulated optimization problem is formulated as follow

$$\max_{\mathrm{f,t}}\left(\alpha \cdot R_{comm}(f,t) + \beta \cdot S_{sense}(f,t)\right) \quad (1)$$

where $R_{comm}(f,t)$ denotes the communication performance such as data transmission rate, and $S_{sense}(f,t)$ denotes the sensing performance such as detection accuracy. The weights α and β adjust the relative importance of communication and sensing. This optimization problem must satisfy the constraints of limited frequency and time resources while minimizing interference between communication and sensing functionalities.

B. *Energy Efficiency*

Energy-efficient operations are particularly important in resource-constrained environments like IoT-enabled smart cities. The optimization problem for energy efficiency is formulated to balance power allocation between communication and sensing. Recent studies have highlighted that enhancing energy efficiency in O-RAN requires power optimization techniques that minimize energy consumption while maintaining operational quality [5-6]. Therefore, energy efficient optimization problem is formulated as follow:

$$\max_{P_{comm},P_{sense}}\left(\frac{R_{comm}(P_{comm}) + S_{sense}(P_{sense})}{P_{comm} + P_{sense}}\right) \quad (2)$$

where P_{comm} and P_{sense} denote the power allocated to communication and sensing, respectively. $R_{comm}(P_{comm})$ is the communication performance as a function of allocated power, and $S_{sense}(P_{sense})$ is the sensing performance. The total power consumption must not exceed the network's power budget, and both communication and sensing must satisfy their minimum power requirements.

C. *Ineteference Minimization*

When communication and sensing share the same frequency band, interference must be minimized while maximizing overall system performance [7]. The formulated optimization problem is formulated as follow:

$$\min_{f,t}\left(I_{comm-sense}(f,t) - \gamma \cdot \left(R_{comm}(f,t) + S_{sense}(f,t)\right)\right) \quad (3)$$

where $I_{comm-sense}(f,t)$ denotes the interference between communication and sensing functionalities at a given frequency f and time t. The parameter γ adjusts the trade-off between interference reduction and performance maximization. This optimization problem ensures that interference remains within acceptable limits while maintaining the performance thresholds required for both communication and sensing.

D. *Joint Sensing and Communication Capacity Optimization*

To address the above challenges, joint optimization strategies [8] are adopted to maximize the capacity of both functionalities while minimizing interference under shared resource constraints. The optimization problem for joint sensing and communication capacity is formulated as follow:

$$\max_{f,P_{comm},P_{sense}}\left[\begin{array}{c} B \cdot \log_2\left(1 + \dfrac{P_{comm} \cdot h_{comm}}{I_{sense} + N}\right) \\ +k \cdot \dfrac{P_{sense} \cdot h_{sense}}{B} \end{array}\right] \quad (4)$$

where parameter B is the total bandwidth shared between sensing and communication. h_{comm} and h_{sense} are the respective channel gains for communication and sensing. The interference caused by sensing on communication is represented by I_{sense}, and N denotes the noise power in the system. The term k is a scaling factor that reflects the relative importance of sensing accuracy in the system. The optimization ensures that the total system performance, combining communication capacity and sensing accuracy, is maximized.

To solve this optimization problem, advanced mathematical techniques are considered to ensure that communication and sensing capacities are maximized while adhering to system constraints. First, *Lagrangian relaxation* is proposed to incorporate the constraints into the objective function with using *Lagrangian multipliers* associated with the power and bandwidth constraints. The Karush-Kuhn-Tucker (KKT) conditions are then applied to derive the optimal allocation of power and bandwidth for both sensing and communication. These conditions ensure that the solution satisfies both the constraints and the optimality of the objective function. In practice, solving this optimization problem can be computationally intensive due to the non-linear nature of the objective function and constraints. Numerical methods, such as gradient descent or interior-point algorithms, are often employed to iteratively compute the optimal resource allocation. These methods dynamically adjust P_{comm}, P_{sense}, B_{comm}, and B_{sense} to maximize overall system performance while maintaining interference below the threshold.

III. Conclusion and Future Work

This paper presented a comprehensive analysis of ISAC and O-RAN integration, focusing on challenges such as resource allocation, energy efficiency, and frequency sharing. By employing mathematical optimization models and game theory-based approaches, the study proposed solutions that enhance the performance of ISAC-based O-RAN systems in real-world scenarios. Future research should focus on incorporating machine learning algorithms to enable adaptive and scalable resource management. Additionally, exploring ISAC applications in emerging domains, such as industrial IoT and telemedicine, could further expand its impact. These advancements will play a crucial role in the realization of next-generation wireless networks.

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