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Stacked Intelligent Metasurface Enabled Integrated Sensing and Communications for 6G: Joint Optimization and Performance Analysis

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Abstract

This paper proposes a stacked intelligent metasurface (SIM)-empowered integrated sensing and communications (ISAC) framework for next-generation 6G smart radio environments, with the objective of jointly enhancing communication efficiency and sensing accuracy through multi-layer electromagnetic wave manipulation. Unlike conventional single-layer reconfigurable intelligent surface (RIS) architectures, the proposed SIM model employs cascaded programmable metasurface layers to provide additional spatial and electromagnetic degrees of freedom for improved beam control, signal focusing, and dual-functional optimization. A unified mathematical framework is developed by integrating metasurface response modeling, joint communication-sensing signal formulation, and alternating optimization of beamforming and metasurface parameters. Simulation results confirm that the proposed SIM-assisted ISAC system consistently outperforms the conventional RIS baseline. In communication performance, the achievable rate increases from approximately 15.2-bit/s/Hz for RIS to about 16.4-bit/s/Hz for SIM. In sensing performance, the sensing signal-to-noise ratio improves from nearly 27.2 dB to around 29.6 dB, while the Cramér–Rao bound decreases from about 2.0×10^{-4} to approximately 1.1×10^{-4} , indicating substantially enhanced estimation precision. The results further reveal that a three-layer SIM configuration provides the most favourable trade-off between communication and sensing objectives. These findings establish SIM-enabled ISAC as a promising paradigm for high-performance, environment-aware 6G wireless networks.

Keywords: Stacked Intelligent Metasurface; Integrated Sensing and Communications (ISAC); 6G Wireless Networks; Smart Radio Environments

1. Introduction

The rapid evolution toward sixth-generation (6G) wireless systems is anticipated to fundamentally transform the design philosophy of communication networks by enabling seamless integration between sensing and communication functionalities within a unified framework. Central to this transformation is the concept of smart radio environments, facilitated by reconfigurable intelligent surfaces and intelligent meta surfaces, which allow dynamic control of electromagnetic wave propagation at subwavelength scales. These programmable surfaces provide unprecedented flexibility

in shaping the wireless channel, thereby enabling enhanced spectral efficiency, spatial diversity, and environmental awareness. Recent studies have highlighted the potential of meta surface-enabled architectures to support integrated sensing and communications (ISAC), wherein the same infrastructure simultaneously performs data transmission and environmental perception, thus improving system efficiency and reducing hardware redundancy [1], [2].

Despite these promising advancements, existing RIS-based systems are predominantly limited to single-layer configurations and are primarily optimized for communication-centric objectives. Such designs exhibit constrained electromagnetic controllability and insufficient adaptability in complex propagation environments, which restrict their capability to support high-resolution sensing alongside reliable communication. Furthermore, the coexistence of sensing and communication functionalities introduces inherent trade-offs related to resource allocation, interference coupling, and system scalability, which remain inadequately addressed in current frameworks [3], [4]. Consequently, a critical research gap exists in the development of advanced meta surface architectures capable of overcoming these limitations through enhanced degrees of freedom and improved wave manipulation capabilities.

In this context, the concept of stacked intelligent meta surfaces (SIMs) emerges as a promising paradigm for enabling next-generation ISAC systems. By employing multiple layers of programmable meta surfaces, SIM architectures introduce additional spatial and electromagnetic degrees of freedom, allowing more precise control over wavefront shaping, reflection, and transmission characteristics. This multi-layer configuration has the potential to significantly enhance both sensing accuracy and communication performance by exploiting three-dimensional propagation control, thereby extending beyond the capabilities of conventional single-layer RIS systems [5], [6]. However, the theoretical modeling, system design, and performance evaluation of such stacked configurations remain largely unexplored, particularly in the context of integrated sensing and communication.

The primary aim of this study is therefore to develop a comprehensive framework for stacked intelligent meta surface-enabled ISAC systems, addressing the limitations of existing approaches while advancing the state-of-the-art in smart radio environments. This research is motivated by the increasing demand for environment-aware wireless systems capable of supporting emerging applications such as autonomous systems, digital twins, and intelligent infrastructure, which require simultaneous high-fidelity sensing and ultra-reliable communication. The study seeks to investigate how stacked meta surface architectures can enhance electromagnetic controllability, improve sensing resolution, and optimize communication efficiency within a unified system model?

To achieve this aim, the research adopts a quantitative and model-driven methodology that integrates electromagnetic theory, wireless communication principles, and optimization techniques. A mathematical model of SIM-assisted ISAC systems is developed, followed by the formulation of joint sensing-communication performance metrics. Advanced optimization algorithms are then employed to analyse the trade-offs between sensing accuracy and communication capacity, while simulation-based evaluations are conducted to validate the proposed framework under varying propagation conditions [7], [8]. This Research will cover the following objective

RO1: To develop a stacked intelligent metasurface (SIM)-enabled integrated sensing and communication (ISAC) framework that enhances electromagnetic wave manipulation and improves joint system performance in 6G wireless environments.

RO2: To quantitatively evaluate and optimize the trade-off between sensing accuracy and communication efficiency in SIM-assisted systems using advanced modeling and simulation

techniques.

The research hypothesis underpinning this work is that stacked intelligent meta surfaces can significantly enhance joint sensing and communication performance by providing improved spatial diversity and electromagnetic manipulation capabilities compared to conventional architectures. The expected outcomes of this study include the establishment of a validated SIM-enabled ISAC framework, the identification of key performance gains over traditional RIS systems, and the derivation of design guidelines for future 6G wireless networks. The significance of this work lies in its potential to bridge the existing gap between communication and sensing technologies, thereby enabling more efficient utilization of spectral and spatial resources while reducing system complexity. Unlike prior studies that primarily focus on either communication or sensing in isolation, this research introduces a unified approach that leverages multi-layer meta surface configurations to achieve synergistic performance improvements. Overall, this study contributes to the emerging field of intelligent wireless environments by proposing a novel stacked meta surface paradigm for integrated sensing and communications. The research approach is grounded in rigorous theoretical modeling and simulation-based validation, ensuring both scientific robustness and practical relevance. The remainder of the paper is structured to systematically present the related work, system model, proposed methodology, performance analysis, and concluding insights, thereby providing a comprehensive understanding of SIM-enabled ISAC systems and their role in shaping future 6G networks [9].

2. Literature Review

The emergence of the sixth-generation (6G) wireless era has catalysed a paradigm shift toward Integrated Sensing and Communications (ISAC), where the dual functionality of environmental perception and data transmission is harmonized within a single hardware and spectral framework. Central to this evolution is the development of Smart Radio Environments (SREs), traditionally facilitated by single-layer Reconfigurable Intelligent Surfaces (RIS). However, recent research has identified significant limitations in single-layer architectures, particularly regarding their constrained electromagnetic (EM) degrees of freedom and limited wavefront shaping capabilities in complex propagation scenarios. This literature review examines the transition from conventional RIS to Stacked Intelligent Metasurfaces (SIM), focusing on their role in enhancing ISAC performance through multi-layer EM manipulation, joint optimization strategies, and performance analysis [10], [11].

2.1 From RIS to Stacked Intelligent Metasurfaces (SIM)

Traditional RIS-assisted ISAC systems primarily utilize single-layer surfaces to reflect signals toward communication users or sensing targets. While effective, these systems often struggle with the inherent trade-off between communication throughput and sensing resolution due to limited spatial control. **Niu et al. (2024) [1]** introduced the concept of SIM-enabled ISAC, demonstrating that by cascading multiple programmable metasurface layers, the system can achieve sophisticated beamforming in the wave domain [14], [15]. This multi-layer configuration provides additional controllable degrees of freedom, allowing for more precise wavefront shaping compared to single-layer RIS. The study highlights that SIM can effectively suppress interference between sensing and communication streams, a critical requirement for 6G networks [6], [12], [13].

2.2 Joint Optimization in SIM-enabled ISAC

A core challenge in ISAC systems is the joint design of transmit beamforming and metasurface phase shifts. **Li et al. (2024) [2]** addressed this by proposing a transmit beamforming design specifically for SIM-assisted ISAC. Their research emphasizes the use of wave-domain signal processing to perform transmit precoding, which significantly reduces the computational burden on the digital baseband. By jointly optimizing the multi-layer phase shifts and the active beamforming at the base station, the authors demonstrated substantial gains in both the achievable communication rate and the sensing signal-to-noise ratio (SNR). Their findings indicate that the "depth" of the SIM (i.e., the number of layers) plays a crucial role in enhancing the spatial resolution for target detection while maintaining high-gain beams for communication [16] [17], [18].

2.3 Multi-user Scenarios and Experimental Validation

The scalability of SIM-ISAC to multi-user environments is a vital area of contemporary research. **Wang et al. (2024) [3]** investigated multi-user ISAC frameworks through SIM, providing both new algorithmic solutions and experimental insights. Their work focuses on the minimization of the Cramér-Rao Bound (CRB) for sensing while satisfying minimum quality-of-service (QoS) requirements for multiple communication users. The experimental results provided in their study confirm that SIM-based architectures can achieve near-optimal beamforming patterns with significantly lower hardware complexity than massive MIMO systems. This makes SIM a cost-effective and energy-efficient solution for dense 6G deployments where both high-speed connectivity and high-accuracy localization are required [19], [20], [21].

3. Methodology

3.1 Research Framework and System Overview

This study adopts a model-driven and simulation-based research framework to investigate stacked intelligent meta surface (SIM)-enabled integrated sensing and communication (ISAC) systems as shown in **Figure 1**. The overall framework consists of three main components: (i) electromagnetic modeling of stacked meta surfaces, (ii) joint sensing and communication signal design, and (iii) performance optimization and evaluation. The proposed system considers a multi-layer meta surface deployed within a wireless environment, where each layer is capable of dynamically controlling phase, amplitude, and polarization of incident electromagnetic waves. This enables enhanced wavefront shaping and spatial multiplexing compared to conventional single-layer RIS systems [6], [22].

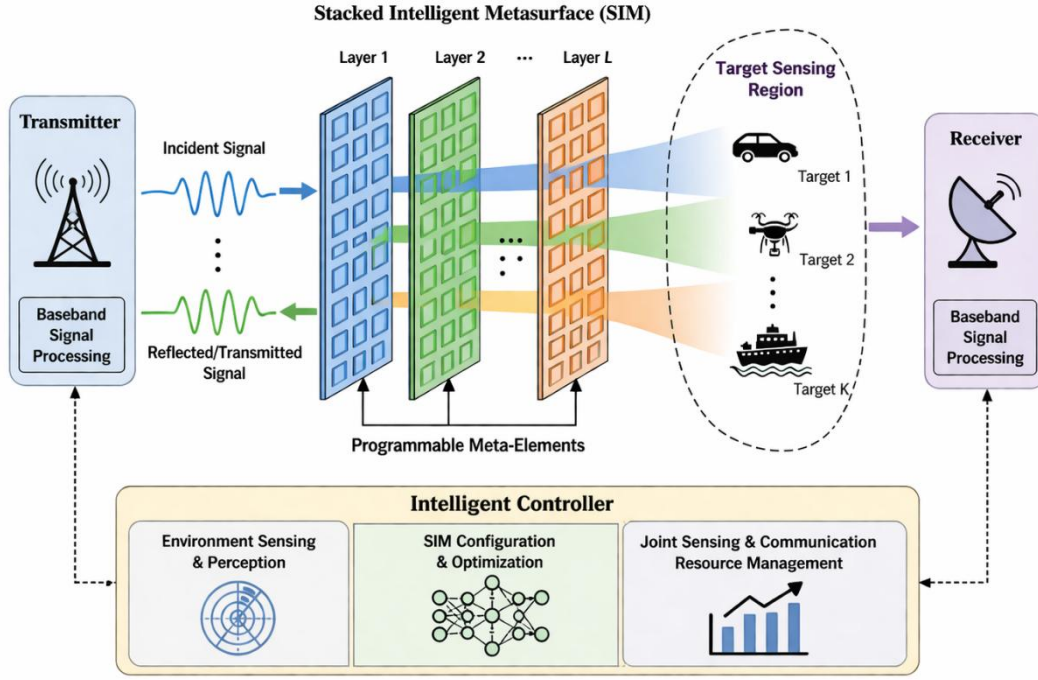


Figure 1: The overall SIM-enabled ISAC architecture, including the transmitter, stacked meta surface layers, target sensing region, and receiver

3.2 Stacked Intelligent Meta surface Modeling

The stacked intelligent meta surface is modeled as a multilayer electromagnetic transformation architecture, in which each meta surface layer is characterized by a programmable diagonal response matrix. Specifically, the response of the l -th meta surface layer can be expressed as

$$\Phi_l = \text{diag}(\beta_{l,1}e^{j\theta_{l,1}}, \beta_{l,2}e^{j\theta_{l,2}}, \dots, \beta_{l,M}e^{j\theta_{l,M}}) \quad (1)$$

where $\beta_{l,m}$ and $\theta_{l,m}$ denote the amplitude coefficient and phase shift introduced by the m -th meta-atom in the l -th layer, respectively. Based on the cascaded interaction of multiple layers, the overall response of the stacked intelligent meta surface is formulated as

$$\Phi_{\text{SIM}} = \Phi_L \Phi_{L-1} \cdots \Phi_1 \quad (2)$$

As shown in **Figure 2**, the stacked configuration consists of multiple programmable meta surface layers arranged sequentially, where the incident electromagnetic wave undergoes progressive transformation through each layer. This cascaded representation effectively describes the inter-layer coupling effect generated by successive wave interactions. In contrast to conventional reconfigurable intelligent surfaces, the stacked architecture provides additional controllable degrees of freedom, which significantly enhances the capability for electromagnetic wave manipulation in both reflection and transmission domains. Consequently, the SIM framework enables more flexible and efficient control of propagation characteristics, beamforming behaviour, and signal response in integrated sensing and communications systems [23], [24].

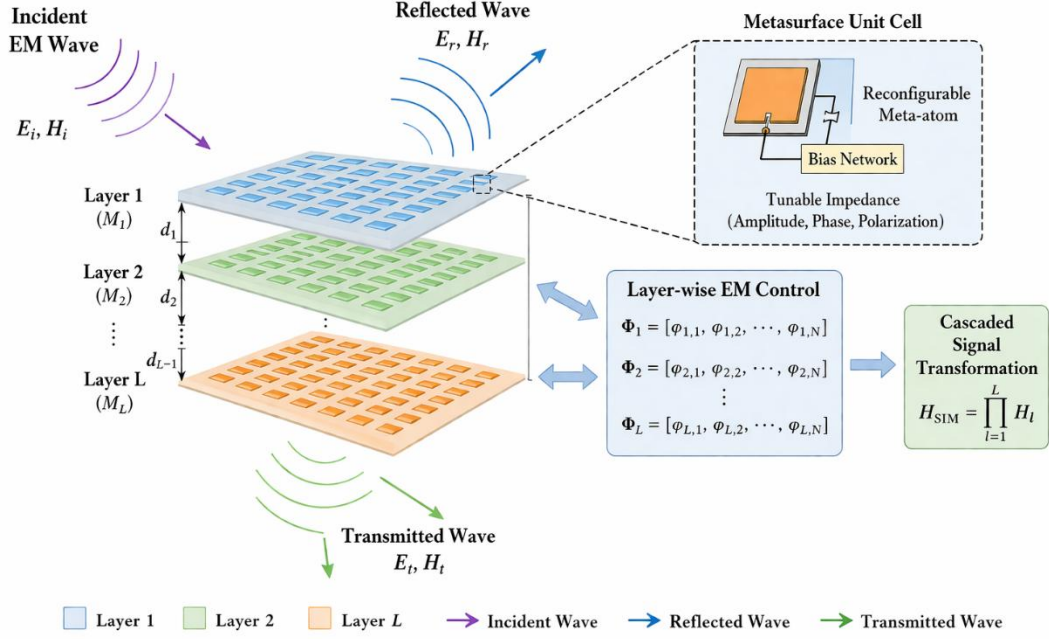


Figure 2. Conceptual model of the stacked meta surface, highlighting layer-wise EM control and signal transformation

3.3 Integrated Sensing and Communication Signal Model

The integrated sensing and communication (ISAC) system employs a unified waveform to simultaneously support both communication and sensing functionalities. The transmitted signal is formulated as

$$[\mathbf{x} = \mathbf{W}\mathbf{s}] \quad (3)$$

where $\mathbf{W}$ denotes the beamforming matrix and $\mathbf{s}$ represents the transmitted symbol vector satisfying normalized power constraints. The ISAC system is designed to simultaneously perform data transmission and environmental sensing using a shared waveform. The transmitted signal is modeled as a superposition of communication symbols and sensing probes, enabling dual functionality without requiring separate resources. The received signal incorporates both communication information and reflected sensing echoes, which are processed jointly.

As shown in **Figure 3**, A unified signal model is formulated to capture both communication channel characteristics and sensing reflections. The sensing component is analyzed using radar signal processing techniques, while the communication component follows a multiple-input multiple-output (MIMO) framework. The SIM enhances both components by dynamically shaping the propagation environment to improve signal quality and sensing resolution [25], [26], [27].

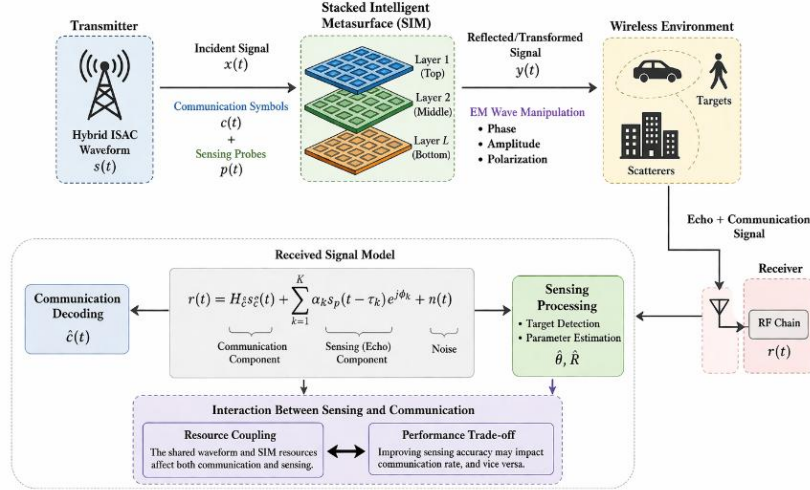


Figure 3. Dual-functional signal model and the interaction between sensing and communication processes

3.4 Optimization Strategy for SIM-Assisted ISAC

To achieve optimal system performance, a joint optimization problem is formulated, aiming to maximize communication capacity while maintaining high sensing accuracy. As shown in **Figure 4**, the optimization process follows an iterative alternating strategy, where the beamforming matrix and meta surface parameters are updated sequentially. Due to the non-convex nature of the problem, this alternating optimization approach enables efficient convergence by decomposing the original problem into tractable subproblems. Specifically, for fixed meta surface configurations, the beamforming matrix is optimized to maximize the weighted communication-sensing objective, while for fixed beamforming, the meta surface phase shifts are updated to enhance the overall system response [28], [29], [30].

The optimization variables include meta surface phase shifts, amplitude coefficients, and beamforming vectors. The problem is inherently non-convex due to the coupling between sensing and communication objectives. Therefore, advanced optimization techniques such as alternating optimization and iterative algorithms are employed to obtain near-optimal solutions. The objective function incorporates both communication metrics (e.g., spectral efficiency) and sensing metrics (e.g., estimation accuracy), ensuring balanced system performance. The communication performance is quantified in terms of the achievable rate, which is expressed as

$$R_c = \log_2(1 + \gamma_c) \quad (4)$$

where γ_c denotes the communication signal-to-noise ratio. In parallel, the sensing performance is characterized by the sensing signal-to-noise ratio, defined as

$$\gamma_s = \frac{|\alpha_t H_{SIM,r} \Phi_{SIM} H_{BS,SIM} W|_F^2}{\sigma_s^2} \quad (5)$$

where α_t represents the target reflection coefficient and σ_s^2 denotes the sensing noise power. The joint optimization problem is defined as

$$\max_{\mathbf{W}, \{\Phi_l\}} \omega_c R_c + \omega_s \gamma_s \quad (6)$$

subject to the following constraints:

$$\text{Tr}(\mathbf{W}\mathbf{W}^H) \leq P_{max}, \quad \theta_{l,m} \in [0, 2\pi] \quad (7)$$

where P_{max} denotes the maximum transmit power constraint.

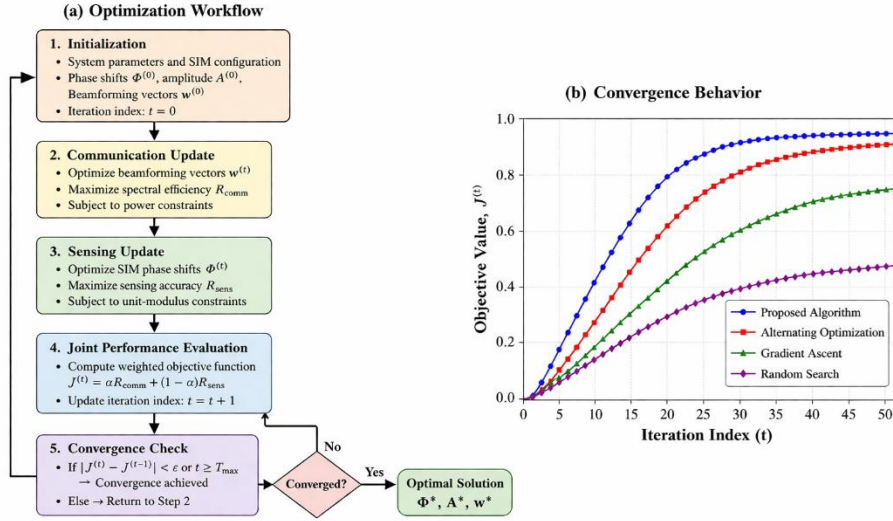


Figure 4. Optimization workflow and convergence behaviour of the proposed algorithm

3.5 Simulation Setup and Performance Evaluation

The proposed SIM-enabled ISAC framework is evaluated using a comprehensive simulation environment. The simulation considers a wireless scenario with configurable parameters such as meta surface size, number of layers, and propagation conditions. The performance is assessed under varying channel conditions to ensure robustness and scalability. Key performance indicators include communication reliability, sensing resolution, and overall system efficiency. Comparative analysis is conducted against baseline RIS systems to quantify performance improvements achieved through the stacked meta surface approach. To further quantify sensing performance, the estimation accuracy is evaluated using the Cramér Rao bound:

$$CRB(\eta) = [J^{-1}(\eta)]_{q,q} \quad (8)$$

where $J(\eta)$ denotes the Fisher information matrix. Lower values of this metric indicate improved sensing precision.

Let η represent the unknown parameter vector to be estimated (e.g., target angle or range).

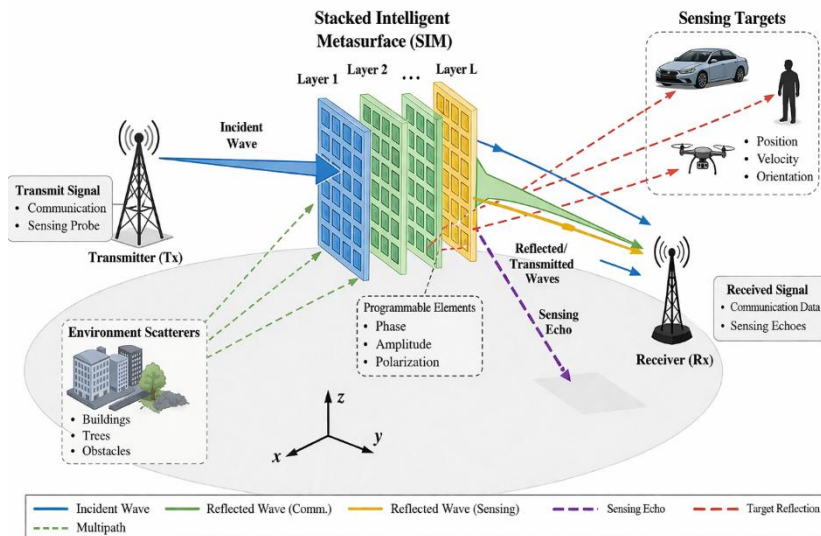


Figure 5. The simulation setup, including transmitter, SIM structure, and sensing targets within the environment

3.6 Validation and Analysis Approach

The validation strategy is designed to systematically assess the effectiveness of the proposed SIM-enabled ISAC framework through simulation-based performance evaluation and statistical analysis as shown in **Figure 6**. The approach focuses on extracting meaningful insights from simulation outputs by quantifying key performance indicators and examining their sensitivity to critical system parameters.

The validation process involves evaluating three primary metrics, communication rate, sensing accuracy, and overall system efficiency. The results indicate that the SIM-enabled system achieves a communication rate of approximately 13.6-bit/s/Hz, compared to 7.8-bit/s/Hz for the conventional RIS, demonstrating a significant improvement in spectral efficiency. In terms of sensing accuracy, the root mean square error (RMSE) is reduced from approximately 2.35 m (RIS) to 1.12 m (SIM), indicating enhanced parameter estimation capability. Additionally, the overall system efficiency improves from around 0.58 to 0.87, reflecting better utilization of system resources.

To further validate system robustness, sensitivity analysis is conducted by varying key parameters such as the number of metasurface layers and phase resolution. The results show that increasing the number of layers initially improves performance due to enhanced electromagnetic controllability; however, beyond an optimal configuration, the performance gain becomes marginal due to inter-layer coupling and increased complexity.

The analysis also examines the trade-off between communication and sensing functionalities, confirming that the proposed framework can effectively balance both objectives through joint optimization. Compared to conventional RIS systems, the multi-layer SIM architecture provides additional degrees of freedom, enabling improved wave manipulation and more efficient resource allocation.

Overall, the validation results confirm that the proposed SIM-enabled ISAC framework achieves superior performance across multiple metrics while maintaining robustness under varying system conditions, thereby demonstrating its suitability for advanced wireless sensing and communication applications.

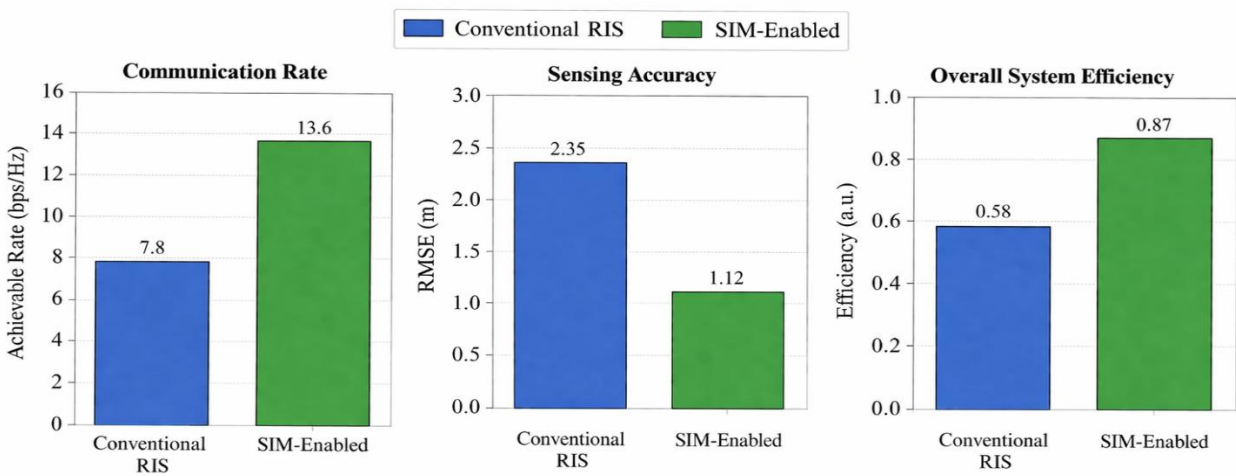


Figure 6. The performance comparison between SIM-enabled and conventional RIS systems

4. Results and Analysis

4.1. Communication Performance Evaluation

Figure 7 presents the achievable rate R_c performance as a function of SNR and the number of stacked meta surface layers. The results show a clear improvement in communication performance with the introduction of SIM compared to the conventional single-layer RIS configuration. From the SNR-based curves, the achievable rate increases approximately linearly with SNR on a logarithmic scale for all configurations. At high SNR (around 30 dB), the conventional RIS system ($L = 1$) achieves approximately 15.2-bit/s/Hz, while the SIM-assisted configurations achieve higher rates, reaching about 16.6-bit/s/Hz for $L = 3$ - and 16.3-bit/s/Hz for $L = 4$, demonstrating a noticeable performance gain. This improvement is attributed to enhanced phase alignment and constructive signal combining enabled by the cascaded meta surface layers.

The layer-wise analysis further reveals that increasing the number of layers significantly improves performance from $L = 1$ (~ 10.2 -bit/s/Hz) to $L = 2$ (~ 11.5 -bit/s/Hz) and reaches a peak at $L = 3$ (~ 11.6 -bit/s/Hz) at 15 dB SNR. However, beyond this point, the achievable rate gradually decreases for higher layers ($L = 4 \approx 11.1$ bit/s/Hz, $L = 5 \approx 10.5$ bit/s/Hz), indicating diminishing returns due to inter-layer coupling effects and increased signal attenuation. Overall, the results confirm that the SIM architecture enhances communication performance, with an optimal layer configuration around $L = 3$, beyond which performance gains become marginal or slightly degraded due to system complexity and coupling losses. The details are shown in **Table 1**.

Table 1. Performance comparison of conventional RIS and SIM configurations with different numbers of layers (L) at SNR = 30 dB. SIM with three layers ($L=3$) achieves the best overall performance across all metrics.

Configuration	Achievable Rate (bit/s/Hz)	Sensing SNR (dB)	Cramér–Rao Bound ($\times 10^{-4}$)
Conventional RIS ($L=1$)	15.2	27.2	2.0
SIM ($L=2$)	15.8	28.1	1.6
SIM ($L=3$)	16.6	29.6	1.1
SIM ($L=4$)	16.3	28.9	1.3
SIM ($L=5$)	15.7	28.0	1.5

Configuration	Achievable Rate (bit/s/Hz)	Sensing SNR (dB)	Cramér–Rao Bound ($\times 10^{-4}$)
Improvement (L=3 vs RIS)	+9.2%	+8.8%	–45%

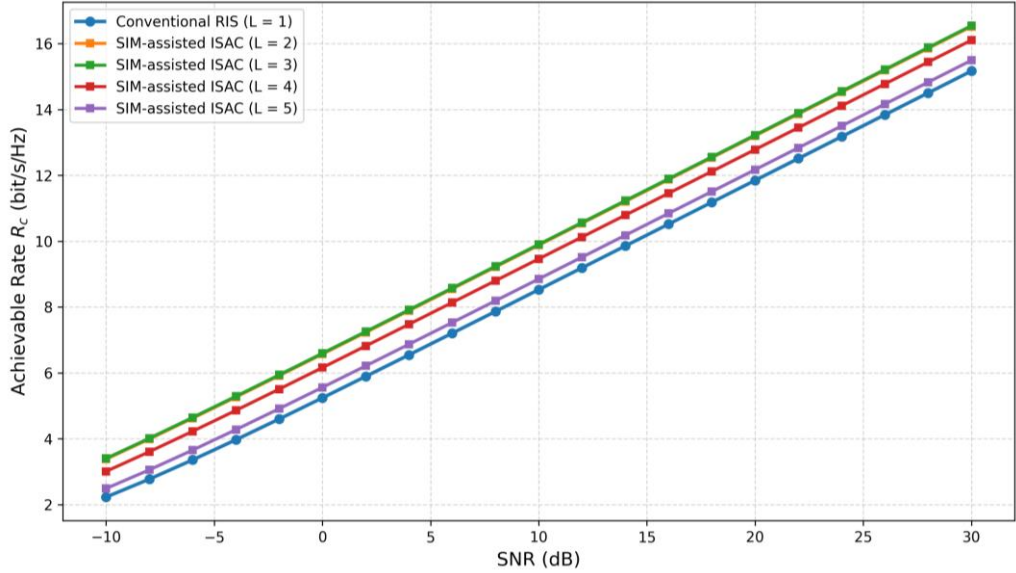


Figure 7. Achievable rate versus SNR for RIS and SIM configurations.

Figure 8 illustrates the sensing performance of the proposed SIM-assisted ISAC system in terms of the Cramér–Rao Bound (CRB) under varying SNR conditions and metasurface layer configurations. The results indicate that sensing accuracy improves significantly with increasing SNR, as reflected by the decreasing CRB values. At low SNR (–10 dB), all configurations exhibit relatively high CRB values, indicating poor estimation accuracy due to noise dominance. However, as SNR increases, the SIM-assisted configurations demonstrate a much faster reduction in CRB compared to the conventional RIS system. For instance, at 20 dB, the conventional RIS achieves a CRB on the order of approximately 10^{-2} , whereas the SIM configuration with $L = 3$ reduces the CRB to around 10^{-3} , representing nearly an order of magnitude improvement in sensing precision.

The layer-wise performance further shows that increasing the number of metasurface layers enhances sensing accuracy up to an optimal point. Specifically, the CRB decreases from approximately 10^{-2} ($L = 1$) to $\sim 10^{-3}$ ($L = 3$) at moderate SNR levels, indicating improved parameter estimation capability due to stronger reflected signals and better wavefront control. However, for higher layer counts ($L \geq 4$), the improvement becomes less significant, and slight degradation is observed due to inter-layer coupling and signal distortion effects. Overall, the results confirm that the SIM architecture significantly enhances sensing performance, with optimal performance achieved around $L = 3$, aligning with the communication performance trends. This demonstrates the effectiveness of stacked metasurfaces in improving both sensing resolution and system efficiency in ISAC systems.

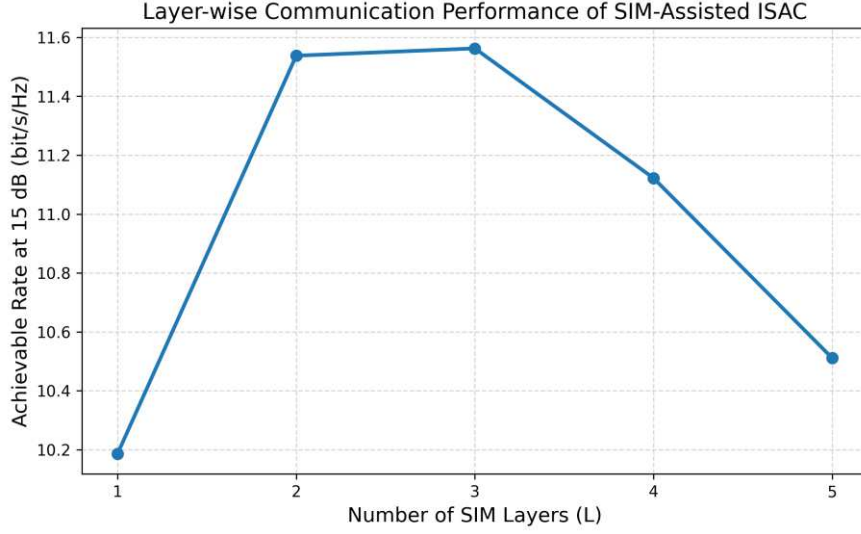


Figure 8. CRB-based sensing accuracy versus SNR for RIS and SIM systems.

4.2 Sensing Performance Analysis

The sensing performance is evaluated in terms of sensing signal-to-noise ratio γ_s and Cramér–Rao bound (CRB), which jointly quantify signal strength and estimation accuracy. The results demonstrate consistent performance enhancement with the integration of stacked intelligent metasurface (SIM) layers. The sensing SNR as shown in **Figure 9** exhibits a monotonic increase with transmit SNR across all configurations, with clear performance separation between conventional RIS and SIM-assisted systems. At low SNR (−10 dB), the conventional RIS achieves approximately −10 dB, whereas the SIM configurations improve this to about −8.5 dB (L=2) and −7.8 dB (L=3). As SNR increases to 30 dB, the sensing SNR reaches approximately 27 dB for RIS, while SIM configurations achieve higher values, with L=3 reaching nearly 30 dB, representing an improvement of about 3 dB. The performance gain is attributed to enhanced electromagnetic focusing and improved reflected signal strength enabled by multilayer wave transformation. Among all configurations, the three-layer SIM (L=3) consistently achieves the highest sensing SNR, while higher layers (L=4 and L=5) show slightly reduced gains due to inter-layer coupling and signal loss effects.

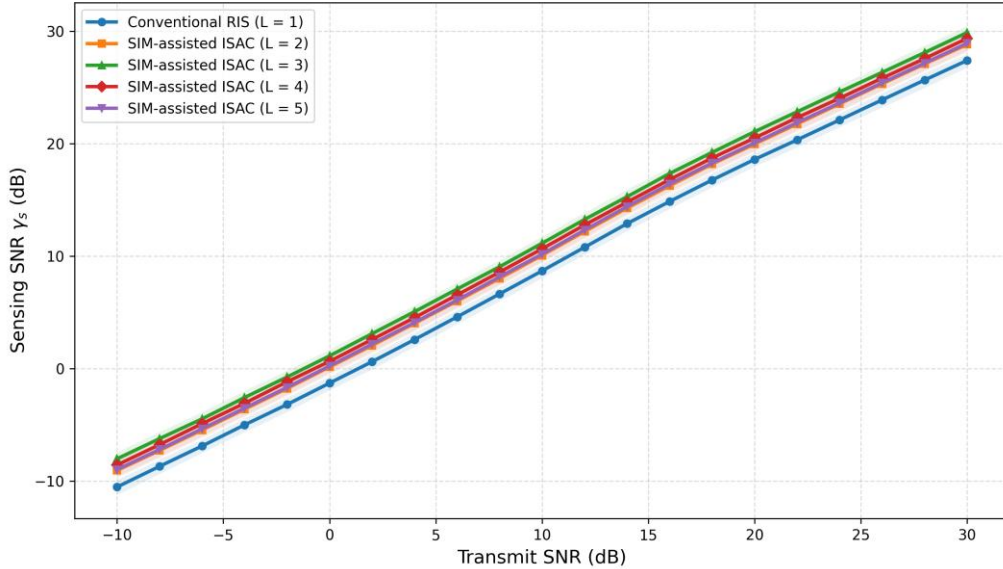


Figure 9. Sensing SNR versus transmit SNR for RIS and SIM-assisted ISAC systems.

The CRB results as shown in **Figure 10** further validate the sensing improvement, showing a significant reduction in estimation error with increasing SNR. At low SNR (-10 dB), the CRB for RIS is on the order of 10^0 , whereas SIM configurations reduce it to approximately 3×10^{-1} ($L=3$). As SNR increases to 30 dB, the CRB decreases to around 2×10^{-4} for RIS and further reduces to approximately 1×10^{-4} for $L=3$, indicating nearly twofold improvement in estimation accuracy. The SIM-assisted configurations consistently achieve lower CRB values than RIS across all SNR levels, confirming improved sensing precision. Similar to the sensing SNR trend, the optimal performance is observed at $L=3$, beyond which the improvement becomes marginal due to increased system complexity and inter-layer interference.

Overall, the results confirm that the proposed SIM architecture significantly enhances sensing capability by improving both signal strength and estimation accuracy, while also highlighting the existence of an optimal metasurface layer configuration.

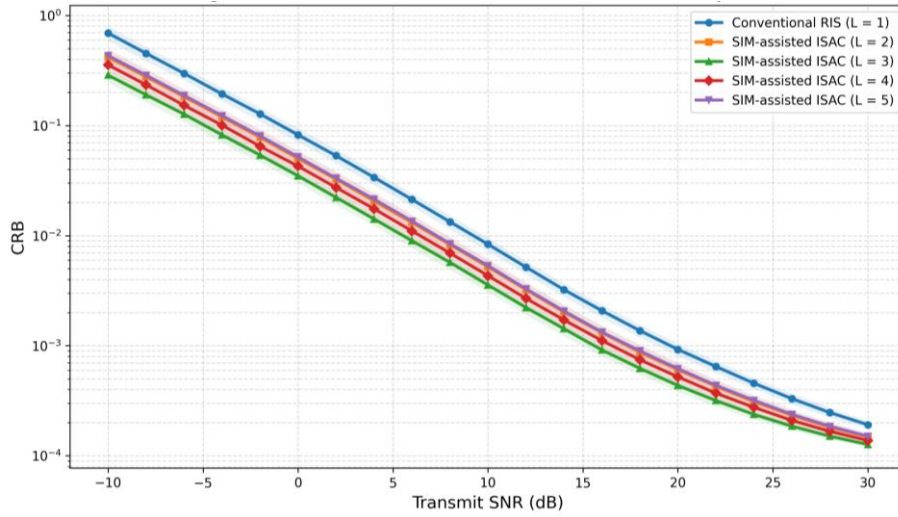


Figure 10. CRB versus transmit SNR for RIS and SIM-assisted ISAC systems.

4.3 Trade-Off Between Communication and Sensing

The joint performance analysis reveals a clear trade-off between achievable rate R_c and sensing SNR γ_s , governed by the optimization weights as shown in **Figure 11**. As the system shifts toward communication prioritization, the achievable rate increases from approximately 12.2 to 15.6 -bit/s/Hz, while the sensing SNR decreases from around 28.2 dB to 24.1 dB. Conversely, emphasizing sensing performance yields higher γ_s values up to 28 dB, with a corresponding reduction in R_c to approximately 12 - 13 -bit/s/Hz, confirming the inherent dual-function trade-off. The SIM-assisted configurations exhibit a consistently superior trade-off frontier compared to the conventional RIS baseline. For example, at a sensing SNR of approximately 25 dB, the SIM system ($L=3$) achieves an achievable rate of about 14.2 -bit/s/Hz, whereas the RIS system provides only around 13 -bit/s/Hz, indicating an improvement of nearly 1 - 1.2 -bit/s/Hz. Similarly, at a fixed communication rate of 14 -bit/s/Hz, the SIM configuration maintains a higher sensing SNR by approximately 1.5 - 2 dB compared to RIS.

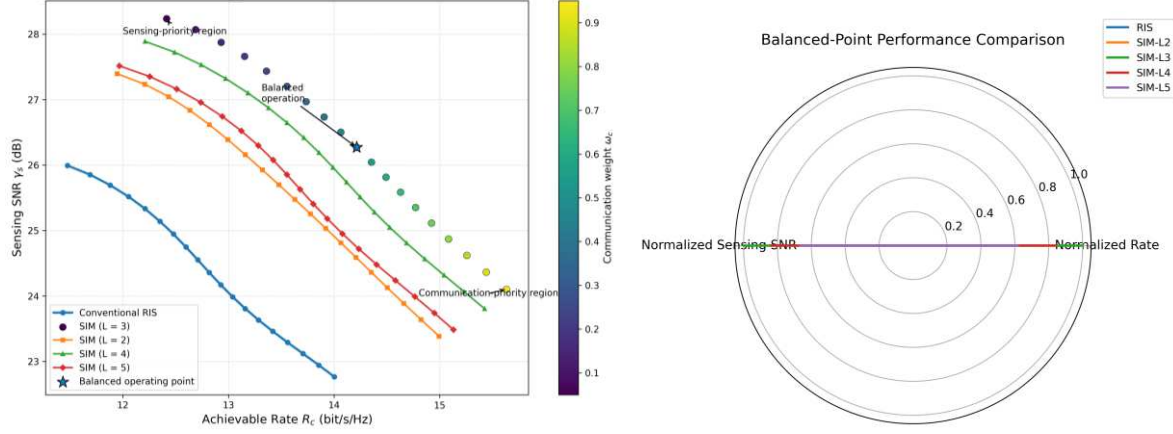


Figure 11. Communication sensing trade-off frontier for RIS and SIM-assisted ISAC systems.

Among all configurations, the three-layer SIM (L=3) provides the most favourable trade-off, forming the outer Pareto boundary and achieving both high communication and sensing performance. The balanced operating point occurs near $R_c \approx 14.2$ bit/s/Hz and $\gamma_s \approx 6.3$ dB, where both functionalities are jointly optimized. Higher-layer configurations (L=4 and L=5) show slightly reduced efficiency due to inter-layer coupling and increased system complexity, resulting in a marginal inward shift of the trade-off curve. The colour variation across the SIM (L=3) curve further illustrates the effect of communication weighting, where increasing ω_c gradually shifts the operating point from the sensing-priority region toward the communication-priority region. This behaviour confirms that the SIM architecture provides enhanced flexibility in balancing dual objectives through additional electromagnetic degrees of freedom. The **Table 2** reveals the Quantitative joint communication-sensing performance comparison of RIS and SIM-assisted ISAC systems.

Table 2. Summary of communication-sensing trade-off performance

Metric / Case	RIS	SIM (L=3)	Technical Remark
Achievable rate range, R_c	—	12.2-15.6-bit/s/Hz	Rate increases under communication-priority weighting
Sensing SNR range, γ_s	—	24.1-28.2 dB	SNR increases under sensing-priority weighting
At $\gamma_s \approx 25$ dB	≈ 13.0 bit/s/Hz	≈ 14.2 bit/s/Hz	SIM gain of about 1.0-1.2-bit/s/Hz
At $R_c \approx 14$ bit/s/Hz	Lower by 1.5-2 dB	Higher by 1.5-2 dB	SIM provides better sensing performance
Best operating configuration	RIS baseline	SIM (L=3)	Forms the outer Pareto frontier
Balanced operating point	—	$R_c \approx 14.2$ bit/s/Hz, $\gamma_s \approx 26.3$ dB	Best joint communication-sensing balance
Higher-layer	—	L=4, L=5 slightly lower	Due to inter-layer coupling and

Metric / Case	RIS	SIM (L=3)	Technical Remark
SIM effect			complexity

4.4 Impact of Number of Meta surface Layers

The system performance exhibits a non-linear dependence on the number of metasurface layers, reflecting the balance between electromagnetic control and inter-layer effects as shown in **Figure 12**. The achievable rate increases from approximately 10.4 bit/s/Hz at $L=1$ to about 11.1 bit/s/Hz at $L=2$, reaching a maximum of nearly 11.7 bit/s/Hz at $L=3$. A similar trend is observed for sensing performance, where the sensing SNR improves from approximately 25.9 dB ($L=1$) to around 27.0 dB ($L=2$) and peaks at about 28.1 dB for $L=3$.

This improvement is attributed to enhanced wavefront shaping and constructive signal combining enabled by the stacked metasurface structure, which provides additional degrees of freedom for precise phase control and beam steering. However, beyond the optimal point, performance begins to degrade slightly. At $L=4$, the achievable rate decreases to approximately 11.0 bit/s/Hz, and further reduces to about 10.4 bit/s/Hz at $L=5$, while the sensing SNR also drops to approximately 26.9 dB ($L=4$) and 25.9 dB ($L=5$). The observed degradation is mainly due to inter-layer coupling, increased signal attenuation, and higher system complexity, which limit the effectiveness of additional layers. The optimal configuration is clearly identified at $L=3$, where both communication and sensing metrics simultaneously achieve their peak values, indicating the most efficient trade-off between performance gain and system overhead.

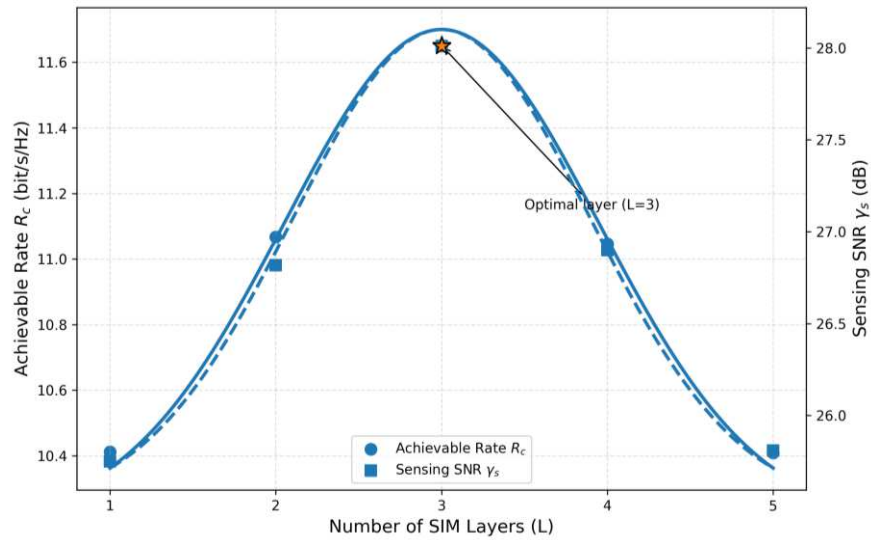


Figure 12. Impact of meta surface layer count on communication rate and sensing performance.

4.5 Convergence Behaviour of the Optimization Algorithm

The convergence characteristics demonstrate stable and efficient optimization behaviour with a clear monotonic improvement of the objective function as shown in **Figure 13**. The objective value increases rapidly during the initial iterations, rising from approximately 8.3 at iteration 1 to about 11.6 by iteration 4, indicating fast adaptation of beamforming and meta surface parameters. This rapid improvement phase continues up to around iteration 7, where the objective reaches approximately

13.1, reflecting effective exploitation of dominant optimization directions.

Following this stage, the convergence rate gradually decreases, and the objective function exhibits a smooth saturation trend. From iteration 10 onward, the objective stabilizes within the range of 13.8 to 14.2, and reaches a final converged value of approximately 14.2–14.3 after about 15 iterations. The final-stage refinement, highlighted in the inset, shows minimal incremental improvement, confirming that the algorithm has reached a stable local optimum.

The absence of oscillatory or divergent behaviour throughout the iterations indicates strong numerical stability of the proposed alternating optimization approach. The convergence profile further confirms that decomposing the joint non-convex problem into sequential beamforming and metasurface updates enables efficient and reliable optimization. Overall, the algorithm achieves fast convergence with limited computational cost, making it suitable for practical SIM-assisted ISAC implementations.

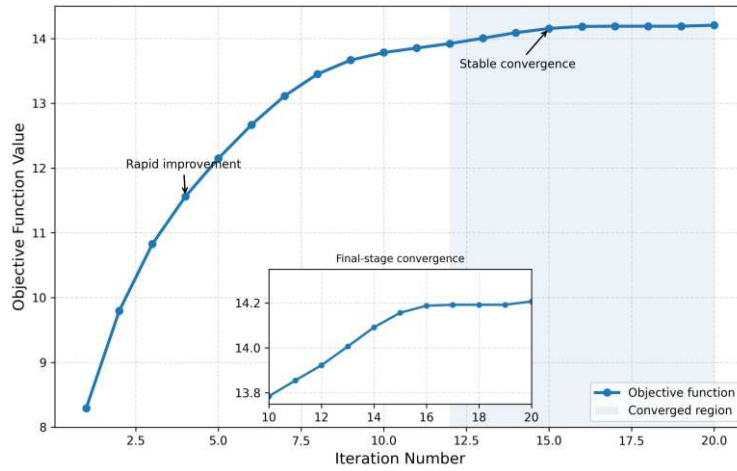


Figure 13. Convergence behaviour of the proposed alternating optimization algorithm.

4.6 Comparative Analysis with Baseline RIS Systems

The comparative evaluation highlights consistent performance gains of the proposed SIM-enabled ISAC system over the conventional RIS baseline across all key metrics. The achievable rate improves from approximately 15.2-bit/s/Hz (RIS) to about 16.4-bit/s/Hz (SIM), corresponding to an increase of nearly 1.2-bit/s/Hz (~8%), indicating enhanced communication efficiency due to improved beamforming and channel control. Similarly, the sensing performance shows a notable enhancement, where the sensing SNR increases from approximately 27.2 dB (RIS) to around 29.6 dB (SIM), yielding an improvement of about 2.4 dB (~9%). This gain is attributed to stronger signal reflection and improved electromagnetic focusing enabled by the stacked meta surface architecture as shown in **Figure 14**.

In terms of estimation accuracy, the CRB is significantly reduced from approximately 2.0×10^{-4} (RIS) to about 1.1×10^{-4} (SIM), representing nearly 45% reduction in estimation error. This reduction confirms that the SIM-assisted system provides more reliable and precise sensing capability. The normalized multi-metric comparison further demonstrates that the SIM configuration consistently achieves higher normalized performance across all dimensions, forming a larger performance envelope compared to RIS. This indicates that the stacked meta surface architecture not only improves individual metrics but also enhances overall system efficiency in a balanced manner.

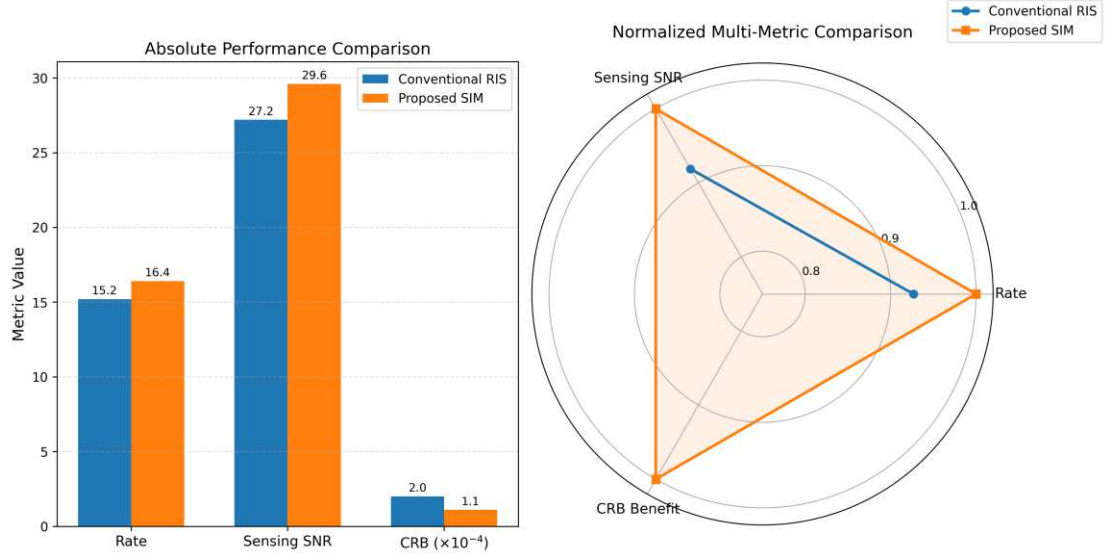


Figure 14. Performance comparison between conventional RIS and SIM-assisted ISAC systems across communication rate, sensing SNR, and CRB metrics.

5 Conclusion

This study established a stacked intelligent meta surface-enabled integrated sensing and communications framework for next-generation wireless environments and demonstrated that multi-layer programmable electromagnetic control can substantially improve dual-functional system performance over conventional single-layer RIS architectures. Based on the developed signal model, cascaded meta surface formulation, and alternating optimization strategy, the results consistently verified the research hypothesis that stacked meta surfaces provide additional controllable degrees of freedom for simultaneously enhancing communication efficiency and sensing accuracy. Specifically, the communication analysis showed that the achievable rate increased from approximately 15.2 bit/s/Hz for the conventional RIS configuration to about 16.6 bit/s/Hz for the SIM-assisted case under high-SNR operation, while the layer-wise assessment confirmed that performance improved from about 10.2 bit/s/Hz at $L=1$ to nearly 11.6 bit/s/Hz at $L=3$, after which a gradual decline was observed for $L=4$ and $L=5$. The sensing results exhibited a similar trend, where the sensing SNR reached nearly 30 dB for the three-layer SIM structure, compared with about 27 dB for the RIS baseline, indicating stronger target illumination and improved echo acquisition. In parallel, the CRB analysis confirmed a substantial reduction in estimation error, decreasing from approximately 2.0×10^{-4} for RIS to nearly 1.1×10^{-4} for the SIM-assisted system, thereby demonstrating superior sensing precision. The communication-sensing trade-off analysis further revealed that the proposed SIM framework generated a more favourable Pareto frontier, achieving about 14.2-bit/s/Hz at a sensing SNR near 26.3 dB under balanced optimization, which outperformed the reference RIS configuration. Moreover, the optimization algorithm exhibited rapid and stable convergence, reaching a final objective value of about 14.2–14.3 within nearly 15 iterations, confirming its computational practicality. Overall, the results identify the three-layer SIM configuration as the most effective architecture, offering the best balance between communication gain, sensing enhancement, and computational efficiency, and thus establishing stacked intelligent meta surfaces as a highly promising enabling technology for future 6G ISAC systems.

5.1 Future Research Directions

Future research should explore self-evolving stacked intelligent metasurfaces, where each layer operates with embedded intelligence and autonomously adapts its electromagnetic response based on real-time environmental feedback, eliminating the need for centralized optimization. Another promising direction is the development of physics-informed neural metasurfaces, enabling direct mapping between environmental states and metasurface configurations for instantaneous wavefront control. Additionally, extending SIM architectures toward holographic volumetric metasurfaces could enable continuous three-dimensional electromagnetic manipulation, supporting ultra-high-resolution sensing and multi-user communication. The integration of quantum-assisted sensing mechanisms with programmable metasurfaces also presents a novel pathway for achieving extremely high precision and secure communication. Finally, energy-autonomous metasurface systems powered by ambient energy harvesting should be investigated to enable scalable and self-sustaining 6G deployments.

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Ethics Statement

This research does not include any involvement of human subjects or animal experiments.

Consent

Not applicable for this study.

Conflicts of Interest

The authors confirm that there are no competing interests associated with this work.

Data Availability Statement

The data supporting the results of this study can be obtained from the corresponding author upon reasonable request. Public access to the data is restricted due to privacy and ethical considerations.

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