Two Birds With One Stone: Enhancing Communication and Sensing via Multi-Functional RIS

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***Abstract*—In this article, we propose new network architectures that integrate multi-functional reconfigurable intelligent surfaces (MF-RISs) into 6G networks to enhance both communication and sensing capabilities. Firstly, we elaborate how to leverage MF-RISs for improving communication performance in different communication paradigms including unicast, multicast, and broadcast and for different multiple access schemes. Secondly, we emphasize the synergistic benefits of integrating MF-RISs with wireless sensing, enabling more accurate and efficient target detection in future mobile networks. Thirdly, we utilize MF-RISs to simultaneously enhance the sensing and communication performance of an integrated network, where we study the multi-objective optimization to achieve the performance trade-off between communication and sensing metrics. Additionally, the Pareto boundary is provided to demonstrate the performance conflicts under the given system constraints. Then, we present numerical results to show the significant performance improvements offered by MF-RISs compared to conventional RISs in the integrated network. Finally, we outline potential research directions for MF-RISs under the ambition of 6G.**

I. Introduction

In the upcoming 6G era, cutting-edge applications, such as metaverse, high-resolution video, autonomous vehicles, and intelligent robots, necessitate a significant enhancement in both transmission rate and sensing accuracy to deliver unprecedented user experiences and network performance [1]. To fulfill these requirements, several improvements are required in next-generation wireless networks, including advanced network architecture, enhanced spectrum utilization, and expanded sensing range. Traditional sensing and communication systems are designed separately which inevitably causes low resource utilization at the network edge [2]. To address this challenge, recently, integrated sensing and communication (ISAC) technology has been proposed, which significantly boosts the spectral, energy, and hardware efficiency by sharing sensing and communication resources [3]. However, ISAC systems still face challenges in practical applications. One key issue is the limited sensing and communication range, especially in high-frequency bands, due to blockages and high path loss [4]. This restricts signal propagation and coverage, thereby adversely affecting system performance. Another challenge lies in the efficient management of multiple beams when communication and sensing coexist [3]. Thus, how to design a joint waveform that satisfies both the communication and sensing requirements is a crucial issue to be addressed.

Recent research has investigated the incorporation of reconfigurable intelligent surfaces (RISs) into ISAC systems to enhance performance in both sensing and communication domains [4]–[6]. However, traditional RISs face several challenges, such as half-space coverage and double-fading effect, which hinder their practical implementation. To overcome these limitations, we introduce multi-functional RISs (MF-RISs) that support signal reflection, refraction, and amplification simultaneously on a single surface [7]–[9]. Then, a low-complexity channel estimation method was designed in [10] for MF-RIS-aided communication systems. As shown in Fig. 1, MF-RIS can serve users across the entire space and mitigate the double-fading effect through signal amplification. Although MF-RIS builds upon existing RIS technologies, integrating multiple functionalities within a single surface poses new challenges in hardware design and optimization. Specifically, the phase shift and amplitude coefficients are tightly-coupled in MF-RIS, rendering traditional methods for independent optimization ineffective [9]. Consequently, it is necessary to redesign algorithms to ensure the operating performance of MF-RISs in various scenarios. MF-RISs may face unintended interference from two aspects: external interference due to simultaneous transmission and reception, and internal interference caused by coupling between elements. For external interference, advanced beamforming techniques can help reduce its impact. As for internal interference, it can be mitigated by optimizing the spacing and layout design. In summary, although MF-RISs have significant potential to enhance performance in both communication and sensing scenarios, they also present new challenges for future networks.

In this article, we investigate the utilization of MF-RISs in communication, sensing, and integrated networks. The main contributions are summarized as follows:

- **MF-RIS for communications:** The multifaceted functionality allows MF-RISs to optimize signal propagation, mitigate double-fading attenuation, and achieve full-space coverage, going beyond the capabilities of traditional

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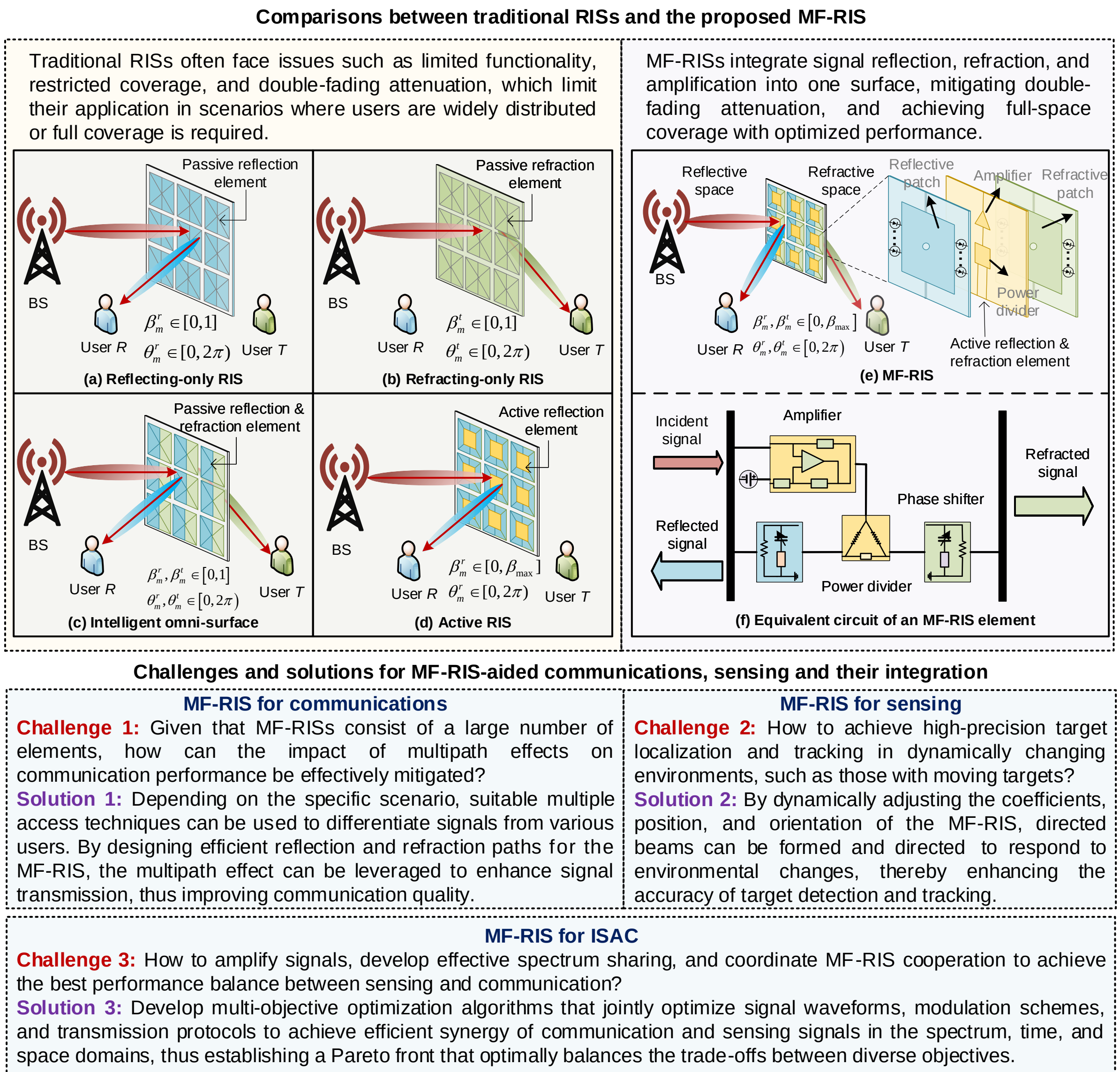


Fig. 1. Comparison between MF-RISs and conventional RISs. The hardware circuit of each MF-RIS element comprises an amplifier, a power divider, and two phase shifters. The amplifier and power divider manage the amplitude of the reflected and refracted signals. The phase shifter, which includes multiple PIN diodes, is responsible for adjusting the phase shift of the output signal.

passive and active RISs. In Section II, we utilize MF-RISs to strengthen coverage and mitigate interference in various communication paradigms. Then, we discuss the application of MF-RISs in multiple access technologies.

- **MF-RIS for sensing:** MF-RISs can be used not only for communication but also for wireless sensing, such as target detection and localization. To achieve high-precision sensing, we discuss the interplay between MF-RISs and sensing in Section III, where a closed-loop feedback mechanism for bidirectional sensing are provided for moving targets.
- **MF-RIS for ISAC:** Cooperative waveform design is a key issue in ISAC systems. MF-RISs help to achieve efficient data transmission and target sensing with flexible beam steering. In Section IV, we emphasize the importance of multi-objective optimization in MF-RIS-aided ISAC systems, and exhibit the trade-off relationship between communication and sensing.

II. MF-RIS for Communications

A. *MF-RIS-Aided Communications*

MF-RIS has three main operating strategies: energy splitting (ES), mode switching (MS), and time switching (TS) [8]. In Figs. 2(a)-(c), we provide a clear distinction on how MF-RISs enhance the performance of various communication paradigms, including unicast, multicast, and broadcast.

1) MF-RIS-aided unicast communications: Unicast is a peer-to-peer communication paradigm that requires information to be transmitted precisely from a sender to a specified receiver. In this scenario, the operating strategy of MF-RISs can be designed as follows: When the user's position is stable or changes minimally, MF-RIS can operate in ES mode

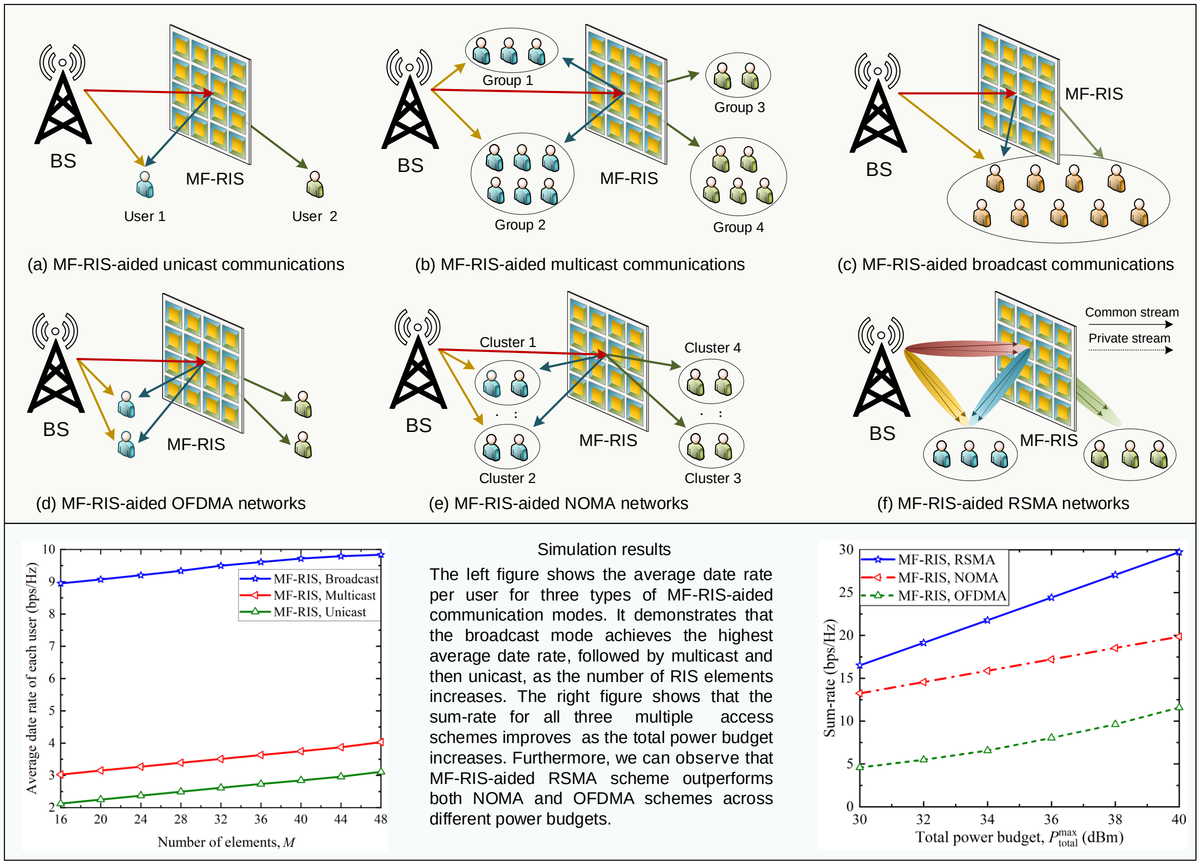


Fig. 2. MF-RIS-aided wireless communications and simulation results.

to maximize the received signal quality of a specific user by adjusting the energy distribution ratio. For cases where the main service direction can be clearly distinguished, MF-RIS can operate in MS mode, selecting the most appropriate operation mode based on the actual location of users. For low-frequency data transmission with low real-time requirements, MF-RIS can work in TS mode to effectively avoid interference between reflected and refracted signals.

2) MF-RIS-aided multicast communications: In multigroup multicast systems, the transmitter sends the same information to each group of receivers, but the information varies from one group to another. Unlike unicast, the multicast transmission rate is often determined by the user with the worst channel condition. Specifically, when users are widely distributed, MF-RIS can work in ES mode to balance the performance among different users. If the distribution of users makes it possible to roughly divide them into two groups (one more suitable for refraction mode and the other more suitable for reflection mode), then MF-RIS should work in MS mode. However, it is not recommended to use TS mode for multicast because frequent switching may lead to an increased latency.

3) MF-RIS-aided broadcast communications: Broadcast involves sending data from the transmitter to all receivers within the network coverage. This paradigm is essential for scenarios that need to disseminate information to all users, such as emergency alerts or system-wide updates. For broadcast, ES mode is the default choice because it supports full spatial coverage, ensuring that information can be received by as many users as possible. The MS and TS modes are not generally used in broadcast scenarios, but they can also be used as a complementary scheme if the goal is to take turns serving two significantly different user groups and do not mind a certain time delay.

In summary, when integrating MF-RIS with different communication models, the key distinction lies in how the MF-RIS coefficients are optimized for different purposes. For unicasting, MF-RISs primarily optimize the reflection/refraction link for each user, tailoring the amplitude and phase shift of each user's signal. For multicasting, it requires a joint optimization of user clustering and MF-RIS configuration to ensure balanced signal quality across different clusters. For broadcasting, the goal of MF-RIS is to cover as large an area as possible so that all users can be served effectively.

B. MF-RIS-Aided Multiple Access

In wireless communication systems, multiple access (MA) technologies are continually emerging to meet the increasingly more stringent user requirements, such as increased spectral efficiency, lower latency, and higher device density. These advancements have evolved from orthogonal frequency division MA (OFDMA) and spatial division MA (SDMA) to non-orthogonal MA (NOMA) as well as rate-splitting MA

(RSMA). Figs. 2(d)-(f) demonstrate different MA technologies aided by MF-RISs, which are detailed as follows:

1) MF-RIS-aided OFDMA networks: In OFDMA networks, spectrum resources are divided into multiple orthogonal subcarriers. Each subcarrier is assigned to different users, allowing multiple users to communicate at once and boosting spectral efficiency through fine-grained time-frequency resource allocation. Compared to existing passive or active RIS-aided OFDMA networks, MF-RISs have more variables to optimize, thus providing additional degrees of freedom (DoFs) for signal manipulation. Additionally, in OFDMA networks, inter-user interference can arise due to the proximity of users or channel conditions. MF-RISs can help mitigate this interference by creating nulls in the direction of interfering users or by enhancing the desired signal paths. This is particularly beneficial in scenarios with dense user deployments or in environments with strong multipath effects.

2) MF-RIS-aided SDMA networks: Instead of dividing resources in the time or frequency domains, SDMA leverages multiple antennas to serve multiple users simultaneously on the same time-frequency resources. This is achieved by employing superposition coding at the transmitter and separating user signals in the spatial domain. In scenarios where users are closely spaced, the spatial separation between channels may become challenging, limiting the effectiveness of SDMA. However, the integration of MF-RIS offers a promising solution to dynamically adjust radio propagation paths, thus enhancing the spatial differentiation between users and mitigating interference. This capability allows for more efficient utilization of spectral and spatial resources, better adaptation to user distribution and channel variations.

3) MF-RIS-aided NOMA networks: By allowing multiple users to share the same time-frequency resource, NOMA can improve spectrum efficiency to support massive connectivity in wireless networks. Unlike SDMA, which relies on spatial-domain multiplexing, NOMA achieves this by carefully assigning distinct signal power levels to different users, and then employs successive interference cancellation (SIC) at the receiver to decode signals. However, the inherent complexity and capability limits of SIC pose significant challenges when a large number of users share the same channel. This can lead to difficulties in eliminating co-channel interference, potentially resulting in the failure of NOMA technology. Consequently, it is crucial to divide NOMA users into multiple clusters and serve them on different channels to ensure accurate SIC decoding in practical scenarios. Additionally, by smartly adjusting the cascaded channels, MF-RISs can create more distinguishable channels that facilitate more efficient SIC, thus enhancing NOMA performance. Simulation results in [7] revealed that MF-RISs achieve approximately a 50% improvement in throughput compared to passive RISs.

4) MF-RIS-aided RSMA networks: RSMA seeks to strike a balance between the efficiency gains of NOMA and the interference management of SDMA. Although NOMA improves spectral efficiency by sharing resources among users, it poses challenges in signal processing complexity and inefficient utilization of multiple antennas, particularly for weak users who must decode all interference signals. RSMA tackles this issue by splitting user messages into common and private parts. The common part is decoded by all users, while the private part is for the intended user. This allows partial interference cancellation, where some interference is decoded and removed, while the rest is treated as noise. By dynamically adjusting the power and content of common and private streams, RSMA can adapt to varying channel conditions, effectively transitioning from SDMA-like behavior when interference is weak to NOMA-like behavior when interference is strong. However, the data rate of the common stream is limited by the weakest user's channel. Since MF-RISs support signal adjustment with more DoFs compared to conventional RISs, integrating MF-RISs with RSMA can overcome this issue by strategically improving the channel quality for weak users.

Overall, when integrating MF-RISs with different MA schemes, the role of MF-RISs depends on the specific needs. For instance, in OFDMA, the role of MF-RISs is to provide selective phase adjustment for different subcarriers in the frequency domain. In SDMA, the key role of MF-RISs lies in their abilities to enhance spatial separation between users. In NOMA, MF-RISs are primarily used to manage signal superposition and decoding order in power domain. In RSMA, MF-RISs can be optimized along with the rate allocation of public and private information to balance interference and ensure fairness among users. These distinctions highlight the adaptive role of MF-RISs in enhancing the performance of different MA schemes.

III. Interplay Between MF-RIS and Sensing

In this section, we discuss the interplay between MF-RIS and wireless sensing, exploring how this convergence empowers 6G networks with enhanced sensing capabilities.

A. MF-RIS-Assisted Wireless Sensing

In wireless sensing systems, radar uses radio frequency (RF) signals to detect the environment and targets. However, the low spatial and angular resolution of existing sensing systems often makes it difficult to distinguish signals accurately, particularly in non-line-of-sight (NLoS) situations [11]. In addition, multipath fading and Doppler shift can seriously affect the sensing performance. Compared to traditional sensing schemes, MF-RISs offer a flexible solution to control beamwidth in wireless sensing applications, thus achieving a balance between angular resolution and sensing range. As shown in Fig. 3(a), the directional beamforming in reflection and refraction spaces of MF-RIS effectively mitigates the interference caused by multipath effects, enabling accurate sensing of targets. Moreover, by reasonably deploying MF-RIS, the echo path (i.e., radar →MF-RIS →target →MF-RIS →radar) can be constructed to create a virtual LoS sensing link. In addition to optimizing the transmit beamforming at the radar, the coefficients of MF-RIS can be dynamically adjusted to quickly adapt to environmental changes. This real-time control over the amplitude and phase of electromagnetic waves also compensates for Doppler shifts, ensuring stable

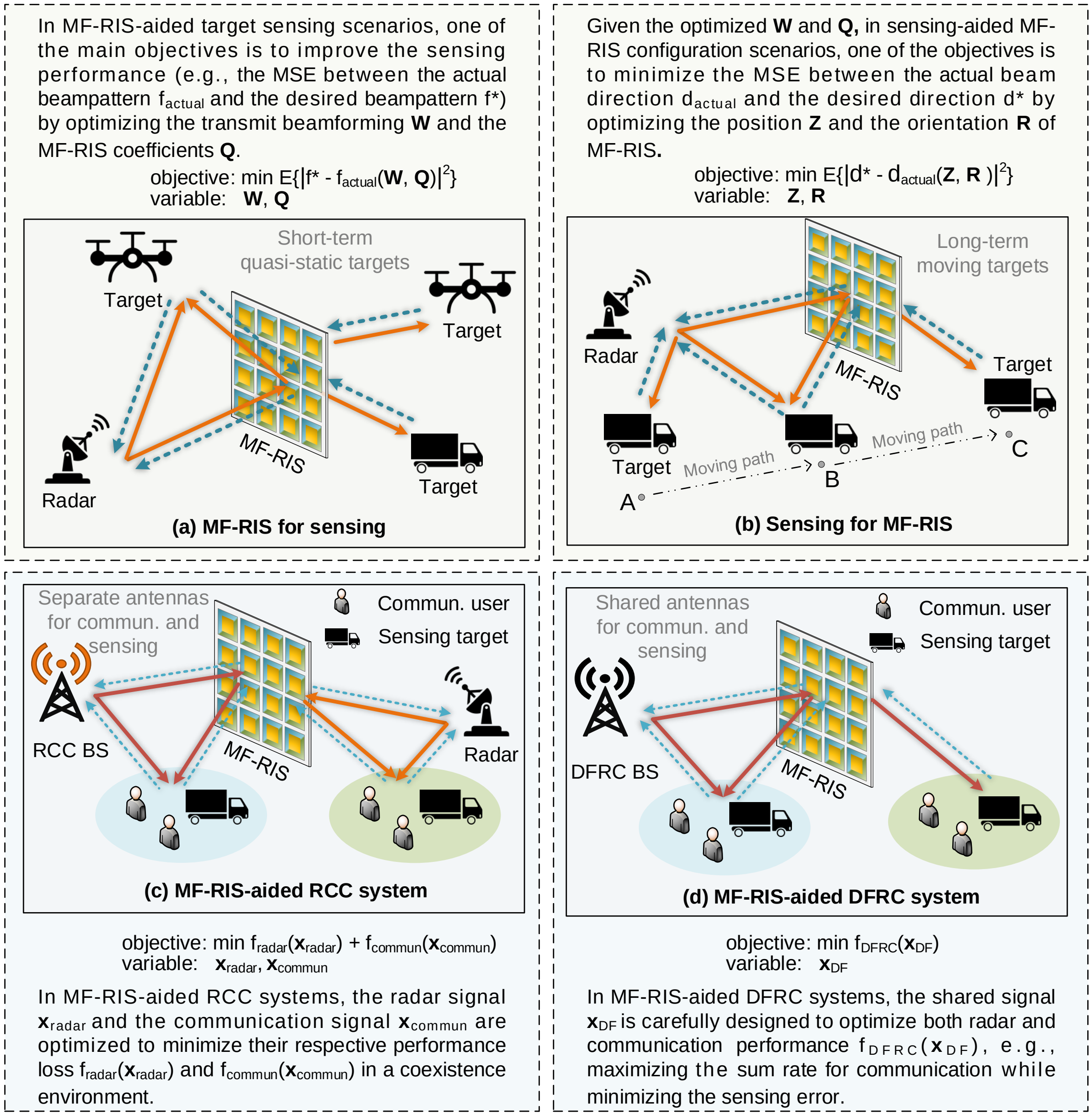
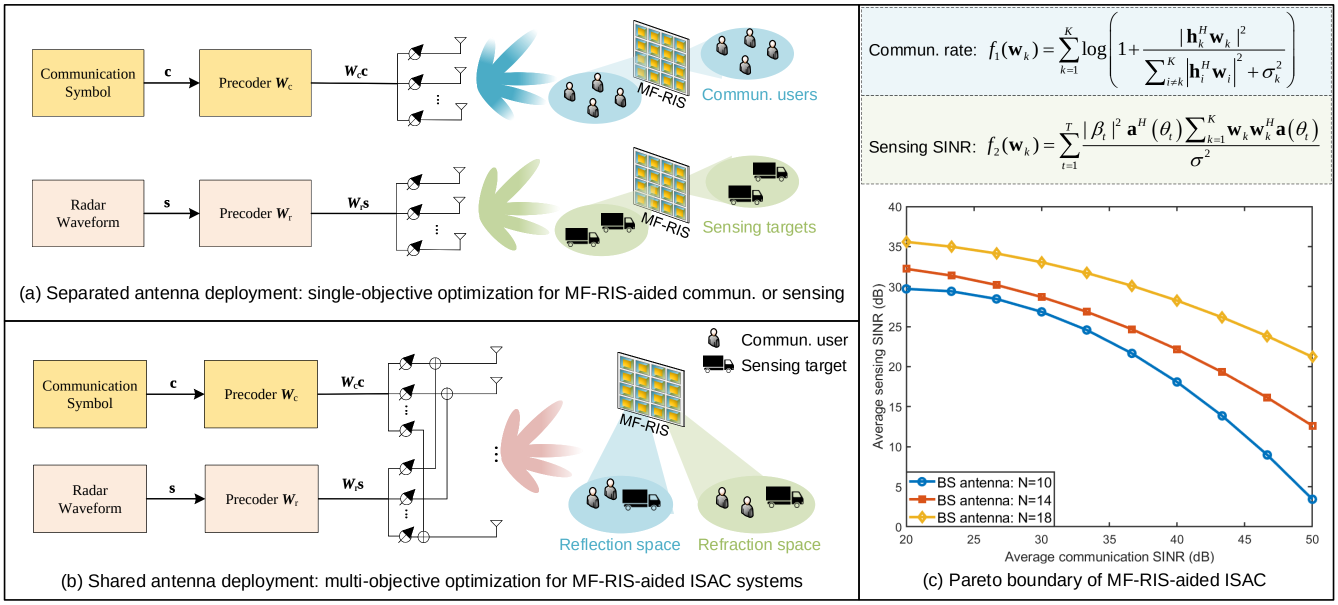


Fig. 3. The interplay between MF-RISs and sensing is illustrated in (a) and (b). MF-RIS-aided ISAC systems are illustrated in (c) and (d). The forward signals are transmitted from the radar/BS towards the MF-RIS, users, and targets. The MF-RIS reflects, refracts, and amplifies the incident signals, creating virtual line-of-sight links. The echo signals (returning to the radar/BS) are reflected from the target, manipulated by the MF-RIS, and received by the radar/BS for accurate target detection.

performance even for fast-moving targets. Overall, through mathematical modeling and optimization, some key metrics such as sensing resolution, localization accuracy, and clutter rejection can be significantly improved by MF-RISs [12].

B. Sensing-Assisted MF-RIS Configuration

The integration of wireless sensing with MF-RIS not only enhances sensing capabilities but also provides valuable feedback to optimize the configuration of MF-RIS itself. In sensing-assisted MF-RIS configuration, the real-time sensing data of targets can be utilized to dynamically adjust the parameters of MF-RIS, such as its position, orientation, and operating strategy. Specifically, as illustrated in Fig. 3(b), consider a scenario where a target gradually approaches an MF-RIS and then moves away. Initially, when the target is distant from the MF-RIS (e.g., at point A), the radar may sense the target independently without the help of MF-RIS due to its limited coverage area. Then, as the target moves closer, the sensing data collected at point A can be utilized to optimize the MF-RIS configuration before the target reaches point B for providing better services. Namely, these information sensed at point A can be leveraged to proactively optimize the MF-RIS configuration at point B. Regarding the position and orientation of the MF-RIS, they can be adjusted using adaptable mounting systems (e.g., movable tracks, support bars, or drones, determined by the specific requirements and constraints of different scenarios) to better align with the predicted target location and direction. It can be seen that sensing-assisted MF-RIS communication can not only enhance the overall performance for these upcoming users



(a) Separated antenna deployment: single-objective optimization for MF-RIS-aided commun. or sensing

(b) Shared antenna deployment: multi-objective optimization for MF-RIS-aided ISAC systems

(c) Pareto boundary of MF-RIS-aided ISAC

Fig. 4. Single-objective optimization versus multi-objective optimization in MF-RIS-aided ISAC systems. (a) depicts a scenario with separate antennas for communication and sensing. (b) represents a shared antenna deployment, where both communication and sensing signals share the same set of antennas. (c) shows the Pareto boundary obtained through multi-objective optimization in the shared antenna configuration.

and targets, but also reduce the latency of configuring MF-RIS. Furthermore, as the target continues to move (e.g., at point C beyond the MF-RIS's range), the sensing information gathered with the assistance of the MF-RIS (e.g., at point B) can further support subsequent independent sensing by the radar. During this process, the collaboration between the radar and the MF-RIS creates a closed-loop feedback mechanism for bidirectional sensing in high mobility scenarios. Overall, the two optimization problems depicted in Fig. 3(a) and (b) are not entirely independent; instead, they are solved sequentially, with the overall solution being obtained through an iterative process that adapts to dynamic environments.

On the whole, the integration of wireless sensing with MF-RIS facilitates high-resolution environmental monitoring, which is beneficial for real-time target sensing and user localization. Additionally, based on the sensing data of physical world, the network operator can dynamically adjust MF-RIS configuration, leading to more efficient use of the wireless resources such as radio spectrum and transmit power. As a result, the bidirectional feedback between wireless sensing and MF-RIS configuration bolsters the robustness and reliability of communication systems under time-varying fading channels, particularly when involving moving targets.

IV. MF-RIS-Aided ISAC Systems

In this section, we first discuss the potential of MF-RISs to enhance ISAC system performance, and then introduce the multi-objective approach for optimizing ISAC systems.

A. Enhancing ISAC Systems with MF-RIS

Both radar-communication coexistence (RCC) and dual-functional radar-communication (DFRC) systems belong to the broader ISAC framework, yet they exhibit distinct operational characteristics [13]. RCC employs separate BS and radar hardware for independent sensing and communication [2], as shown in Figs. 3(c). Conversely, DFRC integrates both radar and communication functionalities seamlessly within the same BS infrastructure [4], [5], as shown in Figs. 3(d). Specifically, Fig. 3(c) emphasizes coexistence, whereas Fig. 3(d) highlights integration. Fig. 3(c) and 3(d) complement each other by depicting distinct ISAC paradigms facilitated by MF-RIS. In improving the performance of ISAC systems, several issues have to be addressed. Firstly, the shared spectrum resource between sensing and communication signals inevitably leads to interference. [14] Secondly, both sensing and communication signals are susceptible to attenuation and distortion caused by factors such as path loss and multipath effects, which can compromise the quality of both functions. Moreover, it is difficult to design dual-purpose waveforms that maximize the communication throughput while minimizing the sensing error. To meet these multifaceted demands, MF-RIS introduces a novel paradigm for ISAC system enhancement. By dynamically tailoring spatial signal responses, including amplitude, phase, direction, and gain, MF-RIS enables fine-grained control over waveform propagation. This ensures that excessive interference in ISAC systems is effectively mitigated, fostering seamless coexistence of sensing and communication functionalities. Especially for radar operations, MF-RIS enhances echo reception by suppressing unwanted signal paths and reinforcing desired directions, thereby improving sensing accuracy. Likewise, the dual-domain signal manipulation capability of MF-RIS effectively combats path loss and multipath fading, yielding improved link reliability for communication and sensing alike. Furthermore, the enhanced spatial diversity and controllability offered by MF-RIS facilitate adaptive reconfiguration in time-varying environments, which is critical for mobile ISAC scenarios such as vehicular networks or drone-based sensing platforms. These features make MF-RIS not only a feasible integration of existing RIS capabilities, but a comprehensive and scalable solution tailored to the core challenges of future ISAC systems. The above discussions of MF-RIS-aided RCC and DFRC systems can be easily extended to the bi-static and multi-static ISAC systems, which is omit here for brevity.

B. Multi-Objective Optimization for MF-RIS-Aided ISAC

Most previous studies have focused on single-objective optimization that puts one performance (e.g., communication rate) as the objective and another performance metric as a constraint (e.g., sensing accuracy). Since ISAC systems integrate communication and sensing functions at the same time, their performance evaluation is not limited to communication quality or sensing accuracy only, but needs to simultaneously consider multiple interrelated and possibly conflicting optimization objectives [15]. However, due to the conflicts among different objectives, multi-objective optimization generally has higher complexity than single-objective optimization Fig. 4 demonstrates a comparison between single-objective and multi-objective optimization in MF-RIS-aided ISAC systems. Specifically, Figs. 4(a) and 4(b) showcase scenarios with separate and shared antenna deployments, respectively. The simulation results in Fig. 4(c) show that there exists a conflict between communication signal-to-interference-plus-noise ratio (SINR) and sensing SINR, where improving one often comes at the expense of the other. Furthermore, we observe that increasing the number of BS antennas can expand the performance boundary, indicating that additional DoFs in ISAC systems can enable more flexible trade-off between communication and sensing. Based on the obtained Pareto boundary, the transmit beamforming and MF-RIS coefficients can be designed according to different communication and sensing performance preferences. For example, in the scenario of autonomous vehicles, the ISAC BS not only provides high-speed communication to facilitate information transmission between vehicles, but also needs to gather crucial data about the surrounding environment through high-precision sensing to ensure driving safety. However, these two goals can often conflict with each other due to the limited resources. Achieving this intricate trade-off requires multi-objective optimization techniques to strike an optimal balance and alleviate resource competition among communication users and sensing targets. Importantly, the capability of MF-RIS to amplify and steer signals independently for different directions creates new opportunities for performance decoupling between communication and sensing. By allocating spatial resources more flexibly, MF-RIS can alleviate the fundamental resource competition and mitigate interference more effectively than conventional RISs. Please refer to our previous work in [12] for more details about the Pareto optimization in ISAC systems, which is omitted here for brevity.

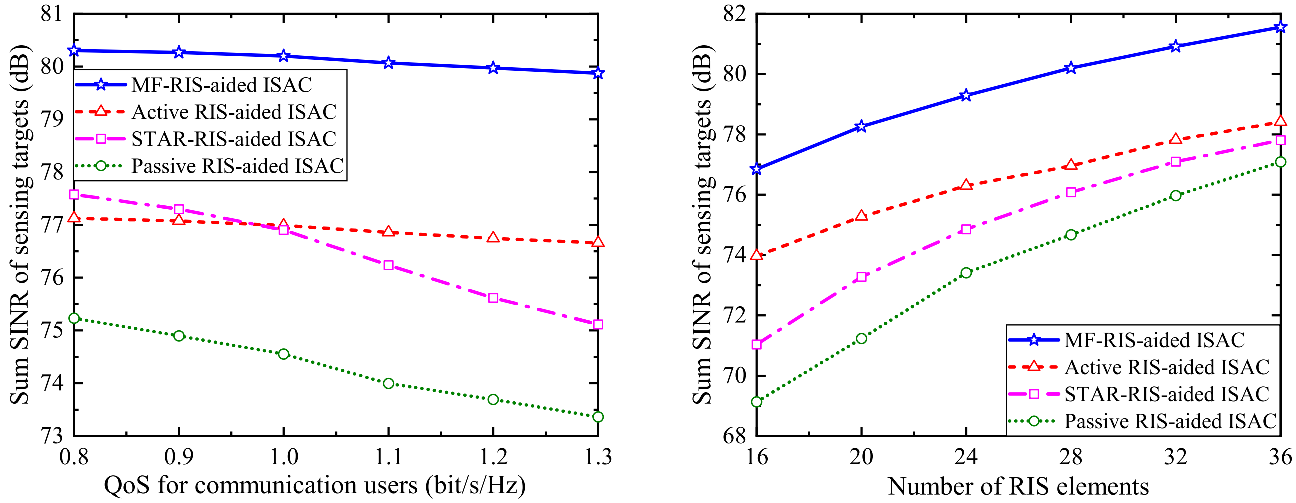
Generally, although MF-RISs can enhance both the reliability of communication links and the accuracy of target sensing, it also introduces new challenges, e.g., enabling the effective collaboration among multiple distributed MF-RISs in multi-cell ISAC systems. Furthermore, establishing the theoretical limits of MF-RIS-aided ISAC systems remains challenging yet crucial for setting realistic performance expectations. In the future, MF-RISs are expected to be incorporated with other emerging technologies within the ISAC domain, such as human gesture and posture recognition as well as artificial intelligence (AI)-based imaging.

V. Numerical Results

In this section, we present numerical results to demonstrate the performance of our proposed MF-RIS-aided ISAC system, where a DFRC BS is considered to serve four communication users and four sensing targets. The distance between the BS to the MF-RIS is 50 meters (m). Additionally, all users and targets are randomly dispersed around the BS within a radius of 100 m. The numbers of transmit and receive antennas at the BS and users are set as $N_t = N_r = 8$. The total power budget of the BS and the MF-RIS is $P_{\max} = 25$ dBm. The SINR and mean-square-error (MSE) thresholds of communication users and sensing targets are set to 10 dB and 0.25, respectively. We adopt passive RIS, STAR-RIS, and active RIS as three benchmarks for performance comparison in the considered ISAC systems.

Fig. 5a shows the sum SINR of sensing targets versus the QoS of communication users. It is observed that as the QoS requirement for communication increases, the sum SINR for sensing decreases for all schemes. This result is expected as there exists an inherent competition between communication and sensing goals in terms of resource allocation. Specifically, increasing the communication rate often requires more spectrum resources and energy consumption, which leads to less resources available for sensing. However, compared to the benchmarks, the proposed MF-RIS exhibits best performance. This confirms that MF-RISs can achieve better overall system performance by flexibly engineering its reflective, refractive, and amplifying properties to better trade off communication and sensing resource allocation. Another interesting phenomenon is that the sensing performance of active RIS types (active RISs and MF-RISs) is less affected by changes in the required communication performance compared to passive RIS types (passive RISs and STAR-RISs). This is because active RIS types are able to flexibly manage the RIS available power to compensate for communication performance on-demand.

Fig. 5b depicts the sum SINR of the sensing targets versus the number of RIS elements. We observe that due to the increased number of elements providing more optimization DoFs, all curves exhibit an increasing trend. Moreover, MF-RISs always outperform the benchmarks, while passive RISs appear to be the worst. This is because passive RISs, STAR-RISs, and active RISs can all be regarded as special cases of



(a) Sum SINR of sensing targets versus the QoS of communication users

(b) Sum SINR of sensing targets versus the number of RIS elements

Fig. 5. Performance evaluation of ISAC systems aided by different RIS types: (a) sum SINR of sensing targets versus the quality-of-service (QoS) of communication users, and (b) sum SINR of sensing targets versus the number of RIS elements. Here, the QoS is measured by the spectral efficiency.

MF-RISs, and passive RIS are further special cases of STAR-RISs and active RISs. Among two dual-functional RISs, the superiority of active RISs over STAR-RISs evidently demonstrates that signal amplification directly and efficiently boosts DFRC signal reception compared to omnidirectional signal emission. The reasons why MF-RISs outperform active RISs are twofold: ① Active RIS achieves full-space coverage by deploying a reflective RIS and a refractive RIS, with coefficient adjustments based on fixed elements. ② In contrast, MF-RIS adjusts phase shift and amplitude coefficients on a per-element basis, allowing it to leverage the DoFs of each element to manipulate DFRC signals and enhance signal reception across the entire space. However, as the RIS scale increases, the growth rate of the performance gain slows down due to the limitation of the total RIS amplification power. The plot also shows that the performance gap between the MF-RIS-aided ISAC system and the other types of RIS-aided systems grows larger as the number of RIS elements increases.

VI. Conclusions and Future Directions

In this article, we integrated MF-RISs into 6G networks to enhance communication and sensing capabilities. First, MF-RISs were used to intelligently manipulate the wireless environment to optimize user experience and data transmission efficiency across unicast, multicast, and broadcast systems. Additionally, we designed MF-RIS-aided multiple access schemes to improve spectral efficiency and support large-scale connectivity. Furthermore, we discussed the synergistic relationship between MF-RISs and wireless sensing. Moreover, we presented cooperation schemes for MF-RIS-aided RCC and DFRC systems, highlighting the advantages of MF-RISs in improving both communication and sensing performance. Subsequently, we advocated for multi-objective optimization approaches in MF-RIS-aided ISAC systems to balance various trade-offs. Finally, we provided numerical results to validate the effectiveness of MF-RISs in enhancing ISAC performance as compared to other RIS counterparts. In the following, we outline several unresolved open problems that warrant further exploration in future work.

1) MF-RIS-aided near-field ISAC: Unlike plane waves commonly encountered in far-field communications, spherical waves in near-field ISAC inherently have a curved wavefront. This curvature is particularly relevant for devices located within the near-field region of the MF-RIS, where the wavefront does not behave as a plane wave. The size of this near-field region is closely related to the physical dimensions of the MF-RIS. As the MF-RIS size increases, the near-field region expands accordingly. This affects how electromagnetic waves propagate and interact with objects in the near-field region, necessitating sophisticated advanced algorithms and control strategies for MF-RISs to accurately manipulate these curved wavefronts.

2) AI-based beamforming design for MF-RIS-aided ISAC: Usually, ISAC systems operate in dynamic environments with moving targets, users, and electromagnetic interference. Moreover, the additional DoF introduced by MF-RISs makes accurate channel estimation a challenging task. Integrating AI into MF-RIS-aided ISAC systems may opens up new possibilities for enhancing the performance and adaptability by training AI model on large datasets. Furthermore, AI-driven optimization frameworks can balance the competing objectives of sensing accuracy and communication throughput, finding Pareto-optimal solutions that satisfy both requirements. Overall, AI has the potential to revolutionize MF-RIS-aided ISAC systems by enabling more intelligent and adaptive channel estimation, beamforming, and resource allocation strategies.

3) Practical implementation challenges of MF-RIS: The practical implementation of MF-RIS-aided ISAC systems faces several critical challenges, including the inherent hardware complexity and substantial manufacturing costs of MF-RIS components. Addressing these limitations requires innovative metamaterial and nanocomposite solutions capable of efficiently controlling electromagnetic waves across wide frequency bands. Moreover, the current high production costs pose significant barriers to large-scale deployment, necessitating research into cost-effective materials and scalable fabrication processes to enable commercial viability. Furthermore, while MF-RISs provide adjustable signal amplification capabilities, this functionality comes with increased power consumption that demands energy-efficient solutions such as dynamic power management and sleep-mode operations, particularly for battery-dependent or energy-harvesting configurations. Additionally, the effective coordination of multiple MF-RIS in operational environments presents a technical hurdle that must be overcome through the development of advanced synchronization algorithms and robust control protocols to ensure system-level performance.

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