Transforming ISAC with STAR-RIS: Design, Challenges, and Opportunities

Muhammad Umer, Sarah Basharat, Syed Ali Hassan, Aamir Mahmood, and Mikael Gidlund

***Abstract*—Integrating sensing and communication functionalities is essential for realizing the vision of ubiquitous connectivity and supporting emerging applications in future wireless networks. Integrated sensing and communication (ISAC) offers an efficient approach for sharing resources, such as spectrum and hardware, however, traditional wireless systems face significant challenges in complex real-world environments. Reconfigurable intelligent surfaces (RISs) have emerged as a promising solution, enabling intelligent manipulation of wireless signals to enhance both sensing and communication in an energy-efficient manner. However, conventional RISs, which rely solely on reflection, are limited to half-space coverage. To overcome this limitation, simultaneously transmitting and reflecting RIS (STAR-RIS) has been introduced, expanding network coverage and providing a higher degree of freedom for signal manipulation. This article explores integrating STAR-RIS into ISAC systems, highlighting their potential to revolutionize wireless networks. We examine various deployment scenarios for STAR-RIS-enabled ISAC, discuss their advantages and challenges, and present a case study showcasing performance gains. Furthermore, we identify crucial research directions to address challenges in modeling, deployment, and application, paving the way for the future of intelligent and connected wireless systems.**

I. Introduction

The wireless landscape is continually evolving due to the growing demand for ubiquitous connectivity and the emergence of new applications. The sixth generation (6G) of wireless networks, currently in its nascent stages, aims to deliver seamless connectivity that integrates communication, sensing, localization, and computing functionalities across various devices and applications [1]. This vision foresees a highly interconnected and intelligent world, facilitating advancements in critical areas such as autonomous vehicles, smart cities, and the Internet of things (IoT). To achieve this goal, next-generation wireless networks must move beyond traditional communication-centric designs and embrace a paradigm shift that incorporates a broader spectrum of functionalities.

Integrated sensing and communication (ISAC) has emerged as a pivotal technology for realizing this vision. ISAC offers an efficient approach to sharing resources such as spectrum, hardware, and signal processing platforms, providing both communication and sensing capabilities [2]. This joint resource utilization creates a synergistic effect, leading to significant performance gains in terms of spectral efficiency, energy consumption, and hardware cost [3]. Moreover, ISAC fosters mutual assistance between sensing and communication through information sharing; leveraging sensor knowledge, communication systems can optimize their performance through sensing-aided beam tracking and blockage prediction, while sensing systems can benefit from communication signals in the realization of extended sensing capabilities and distributed sensing.

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However, the realization of ISAC systems in complex real-world scenarios presents significant challenges. The uncontrollable nature of electromagnetic environments and path loss can hinder both communication and sensing performance. While this deterioration is inevitable, reconfigurable intelligent surfaces (RISs) emerge as a promising solution owing to their ability to intelligently reshape electromagnetic environments. An RIS is generally composed of a planar metasurface with low-cost, passive elements that can independently adjust the properties of incident signals, effectively controlling wireless signal propagation. This has enabled new avenues for enhancing coverage, reliability, and security in communication systems [4]. Despite their potential, traditional RIS offer only half-space coverage, requiring communication users and sensing targets to be on the same side of the RIS. This limitation can restrict network deployment flexibility and hinder the realization of ISAC systems in practical scenarios.

To address the half-space problem inherent in RIS, the concept of simultaneously transmitting and reflecting RIS (STAR-RIS) was introduced. STAR-RIS, by simultaneously transmitting and reflecting signals, achieve full-space coverage, effectively extending the coverage of wireless networks and providing greater flexibility in deployment [5]. This opens up exciting opportunities for enhancing the performance of ISAC systems, which is the focus of this article. We explore the integration of STAR-RIS within ISAC systems, focusing on the design, challenges, and opportunities. To this end, we examine the deployment of STAR-RIS-enabled ISAC in downlink scenarios and present a case study to validate the performance gains thus achieved. Additionally, we highlight the key challenges associated with the practical realization of this technology in real-world applications and propose potential research directions to address these challenges.

The rest of the article is organized as follows. The following section explores the fundamentals of STAR-RIS, highlighting its architecture, signal manipulation capabilities, and operating protocols. Next, we examine how STAR-RIS can be intergrated with ISAC systems, discussing potential deployment scenarios that leverage the division of reflection and transmission spaces for dual functionalities. To demonstrate the potential benefits of this integration, a case study is presented to showcase the performance gains achieved. Subsequently, we outline the open challenges and future research directions for

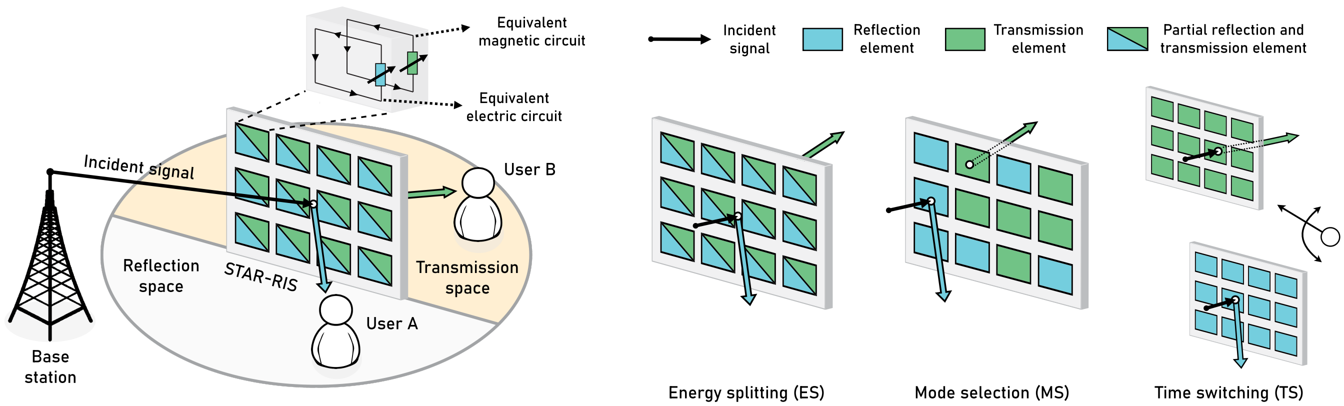

Fig. 1. Conceptual illustration of full-space service coverage and operating protocols of STAR-RIS aided communication.

STAR-RIS-enabled ISAC systems. Finally, we conclude the article.

II. STAR-RIS: A Systematic Overview

We commence by introducing the fundamental principles of STAR-RIS by exploring its architecture, signal manipulation capabilities, operating protocols, and applications in communication and sensing.

A. Fundamental Principles of STAR-RIS

STAR-RIS is an innovative metasurface that addresses the limitations of traditional RIS by offering full-space coverage through both transmission and reflection of impinging signals. At its core, a STAR-RIS is composed of sub-wavelength elements, each capable of independently controlling the amplitude and phase of incoming signals. Each element is designed to split the incident signal into two distinct portions: one transmitted and one reflected. This split is achieved through a combination of electrical and magnetic circuits, as illustrated in Fig. 1. By dynamically adjusting the phase and amplitude of both the reflected and transmitted signals, STAR-RIS can effectively reshape the electromagnetic environment to achieve desired communication and sensing outcomes.

B. STAR-RIS Operating Protocols

To achieve simultaneous transmission and reflection, three primary operating protocols have been proposed for STAR-RIS, as showcased in Fig. 1.

- *Energy Splitting (ES) Protocol:* Enables each element in the STAR-RIS to split the incident signal into two separate signals, one for transmission and the other for reflection. The amplitude and phase of the transmitted and reflected signals can be independently adjusted, providing a high degree of flexibility. However, this protocol entails a relatively high overhead for configuration information exchange between the controller and the base station (BS).
- *Mode Selection (MS) Protocol:* Allows for partitioning the STAR-RIS elements into two separate groups; one operates in transmission mode, while the other operates in reflection mode. This approach requires less complex hardware but sacrifices the flexibility of the ES protocol since full-dimensional transmission and reflection are not possible.
- *Time Switching (TS) Protocol:* Employs a time-division multiplexing scheme, where the STAR-RIS elements switch between transmission and reflection modes in different time slots. This protocol simplifies the design of transmission and reflection coefficients but introduces stringent time synchronization requirements, leading to higher hardware complexity.

C. STAR-RIS Aided Sensing/Communication

The unique capabilities of STAR-RIS unlock a wide range of opportunities for enhancing both sensing and communication functionalities in wireless networks.

Specifically, in the context of **communication**, STAR-RIS can significantly improve coverage, reliability, and energy efficiency by providing additional signal paths and virtual line-of-sight (vLoS) links. This is particularly beneficial for users located in shadowed or obstructed areas where traditional communication systems may struggle to provide adequate coverage. Furthermore, STAR-RIS enhances communication quality by mitigating interference and boosting signal strength; the ES protocol allows for simultaneous optimization of both transmission and reflection spaces, which, when designed appropriately, minimize interference and maximize signal power at desired locations. Research efforts have actively investigated the potential of STAR-RIS in communication systems. In this regard, in [6], the authors focused on optimizing the weighted sum rate in STAR-RIS-assisted MIMO systems. Similarly, the authors in [7] addressed the transmission design of STAR-RIS in multi-cell systems to eliminate inter-cell interference and boost desired signals.

In the context of **sensing**, STAR-RIS can significantly enhance the performance of radar systems. By reshaping the electromagnetic environment, it can improve the detection probability and estimation accuracy. The creation of vLoS links and additional degrees of freedom associated with STAR-RIS deployment can boost sensing capabilities in various ways. For example, STAR-RIS can be used to minimize the

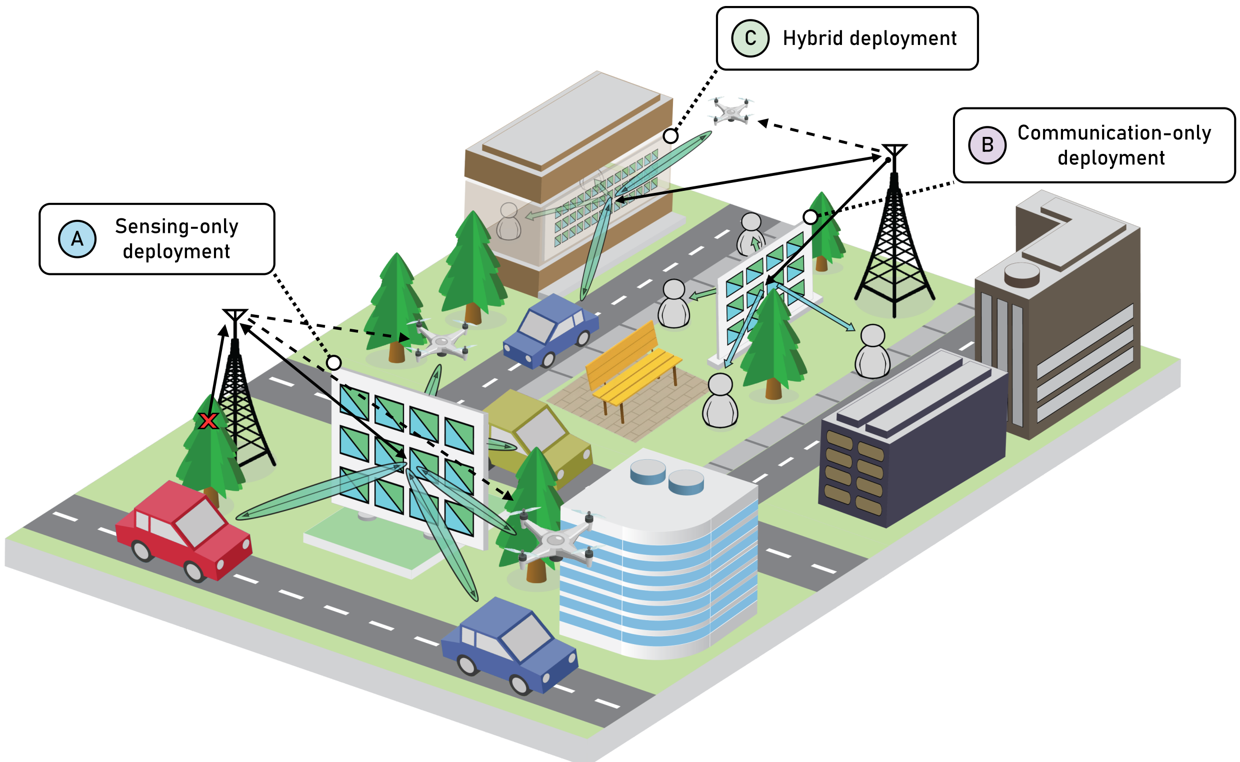

Fig. 2. Illustration of potential downlink deployment scenarios for STAR-RIS-enabled ISAC.

Cramér-Rao Lower Bound (CRLB), a fundamental metric that quantifies the minimum achievable variance of an unbiased estimator. In this regard, in [8], the authors study the limits of CRLBs and investigate the impact of power splitting between the STAR-RIS coefficients on 3D localization performance via Fisher information analysis. STAR-RIS has also been shown to improve the signal-to-noise ratio (SNR) of radar systems [9]. By designing the reflecting coefficients of the STAR-RIS to maximize the SNR of received echo signals, the probability of target detection can be increased. Furthermore, STAR-RIS facilitates accurate direction-of-arrival (DoA) estimation by establishing multiple virtual LoS links [10], proving particularly beneficial in scenarios where the direct path between the radar transmitter and the target is blocked.

III. STAR-RIS-enabled ISAC Systems

The integration of STAR-RIS into ISAC systems unlocks a lot of possibilities for simultaneously performing communication and sensing tasks. We now examine various downlink deployment scenarios for STAR-RIS-enabled ISAC and discuss their potential applications and challenges, as illustrated in Fig. 2.

A. Sensing-only Deployment

One potential scenario is to dedicate both the transmission and reflection spaces of the STAR-RIS to sensing. This configuration can be especially useful for scenarios requiring high-sensitivity target detection, such as in environments with high clutter levels, highly mobile targets, or when the LoS path between the transmitter and target is blocked. Such a setup could also be used to perform surveillance or environmental monitoring. However, this scenario necessitates a dedicated sensor array on both sides of the STAR-RIS, leading to an increased hardware complexity and cost. Additionally, the absence of communication through the STAR-RIS limits the applicability of this deployment scenario in situations where both communication and sensing are essential.

B. Communication-only Deployment

Another scenario is to utilize both the reflection and transmission spaces for communication. This configuration can be beneficial for extending the coverage of wireless networks and improving communication reliability in challenging environments. However, this scenario poses an intricate design problem and may lead to an increase in interference if the system is not designed carefully. For instance, communication signals reflected by the STAR-RIS could interfere with the detection of targets that the BS senses. Furthermore, ensuring proper coordination and resource allocation between users on both sides of the STAR-RIS is crucial for ensuring correct operation.

C. Hybrid Deployment

The most flexible scenario involves utilizing one side of the STAR-RIS for sensing and the other for communication. This approach combines the advantages of the previous two scenarios. For example, one particular case could be that of indoor communication and outdoor sensing, as shown in Fig. 2. The combined scenario presents significant challenges

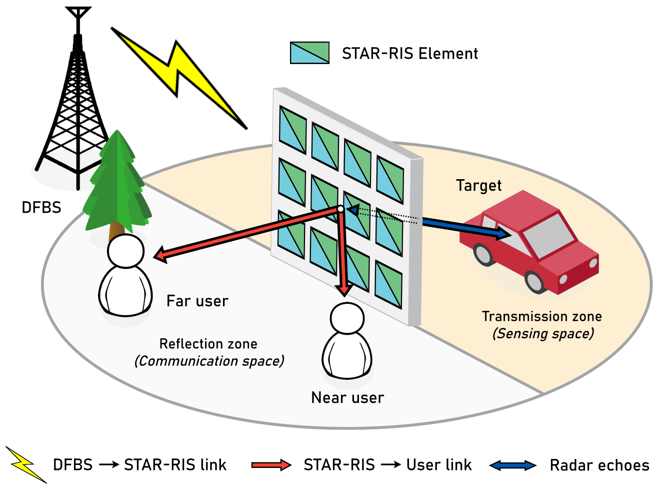

Fig. 3. An illustration of STAR-RIS-enabled downlink NOMA-ISAC network.

in terms of interference management and resource allocation; one must carefully address the tradeoffs between maximizing sensing and communication performance.

IV. STAR-RIS-Enabled Downlink NOMA-ISAC: A Case Study

In pursuit of enhanced spectral efficiency for both sensing and communication in future wireless networks, non-orthogonal multiple access (NOMA) emerges as a key enabling technology for ISAC systems. NOMA achieves this enhanced efficiency by allowing multiple users to share the same time-frequency resources through superposition coding at the transmitter and successive interference cancellation (SIC) at the receivers. By exploiting power domain multiplexing, NOMA enables the BS to serve multiple users simultaneously, allocating distinct power levels based on their channel conditions. This efficient spectrum utilization makes NOMA particularly suitable for ISAC systems, where the superimposed NOMA communication signals can also be exploited for target sensing, enabling efficient resource utilization and a flexible design for balancing sensing and communication performance. Motivated by these advantages, this section explores a STAR-RIS-enabled downlink NOMA-enhanced ISAC (NOMA-ISAC) network.

A. System Model

As illustrated in Fig. 3, we consider a STAR-RIS-enabled downlink NOMA-ISAC network, where a dual functional BS (DFBS), equipped with a single transmit/receive antenna, serves two single antenna users, near user and the far user, while detecting the target, under the assistance of a STAR-RIS with N elements. Without loss of generality, we assume that the communication space is on the reflection side, while the sensing space is on the transmission side. We consider that the direct links from the DFBS to users/target are not available due to the blockage. We assume that all communication channels undergo the Nakagami-*m* fading distribution with fading parameter m.

For the operation of STAR-RIS, we consider the *energy-splitting protocol*, with the energy-splitting coefficients ζ_r and ζ_t, respectively [11]. Furthermore, to simultaneously serve the near and far users in the communication space, we consider that the STAR-RIS elements are split between the near and far users under the element-splitting protocol [12]. Without loss of generality, we assume that the near user has better channel conditions than the far user.

B. Performance Evaluation

In this subsection, we demonstrate the performance gains of the STAR-RIS-enhanced NOMA-ISAC network. Unless mentioned otherwise, the simulation parameters are as follows. The energy splitting coefficients of the STAR-RIS, ξ_r and ξ_t, are assumed to be 0.8 and 0.2, respectively. The power allocation coefficients of the near and far users are 0.6 and 0.4, respectively. The simulation results are presented as follows.

1) ***Comparing the STAR-RIS-enhanced NOMA-ISAC to a FDSAC Network****:* In Fig. 4, we evaluate the performance of the proposed STAR-RIS-assisted NOMA-ISAC network, as well as that of its frequency division sensing and communication (FDSAC) counterpart, against the number of STAR-RIS elements for different values of DFBS transmit power. It can be observed that for a given value of the transmit power, the radar and the sum communication SNRs increase with the increase in the number of STAR-RIS elements. Moreover, the STAR-RIS-enhanced ISAC network outperforms the conventional FDSAC network.

2) ***Comparing the STAR-RIS-enhanced NOMA-ISAC to a Conventional Reflecting-only RIS****:* In Fig. 5, we evaluate the performance of the proposed STAR-RIS-assisted NOMA-ISAC network, as well as that of its conventional reflecting-only RIS counterpart, against the number of STAR-RIS elements. For the conventional RIS, we consider one reflecting-only RIS and one transmitting-only RIS, which are deployed adjacently at the same location as the STAR-RIS to realize full space coverage. To ensure a fair performance comparison, we consider that each reflecting- and transmitting only RIS is equipped with $N/2$ elements. As can be observed, the SNR performance of the STAR-RIS is better than the conventional RIS for both the radar and wireless communications.

3) ***Effect of the Energy Splitting Coefficients****:* The effect of the energy splitting coefficients on the radar and communication performance is demonstrated in Fig. 6. As can be observed, for a fixed number of STAR-RIS elements, with the increase in the energy splitting coefficient of the reflecting zone, i.e., ξ_r, the communication SNR increases while the radar SNR decreases due to the law of the conservation of energy, i.e., $\xi_r + \xi_t = 1$.

V. Open Challenges and Research Directions

While STAR-RIS-enabled ISAC holds immense promise for 6G and beyond, several open challenges remain before its full potential can be unlocked. These challenges range from the complexities of modeling and analysis to the practicalities of deployment and application. Addressing these challenges will

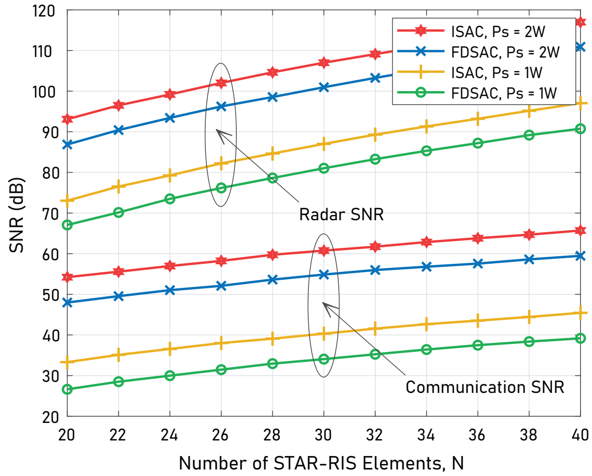

Fig. 4. SNR versus the number of STAR-RIS elements for different values of DFBS transmit power.

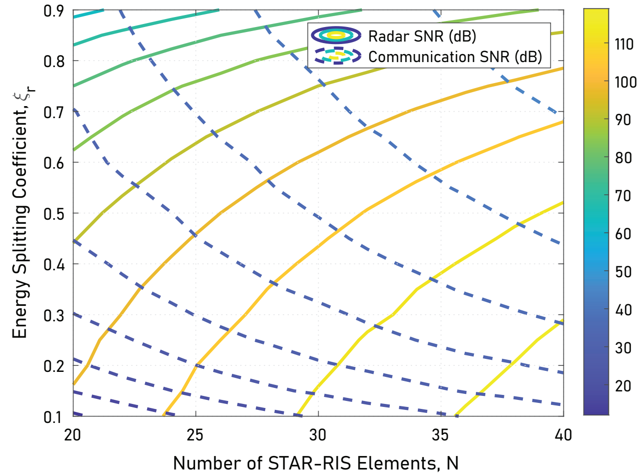

Fig. 6. SNR versus the number of STAR-RIS elements and energy splitting coefficient.

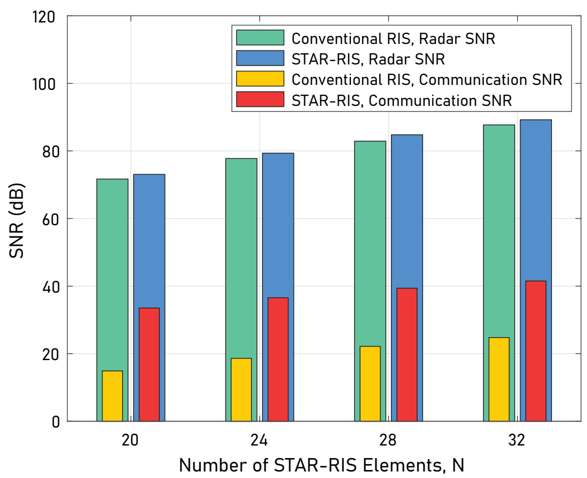

Fig. 5. The SNR comparison of the STAR-RIS-enhanced NOMA-ISAC network and the conventional RIS-enhanced NOMA-ISAC network.

require concerted research efforts, focused on developing innovative solutions and pushing the boundaries of this emerging technology.

A. Challenges in Analysis and Practicality

A primary challenge lies in accurately modeling and analyzing STAR-RIS-enabled ISAC systems in realistic scenarios. The complexities of multipath propagation, channel fading, and interference present significant obstacles to developing tractable and accurate mathematical models.

- *Propagation Modeling:* Traditional channel models, often based on simplified assumptions, may not adequately capture the intricacies of electromagnetic wave propagation in real-world environments. More sophisticated models that incorporate factors such as shadowing, blockage, and multipath scattering are essential for accurate prediction and analysis. Existing research has explored techniques such as ray tracing [13] for characterizing far- and near-field propagation, but further advancements are needed to handle the complexities of the STAR-RIS environment.
- *Hardware Limitations:* STAR-RIS faces practical hardware constraints, including coupled phase shifts, phase-dependent amplitude, discrete amplitude levels, and correlated channels [5], that can affect system performance and require novel hardware designs and control techniques. Efforts are being made towards exploring graphene-based dynamic metasurfaces [14] and multi-layer metasurfaces [15] for overcoming limitations of traditional materials and achieving more flexible control.
- *Interference Management:* Managing interference between communication signals and sensing signals, especially in scenarios where both functionalities are operating simultaneously, is a critical challenge. Effective techniques for interference mitigation, such as beamforming, resource allocation, and interference cancellation, will be essential for ensuring high-quality communication and sensing performance. Recent research efforts have already produced promising results, like the simultaneous-signal-enhancement-and-cancellation-based (SSECB) design proposed by Hou et al. [7], which aims to eliminate inter-cell interference and boost desired signals.

B. Challenges in Deployment

Deploying and managing STAR-RIS-enabled ISAC systems in real-world applications pose a set of challenges that need to be addressed:

- *Scalability:* Scaling STAR-RIS systems to support large-scale deployments, especially in dense urban environments, will be critical. The design of STAR-RIS must be scalable to handle numerous elements and ensure efficient control mechanisms for managing large-scale configurations.
- *Control Mechanisms:* Developing robust and efficient control mechanisms for STAR-RIS is vital for dynamically adapting to changes in the environment and user

demands. This will require advanced algorithms for channel estimation, beam tracking, and resource allocation. Researchers are actively exploring the potential of machine learning (ML) and deep reinforcement learning (DRL) algorithms to address the challenges of dynamic environments and complex control requirements.
- *Standardization:* To facilitate the widespread adoption of STAR-RIS-enabled ISAC, standardization efforts are crucial. This will involve developing industry standards for hardware specifications, communication protocols, and control procedures, ensuring interoperability and compatibility.

C. Challenges in Applications

Applying STAR-RIS-enabled ISAC to specific applications will require addressing unique challenges related to specific use cases and requirements.

- *Autonomous Vehicles:* STAR-RIS can be a game-changer for vehicular communication, offering enhanced coverage and reliable communication links in challenging environments. However, the dynamic nature of vehicular networks, with high mobility and rapidly changing environments, presents significant challenges for channel estimation, beam tracking, and resource allocation.
- *Smart Cities:* The massive deployment of IoT devices will require efficient and robust STAR-RIS-enabled ISAC systems. This will necessitate designing energy-efficient solutions, exploring low-latency communication protocols, and developing secure and reliable sensing mechanisms. The combination of non-orthogonal multiple access (NOMA) and STAR-RIS offers promising possibilities for achieving higher spectrum efficiency and accommodating a greater number of IoT devices in this context.
- *IoT Applications:* STAR-RIS can play a crucial role in realizing the vision of smart cities by enabling seamless connectivity and highly accurate sensing. However, the complex urban environment, with numerous obstacles and dense deployments of devices, presents unique challenges for signal propagation, interference management, and data processing.

D. Research Directions

To overcome the challenges outlined above, several promising research directions offer significant potential.

- *Accurate Channel Estimation:* Designing efficient and robust channel estimation algorithms for STAR-RIS-enabled ISAC systems is crucial to managing their unique characteristics, such as coupled phase shifts and dual-path propagation. Exploring techniques based on tensor decomposition and machine learning could provide promising solutions for achieving accurate channel estimation in these complex environments.
- *Dynamic Resource Allocation:* Developing dynamic and intelligent resource allocation schemes that can adapt to changing user demands and environmental conditions is essential for realizing STAR-RIS-enabled ISAC systems. These schemes must be able to balance communication and sensing requirements, manage interference, and ensure efficient utilization of power and bandwidth. Deep learning (DL) and reinforcement learning (RL) techniques could be explored to design adaptive resource allocation algorithms, capable of learning and optimizing system performance over time.
- *Efficient Hardware Design:* Research efforts should also focus on developing cost-effective, scalable, and energy-efficient hardware designs for STAR-RIS. This will involve exploring new materials, circuit topologies, and manufacturing techniques to overcome existing limitations and facilitate the widespread deployment of STAR-RIS-enabled ISAC systems.
- *Stacked Intelligent Metasurfaces:* The stacked intelligent metasurfaces (SIMs) are advanced engineered surfaces composed of multiple layers of metasurfaces, each designed to manipulate electromagnetic waves in specific ways, which are capable of outperforming the single-layer metasurface counterparts, such as the traditional RIS. Therefore, SIM-enabled ISAC networks are worth investigating for next-generation wireless networks.
- *Flexible Intelligent Metasurfaces:* Flexible intelligent metasurfaces (FIMs) combine flexibility with intelligent capabilities, allowing them to bend, stretch, or deform while dynamically adjusting the electromagnetic properties. This opens up new possibilities for advanced applications in various fields, ranging from consumer electronics to healthcare and beyond. The integration of FIMs with ISAC networks is a promising area of research and development, holding the potential to revolutionize various fields by providing more efficient, adaptive, and multi-functional systems.

VI. Conclusion

This article highlighted the transformative potential of STAR-RIS-enabled ISAC systems for future wireless networks. We examined STAR-RIS designs, utilizing both transmission and reflection spaces, to enhance communication and sensing capabilities in diverse real-world applications. Through a case study, we demonstrated the significant performance gains achievable by integrating STAR-RIS into NOMA-ISAC networks. However, several critical challenges, including complexities in propagation modeling, hardware limitations, and interference management, stand in the way of practical implementations. To overcome these obstacles, we proposed promising research directions, such as advancements in channel estimation, dynamic resource allocation, and innovative hardware designs, including the exploration of SIMs and FIMs. Ultimately, continued research and development in these areas will be crucial for fully unlocking the potential of STAR-RIS-enabled ISAC, paving the way for a new era of intelligent and connected wireless networks.

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