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SURVEY

A Survey on Resource Allocation and Energy Efficient Maximization for IRS-Aided MIMO Wireless Communication

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ABSTRACT This survey paper provides a comprehensive overview of integrating Multiple-Input Multiple-Output (MIMO) with Intelligent Reflecting Surfaces (IRS) in wireless communication systems. IRS is known as reconfigurable metasurfaces, have emerged as a transformative technology to enhance wireless communication performance by manipulating the propagation environment. This work delves into the fundamental concepts of MIMO and IRS technologies, exploring their benefits and applications. It subsequently investigates the synergies of resource allocation and energy efficiency that emerge when these technologies are combined, elucidating the IRS improved in MIMO systems through signal manipulation and beamforming. Through an in-depth analysis of various techniques and cutting-edge algorithms in resource allocation and energy efficiency can explore the key research areas such as optimization techniques, beamforming strategies and practical implementation consideration. Furthermore, it provides open research directions, individually addressing topics such as limitations of resource allocation and energy efficiency in the MIMO IRS system. This paper offers insights into MIMO-enabled IRS systems challenges and future trends. Through presenting a consolidated view of the current state-of-the-art, this survey underscores their potential to revolutionize wireless communication paradigms, ushering in an era of enhanced connectivity, spectral efficiency and improved coverage.

INDEX TERMS Multiple-input multiple-output (MIMO), intelligent reflecting surfaces (IRS), resource allocation, energy efficiency, optimization technique.

I. INTRODUCTION

The Multiple-Input Multiple-Output (MIMO) technology utilizes multiple antennas at the transmitter and receiver to improve the capacity and reliability of wireless communications. MIMO systems can exploit spatial diversity and multipath propagation to increase data throughput, improve signal quality, and reduce the impacts of fading and interference by concurrently transmitting numerous streams of data over the same frequency band [1]. Conventional cooperative MIMO transmission techniques, such as amplify/decode-and-forward relay, are currently experiencing significant applications in wireless communications. Moreover, it optimizes the effective utilization of the networks spectrum through coordinated efforts among the various devices in the network [2]. Some critics believe that the technology needed for widespread practical has too complex and costly, making it unlikely to be implemented on a large scale. Moreover, the

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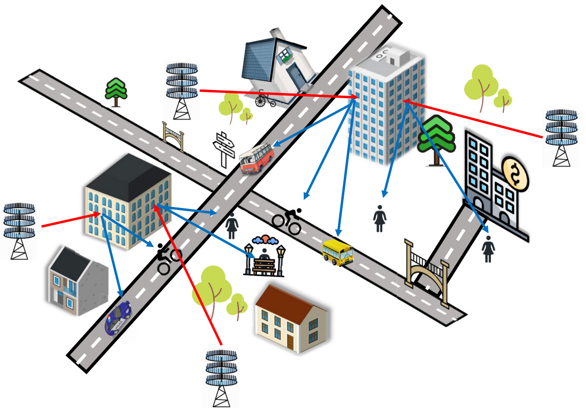

FIGURE 1. System model for multi-IRS-assisted massive MIMO system.

challenges of integrating MIMO into existing infrastructure could further impede its feasibility. The wireless MIMO transmission medium is an uncontrollable factor in the current communication paradigm and is not explicable in optimization formulas. Meanwhile, to enhance the resource allocation, spectral, and energy efficiency performance in wireless networks, the channel fading impact caused by the unpredictability in the communication environment is typically a significant problem [3].

Intelligent Reflecting Surface: Recently, a ground-breaking idea known as Intelligent Reflecting Surfaces (IRS) has been promoted in wireless networking research as a cutting-edge technology that can overcome the stochastic nature of wireless transmission medium and establish a controllable broadcast environment for better signal quality and enhanced network performance [4]. The deployment of IRS in wireless communication networks has shown great promise. The IRS surfaces consist of a large number of small reflecting elements that can independently adjust the phase and amplitude of the reflected signals. This integration enables IRS to manipulate the wireless propagation environment by intelligently reflecting the incident signals in desired directions [5].

MIMO in IRS: Incorporating MIMO techniques can significantly enhance the IRS overall system performance. MIMO in IRS provides multiple antennas at both the transmitter and receiver ends, allowing for improved diversity gains and spatial multiplexing. Moreover, carefully manipulating the reflected signals of MIMO in IRS can optimize the signal paths, create constructive interference, mitigate interference and signal degradation caused by obstacles or environmental conditions [6]. Integrating MIMO in IRS can lead to several benefits in wireless communication systems. It enables enhanced beamforming capabilities, creating highly focused and directed beams toward specific users or areas of interest. The combination of MIMO with IRS empowers the development of a virtually massive MIMO system capable of achieving excellent spatial resolution and geometric reconfiguration, avoiding the usage of several radio frequency chains as shown in Figure 1. This system enables the transmission of intense directional beams to the intended receiver, minimizing energy leakage to potential eavesdroppers and improving the overall security of the covert communication channel [7].

Additionally, this covert communication performance enhancement ensures a more reliable and confidential transmission. Some recent publications have examined the feasibility of implementing IRS with finite/low-resolution phase changes. When Intelligent Reflecting Surfaces (IRSs) are adequately positioned in wireless networks, the channels can be dynamically modified by jointly configuring the reflecting components of all IRSs for better transmission throughput. It is important to emphasize that this strategy directly contrasts conventional wireless methods, which can only mitigate or adjust for fading communication channels. For instance, IRS can be employed to prevent impediments/blockades in wireless channels, increase their realizations/distributions, and enhance the multiuser channel ranking circumstance [8]. IRS has a significantly higher spectral efficiency than active relays since it solely utilizes passive reflection during full-duplex operation, eliminating signal amplification noise.

A. SINGLE REFLECTION IRS-ASSISTED WIRELESS MIMO COMMUNICATION SYSTEM

Existing research on IRS structure and reflection optimization has concentrated chiefly on the virtual configuration of single-IRS-assisted wireless systems, wherein an IRS is typically placed at the users side to improve local interaction coverage and throughput performance. The alternative single-IRS installation method builds the IRS close to the access point or base station, assisting extremely fine passive beamforming to its served users [9]. This method allows an access point with suitable antennas to attain comparable communication efficiency to a massive MIMO access point. Strategically placing the two single IRS close to either end of the communication link, the signal strength can be significantly enhanced, improving overall system performance as shown in Figure 2. This approach effectively mitigates the path-loss effects and ensures efficient signal transmission between the transmitter and receiver, resulting in a more reliable and robust wireless communication system [10]. However, using a single IRS across each wireless connection usually provides limited control over its communication channel, which can hinder IRSs communication abilities due to these reasons:

- Firstly, the wireless channel conditions can vary significantly over time and space, making it challenging for a single IRS to adapt and optimize its reflection coefficients in real-time. This limitation can result in suboptimal performance and reduced overall communication capacity.
- Secondly, multiple users or devices in a wireless network further complicates the control problem for a single IRS.

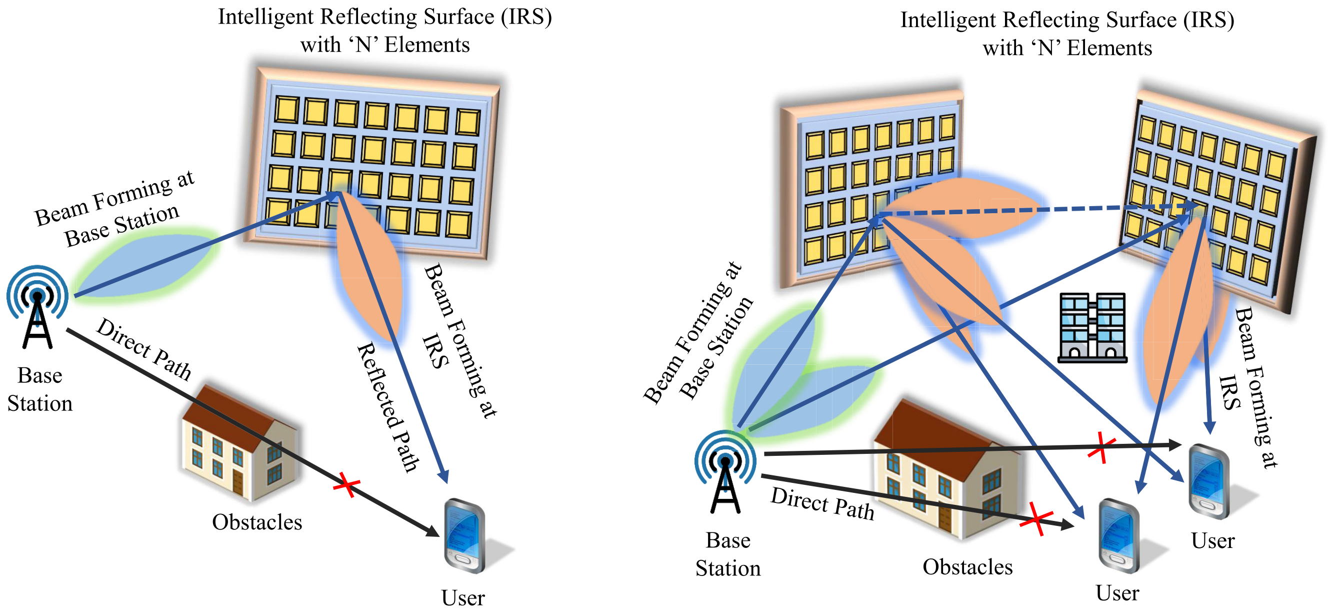

FIGURE 2. Single and double-IRS-aided multiuser MIMO system.

With multiple users, the IRS must allocate its resources efficiently to serve different users.

- Thirdly, a single IRS can only provide a tiny portion of passive beamforming due to practical restrictions on the maximum dimension of each IRS. Hence it is unable to increase the feasible transmission rate significantly.
- Finally, low-rank multiple user channels between IRS reflecting elements and the assisted base station can restrict spatial multiplexing gain in the single-IRS-enabled system.

B. DOUBLE REFLECTION IRS-ASSISTED WIRELESS MIMO COMMUNICATION SYSTEM

In the double-IRS-assisted interaction system, a pair IRSs can be placed across the base and users sides to improve collaborative performance. Note that the double-IRS-assisted system presents an updated double-reflection link through the two IRSs for any user, thereby providing a more significant number of degrees of freedom for enhancing the wireless channel, especially when the direct and two single-reflection links are blocked as shown in Figure 2. When the total number of reflecting components is N, it grows asymptotically large. The double-reflection link can reach a more excellent scaling ratio associated with the passive beam forming gain rather than the single-reflection channel [11]. This is primarily because joint passive beamforming gain exceeds the inter-IRS line-of-sight link. Considering the performance benefits of the double-IRS structure, it is feasible to utilize more IRSs to further improve the performance of each connected device by introducing more IRSs in the wireless environment and effectively assigning them to collaborate on numerous links to communicate simultaneously.

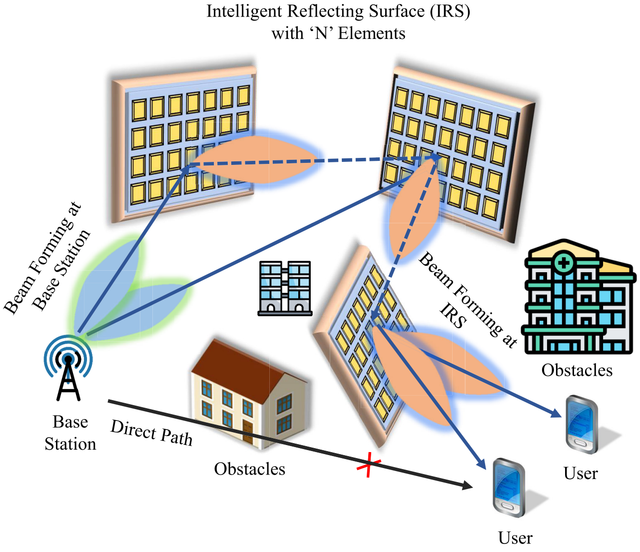

FIGURE 3. Multi-IRS-aided multiuser MIMO system.

C. MULTI-IRS-ASSISTED WIRELESS MIMO COMMUNICATION SYSTEM

Recently, multi-IRS-assisted wireless communication systems with two or more IRSs supporting individual wireless links are being designed to overcome the impedes of single-IRS-enabled communications Figure 3. Several studies have looked into strategies to coordinate multiple IRSs to get the most benefit from the performance improvement that IRSs provide. These communication systems refer to advanced networks that utilize multiple IRS to enhance signal transmission and reception. These systems leverage the passive reflecting

TABLE 1. Literature survey on massive MIMO in IRS.

Reference	Research Summary
Wang et al. (2022) [12]	• The author provides a unique protocol to improve long-term reliability and optimize the MIMO in IRS reflective coefficients determined by the channel convergence matrices often fixed across several coherence blocks.
Do et al. (2022) [13]	• This study discusses the line of sight massive MIMO interaction through an IRS. The author proposed an upper bound limit upon IRS channel bandwidth and a specific solution addressing IRS transitions that significantly meets a similar constraint in a particular condition.
Cao et al. (2022) [14]	• This study introduced a two-timescale beam formation technique to optimize IRS-aided MIMO networks average feasible rate. A power allocation-based particle swarm optimization technique is developed to maximize the efficiency of IRS large-timescale setup with fewer channel samples.
Lima et al. (2022) [15]	• This study delivers a complete discussion of the architecture, functional concepts, and performance improvements of aerial IRS with MIMO networks. The article highlights appealing advantages in sum rate maximization, user integrity and energy efficiency.
Chu et al. (2021) [16]	• This study analysed IRS-aided secure MIMO communication systems to improve security and artificial noise that interferes with the eavesdroppers reception. The author integrates encrypted precoding, artificial noise blockage, and IRS phase transformation to enhance the secrecy rate under power transmission constraints.
Jiang et al. (2021) [17]	• In this manuscript, the author offers an inclusive wideband non-stationary network approach to MIMO telecommunication contexts to precisely capture the fundamental propagation properties of IRS-assisted communication infrastructures.
Li et al. (2021) [9]	• This paper streamlined the realistic IRS model and evaluated them through numerical simulations. Researchers adopted sum-rate optimization and error minimization equivalence using a sub-optimal iterative to achieve minimum resolution in phase transition and average sum rate.
Ning et al. (2021) [8]	• The author considered a low-complexity beam learning and hybrid beamforming concept for a terahertz (THz) massive MIMO network with IRS. A pair of inexpensive hybrid beamforming approaches are provided to a base station and users that can employ an effective ternary-tree search to minimize search complexity.
Lu et al. (2021) [18]	• In this manuscript, the author demonstrates IRS-assisted target recognition in grouped MIMO radar platforms. The suggested technology outperforms superior angle precision and detection forecasting compared to non-IRS multichannel MIMO radar networks.
Xiao et al. (2021) [19]	• This letter provides a low-complexity channel determination approach for IRS-enabled massive MIMO communication systems, wherein the base station IRS signal and IRS users signal can be accurately estimated immediately and respectively utilizing the constrained RF chains.
Lu Lin et al. (2021) [20]	• The author implemented the IRS with distributed MIMO surveillance radars to enhance target detection analysis, which is encouraged by the potential uses of IRS in MIMO communication networks that can boost capacity and energy efficiency.
Mei et al. (2021) [11]	• This work investigates an intriguing multi-beam multi-hop routing issue for a multi-IRS-enabled massive MIMO network which employs selected IRSs cooperative beam reflections to establish a cascaded line of sight linkages between the multiple users and base stations.
Chen et al. (2021) [21]	• The author develops a minorization-maximization method of an IRS-assisted MIMO hidden communication network that seeks to optimize the hidden communication rate by concurrently optimizing the IRS phase shift vector and transmission covariance matrix.
Pan et al. (2020) [22]	• This research exploits an IRS near the cell-edge boundary to improve multi-cell network performance. Considering this non-convex issue, the Block Coordinate Descent (BCD) and complex circle manifold method were employed to optimize them alternately.
Dong et al. (2020b) [23]	• The author considered the IRS-aided Gaussian MIMO eavesdropping channel. To enhance the channels secrecy rate, an alternating optimization and minorization-maximization technique improves the local optimum, signal covariance at the source, and phase shifting factor at IRS.
Bjornson et al. (2020) [24]	• This work incorporates a deterministic transmission model to represent a planar array of any dimension that demonstrates the Signal-to-Noise Ratio (SNR) behaviors and power scaling rules are only effective during the far field.

TABLE 1. *(Continued.)* Literature survey on massive MIMO in IRS.

Zhang et al. (2020) [25]	• In this manuscript, the author adopts IRS equipment to aid MIMO cognitive radio for downlink data delivery. The BCD-inner approximation approach addresses the maximum sum rate optimization problem.
Hong et al. (2020) [7]	• The author recommends utilizing an IRS to improve artificial noise-assisted MIMO secure network communication security. BCD is offered to optimize the secrecy rate, artificial noise covariance matrix, precoding matrix, and IRS phase shifts.
Ning et al. (2020) [26]	• The author established the sumpath-gain maximization metrics to generate a highly efficient and reliable suboptimal solution for an IRS-aided MIMO system. Moreover, it strives to optimize the sum rate gains of the spatial pathways between the users.
Ma et al. (2020) [27]	• In this study, the deep neural network approach optimizes computational demands and data transmission performance. Since the training datasets are sufficiently massive, this approach can attain near-optimum results with a lower computation cost.

properties of IRS to manipulate and redirect radio waves by integrating multiple IRS units; these communication systems can achieve even greater signal enhancement and optimization [22]. With proper IRS allocation and incorporation, a multi-reflection connection can enable more degrees of freedom to navigate through dense and distributed obstacles in a complicated environment. Additionally, the multi-IRS-assisted system encounters greater path diversity than the single and double IRS-assisted systems, contributing more significant spatial multiplexing gains promoting multiple users as shown in Figure 1.

This diversity further provides greater versatility in determining numerous users reflection paths and fulfilling their distinct QoS requirements. These studies aim to explore the potential benefits of deploying multiple IRSs co-ordinately. Integrating the phase shifts of multiple IRSs, researchers aim to optimize the signal propagation and achieve even more significant performance gains than using a single IRS [28]. A significant portion of the current study has been focused on IRS designs emphasizing power, resource, and energy allocation beam formers for single and multi-user systems utilizing various criteria, such as max-min fairness, power minimization, energy and spectral efficiency maximization. The authors in [29] provides an extensive overview of the latest advancements in research on Reconfigurable Reflecting Surface (RIS)-aided wireless systems. It focuses on signal processing techniques for channel estimation, radio localization and transmission design challenges. The paper reviews existing results on channel estimation, discusses optimization techniques for RIS, and considers different scenarios for Channel State Information (CSI) availability.

Decoupling beamforming at the base station and phase shifting at the RIS can be efficiently achieved by employing separate optimization algorithms for each component. For instance, an alternating optimization algorithm is used to optimize beamforming weights at the base station based on CSI, and majorization-minimization is used to optimize phase shifts at the RIS to maximize SNR to achieve specific performance metrics. This decoupling allows for more flexible and efficient optimization of the overall system. The author demonstrates the simulation results with the effectiveness of two-timescale CSI schemes and the paper thoroughly examines radio localization applications of Reconfigurable Reflecting Surfaces (RISs) by considering the various deployment scenarios and channel models. Machine Learning (ML) is a potent tool for maximizing the benefits of RIS-aided communication systems, especially in scenarios where the computational complexity escalates rapidly due to increased interactions between users. ML techniques in [30] enable efficient operation and deployment of RIS by automating tasks and optimizing system performance in dynamic environments, thus addressing the challenges posed by the growing complexity of RIS-enabled networks. The authors in [31] established a research study that delved into robust beamforming strategies for a multi-user system with an IRS and imperfect CSI at user terminals. The study aims to reduce the transmit power while meeting rate constraints under different CSI error models, using mathematical techniques like the S-procedure and Bernstein-type inequality. The proposed technique performs better under the statistical CSI error model. Also, it identifies the detrimental effect of significant CSI errors on system performance, particularly with a high number of IRS elements. These studies can improve signal strength, extend coverage, and increase spectral efficiency.

Furthermore, MIMO in IRS can adaptively adjust the reflecting elements based on the changing channel conditions, optimizing the signal paths and improving the overall system performance. This adaptability makes MIMO IRS suitable for various communication scenarios, including indoor and outdoor environments, cellular networks, smart cities, Internet of Things (IoT) applications, and beyond. These technologies hold promise for significantly enhancing the capabilities of wireless communication systems, increasing network capacity, improving coverage and enabling new applications in the era of advanced wireless connectivity. Table 1 shows an analysis of the literature survey on massive MIMO in IRS.

D. MOTIVATION

The necessity to optimize the performance of wireless communication systems is the impetus for resource allocation

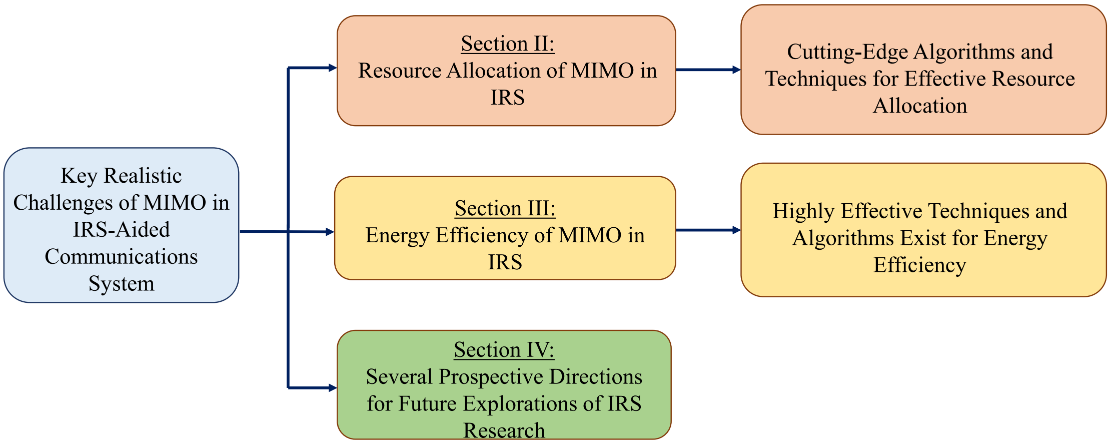

FIGURE 4. **The organizational structure of this survey paper.**

and energy efficiency in MIMO IRS. Through intelligently allocating resources and managing energy utilization, MIMO IRS can improve signal strength, spectral efficiency and power consumption. This system enables more reliable and faster communication, enhanced utilization of available resources, and an expansion of the networks overall capacity. Moreover, MIMO IRSs resource allocation and energy efficiency are crucial in facilitating sustainable and environmentally friendly wireless communications. The structure of this comprehensive survey paper is organized as shown in Figure 4. The abbreviations and acronyms used in this survey paper are listed in Table 2.

E. THE MAIN CONTRIBUTION OF THIS COMPREHENSIVE SURVEY PAPER

In this work, the significant contributions of MIMO systems are enhanced by IRS technology. Integrating IRS into MIMO systems introduces additional dimensions for optimization techniques and algorithms for resource allocation and energy efficiency for both the transmit antennas and IRS elements jointly. These strategies play a critical role in harnessing the benefits of MIMO IRS systems while managing energy consumption effectively. Our primary contributions are as follows:

- The manuscript introduces innovative resource allocation algorithms tailored to MIMO IRS systems. These algorithms optimize the allocation of antennas, reflectors and power resources, resulting in enhanced spectral efficiency and improved energy utilization.
- The research focuses on energy efficiency, proposing energy-aware techniques and algorithms that leverage IRS technology to minimize power consumption while maintaining high system performance. This is especially relevant in green and sustainable communication networks.
- The manuscript comprehensively explains the potential to significantly impact future wireless communication networks, including 5G and beyond, by addressing resource allocation and energy efficiency challenges and limitations by promoting energy-efficient operation in MIMO IRS systems.
- Finally, several prospective directions for future explorations of MIMO in IRS research are outlined. Meanwhile, the various emerging applications in MIMO IRS are also illustrated. These applications and prospective directions demonstrate the versatility and potential of MIMO IRS technology across multiple domains.

II. RESOURCE ALLOCATION FOR IRS-AIDED MIMO SYSTEM

IRS systems rely heavily on proper resource allocation to ensure optimal wireless communication performance and efficiency. However, optimizing system capacity, QoS and coverage depends upon successfully deploying resources, including power, time and frequency. In MIMO-IRS systems, effective resource allocation is essential for maximizing system performance. The main challenge is efficiently allocating resources, including time slots, transmit power, subcarriers and beamforming weights. The objective is to enhance resource management by assessing the base station MIMO potential alongside the IRSs manipulation and reflection proficiencies. The resource allocation in MIMO-IRS aims to address these challenges and optimize the allocation of resources to enhance the systems overall performance, accommodate multiple users or communication links, manage interference and energy efficiency considerations.

Moreover, dynamic resource allocation schemes are being explored to adaptively allocate resources based on changing network conditions. Various optimization techniques and cutting-edge algorithms, including alternating optimization, greedy algorithm, reinforcement learning, heuristic algorithm, iterative algorithm, genetic algorithm, particle swarm optimization and max-min fairness, as shown in Figure 5 can be applied to solve the resource allocation problem in MIMO-IRS systems.

TABLE 2. List of abbreviations and acronyms.

Abbreviatons/Acronyms	Definitions
MIMO	Multiple-Input Multiple-Output.
IRS	Intelligent Reflecting Surfaces.
IoT	Internet of Things.
SINR	Signal-to-Interference-plus-Noise Ratio.
WMMSE	Weighted Mean Square Error Minimization.
BER	Bit-Error-Rate.
MMSE	Mean Square Error Minimization.
MSE	Mean Square Error.
UAV	Unmanned Aerial Vehicle.
AIRS	Aerial Intelligent Reconfigurable Surfaces.
DDPG	Deep Deterministic Policy Gradient.
DRL	Deep Reinforcement Learning.
CB	Contextual Bandit.
PR-MIMO	Pattern Reconfigurable MIMO.
WSC	Wireless Signal Coverage.
VH	Vector Heuristic.
FRA	Forward-Reverse Auction.
SFP	Sequential Fractional Programming.
RIS	Reconfigurable Reflecting Surface.
R-PSO	Rotation-based Particle Swarm Optimization.
SNR	Signal-to-Noise Ratio.
CSI	Channel State Information.
BCD	Block Coordinate Descent.
QoS	Quality of Service.
BPCU	Bits Per Channel Use.
ECF	Element-wise Closed-Form.
GAPSCN	Global Attention Phase Shift Compression Network.
HPS	Hybrid Phase Shift.
UM-MIMO	Ultra Massive-Multiple-Input Multiple-Output.

A. SEVERAL TECHNIQUES AND CUTTING-EDGE ALGORITHMS FOR EFFECTIVE RESOURCE ALLOCATION

1) GREEDY ALGORITHM

The greedy algorithm is to explore the advancements in the realm of MIMO IRS wireless network systems and their application. One significant benefit of the IRS is to boost the Signal-to-Interference-plus-Noise Ratio (SINR) without requiring modifications to the current communication network infrastructure or additional power. The authors in [32] utilize the combination of the greedy algorithm, beamforming optimization, resource allocation and interference cancellation to optimize the SINR effectively and enhances the Bit-Error-Rate (BER) performance of MU-MIMO in IRS. The authors in [33] proposed a greedy algorithm that breaks down the main problem into subproblems. Through this optimization author improve the configuration of the IRS, including detection matrices and precoding, ultimately minimizing the Mean Square Error (MSE). The authors in [34] address the issue of IRS-user association and resource allocation by implementing a greedy search algorithm.

However, incorporating additional passive reflecting elements can result in a significant MIMO, which lower power consumption at the base station even with a limited number of active antennas. The study in [35] associated a greedy algorithm to choose pairs of users, resource allocation, and improve the precoding vectors for each pair. This algorithm balances performance and simplicity, effectively pairing users and improving precoding in MIMO-IRS systems. The authors in [36] proposed a greedy algorithm for optimizing resource allocation in multi-user MIMO-IRS systems. Thus, it assigns transmit power and phase shifts to users sequentially, resulting in improved spectral efficiency with lower computational complexity. Efficient MIMO assists IRS demands, addressing the challenge of optimal placement of the IRS.

Moreover, this pivotal aspect of network planning requires an algorithm that accurately represents the IRSs essential features and is mathematically feasible for large-scale networks. The authors in [37] implemented a coverage-cost greedy algorithm that utilizes submodular optimization to solve the IRS placement problem. The study in [38] proposed a greedy detector concept that involves equipping an Unmanned Aerial Vehicle (UAV) with Aerial Intelligent Reconfigurable Surfaces (AIRS) and utilizing joint placement and passive beamforming techniques to enhance its capabilities. The authors in [39] exploit this algorithm to tackle a challenging problem

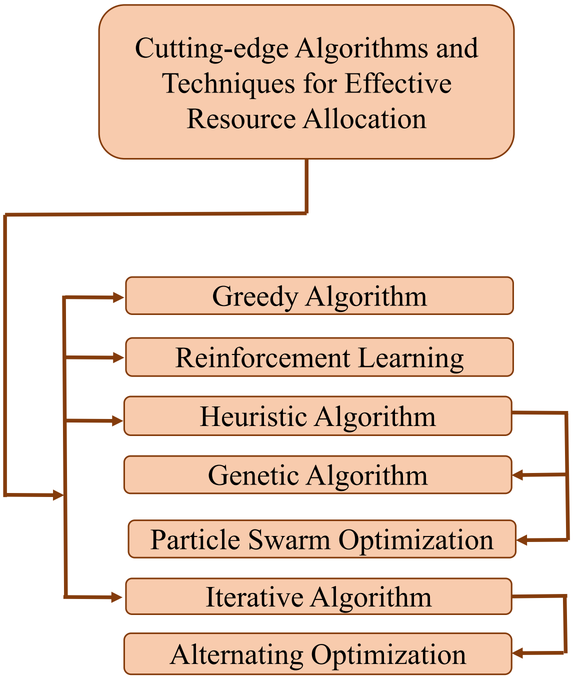

FIGURE 5. Various cutting-edge algorithms and techniques for effective resource allocation in MIMO IRS system.

involving reducing energy consumption across devices. This algorithm is accomplished by optimizing various variables, including offloading time and power, frequencies, phase shift and binary offloading modes for all network devices. The authors in [40] implemented a two-stage greedy algorithm that effectively selects active users and resource allocation to enhance beamforming vectors sequentially, resulting in an overall increase in the sum rate. This algorithm boasts a performance almost comparable to an exhaustive search method with a significantly reduced level of complexity.

2) REINFORCEMENT LEARNING ALGORITHM

Analysing the resource allocation and beamforming matrices of the IRS and MIMO base station poses a challenge because of time-varying and non-convexity factors. To address these challenges, the [41] proposed a reinforcement learning algorithm that uses the Deep Deterministic Policy Gradient (DDPG) method results in enhancing the throughput of system performance. Through trial and error, the [42] proposed a highly effective Deep Reinforcement Learning (DRL) to determine the optimal spectral sharing and resource allocation strategy, even in the absence of prior knowledge of the primary users spectrum distribution. The authors in [43] suggest a novel DRL technique exhibiting improved learning efficiency to reduce the access points transmit power in an IRS-aided MIMO system under uncertain channel conditions. One solution to optimizing the resource and spectrum allocation system is through non-convex optimization techniques, but these methods can be complex and computationally intensive. However, [44] the recommend using a reinforcement learning algorithm based on the DDPG approach, effectively overcoming this challenge. Using DRL, the authors in [45] obtained a solution to a complex problem. This approach outperformed other benchmark schemes by configuring phase shift and beamforming matrices, resulting in a higher achievable sum rate. The study in [46] addressed the energy efficiency enhancement problem by utilizing the DDPG optimization technique.

Meanwhile, the author demonstrates the DRL algorithm to develop effective, secure communication, promote computing performance, reduce service latency and boost the execution of tasks. Contextual Bandit (CB) is gaining popularity in addressing wireless communication challenges. CB involves finding the best actions for maximizing immediate rewards, falling between reinforcement learning and the k-armed bandit problem. The authors in [47] demonstrated a new framework called deep contextual bandit-DDGP which uses a CB approach with action spaces and a continuous state. This results in the highest sum rate for each channel realization. This present a novel twin-delayed DRL-based algorithm to deal with the significant dimensionality of the joint optimization between the MIMO precoder and the IRS analog phase shift. The authors [48] establish a distributed multi-agent reinforcement learning algorithm to enhance the standard deviation of the secrecy rate with the latency restriction and to optimize the throughput concerning the latency and secrecy constraints. The IRS reflects beamformers. Base station combiners and integrated user transmission powers have been improved by employing the sum-rate maximization issue. The authors [49] develop a multi-agent DRL approach to address and reframe this issue as sequential decision-making considering the interrelated relationships between the design factors across several cells. Consequently, well-designed matrices of MIMO precoding and IRS analog phase-shift result in enhanced system performance in terms of maximum transmission rates, better power, resource allocation, reduced power consumption and latency and improved communication security.

3) HEURISTIC ALGORITHM

MIMO-aided IRS can enhance channel quality by intelligently reconfiguring the wireless networking environment. Pattern Reconfigurable Multiple-Input Multiple-Output (PR-MIMO) can improve inter-user interference management and resource allocation over conventional MIMO, avoiding the additional signalling interaction needed in IRS-based instances. Concentrate on the capacity optimization of pattern layout in PR-MIMO systems, The authors in [50] proposed a pattern layout strategy that utilizes eigenvalue optimization and a heuristic closed-form algorithm dependent on the physical framework of the reconfigurable pattern on the channel of wireless communication. With PR-MIMO, users can experience faster data transfer rates, improved signal quality and enhanced network coverage. NP-hard problems are impossible to discover the optimal solution using exact algorithms. The authors in [51] implemented meta-heuristic algorithms that are being applied to resource allocation in wireless communications by emulating the intelligent actions of natural systems in seeking the optimal solution. The authors in [52] proposed two heuristic algorithms to tackle the NP-hardness problem: Wireless Signal Coverage (WSC) and tree-based WSC algorithms. Both algorithms have been tested on multiple datasets and performed well compared to existing methods. The authors in [53] suggest a Vector Heuristic (VH) algorithm that runs in linear time coefficients for passive beamforming in the specific case when the available time for beamforming is limited. This algorithm optimises the beamforming process by minimizing the time required to obtain the desired beamforming coefficients. The authors in [54] proposed a heuristic greedy search-based algorithm that has the potential to significantly enhance the performance of wireless communication systems by optimizing array response vector selection. The authors in [55] proposed a VH algorithm to determine the phase shifts of the IRS components. Subsequently, it discovered the multipath fading and doppler effects caused by the motion of the mobile station that can be efficiently reduced by modifying the phase shifts associated with the IRS component. The authors in [56] implemented the heuristic algorithms for increasing the total power of the channel by raising its lower bound.

Meanwhile, it achieves an even power distribution among all sub-channels by allocating power to sub-channels based on their respective channel gains. The study in [57] proposed a heuristic low-complexity algorithm that can achieve equivalent performance to alternating optimization. In addition, the IRS could offer a more significant end-to-end channel gain when located near the transmitter or receiver. IRS blocks can reflect signals in specific directions to boost signal strength and reduce interference. However, optimizing the IRS design requires determining the optimum resource block states to maximize the signal quality. To tackle this issue, the authors in [58] formulated a nonlinear integer problem and utilized the heuristic algorithm to obtain the optimal solution.

- **Genetic Algorithm:** The genetic algorithm based IRS-aided MIMO phase shift control allowed for more efficient utilization of the available resources, leading to higher spectral efficiency and better overall performance. The authors in [59] state the genetic algorithm was found to be an effective tool for optimizing the IRS phase shift. The study also highlighted the importance of instantaneous CSI exploitation in achieving higher data rates. Through maximizing the sum data rate, it is possible to increase the capacity of wireless networks and improve their performance. The authors in [60] introduced a strategy based on a genetic algorithm to increase the number of active users at the lowest possible phase shift rate during a RIS.

  Consequently, the authors provides extensive simulations to validate the advantages of incorporating RIS into traditional massive MIMO systems. This research has significant implications for developing wireless communication networks, offering a practical solution to the localization accuracy problem. Manipulating the phases of IRS, the study in [61] can improve the performance of passive wireless communication networks and achieve high-precision localization. This approach is based on a combination of theoretical analysis and empirical testing. The genetic algorithm developed is particularly effective in optimizing phase modulation for IRS. At the same time, the approximation method provides a practical way to implement this technique in a passive wireless communication network. Based on the accuracy of the estimated phase associated with every IRS element, the authors in [62] proposed a low-complexity heuristic approach to solve the optimization problem. This proposed method is contrasted with industry standards like the genetic algorithm and uniform allocation process. The results demonstrate that the proposed method achieves comparable performance while significantly reducing computational complexity. This makes the proposed method a superior choice for resource allocation in various applications. The authors in [63] proposed a genetic algorithm that can effectively optimize the phase shifts at the IRS to maximize the sum rate or minimum user rate. It generates a population of candidate solutions and iteratively improves them through genetic operations such as mutation and crossover.

  Moreover, this algorithm is designed to balance exploration and exploitation, ensuring it can converge to a near-optimal solution in a reasonable amount of time. The study in [51] utilize the genetic algorithm for a potential-based search strategy to explore the solution space and identify the optimal sub-carrier assignment. The fitness estimator combines the optimization algorithms, namely simulated annealing and particle swarm optimization, to evaluate the fitness of each potential solution. This approach ensures that the genetic algorithm can converge on a globally optimal solution while avoiding local optima. The proposed algorithm outperforms existing sub-carrier assignment methods in terms of computational efficiency and solution quality. On the other hand, particle swarm optimization is a continuous optimization algorithm that is well-suited for solving continuous optimization problems. Both algorithms have their strengths and weakness and the choice of which algorithm depends on the nature of the issue being addressed.
- **Particle Swarm Optimization:** Among the swarm intelligent algorithms, particle swarm optimization stands out for its ability to quickly find approximation solutions to complex problems while maintaining an inexpensive complexity and robust convergence feature. This algorithm is typically the best solution when dealing with a vast hyper-parameter space since it

outperforms other algorithms like genetic algorithms based on complexity, precision and ease of use. Therefore, employ particle swarm optimization to the IRS-aided secure MIMO optimization problem and evaluate it against alternating optimization. The authors in [64] proposed a Rotation-based Particle Swarm Optimization (R-PSO) method that seeks to maximize the secrecy sum rate while satisfying the total power and intermittent unit-modulus constraints. Using rotation modelling, which transforms the covariance matrices into rotation angles, resource and power allocation coefficients, can reframe the optimization problem as a multi-variable parameter optimization problem. Considering numerous elements at the IRS, CSI acquisition involves abundant radio-frequency chains and training expenses, which is restrictive in practice. The authors in [65] introduced an innovative strategy based on the particle swarm optimization algorithm to tackle this issue by reducing the transmit power while maintaining a minimum SNR.

Moreover, the author intends to optimize beamforming at the base station and IRS without CSI. The authors in [66] utilized the particle swarm optimization technique to collaboratively optimizes the phase shifts and transmission beam forming on two IRS to improve the received signal strength. It enhances user service quality, reduces energy consumption and increases network efficiency. The study in [67] proposed the R-PSO algorithm to determine the IRS phase changes that result in a minimal amount of rotation error bound and position error bound. IRS can boost device-to-device communication throughput; however, new networks struggle with interference suppression. Thus, IRS-assisted device-to-device communication requires efficient and simple radio resource allocation. To tackle this problem, the authors in [68] provided a low-complexity particle swarm power and phase shift joint optimization method. The study in [69] compare the particle swarm optimization technique with the successive convex approximation approach. The author states that the particle swarm optimization algorithm seeks the best solution through group cooperation and information sharing. It can establish the objective function and then discover the local optimal solution by optimizing each particles velocity and displacement parameters. The authors in [70] demonstrated a hybrid active and passive beam training approach using revised particle swarm optimization to improve sensing and communication devoid of high-overhead transmitted channel estimation.

4) ITERATIVE ALGORITHM

The conventional approach of wireless communication techniques has a significant computational complexity because of its multi-tier structure. The authors in [71] tackle this issue by implementing two simpler iterative techniques. These algorithms simplify the computational complexity by combining numerous inner loops of BCD layers. Meanwhile, the precoding and phase shift adjustment was developed over IRS-aided MIMO systems. The non-convex issue makes IRS phase value selection difficult. The authors in [72] present an iterative algorithm for the alternating optimum solution in single-user MIMO systems. This algorithm provides an alternating ideal solution corresponding to the IRS phase value unit. This proposed method outperforms randomized IRS systems. It performs better than the fixed phase shift and random phase shift methods. The study in [73] proposed the iterative mechanism based on iterative hard thresholding is included in the local search results improvement, which is treated as a specific case of the subsequent optimization issue. The proposed algorithm aims to find the optimal solution by minimizing the objective function and satisfying the constraints. The authors in [74] implemented an iterative approach that leverages the CSI to update the transmit covariance matrix and IRS phase-shift matrix iteratively. The iterative algorithms can enhance signal strength and mitigate interference by jointly optimizing these matrices.

Moreover, the closed-form solution for the transmit covariance matrix and semi-closed form for the IRS phase shift matrix enable fast convergence and efficient implementation. The authors in [75] demonstrate the iteration algorithms that optimize IRS transmission beamforming and phase shifting alternately. Moreover, beamforming optimization uses closed-form formulations of optimal beamforming parameters. The authors offers two approaches for IRS phase shifting optimization in this work. The semidefinite relaxation-oriented iteration approach has a high data rate, and the consecutive convex approximation approach has minimal complexity. Both approaches achieved near-optimal performance in simulations. To optimize the IRSs passive beamforming, power allocation, resource allocation, and user association in multi-base station Millimeter Wave (mmWave) MIMO systems. To achieve a maximum sum rate, the study in [76] proposed a computationally cost-effective iterative algorithm using alternating optimization, Forward-Reverse Auction (FRA) and Sequential Fractional Programming (SFP) to solve this challenging non-convex problem. SFP optimizes IRSs passive beamforming, standard convex optimization solves resource and power allocation and network optimization-oriented FRA algorithm handles user association. Overall, these advancements in optimization algorithms contribute towards addressing the challenges posed by practical discrete phase shifts in MIMO networks with IRS as shown in Figure 6.

- **Alternating Optimization Algorithm:** The utilization of the IRS has been highly effective in enhancing the capabilities of the MIMO system. This system is accomplished by strategically allocating resources, power and phase shift to improve the SINR, spectral efficiency and sum rate [77] optimized the receiver filter coefficients, power allocation, resource allocation, and phase shifts on the IRS. Thus, resulting in a minimum of SINR through an alternating optimization algorithm [78]. demonstrated the Weighted Mean Square Error Minimization (WMMSE) – alternating optimization to achieve a low-complexity and low-latency solution for complex non-convex issues by utilizing the equivalence between WMMSE and spectral efficiency maximization [71]. Confidently and iteratively determine the optimal beam formers, resource allocation and phase shifts that yield the highest achievable weighted secrecy sum rate.

Moreover the authors in [79] provide highly efficient, delivering superior performance with minimal computational time.

The top priority is significantly improving the performance of the IRS reflection coefficients and the covariance matrices of MIMO transmission, explicitly focusing on narrowband transmission in frequency-flat fading channels. To accomplish this, authors in [80] developed a highly effective alternating optimization algorithm that continually fine-tunes the transmit covariance matrix or one of the reflection coefficients while maintaining the other constant parameters. Moreover, this algorithm discovered the most optimal solution within the local scope. To examine the impact of rank-deficient channels on the performance of MIMO IRS and devise effective strategies to mitigate any adverse effects. The study in [81] proposed an alternating algorithm that effectively maximizes the deterministic approximation by optimizing signal covariance matrices and phase shifts to rectify this. Thus, it significantly reduces the performance loss caused by channel rank deficiency. The utilization of IRS technology has gained significant traction recently as the preferred solution for addressing blockage issues in mm-Wave frequencies and elevating the performance of massive MIMO systems. The authors in [82] solve the problem of channel estimation and blockage issues in mm-Wave MIMO channels by exploiting their sparseness on the angular domain. To accomplish this, the author employed a regularized optimization issue and fixed rank constraints that can effectively determine the local optimal solution by utilizing manifold and alternating optimization. Nonetheless, the error performance of IRS-assisted mm-Wave massive MIMO has received minimal scrutiny. The authors in [83] focus on utilizing an IRS in mm-Wave massive MIMO system through hybrid beamforming. To collaboratively develop the IRS phase shifts and X-precoder, the author implemented alternating and gradient ascent optimization. These algorithms proved highly efficient and trustworthy in substantially improving error performance and reducing the word error rate.

5) MAX-MIN FAIRNESS

In an IRS-enabled massive MIMO communication network, the unfortunate users with closed channels directly connected to the base station or significant path losses will gain the maximum IRS phase shift coefficient to achieve the highest SNR. A minor network spectral efficiency enhances performance over traditional massive MIMO networks. This network will concentrate on max-min fairness. To achieve this, the authors in [84] state that the fixed-point technique over the max-min fairness iteratively adjusts the transmit powers of each users equipment in a wireless network. It aims to balance maximizing the overall system capacity and ensuring fairness among all user equipment. Continuously updating the power levels, the algorithm guarantees that no user equipment is unfairly disadvantaged by receiving significantly lower signal quality than others. This approach improves the minimum spectral efficiency and enhances the overall network performance. The algorithms iterative nature allows to converge towards an optimal solution where all user equipment experience fair and efficient power allocation. This process maximizes the minimum spectral efficiency among all user equipment without compromising fairness or causing unnecessary redundancy in power allocation decisions. The authors in [85] developed the quadratic transform, making the max-min ratio function more straightforward, making it possible to address the unresolved max-min fairness problem more effectively. It provides a novel viewpoint and cutting-edge methods that improve the optimization strategy. This strategy reduces repetition and redundancy while approximating the desired result more closely. Through investigating this alternative course, we create opportunities for ground-breaking solutions that could revolutionize the industry and open the door for further developments in dealing with fairness issues. To tackle the complexity of the max-min SINR problem in MIMO networks with IRS, the authors in [86] have proposed various efficient algorithms.

One approach decomposes the problem into beamforming and phase shift optimization. Iteratively optimizing these two subproblems, a feasible solution can be obtained. Another method is to use convex relaxation techniques, such as semidefinite programming, to approximate the original problem and find a suboptimal solution with reduced complexity. ML techniques have also been employed to learn the optimal beamforming and phase shift policies from historical data, enabling faster convergence and improved performance. The study in [87] encapsulates the advantages of integrating an IRS into multigroup multicast systems. It highlights the enhancement of received signal strength through precise adjustment of reflection coefficients at the IRS. The study addresses the optimization challenge of maximizing sum rates by jointly optimizing precoding at the base station and IRS reflection coefficients while adhering to power constraints. Leveraging the majorization–minimization algorithm, the study derives a concave lower bound for the objective function and employs alternating optimization to update variables iteratively. Moreover, intelligent metaheuristic algorithms like genetic algorithms and particle swarm optimization have shown promising results in solving the

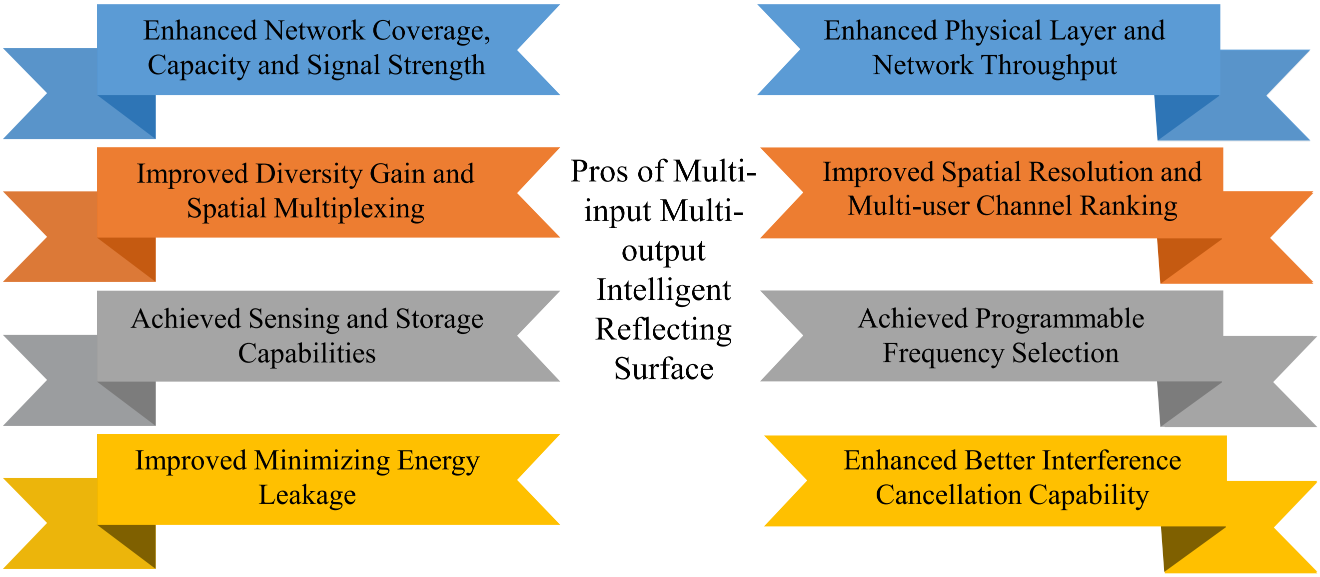

FIGURE 6. Significant pros of MIMO in IRS wireless communication system.

TABLE 3. Comparison analysis of several technique with various performance metrics on resource allocation in MIMO IRS.

Related Works	Contributions															
	Several Techniques/ Algorithms								Performance Metrics							
	AO	GRA	RL	HA	IA	GA	PSO	MMF	General	MSE	MI	WMSE	WMI	WMMSE	MMSE	Others
Chen et al. (2022) in [78]	✓	×	×	×	×	×	✓	×	⋆	⋆	×	⋆	×	✓	✓	×
Nadeem et al. (2022) in [77]	✓	×	×	×	×	×	×	✓	✓	×	⋆	⋆	✓	⋆	✓	×
Kumar et al. (2022) in [88]	✓	×	×	×	✓	×	×	×	×	✓	✓	⋆	⋆	✓	⋆	×
Nguyen et al. (2022) in [89]	✓	×	✓	×	×	✓	×	×	✓	⋆	×	✓	⋆	×	×	✓
Xu et al. (2022) in [90]	⋆	×	×	⋆	×	✓	×	⋆	✓	⋆	×	⋆	×	×	✓	✓
Hu et al. (2021) in [91]	×	✓	×	⋆	✓	×	⋆	×	×	⋆	×	⋆	×	✓	✓	⋆
Asim et al. (2022) in [38]	✓	✓	×	×	⋆	×	✓	×	⋆	✓	⋆	✓	✓	×	⋆	×
L. Yashvanth and Murthy (2022) in [92]	×	⋆	×	✓	×	×	⋆	✓	×	✓	×	⋆	×	×	⋆	✓
Lin et al. (2022) in [82]	⋆	×	×	✓	✓	×	×	⋆	✓	×	✓	×	✓	×	✓	⋆
Chen et al. (2023) in [93]	×	×	×	⋆	✓	×	×	✓	×	×	✓	×	✓	⋆	⋆	✓
Chen et al. (2021) in [73]	✓	⋆	×	×	✓	×	×	×	×	×	×	✓	×	✓	×	×
Lan and Yin (2023) in [94]	×	×	×	✓	⋆	×	✓	⋆	✓	⋆	⋆	✓	×	×	⋆	✓

NP-hard combinatorial optimization problem associated with IRS phase shifts. These algorithms explore the search space efficiently and converge to near-optimal solutions.

B. CHALLENGES AND LIMITATIONS OF RESOURCE ALLOCATION IN MIMO IRS

Resource allocation in MIMO systems with IRS involves allocating various system resources such as transmit power, subcarriers, time slots, or bandwidth to optimize performance and energy efficiency. However, there are several limitations and constraints associated with resource allocation in MIMO IRS systems. Here are some key limitations to consider:

1) COMPUTATIONAL COMPLEXITY

The computational complexity of resource allocation in MIMO systems with IRS can vary based on the allocation problem and the complexity of the employed optimization algorithm. Several factors influence the computational complexity of resource allocation in MIMO IRS, including the number of antennas, IRS elements, users and the desired system performance [19]. Here is an analysis of the computational complexity of the algorithms mentioned earlier:

a: GREEDY ALGORITHM

The computational complexity of a greedy algorithm in the RIS depends on the specific problem being solved and the implementation details. Generally, greedy algorithms have a time complexity of $\mathcal{O}(nlogn)$ or $\mathcal{O}(n^2)$, where n is the size of the input. In RIS [95], the author attained a computational complexity of $\mathcal{O}(K_3 + LK_2)$. Mostly it can vary based on the problem and the random choices made during the algorithms execution.

b: GENETIC ALGORITHM

In general, the computational complexity of a genetic algorithm is typically described in terms of the population size (N), the number of generations (G), and the complexity of the fitness evaluation function (f). The time complexity of a basic genetic algorithm can be approximated as $\mathcal{O}(N * G * f)$. whereas N, G, and f are defined as the population size, number of generations, and time complexity of the fitness evaluation function. As shown in [96], the author achieved $\mathcal{O}(N_S^3)$ computational complexity and the actual computational complexity of a genetic algorithm can vary significantly depending on the specific implementation details. This includes the efficiency of the operators used for selection, crossover and mutation.

c: PARTICLE SWARM OPTIMIZATION

Generally, the time complexity of a basic particle swarm optimization algorithm can be approximated as $\mathcal{O}(N * D * G)$. In contrast, N, D, and G are represented as a number of particles, the dimensionality of the search space (i.e., the number of parameters being optimized) and several iterations. This analysis provides a basic understanding and the actual complexity can vary based on implementation details such as the computational cost of evaluating the fitness function and the efficiency of the velocity and position update mechanisms [97]. The authors in [97] achieves $\mathcal{O}(OKLog(O))$ computational complexity.

d: ALTERNATING OPTIMIZATION ALGORITHM

The computational complexity of alternating optimization in RIS optimization can be approximated as $\mathcal{O}(N * M)$, where N depends on the algorithms convergence rate and M is the complexity of evaluating the objective function and constraints for a single iteration. The complexity of evaluating the objective function and constraints involves simulating electromagnetic wave propagation, analyzing RIS configurations, and computing performance metrics like signal strength or interference. However, it is essential to note that this is a simplified view and the actual computational complexity can vary depending on implementation details, problem characteristics, and convergence behaviour. In [98] authors analyzes the worst-case complexity of running an alternating algorithm $\mathcal{O}(IK(M^3 + D_K N_K L + MDL))$ with I times.

e: REINFORCEMENT LEARNING ALGORITHM

In general, reinforcement learning algorithms involve interacting with the environment through a series of state transitions and actions, while updating a policy or value function to maximize some notion of cumulative reward. The computational complexity of reinforcement learning algorithms is often described in terms of the number of state-action pairs $\mathcal{O}(S * A)$, where S is the number of possible states and A is the number of possible actions [99].

Moreover, it can be challenging to measure the computational complexity precisely. In addition, the computational complexity depends on the systems specific implementation and hardware capabilities. Meanwhile, the presence of interference and channel conditions can further impact the computational complexity of resource allocation in MIMO IRS.

- **Number of Variables and Constraints:** Algorithms for allocating resources are often computationally complex in proportion to the number of variables and constraints in the underlying optimization issue. As the number of antennas, IRS elements and users increases in a MIMO IRS system, the computational complexity of resource allocation algorithms also increases. This is because the number of variables and constraints that need to be considered grows proportionally, making the optimization problem more challenging to solve efficiently. The increased complexity can lead to longer computation times and higher resource utilization, highlighting the need for efficient algorithms that can handle large-scale systems effectively.
- **Optimization Algorithm:** An optimisation algorithms selection heavily influences resource allocations computational complexity. The computational complexity of algorithms like exhaustive search, brute force and dynamic programming may be high when the problem size is enormous. On the other hand, heuristic algorithms like greedy algorithms or suboptimal algorithms can minimise computing complexity at the expense of optimality.
- **Constraints and Optimization Objectives:** The complexity of resource allocation algorithms can increase based on the quantity and nature of constraints imposed on the system. Constraints can include power constraints, service quality requirements, interference restrictions and hardware limitations. Multiple objectives, such as maximizing energy efficiency while maintaining specific QoS levels can further complicate resource allocation optimization. It is essential to consider all these factors when developing resource allocation strategies.

To manage the computational complexity of resource allocation in MIMO IRS, researchers and engineers employ various techniques: One technique is using intelligent algorithms that efficiently allocate resources based on channel conditions and user demands. These algorithms can optimize the power allocation, beamforming, and subcarrier allocation to maximize the systems overall performance. Researchers also explore machine learning techniques to enhance resource allocation in MIMO IRS systems by learning from past data and making real-time adaptive decisions.

- **Approximation Algorithms:** Instead of searching for optimal solutions, approximation algorithms seek to provide near-optimal solutions with reduced computational complexity. These algorithms are often used when finding the optimal solution is computationally infeasible or too time-consuming. Through sacrificing optimality, approximation algorithms can efficiently solve complex problems and still provide solutions close enough to the optimal solution for practical purposes [100].

- **Decomposition Techniques:** Resource allocation problems can be decomposed into smaller sub-problems, reducing the overall complexity. These sub-problems can be solved independently or with limited coordination. Decomposition techniques enable efficient problem-solving by breaking down resource allocation problems into manageable sub-problems [101]. Solving these sub-problems independently or with limited coordination significantly reduces the overall complexity of the resource allocation process. This technique allows for more streamlined and effective allocation strategies to be implemented.
- **Low-Complexity Algorithms:** Simplified algorithms, such as greedy or suboptimal algorithms, trade-off optimality for reduced computational complexity. These methods are frequently applied when time or resource constraints make it impractical to discover the best answer. Though they are unlikely always to yield the optimal result, they provide a trustworthy approximation that can be computed promptly.

Numerous techniques, including algorithmic optimizations, dimensionality reduction and efficient approximation, can reduce the computational complexity of resource allocation in MIMO IRS systems. In addition, utilizing distributed and parallel processing architectures can aid in managing computational complexity and facilitate the practical implementation of resource allocation algorithms in large-scale MIMO IRS systems. Table 3 shows a comparative analysis of several techniques/algorithms with various performance metrics on resource allocation in MIMO IRS.

2) INTERFERENCE MANAGEMENT COMPLEXITY

Interference management in resource allocation for MIMO IRS can be complex due to the interactions between multiple users, IRS elements and base stations. MIMO IRS introduces new interference management dimensions and effectively addressing them is crucial for optimizing system performance. Listed below are several factors that contribute to the complexity of interference management in MIMO IRS resource allocation:

- **Multi-User Interference:** In multi-user scenarios, multiple users can share the same resources provided by the IRS [102]. The phase shifts applied by the IRS elements can cause interference among users, affecting their signal quality and data rates. This interference can be mitigated by carefully controlling the phase shifts at the IRS elements. Optimizing the phase shifts at the IRS elements, the interference among users can be minimized, leading to improved signal quality and higher data rates. This control over phase shifts allows for efficient resource allocation and ensures that each user receives their required level of service without compromising others performance.
- **IRS-User Interference:** The IRS elements can change the propagation environment, leading to a direct impact on user-to-user interference. The phase shifts can amplify or attenuate signals from different users, affecting the overall interference levels [103].
  This interference can ultimately degrade the performance of wireless communication systems. Intelligently adjusting the IRS elements phase shifts can help mitigate the interference caused by multipath propagation. The IRS can enhance signal quality and improve overall system capacity by dynamically controlling the signal reflections.
- **Interference Alignment:** Interference alignment is a technique used in multi-user systems to align interference at specific dimensions, allowing users to coexist without causing excessive interference [104]. However, with MIMO IRS, the complexity of interference alignment increases due to additional degrees of freedom introduced by the IRS phase shifts. This complexity can be mitigated by optimizing the IRS phase shifts and antenna configurations.
- **Interference from IRS Elements:** The phase shifts of IRS elements can introduce constructive or destructive interference at receivers. The challenge lies in finding the optimal phase shifts to enhance desired signals while suppressing unwanted interference. The optimization of phase shifts is crucial to achieving optimal signal performance. This optimization process involves considering various factors, such as the location and number of IRS elements, the frequency of the signals and the desired coverage area. Additionally, advanced algorithms and machine learning techniques can be employed to dynamically adjust the phase shifts based on real-time conditions, further improving signal quality and minimizing interference. Table 4 shows an analysis of the literature survey on resource allocation in MIMO IRS.

3) CHANNEL ESTIMATION ERROR

The channel estimate errors severely impact resource allocation performance in MIMO IRS systems. Accurate CSI is crucial for optimizing resource allocation and achieving the desired gains in MIMO IRS. Channel estimation error refers to the discrepancy between the actual channel conditions and the estimated channel information used for resource allocation. Several factors contribute to channel estimation error in MIMO IRS:

- **Propagation Environment:** Wireless channels are subject to various propagation effects, including multi-path

TABLE 4. Literature survey on resource allocation in MIMO IRS.

Reference	Research Summary
Zhong et al. (2023) [105]	• The authors developed a resource allocation approach that seamlessly enhances energy efficiency using either imperfect or perfect CSI of dual-functional radar and communication systems.
Cheng et al. (2023) [106]	• The authors explored the sum-rate optimization problem by concurrently establishing the successive convex approximation approach with dynamic beamforming of several antennas, the IRS passive beamforming, dynamic resource allocations and the time distribution ratio.
Mitran et al. (2022) [107]	• The authors estimated the resource allocation trade-off among uplink and downlink sum rates attained by the joint design of the IRS. Meanwhile, the weighted-sum problem is formulated using a BCD approach.
Lin et al. (2021) [108]	• In this work, the authors established a unique requirement for canonical polyadic decomposition tensor execution to ignore the channel estimate ambiguity in two-hop communication networks. Moreover, the frequency variant resource allocation of training strategies influences the hybrid IRS network.
Forouzanmehr et al. (2021) [109]	• The authors of this manuscript explored an iterative-based majorization minimization (resource allocation algorithm) to achieve optimal energy efficiency in a MIMO IRS-aided uplink transmission network. Meanwhile, alternative optimization and inner approximation approaches are utilized to examine the beamforming matrices between a base station and IRS.
Huang et al. (2021) [110]	• This research examines the IRS-aided federated learning methods computation and interaction with resource allocation on the basis of imperfect CSI. The practice time minimization issue is formulated using the probabilistic CSI error concept and rate outage probability constraints.
Zeng et al. (2021) [111]	• The authors employed IRS to optimize a MIMO systems resource allocation and energy efficiency. The users transmission power, IRS phase shift and base station beamforming matrix must be optimized together. Findings indicated that integrating IRS elements improved system energy efficiency more than base station antennas.
Zheng et al. (2021) [112]	• This work developed an IRS-enabled wireless communication network employing the relaying capacity of the IRS controller. The authors targeted the IRS controller and proactive beamforming to optimise user rate in decode-and-forward relaying resource and time allocations.
Mu et al. (2021) [113]	• This work studied IRS-aided multiple-user wireless transmission capacity. The IRS reflection coefficient and utilization of resources were optimized for MIMO transmission schemes under sequential phase shifts and finite IRS reconfiguration duration.
Xu et al. (2020) [114]	• This research examines resource allocation for IRS-enabled cognitive radio platforms. The authors utilizes iterative BCD to solve the non-convex approximation optimization issue. Semidefinite ease, a penalty approach and consecutive convex approximation ensure the convergence process to a fixed point of the estimated optimization issue.

fading, shadowing, and scattering. Estimating channels accurately in such complex environments can be challenging. However, advancements in technology have allowed for the development of sophisticated algorithms and techniques to mitigate these effects and improve channel estimation. These algorithms and techniques make use of statistical models, such as Rayleigh or Rician fading, to accurately characterize the wireless channel. Additionally, adaptive antenna systems and beamforming techniques can be employed to enhance signal strength and minimize interference in challenging propagation environments [115].

- **Pilot Contamination:** In multi-user MIMO IRS systems, the pilot signals used for channel estimation from different users can interfere with each other, leading to pilot contamination and degraded channel estimation. Various techniques have been proposed to mitigate this issue, such as time division multiplexing and frequency division multiplexing. These techniques are to design pilot sequences that are orthogonal to each other, reducing the interference between users [116]. Advance signal processing involves exploiting the spatial degrees of freedom provided by the IRS to separate the pilot signals from different users, improving channel estimation accuracy.

Several strategies can be employed to mitigate the effect of channel estimation error on resource allocation in MIMO IRS:

- **Pilot Design:** A well-designed pilot signal can enhance the overall system performance by minimizing interference and maximizing data transmission rates. Optimizing pilot signal design can also lead to improved spectral efficiency and increased network capacity [116].
- **Channel Tracking:** Dynamic channel tracking techniques can continuously update channel estimates to adapt to time-varying conditions and reduce estimation errors. These techniques use feedback information from the receiver to improve channel estimation accuracy. Additionally, dynamic channel tracking can help mitigate the effects of fading and interference in wireless communication systems. The authors in [117] emphasizes the necessity of adjusting phase shifts promptly to direct beams toward mobile users by underlining the significance of streamlined channel tracking methods. This paper presents a novel channel tracking scheme designed for practicality and robustness. First, it leverages the cascaded RIS angles, which are more readily obtainable compared to precise angle information. Second, the scheme functions effectively even under non-Gaussian noise conditions, which offers greater adaptability and practical benefits compared to traditional approaches.

4) LIMITED FEEDBACK CAPABILITY

In MIMO IRS systems, the limited feedback capability for resource allocation is one of the most significant challenges. The limitation on feedback results from practical constraints such as channel estimation overhead, latency and bandwidth constraints. Providing complete CSI feedback for each IRS reflecting element becomes impracticable due to the large number of reflecting elements [118].

- **Channel Quantization:** Instead of providing full CSI feedback, the channel information can be quantized and fed back to the transmitter and IRS. Quantization reduces the feedback overhead by representing the channel state with a finite number of bits. However, quantization also introduces some loss in system performance due to the limited accuracy of the feedback.
- **Codebook-Based Feedback:** Predefined codebooks can be used at the IRS and the transmitter to quantize the channel information. The IRS and transmitter can have matching codebooks and the receiver only needs to feedback on the index of the closest codebook entry corresponding to its observed channel. This reduces feedback overhead compared to explicit CSI feedback.
- **Compressed Sensing:** Using compressed sensing techniques, essential channel information can be extracted with fewer measurements [119]. These techniques recover pertinent CSI from a reduced set of measures by utilizing the sparsity or low-rank structure of the channel.
- **Differential Feedback:** Instead of feeding back absolute CSI values, differential feedback can be used, where the receiver provides feedback on the changes in the channel conditions. This approach reduces the feedback overhead by transmitting the delta changes instead of the entire CSI.
- **Feedback Scheduling:** Based on channel dynamics, the feedback rate can be adjusted adaptively in time-varying environments. When channel variations are rapid, more frequent feedback can be utilized to maintain accurate information for effective resource allocation. During stable periods, feedback can be minimized to conserve bandwidth.

In summary, the limited feedback capability in MIMO IRS systems requires intelligent strategies to balance the trade-off between obtaining sufficient channel information for optimal resource allocation and minimizing the feedback overhead. Various quantization, codebook-based and compressed sensing techniques are essential in achieving efficient and practical resource allocation in such systems.

III. ENERGY EFFICIENCY FOR IRS-AIDED MIMO SYSTEM

Energy efficiency in an IRS-aided MIMO system refers to optimizing the systems wireless communication performance while minimizing energy consumption. It involves maximizing the achievable data rates, coverage, or QoS per unit of energy expended. In other words, an energy-efficient IRS-aided MIMO system aims to achieve reliable and high-quality communication using the least amount of energy possible. Highly effective optimization techniques and various inventive algorithms, including power minimization, dynamic power control, cooperative transmission, hybrid beamforming, QoS-aware energy efficiency, sleep/wake schedule, antenna selection, joint power and phase shift optimization, as shown in Figure 7 can be effectively applied to resolve the energy efficiency issue in MIMO-IRS systems.

A. HIGHLY EFFECTIVE TECHNIQUES AND ALGORITHMS EXIST FOR ENERGY EFFICIENCY

1) POWER MINIMIZATION

Numerous studies have been conducted on IRS-assisted MIMO systems, each with a distinct objective. Most of these studies concentrate on optimizing energy efficiency and demonstrate that incorporating IRS can significantly enhance the systems energy efficiency. Through analysis of the transmit power minimization problem, the authors in [120] demonstrate that IRS can deliver a square gain in power. The transmit power can be reduced while maintaining the same signal strength level. It can potentially improve energy efficiency and reduce interference in wireless networks significantly. The study in [121] proposed an approach to solving the power minimization problem while satisfying QoS constraints. To tackle this issue, the authors used the

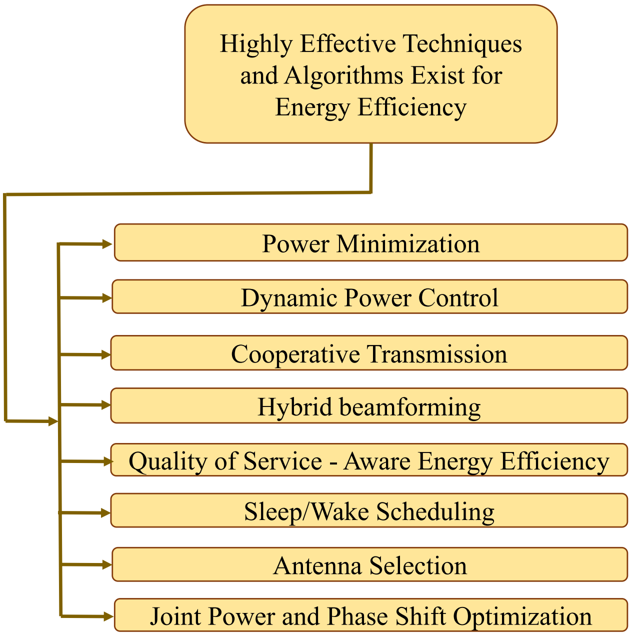

FIGURE 7. **Highly effective techniques and algorithms exist for energy efficiency in MIMO IRS system.**

bisection search and one-by-one optimization combined with alternating optimization algorithms.

The bisection search algorithm finds the optimal solution for the power minimization problem. In contrast, the one-by-one optimization combined alternating optimization algorithm ensures that QoS constraints are met. Combining these two algorithms, limit point solutions can be achieved. This approach is beneficial in scenarios where power consumption needs to be minimized while maintaining a certain QoS. In situations with no direct signal paths through unobstructed space, the authors in [122] implement the minimum amount of power needed for transmission using equal power allocation. Additionally, the authors provides an optimal solution for the subsurface required when the total number of reflecting elements on the IRS is predetermined. The authors in [123] suggested several optimization methods to lower the computation complexity without compromising the algorithm-level performance. The baseline successive refinement algorithm provides a sub-optimal solution for the power minimization issue based on the SINR constraint at each user.

2) DYNAMIC POWER CONTROL

The random and time-dependent wireless channels generate ultra-reliable and high-capacity wireless communication is complicated. To overcome this problem, the authors in [124] implemented dynamic power control and beamforming, space, time and frequency diversity approaches and efficient transmission and coding schemes. The study in [125] stated energy neutrality allows the IRS-MIMO system to outperform IRS-NOMA in energy efficiency. For instance, the conventional IRS-NOMA system can achieve optimal energy efficiency of 159.6 Bits Per Channel Use (BPCU)/Watt at 10 dBm. In contrast, the IRS-MIMO scheme can reach 427.2 BPCU/Watt at 6 dBm. The IRSs energy consumption strongly impacts energy efficiency. It is determined that every single reflecting element adds 0.5 mW to the total power utilization and the highest achievable energy efficiency reduces to approximately 235 BPCU/Watt. If the power utilization per element is 3 mW, it is inferior to the conventional IRS-MIMO system. For optimum energy efficiency, joint beamforming matrix values at the base station and IRS and user power allocation strategies are being investigated. Solving the underlying issue, which is mixed-integer nonlinear programming, is challenging. The authors in [109] suggest an alternating optimization-based iterative algorithm for solution design.

Meanwhile, the authors demonstrates Dinkelbach and majorization minimization techniques to enhance antenna selection and dynamic power allocation on the user side. Pilot power control and rate-optimized power distribution are powerful techniques for improving network performance. Pilot power control is a convex approximation method that reduces pilot contamination, while rate-optimized power distribution employs geometric programming to minimize interference. Both methods effectively improve network performance by reducing interference and optimizing power distribution. Using these techniques, the authors in [126] states that network operators can ensure their network operate efficiently, delivering fast and reliable connectivity to users.

The authors in [127] provided an efficient solution to the nonlinear problem by integrating quadratic programming form and imposing QoS constraints, resulting in the highest sum rate. An alternating optimization algorithm with dynamic power control is employed to achieve the solution. This algorithm leverages the simple alternating direction methods of the multipliers technique to tackle this optimal digital precoder. In addition, gradient projection has the potential to generate a passive reflecting array that corresponds to the active one. This technique avoids redundancy and repetition while effectively solving the nonlinear problem and it represents a significant advancement in wireless communication and signal processing.

3) COOPERATIVE TRANSMISSION

The cooperative transmission of double-IRS with the MIMO communication system is currently a prominent area. The primary challenge is to offer efficient channel models that describe communication scenarios to design and improve the cooperative transmission efficiently assisted MIMO communication system. The authors in [128] stated the two distributed IRSs are stationed nearby a multi-antenna base station and an ensemble of nearby users for a double IRS cooperatively assisted MIMO communication system. Since IRS is passive (it cannot transmit or receive signals), conventional channel estimation methods are ineffective in determining the CSI of an IRS-assisted system. Consequently, the study in [129] stated that the IRS-MIMO-aided system gathering comprehensive channel information is essential. Meanwhile, the form of the acquired channel knowledge should inform the derivation of the cooperative transmission solution. The authors in [130] demonstrated angle aware user cooperation scheme that lowers the possibility of jamming and eavesdropping attacks, thereby improving the security of wireless communication networks. It operates by determining the angle of the user being attacked and routing the cooperative transmission through users not in the attackers line of sight. Since the cooperative transmission is being relayed through a secure channel, the attacker cannot intercept or interfere in this manner. This scheme also considers each users mobility and location to ensure cooperative transmissions are routed along an optimal path.

Additionally, it incorporates a trust-based mechanism to ensure that only reliable users are utilized for relaying cooperative transmission. Cooperative networking has numerous advantages, including improved capacity, reliability, wider coverage area and enhanced overall performance. The authors in [131] devise an innovative cooperative transmission approach that implements the IRS to address channel rank deficiencies and handle inter-user interference. The central idea is to either reflect incident waves through the IRS to improve successful channel matrices rank or neutralize interfering ties incorporating signals reflected via the IRS. The authors in [132] explore a cell-free MIMO communication system that utilizes IRS to aid in cooperative transmission through a network of base stations that can be distributed across a region.

The study in [79] propose and investigate a cooperative transmission based on a double-IRS-aided MIMO communication network over line-of-sight propagation pathways. In contrast, most prior research neglected the cooperation between IRSs. In this work, the authors optimizes the passive beamforming and transmits covariance matrices concerning the cooperative transmission in IRSs to examine the capacity maximization problem.

4) HYBRID BEAMFORMING

Ultra-Massive Multiple-Input Multiple-Output (UM-MIMO) systems using sub-millimetre spectrum arrays have been recommended to enable an alluringly significant array gain to counteract the relatively short transmission range and massive propagation loss. Hybrid beamforming in UM-MIMO systems represents its promising rapid data rate and reduction in power consumption. Considering the unique characteristic of THz, the authors in [133] explore the difficulties and characteristics of the THz hybrid beamforming layout. Moreover, the authors exhibits that the high sparsity in the THz channel results in a spatial degree of freedom of not more than five. Enormous reflection and scattering losses in the range of 15 dB are investigated as a possible root of the interference. The authors in [134] develop a joint architecture of an IRS hybrid beam former and reflection matrix for a narrowband MIMO communication system, utilizing the advantages of the sparse-scattering framework and the significant dimension of mm-Wave platforms, considering the benefit of the angular sparseness of frequency-selective mm-Wave propagation.

Moreover, the authors extends the suggested joint design to narrowband MIMO architectures using orthogonal frequency division multiplexing modulation. The IRS passive, analog and digital hybrid beam formers are designed to accomplish complete digital beam former efficiency while incorporating fewer radio frequency chains. It can be achieved by absorbing a non-convex optimization problem into its constituent parts. The study in [135] solves the channel power optimization problem to acquire the matrices necessary for the IRS phase shifters. Then, the complete digital and hybrid beam formers Frobenius norm difference is minimized sequentially. Blockages in the mmWave line-of-sight path increase signaling overhead. Thus, vehicles, buildings, trees and pedestrians can disrupt system performance. The authors in [136] proposes IRS-aided hybrid beamforming for blockage-aware mmWave MIMO systems to improve the service of communication coverage. To solve the user sub-rate maximization problem, the author presented an iterative algorithm that employs oversight covariance matrix splitting to reduce location error over passive beam forming. THz band UM-MIMO systems can utilize the array-of-subarray and partially oriented hybrid beamforming architecture to minimize algorithm and hardware overheads. It delivers identical beam gain with fewer radio frequency chains and digital ports than digital beamforming. The hybrid beamforming architecture occupies UM-MIMO algorithms solely on the digital-port distribution matrix, enabling low-complexity channel projection and precoding.

5) QUALITY OF SERVICE - AWARE OF ENERGY EFFICIENCY

Security is essential when assessing 6G communications QoS. However, some effort has been invested in the IRS application of various communication scenarios and there is a preliminary study on IRS network security, especially for energy efficiency and secure communication performance. The authors in [76] propose a transmit power/energy management, phase-shift array and hybrid resource allocation method to improve transmission security and quality. Quantum-inspired marine predator algorithm manages system resources adaptively. This algorithm-based solution can conquer the inadequate energy efficiency for transmissions over long distances in the latest research studies and it preserves hardware resources while improving the IoT communication networks QoS. The study in [137] stated that the IRS adjusts its reflecting elements to protect legitimate users from listeners. A feasibility problem for jointly maximizing the base stations beam forming and the IRSs reflected beam forming has been developed to improve system secrecy. QoS requirements and time-varying channel characteristics are considered.

Moreover, a newly developed DRL-oriented secure beamforming technique was offered to accomplish the optimal beamforming procedures against listeners in dynamic environments. The authors in [138] proposed a resilient distance-aware spectrum distribution scheme in the THz band that can gather channel characteristics like distance-bandwidth relationships. To meet THz band cellular network QoS specifications, a parallel scheduling algorithm and joint bandwidth distribution utilize the QoS awareness and bandwidth distribution to improve traffic scheduling and maximum network throughput. The authors in [139] user grouping strategies endure optimizing power consumption for multi-cell MIMO systems. Subsequently, user grouping techniques need to pay more attention to the QoS requirements, like target data rate. QoS requirements can affect power allocation and user grouping. Power is necessary to sustain users QoS requirements, with high-target users data rates receiving more power. Superior target data rates result in more inter-user interference. Reducing the high target users data rate in a group minimizes inter-user interference. Grouping users with various concerns about the QoS reduces inter-user interference and transmits power.

6) SLEEP/WAKE SCHEDULING

The 5G base station can adapt its sleep mode based on the traffic load. In the power model, the deactivation and reactivation intervals on the sleep mode are incorporated in the four stages of sleep modes which are intended to represent the various depths in sleep modes identified by transition latency. Each of the four levels corresponds to a different time interval: the sub-frame level (corresponding to 1ms), the orthogonal frequency-division multiplexing symbol level (corresponding to 71.4us), the deep sleep stand-by level (corresponding to 1s) and the radio frame level (corresponding to 10ms).

The authors in [146] state that 5G can support four distinct sleep modes by adjusting the periodicity of reference signals and employing power-saving strategies like secondary cell dormancy for carrier formation. The study in [147] propose a slotted vision of time, eliminating the duty-cycle concept and replacing it with self-adaptive slotted time. This approach avoids energy-saving and packet delivery delay, allowing nodes to approximate neighbours situations without requiring information exchange. The system uses game theory and reinforcement learning techniques for optimal actions. This method is beneficial for large-scale networks with numerous nodes. Using ML techniques, the authors in [148] analyze switching policies for multi-sleep level enabled base stations in a two-tier cellular network.

They use a support vector machine regression model to predict vacation periods, operation times and energy consumption, deciding the optimal sleep level for base stations. This approach reduces energy consumption and increases network efficiency. The finding of this study has significant implications for the telecommunication industry, as they offer a practical solution to address the growing demand for sustainable and energy-efficient networks.

Meanwhile, this research underscores the need for continued cellular network design and management innovation to achieve sustainable development goals. Duty-cycling is used in wireless sensing MIMO systems, causing nodes to remain in sleep mode and wake up sporadically at predetermined times, affecting latency and reliability in massive sensor networks. However, duty cycling can also lead to increased latency and decreased reliability in large-scale sensor networks. To mitigate these issues, the authors in [149] proposed various solutions, such as adaptive duty-cycling algorithms that adjust the sleep/wake schedule based on network conditions or the use of low-power wake-up radios that allow nodes to remain in a low-power state while still being able to receive wake-up signals. Additionally, advanced routing protocols can be employed to minimize the impact of duty cycling on network performance. Table 5 shows an analysis of the literature survey on energy efficiency in MIMO IRS.

7) ANTENNA SELECTION

The minimal wavelengths in mmWave enable more antennas in a constrained physical space, which promotes the development of massive MIMO in the context of abundant spectrum resources. Due to the complexity and power requirements of the transceivers, traditional antenna architectures, such as full-digital and hybrid antenna architectures, need help to realizing massive MIMO. As a solution, the authors in [150] have looked into the antenna selection method. However, the antenna choice may cause a significant reduction in performance loss. The study in [151] state that MIMO systems increase data rates by increasing complexity, size and hardware cost. This systems need a power-greedy radio frequency chain directly connected to each transmit antenna port. Antenna selection can lessen the number of radio frequency chains by selecting and activating a subset of transmit and receive antennas. Transmit antenna selection is a popular category combining antennas to transfer information and attain full diversity. To be more precise, the authors in [90] used transmit antenna selection to improve the throughput of a single-carrier, IRS-enhanced MIMO channel in the downlink. Extending this study to the wideband and multiuser cases achieved maximum downlink transmission speed.

However, downlink IRS-assisted systems with transmit antenna selection optimized their energy efficiency. These efforts have established a framework for analyzing antenna selection algorithms for IRS-enhanced communication systems. To address the challenges of joint antenna selection and IRS beamforming, the authors in [152] developed innovative algorithms to maximize the ergodic sum data rate. Despite this progress, several open problems must be addressed to optimize joint antenna selection and IRS-assisted wireless energy transfer fully. One of these challenges is system

TABLE 5. Literature survey on energy efficiency in MIMO IRS.

Reference	Research Summary
Li et al. (2022) in [120]	• The IRS was used to enhance the energy efficiency of the aerial MIMO-NOMA system by intelligently reflecting and redirecting signals. The proposed optimization method aimed to allocate the optimal power and phase shifts to each IRS element, maximizing the overall energy efficiency of the system.
Chen et al. (2022) in [51]	• In this manuscript, the authors examined maximizing IRS-aided coordinated multi-point system energy efficiency by jointly improving user association, base station clustering, reflection coefficients and power distribution.
Rezaei et al. (2022) in [140]	• In this manuscript, the authors investigated active and passive beamforming and antenna selection for IRS-aided multi-user downlinks networks to maximize energy efficiency and support radio access network moderation.
Lu et al. (2022) in [141]	• This work enhanced massive users MIMO system energy efficiency performance with coordinated double-IRS. Implementing base station beamforming vectors and phase shifts of IRS simultaneously maximized energy efficiency total while exceeding user SINR requirements. Alternating optimization solved this non-convex challenge.
Forouzanmehr et al. (2021) in [109]	• This letter investigates the combined implementation of active and passive beam formation across the base station and IRS. Meanwhile, the authors established the antenna selection and power allocation strategy across the user sides in a massive MIMO IRS-enabled uplink transmission system to maximize energy efficiency.
Mi and Song (2021) in [142]	• This work studied the energy efficiency optimization issue facing IRS-enabled wireless power networks by jointly enhancing phase changes at the IRS, the time and transmit power allocation to balance the systems energy consumption and throughput.
Zargari et al. (2021) in [143]	• In this letter, the authors designed base station active beamforming and IRS passive beamforming for a massive MIMO IRS-assisted network with the power splitting-based receiver. The energy-efficient indicator was developed to balance transmitting data within the base stations maximum power transfer allowance.
Wang et al. (2021) in [144]	• This paper investigated a secure IRS-enabled MIMO wireless network with mutually cooperative jamming. Optimizing beamforming, blocking precode vectors and IRS transition matrix with known and unknown channel state conditions maximized energy efficiency.
Liu et al. (2020) in [145]	• This letter investigated the energy efficiency for sustainable simultaneous wireless information and power transfer with IRS assistance. Semi-definite relaxation was employed to address the non-convex energy efficiency optimization problem, resulting in a practical solution approach based on alternating optimization.

modelling, which requires a deep understanding of the complex interactions between antenna selection and IRS. Another critical issue is developing low-complexity antenna selection rules that can be implemented efficiently in practical systems.

Additionally, active/passive beamforming design remains an essential area of research, as it can significantly impact the overall performance of joint antenna selection and IRS beamforming systems. Finally, a comprehensive performance analysis is necessary to evaluate the effectiveness of joint antenna selection and IRS-assisted wireless energy transfer in real-world scenarios. Through addressing these open problems, researchers can continue advancing the wireless energy transfer field and unlock new possibilities for wireless communication and power delivery.

8) JOINT POWER AND PHASE SHIFT OPTIMIZATION

A multi-user Integrated Sensing And Communication (ISAC) system based on an IRS-assisted device is analyzed, including its transmit beamforming and phase shift architecture. The potential determined by ergodic conditions to measure the effectiveness of the IRS supported ISAC system works. The challenge of this particular problem originates from the requirement to optimize the phase shift design and transmit beamforming simultaneously. To address this issue, the authors in [153] states that proximal policy optimization and its propagated variants are explored in numerous settings, such as MIMO and multi-input single-output. The paper [154] addresses the joint design of waveforms and passive beamforming for MIMO-ISAC systems, whereas RIS assists in downlink communication. It aims to maximize SINR while minimizing the multi-user interference in the communication network. A BCD method is proposed, utilizing an Element-wise Closed-Form (ECF) technique for optimizing reflection coefficients and a dinkelbatchs-ECF algorithm for optimizing waveforms. Simulation results demonstrate improved joint sensing and communication performance compared to existing methods. Passive beamforming or the phase shifts of reflecting elements in the IRS, must be well-designed to maximize the benefit of IRSs in multi-antenna communication networks. Each antenna is affected by the phase shifts of the reflecting elements at the IRS, making antenna selection for massive MIMO more difficult. In such cases, complexity considerations are especially crucial while building antenna selection.

The sole investigation on antenna selection with multi-user IRS-massive MIMO was described, wherein the authors [36] established schemes to optimize MIMO channel strength. This scheme can be accomplished by employing dirty paper coding. The authors additionally anticipated continuous phase shifts, so each IRS reflecting element is eligible for any phase-shift value between 0 and 2. Various communication scenarios present distinct system design difficulties requiring different performance measures. Previous IRS-assisted MIMO system designs individually examined the recognized mutual information, secrecy rate, SNR, energy efficiency and other performance criteria. The reasonable assumption is that if different performance measures can be consolidated, the IRS-aided communication system can be optimized in a unified design. The study in [155] examines the joint transmission optimization problem with overall performance metrics in single and multiple-user IRS-aided MIMO systems in the context of these problems.

Consequently, an IRS improves energy harvesting in a simultaneous wireless information and power transfer system. In this system, a multi-antenna base station interacts with numerous multi-antenna data receivers while ensuring that energy is generated for the energy receivers [156]. Optimizing the base station transmit precoding and IRS passive phase shift matrices jointly enhances receivers weighted sum rate. The authors in [6] utilize the BCD algorithm to separate the optimization problem into numerous subproblems and alternatively improve the phase shift and transmit precoding matrices to solve this complex optimization challenge. Researchers integrate task offloading, IRS phase shift optimization and power allocation to reduce energy consumption. Three phases address the non-convex optimization issue. The sequential rank-one constraint relaxation and semidefinite relaxation algorithms tackle the IRS phase shift optimization issue with specific power and computational aspects of resource allocation. The authors in [157] then uses differential convex and alternating optimization to obtain the power allocation decision that lowers energy consumption. The study in [158], presents two innovative models, Global Attention Phase Shift Compression Network (GAPSCN) and Simplified-GAPSCN designed to optimize Quantized Phase Shift (QPS) signaling in IRS-assisted wireless communication systems. GAPSCN enhances attention mechanisms to capture spatial and channel correlations while mitigating AWGN effects using multiple layers. S-GAPSCN reduces decoder complexity through a joint attention scheme, maintaining performance with lower computational costs. Simulation results demonstrate GAPSCN superior reconstruction accuracy over existing models, while S-GAPSCN offers comparable performance with reduced computational overhead.

Specifically, the QPS is presumed to be accessible to the IRS, but this assumption could not always be valid to necessitating practical feedback from the IRS. However, the feedback channel is typically constrained in bandwidth and needs help accommodating extensive QPS overhead, particularly with many reflecting elements or high quantization levels. Here, the QPS is compressed towards the receiver end and it can be reconstructed at the IRS end. To address this limitation, the author proposes a convolutional autoencoder-based approach [159]. The authors addresses challenges such as distribution mismatch and gradient vanishing by removing batch normalization layers and incorporating a denoising module. This strategy allows us to achieve high compression ratios with dependable reconstruction accuracy within the bandwidth-limited CSI-based channel. The authors in [160] suggested that protocols for Internet of Things (IoT) devices utilizing time-division multiple access and energy recycling offer promising practical implications. The simulation results underscore the potential of energy recycling to boost device performance in energy harvesting and data transmission. Moreover, this research suggests that the group switching-based algorithm can enhance overall throughput, while the user switching-based algorithm is more efficient in energy harvesting. These findings underscore the practical benefits of innovative protocol design in optimizing IoT device performance.

The study in [161] examines the performance of IRS-assisted communication systems in the presence of quantization phase errors. It introduces a closed-form expression for approximate capacity analysis, explores the effects of quantization phase errors on capacity degradation and investigates the required number of reflectors to maintain a specific rate threshold. Simulation results validate the derived approximations and highlight the advantages of utilizing IRS-assisted systems. The authors in [162] introduces a novel phase shift strategy called Hybrid Phase Shift (HPS), which aims to strike a balance between minimizing the overhead associated with channel phase information feedback and maximizing capacity performance for interference-free transmission among multiple users. It aims to optimize the minimum ergodic capacity while adhering to a transmission time constraint. Furthermore, this study explores the required reflecting elements to ensure a targeted capacity performance gap between HPS and the traditional coherent phase shift approach. Simulation results validate the precision of the calculated ergodic capacities and demonstrate the inherent tradeoff between capacity and feedback in HPS.

B. CHALLENGES AND LIMITATIONS OF ENERGY EFFICIENCY IN MIMO IRS

1) POWER CONSUMPTION

Power consumption is an essential factor to consider in evaluating the energy efficiency of MIMO in IRS technology. MIMO IRS is capable of strengthening energy efficiency at the system level [163]. The following are factors related to the power consumption of MIMO in IRS energy efficiency:

- Power consumption depends on IRS active element count. Power consumption rises with element count. Energy consumption can be significantly reduced by minimizing the number of active elements in the IRS design. This optimization process involves carefully selecting and configuring the necessary active parts, ultimately leading to improved energy efficiency for the system. In a study [164], the authors examines the power consumption characteristics of RISs through modeling and experimental validation. It discusses the components of static and unit cell power consumption and variations in power consumption for different types of RIS unit cells. While varactor-diode-based cells exhibit minimal power consumption, the power consumption of PIN-diode-based cells varies depending on factors of polarization mode. Moreover, the authors provides a concise formula to quantify this relationship, validated through practical measurements. Additionally, power consumption in radio frequency switch cells is determined solely by the number of cells. This analysis includes measurement results for each RIS and a discussion of typical power values for static and unit cell consumption. Furthermore, it highlights the need for further research to optimize RIS design for lower power consumption.
- Another factor to consider is the power consumption of the control circuitry and signal processing units associated with MIMO IRS technology. These components are responsible for managing and manipulating the signals reflected by the IRS. Through utilizing low-power circuit designs and efficient algorithms, it is possible to reduce power consumption without compromising performance.
- **IRS Elements:** MIMO IRS comprises numerous discrete reflecting elements, often implemented using passive elements like reconfigurable metasurfaces or intelligent materials. For example, phase control or reconfigurability, each of these components requires power to function. These components can consume enormous energy, especially during extensive deployments where several IRS units are employed. The IRSs energy efficiency is also influenced by the materials chosen for construction. Certain materials have higher absorption or reflection coefficients, impacting the efficiently of IRS manipulates signals. Utilizing materials with optimal characteristics can increase energy efficiency by reducing signal losses. The paper in [165] investigates optimizing the number of reflecting elements in IRS-assisted communication systems to enhance energy and spectral efficiency. Unlike previous studies, which focused on maximizing efficiency or balancing tradeoffs, this work aims to minimize reflecting elements while considering both efficiency constraints where non-convexity makes deriving efficiency challenging. The authors established bounds analysis to reformulate this challenging problem and find a suitable solution. It proposes coherent, random phase shift solutions and establishes relationships between reflecting elements for practical design insights. In study [166], the authors delve into the issue of determining the optimal number of reflecting surfaces for IRS-aided communications. They aim to reduce the reflecting elements while adhering to outage performance and power constraints. Due to the intricate nature of optimizing outage performance, the authors introduce alternative optimization problems and establish closed-form expressions for the optimized number of reflecting elements. Simulation results established the effectiveness of these bounds analysis in capturing the optimal number configuration, particularly in scenarios with specific noise/power conditions or IRS placements. The study [167] introduces a novel mechanism for switching elements on and off that examines its impact on passive and active RIS-supported wireless communication systems. The paper formulates optimization challenges for passive and active RIS configurations, aiming to maximize overall energy efficiency while adhering to various constraints, including active RIS transmit power limits, QoS requirements and phase-shift matrix considerations. Over the complexity of these problems, iterative algorithms based on alternating optimization are devised. The original problem is simplified into rate maximization problems under a fixed power budget, investigating the balance between activating and deactivating elements and comparing algorithm performance across passive and active RIS setups.
  Simulation results illustrate the superiority of the proposed algorithms over baseline approaches, showcasing their ability to efficiently manage the activation of reflecting elements.
- **Control and Communication:** Phase shifts or beamforming at the reflecting elements must be coordinated using control and communication techniques in MIMO IRS. This technique includes the IRS and the base

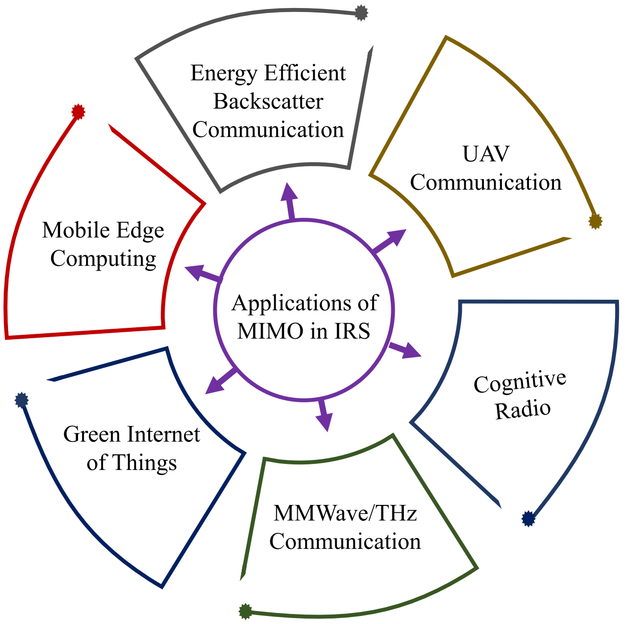

FIGURE 8. Various application of MIMO in IRS wireless communication system.

station or user equipment exchanging information, which increases power consumption due to control signal overhead. It can turn out the desirable control signals to transmit via wired or wireless connections, which require power.

- **Power Management:** Effective power management techniques can reduce excessive power usage in MIMO IRS. Techniques like adaptive power control, sleep modes or dynamic power allocation can optimize power consumption based on the traffic load, channel circumstances and user requirements. Effective strategies for power management can enhance energy efficiency by reducing redundant power consumption [163]. The study in [168] outlines a comparison between active and passive RIS-aided systems, assuming an equal power budget. It delves into determining the optimal power distribution between the base station and RIS in active RIS scenarios, examining the various system parameters influence this distribution. Furthermore, active RIS is an advantage over passive RIS when the power budget is abundant and the number of RIS elements is moderate.

2) CONTROL SIGNALLING OVERHEAD

In MIMO IRS systems, control signaling is necessary to coordinate the operation of the IRS elements and optimize their phase shifts [169]. While IRS technology can improve the energy efficiency of wireless communications, it introduces additional control signaling overhead that must be considered. Several factors can contribute to control signaling overhead in MIMO IRS systems:

- **IRS Configuration and Initialization:** The IRS techniques must be configured and initialized before they can reflect signals optimally. This technique requires transmitting control signals to the IRS elements to configure their phase shifts, update their calibration and synchronize their operation. The overhead correlates to the number of IRS elements and the intricacy of the initialization procedure.
- **Channel estimation:** The CSI must be approximated to reap the benefits of MIMO IRS techniques. This technique entails sending pilot signals from the transmitter to the receiver and IRS components. The IRS elements reflect these signals to the receiver and the receiver assesses the strength of the received signal to estimate the channel response. The authors in [170] describes a proposed scheme by introducing a new channel estimation method for mmWave systems with reflective surfaces to minimize pilot overhead. The technique utilizes static angle information and exploits linear correlation among paths; this proposed scheme achieves superior performance compared to existing methods. The authors in [171] introduces a new two-stage strategy for uplink channel estimation in RIS-assisted multi-user mmWave wireless communication systems. It eliminates the need to select a typical user by leveraging the ambiguity of mmWave cascaded channels and introducing a matching matrix. This method simplifies the estimation process, reduces pilot overhead and outperforms existing algorithms accuracy and efficiency, especially with increasing numbers of users. Channel estimation usually requires additional signalling and computation, thus results increasing overhead.
- **Channel State Information Feedback:** To optimize the phase shifts of the IRS elements, precise CSI is required between the transmitter, the IRS and the receiver. The IRS must receive CSI feedback from the receiver or other system entities to adjust its phase adjustments. This feedback mechanism can result in additional bandwidth consumption and latency. The study in [63] investigates the Rician channel model, utilizing long-term statistical CSI for RIS phase shift design in conjunction with MRC. The study includes deriving closed-form expressions for uplink achievable rates, exploring power scaling laws and addressing optimization challenges using a genetic algorithm. Extensive simulations validate the benefits of integrating RIS into massive MIMO systems and demonstrate the feasibility of deploying large-size but low-resolution RIS. The paper [172] explores a two-timescale transmission scheme to improve RIS-aided massive MIMO systems, adjusting beamforming towards the base station and RIS to different CSI changes. It analyzes spatially independent and spatially correlated fading channels, considering electromagnetic interference. The study applies LMMSE estimation and MRC detection to propose an algorithm for rate maximization. Results show the benefits of RIS deployment for cell-edge users in massive MIMO networks.

- **Dynamic Adaptation:** In scenarios where wireless channel conditions change over time, the IRS must adjust its phase shifts dynamically to ensure optimal performance. This channel necessitates constant monitoring of channel conditions and frequent control signalling to update the IRS configuration [173]. The overhead increases with the frequency of adaptation and the algorithmic complexity of adaptation.
- **Synchronization and Timing:** The IRS and the MIMO system elements must be synchronized to ensure precise operation. Control signalling can become necessary for synchronization purposes, including the distribution of timing information, synchronization of clocks and alignment of transmission and reception processes. The overhead consists of the transmission of synchronization signals and the processing required at the receiver and IRS for synchronization.

Specific techniques can be considered to reduce control signalling overhead and enhance energy efficiency in MIMO IRS systems:

- **Reduced Feedback Strategies:** Techniques like quantization, beamforming codebooks or compressed sensing can be utilized to decrease the amount of feedback necessary instead of offering full CSI feedback. These techniques enable a trade-off between control signalling overhead and the accuracy of CSI estimation [174].
- **Hierarchical Control:** A hierarchical control structure can be implemented as an alternative to regulating each IRS element individually. This structure reduces the control signalling overhead by clustering or analyzing the IRS elements and coordinating the phase shifts at a higher level. In this manner, control signalling is required only at the cluster or zone level, reducing overall overhead.
- **Distributed Control:** Instead of relying on a central controller, distributed control mechanisms can be utilised to disperse control intelligence among the IRS elements or other system entities. This mechanism reduces reliance on centralised control signalling and allows for parallel processing and localised decision-making.

Managing the control signalling overhead in energy-efficient MIMO IRS systems is crucial for maximising performance. Overhead reduction algorithms, feedback reduction, predictive control and distributed control can help reduce control signalling overhead while maximizing energy efficiency. The combination of MIMO and IRS technology has the potential to revolutionize wireless communication across various application sectors by overcoming signal propagation challenges, increasing capacity and improving connectivity in diverse environments as shown in Figure 8.

3) DEPLOYMENT CONSTRAINTS

The deployment of energy-efficient MIMO systems with the IRS is probably subject to several constraints that must be considered [175]. These limitations can affect energy-efficient MIMO IRS deployments design, implementation, and practicability. Here are some typical deployment constraints:

- **Hardware Constraints:** In energy-efficient MIMO IRS systems, specialized hardware is required to implement the IRS components and enable communication between the transmitter, IRS and receiver. Some deployment-related hardware restrictions are cost, size, weight, power consumption and dependability. Hardware solutions must be affordable, portable, power-efficient and dependable for practical deployment scenarios.
- **Line-of-Sight and Obstruction Effects:** MIMO IRS systems rely significantly on a strong line-of-sight between the transmitter, IRS and receiver for optimal performance. Buildings, walls and natural terrain can obstruct the line of sight and diminish the systems performance. The deployment constraints necessitate a thorough evaluation of the environment and strategic placement of the IRS elements to minimize obstruction effects and optimize signal propagation.
- **Regulatory Considerations:** The deployment of energy-efficient MIMO IRS systems must conform to all applicable regulatory requirements and industry standards. These factors may include spectrum allocation, transmit power limitations, interference mitigation and safety regulations. It is crucial to adhere to regulatory constraints to ensure proper operation and avoid interference with other wireless systems.
- **Communication Protocol Compatibility:** Energy-efficient MIMO IRS systems must be compatible with existing communication protocols and standards to facilitate interoperability and compatibility with other wireless devices. Deployment constraints include ensuring seamless integration with standard communication protocols such as Wi-Fi, 4G/5G or other wireless technologies, enabling effective communication between the MIMO IRS system and other wireless devices.
- **Scalability and Complexity:** The deployment of energy-efficient MIMO IRS systems must resolve scalability and complexity issues. Control, coordination and signal processing become more difficult as the number of IRS elements rises [176]. As the number of IRS elements increases, system complexity must be managed by developing scalable algorithms, distributed control mechanisms and effective signal-processing techniques.

Addressing these deployment constraints requires a comprehensive understanding of the specific requirements, limitations and trade-offs associated with energy-efficient MIMO IRS systems. Through carefully contemplating these constraints, suitable solutions can be developed and implemented to facilitate successful deployments in various scenarios.

4) POWER ALLOCATION CHALLENGES

Power allocation is essential in enhancing energy efficiency in MIMO systems with IRS [177]. Nevertheless, power allocation in energy-efficient MIMO IRS deployments poses several obstacles. Here are some significant challenges to consider:

- **Power Allocation Trade-off:** In MIMO IRS systems, power allocation entails allocating the feasible transmit power among the active transmit antennas, IRS elements and data streams. The challenge exists in locating an optimal power allocation strategy that balances the energy efficiency gains attained via IRS reflection and the power consumed by the active elements. It is essential to consider the channel circumstances, user requirements and energy consumption of the IRS elements to achieve the appropriate trade-off.
- **Non-Convex Optimization:** Due to the interdependencies between transmit antennas, IRS elements and data streams, power allocation optimization in MIMO IRS systems frequently leads to non-convex optimization issues. Solving non-convex optimization issues is complex and locating the global optimum becomes computationally expensive. Power allocation for energy efficiency confronts enormous challenges in the development of efficient algorithms which provide substantially optimal solutions with reduced complexity [178].
- **Dynamic Channel and User Conditions:** Power distribution in MIMO IRS systems reflect complications due to user conditions and the dynamic nature of wireless channels. Various factors like fading, interference and user movement can significantly impact the quality and reliability of wireless communication systems. For instance, fading refers to the fluctuation in signal strength due to obstacles or multipath propagation, while interference can arise from other devices operating in the same frequency range. Additionally, user movement can result in varying channel conditions as users change their position relative to the access point or base station. It is challenging to continuously adjust the power allocation method to optimize energy efficiency in light of these changing conditions. Feedback systems and dynamic adaptive algorithms are necessary for effectively meeting these issues.
- **Multi-Objective Optimization:** In MIMO IRS systems, power allocation for energy efficiency frequently involves several competing goals, including maximizing energy efficiency, minimizing transmit power and maintaining QoS standards. Because of the inherent trade-offs between various indicators, balancing these goals and determining the most effective compromise is challenging. Multi-objective optimization approaches are required to address these issues and offer effective power allocation solutions.
- **Joint Optimization with Other Parameters:** Power allocation is often coupled with other system parameters such as phase shifts of the IRS elements, beamforming vectors and modulation schemes. Jointly optimizing these parameters in an energy-efficient manner presents a challenge due to the increased dimensionality and complexity of the optimization problem. Finding an optimal trade-off among these parameters to achieve energy efficiency requires sophisticated algorithms and optimization techniques. It is crucial to develop advanced methods that can efficiently handle such high-dimensional and intricate optimization problems. These methods should consider the dynamic nature of the wireless environment and the varying channel conditions [179]. Additionally, considering the computational complexity and resource constraints of practical systems is essential for developing realistic and implementable solutions.

Addressing these power allocation challenges in energy-efficient MIMO IRS systems requires advanced optimization algorithms, adaptive techniques, robust CSI estimation, interference management strategies and consideration of practical implementation constraints. Overcoming these challenges enables the development of efficient power allocation strategies that enhance energy efficiency in MIMO IRS deployments.

IV. SEVERAL PROSPECTIVE DIRECTIONS FOR FUTURE EXPLORATIONS OF MIMO IN IRS RESEARCH

Several future trends are anticipated for MIMO in IRS, shaping the development of wireless communication systems:

A. DYNAMIC RECONFIGURATION

Investigate methods to dynamically reconfigure the IRS elements to adapt to changing channel conditions, user locations and interference patterns, thereby optimizing the overall system performance.

B. ADVANCED ALGORITHM DEVELOPMENT

Researchers can develop more sophisticated algorithms for optimizing the deployment and configuration of RIS elements within MIMO systems. This algorithm could involve developing novel techniques for RIS phase control, beamforming and channel estimation to enhance system performance and spectral efficiency.

C. MACHINE LEARNING INTEGRATION

Explore the integration of machine learning and artificial intelligence techniques to optimize RIS deployment, configuration, beamforming strategies and enabling self-learning systems that adapt to complex environments. There is a significant potential for integrating ML techniques into RIS-enabled MIMO systems. ML algorithms could be employed for dynamic adaptation of RIS parameters based on real-time channel conditions, user mobility patterns, and traffic load variations. Intelligent adaptation can lead to improved system robustness, energy efficiency and overall performance.

D. DYNAMIC ENVIRONMENT CONSIDERATIONS

Future research could explore the feasibility and effectiveness of RIS-assisted communication in dynamic environments, such as scenarios involving mobile users or rapidly changing channel conditions. This research entails developing adaptive RIS control strategies capable of quickly responding to variations in user locations, channel characteristics and interference levels to maintain reliable communication links.

E. DECENTRALIZED AND COOPERATIVE IRS

Networks of distributed and cooperative IRS elements could emerge, collaborating to optimize signal paths, manage interference and improve overall coverage.

F. MILLIMETRE WAVE EXPLOITATION

MIMO IRS can play a pivotal role in unlocking the potential of millimetre wave frequencies for high-bandwidth, short-range communication and even extending their coverage.

G. SATELLITE AND UNMANNED AERIAL VEHICLE INTEGRATION

Exploring the use of IRS in satellite communication systems and aerial platforms, extending their reach and enhancing communication capabilities by improving connectivity and coverage in remote and challenging environments.

H. CROSS-LAYER OPTIMIZATION

Collaboration between academia, industry, and regulatory bodies to accelerate the adoption of MIMO in IRS, driving innovation and addressing challenges related to regulation, spectrum allocation and infrastructure.

I. STANDARDIZATION AND COMMERCIALIZATION OF IRS

As the technology matures, efforts towards standardizing MIMO IRS functionalities and characteristics will increase, paving the way for commercial deployments.

J. PRACTICAL IMPLEMENTATION CHALLENGES

It is crucial to investigate the practical implementation challenges of RIS technology in large-scale MIMO systems. This challenge includes addressing issues related to hardware complexity, scalability, cost-effectiveness, and compatibility with existing communication standards. Research efforts could focus on developing efficient RIS architectures, low-complexity control mechanisms and cost-effective manufacturing techniques to facilitate the widespread adoption of RIS technology in practical MIMO deployments.

K. SECURITY AND PRIVACY CONSIDERATIONS

As RIS technology becomes more prevalent in MIMO systems, it is essential to address security and privacy concerns. Future research could explore the development of secure RIS communication protocols, authentication mechanisms and privacy-preserving techniques to safeguard against potential threats such as eavesdropping, spoofing and unauthorized access.

L. ACTIVE RIS

Quasi-passive RISs offer cost-effectiveness, but their limitations in intense direct link scenarios prompt the emergence of active RISs. Active RISs, integrating amplifiers can manipulate the phase and magnitude of reflected signals but require additional power. Achieving a balance between performance and energy consumption, addressing challenges in channel estimation and optimizing deployment are key areas for further research in active RIS technology.

Exploring these research directions, the field of RIS-enabled MIMO systems can advance significantly, leading to the development of more efficient, adaptive and secure wireless communication solutions with enhanced spectral efficiency, coverage and reliability. These trends reflect the ongoing evolution of MIMO in IRS technology, demonstrating its potential to revolutionize wireless communication by offering unprecedented control over signal propagation and capacity.

V. CONCLUSION

In conclusion, this survey paper has comprehensively explored the fascinating and rapidly evolving field of Multiple-Input Multiple-Output (MIMO) in Intelligent Reflecting Surfaces (IRS). An in-depth analysis of the literature shows that MIMO-IRS holds immense promise for revolutionizing wireless communication systems. The survey has shed light on diverse research areas, such as highly effective techniques and edge-cutting algorithms for resource allocation and energy efficiency, especially in optimization strategies, beamforming techniques, hardware implementations, limitations and demonstrating the multi-faceted nature of MIMO-IRS systems. Throughout this paper, the underlying principles of this system delved into various reflection design considerations. Also, it examined its potential benefits, including enhanced signal coverage, increased spectral efficiency, reduced interference and improved energy efficiency, positioning them as a promising solution for addressing the ever-increasing demands of wireless networks. Through providing a comprehensive overview of the current state-of-the-art, this survey paper aims to inspire and guide researchers, engineers and practitioners in shaping the future of MIMO-IRS technology. The journey toward harnessing the full potential of technology is ongoing, and this survey paper serves as a stepping stone in this exciting trajectory of innovation and discovery.

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