RIS-Assisted Cell-Free MIMO: A Survey

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Abstract: Cell-free (CF) multiple-input multiple-output (MIMO) is a promising technique to enable the vision of ubiquitous wireless connectivity for next-generation network communications. Compared to traditional co-located massive MIMO, CF MIMO allows geographically distributed access points (APs) to serve all users on the same time-frequency resource with spatial multiplexing techniques, resulting in better performance in terms of both spectral efficiency and coverage enhancement. However, the performance gain is achieved at the expense of deploying more APs with high cost and power consumption. To address this issue, the recently proposed reconfigurable intelligent surface (RIS) technique stands out with its unique advantages of low cost, low energy consumption and programmability. In this paper, we provide an overview of RIS-assisted CF MIMO and its interaction with advanced optimization designs and novel applications. Particularly, recent studies on typical performance metrics such as energy efficiency (EE) and spectral efficiency (SE) are surveyed. Besides, the application of RIS-assisted CF MIMO techniques in various future communication systems is also envisioned. Additionally, we briefly discuss the technical challenges and open problems for this area to inspire research direction and fully exploit its potential in meeting the demands of future wireless communication systems.

Keywords: mmWave; beyond 5G (B5G); Internet of Everything (IoE); cell-free MIMO; RIS; unmanned aerial vehicle (UAV); physical layer security (PLS); wireless energy transfer (WET)

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1 Introduction

With the promising new technologies such as the millimeter wave (mmWave), massive multiple-input multiple-output (MIMO), and ultra-dense network (UDN), 5G wireless communication and beyond can provide increased data rates, as well as reduced latency, higher reliability, and greater connectivity, which further supports novel applications such as telemedicine and remote driving[1–3]. However, there are new challenges in practical deployment of these technologies. For example, mmWave suffers from low penetration and is vulnerable to interference, leading to limited signal coverage. Besides, massive MIMO and UDN require the intensive deployment of more co-located antennas and base stations (BSs). This incurs high costs and power consumption. Furthermore, as cell density increases, inter-cell interference becomes dominant, which negatively affects the system performance[4].

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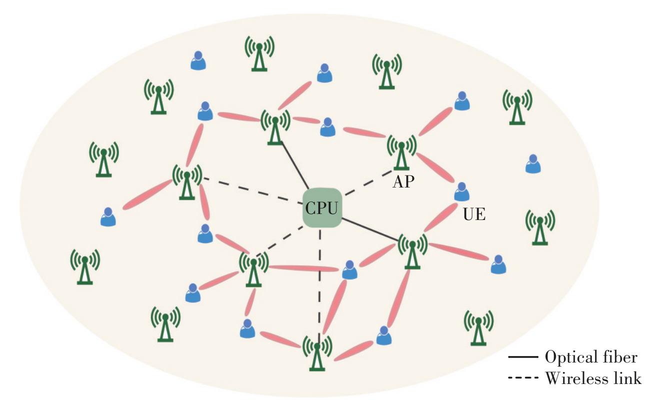
Recently, a novel user-centric network mechanism called cell-free (CF) MIMO was proposed to address the issue[5–7].In CF MIMO systems, geographically distributed access points (APs) cooperate to serve all user equipment (UE) without cell boundaries through coherent transmission, as shown in Fig. 1.



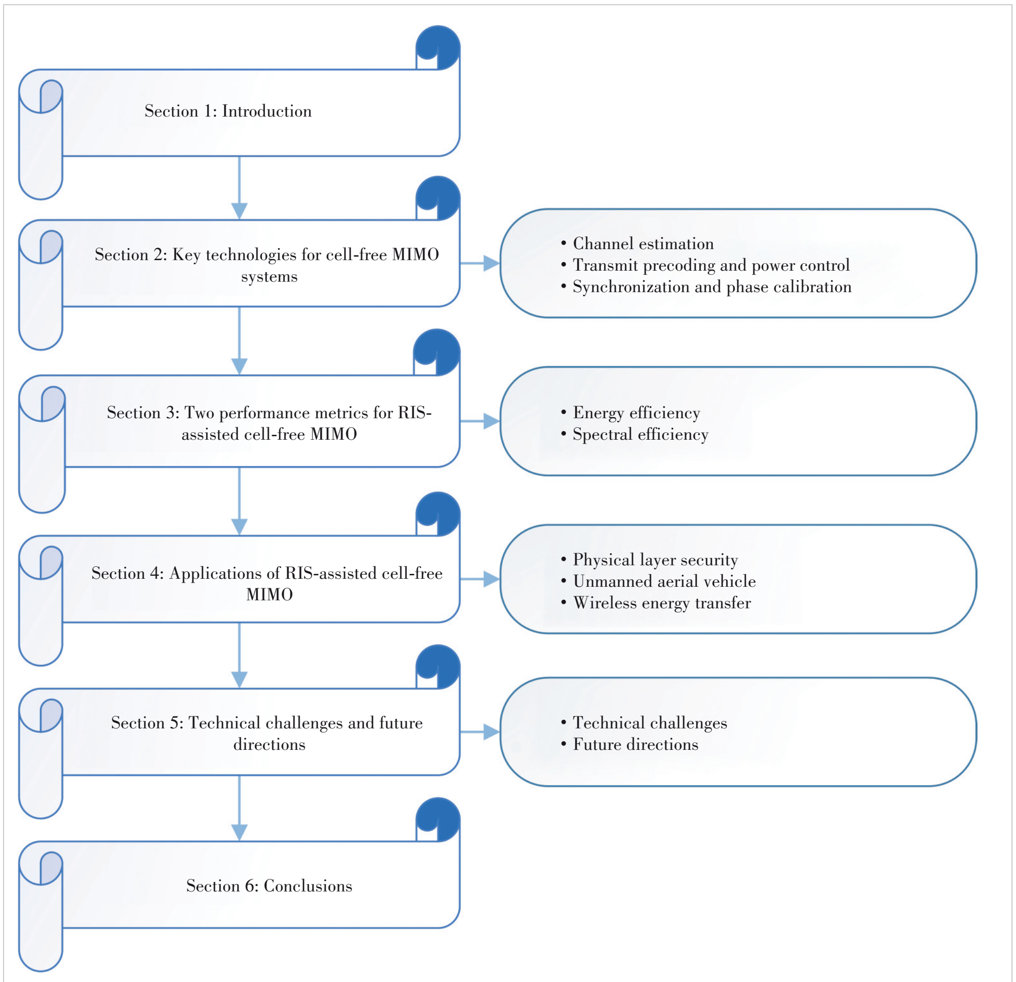
▲**Figure 1. Cell-free multiple-input multiple-output (MIMO) network**

This is achieved under the control of a central processing unit (CPU) via high-speed fiber or wireless backhaul/fronthaul links. The biggest difference between CF MIMO and conventional massive MIMO systems is the absence of clear boundary demarcation between cells, which allows inter-cell interference to be effectively cancelled. According to Refs. [8 – 10], the CF MIMO system outperforms the traditional co-located antenna systems, such as massive MIMO, in terms of 95%-likely per-user spectral efficiency (SE). This is because the received signal at each UE suffers from disparate large-scale fading components from distinct APs, leading to high diversity gain. Besides, good quality of service (QoS) can be guaranteed to the cell-edge UE by deploying more APs in their vicinity, and thus the CF MIMO system often provides wider coverage than its counterpart. Due to these appealing advantages, the CF MIMO technique has been regarded as a promising candidate for future wireless networks[11], and has attracted increasing attention for its wide application in channel estimation[12], transmit beamforming[13] and resource allocation[14].

Nevertheless, to harvest the promising performance gains of the CF MIMO technique, more distributed APs are required, which brings about high costs and power consumption in practical implementations. This issue becomes even more important when considering green and sustainable communications. Among various candidates, the emerging meta-surface technique called reconfigurable intelligent surface (RIS) stands out with its unique capabilities of low cost, low energy consumption and programmability[15 – 19]. Made up of a large number of passive components, RIS can boost communication by reprogramming incident signals and reflecting them in a certain direction under the control of an intelligent controller. In addition, RIS can be handily integrated into existent communication scenarios with low cabling costs and can be densely deployed regardless of interference management among multiple RISs. The above benefits have motivated extensive study interests on the various applications of RISs in channel capacity improvement, coverage extension, and power saving.

Motivated by the above discussions, we try to provide a thorough survey on RIS-assisted CF MIMO for next-generation wireless communications and future network applications in this paper. Specifically, we focus on recent contributions to typical performance metrics such as energy efficiency and spectral efficiency to understand the role of RISs in CF-MIMO systems from the viewpoint of communication optimization. Furthermore, some novel emerging applications of the RIS-assisted CF MIMO technique within various future networks are investigated. Besides, some open problems and technical challenges are pointed out.

The organization of this survey is provided in Fig. 2, where key technologies of CF MIMO are first introduced in Section 2. The interplay between RISs and CF MIMO systems is then introduced in terms of main communication performance metrics and optimization frameworks in Section 3. Emerging applications of RIS-assisted CF MIMO in wireless networks are further discussed in Section 4. Finally, the technical challenges



MIMO: multiple-input multiple-output RIS: reconfigurable intelligent surface

▲Figure 2. Structure of this paper

and future directions are pointed out in Section 5 before the concluding remarks in Section 6.

2 Key Technologies for Cell-Free MIMO Systems

In this section, we introduce the main technologies of CF MIMO for 5G and beyond in terms of two communication protocols, i.e., time division duplexing (TDD) and frequency division duplexing (FDD). More specifically, we emphasize the importance of channel estimation, transmit precoding and power control, synchronization, and phase calibration in CF MIMO systems. These techniques differ from those used in traditional massive MIMO systems when considering the distributed antenna configurations and practical fronthaul constraints. These differences play an important role in the system implementation and parameter design.

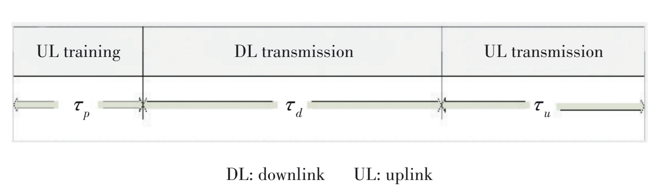
2.1 Channel Estimation

Channel estimation plays a vital role in transmit beamforming and signal detection, as it helps suppress inter-user interference and improve the network capacity. Based on different communication protocols, such as TDD and FDD, various channel estimation techniques have been applied to CF MIMO systems.

Under TDD protocols, existing works mainly focus on the pilot-based channel estimation technique. Specifically, users send orthogonal pilot sequences of length τ_p to all the APs as shown in Fig. 3, and the APs then estimate the corresponding user channel according to different criteria after receiving the training signals[20]. Typical criteria include the least square (LS) method, the minimum mean square error (MMSE) method, the maximum likelihood (ML) method, and so on.

For FDD systems with channel non-reciprocity, the channel estimation problem needs more attention because the feedback overhead of channel state information (CSI) scales linearly with the number of RISs and APs. To solve this issue, the angle-reciprocity principle of the multipath components is utilized, which assumes that if the gap between uplink and downlink frequencies is less than several GHz, the uplink angle-of-arrival and downlink angle-of-departure are similar and the large-scale fading components remain unchanged[21–23].

CF MIMO is essentially a single-cell massive MIMO system, with antennas distributed over a wide geographic area[24]. As a result, the joint channel from the AP to the user is strongly correlated in space, with some APs being closer to the user than others. Therefore, spatial correlation between different APs can be used for channel estimation in CF MIMO, reducing pilot and improving estimation efficiency when compared with traditional MIMO channel estimation.



▲ **Figure 3. Pilot and data transmission under time division duplexing (TDD) communication protocol**

2.2 Transmit Precoding and Power Control

In the transmission phase, the APs utilize the estimated channel coefficients in the channel estimation phase to perform data precoding and power control. In CF MIMO systems, distributed APs are connected to a CPU via the dedicated fronthaul link for payload data and power control coefficients exchange. For this reason, a low-complexity distributed precoding technique is suggested. The most commonly used precoding schemes are maximum-ratio transmit precoding[5] and conjugate precoding[13]. In both the schemes, the APs perform transmit precoding locally in a distributed manner, reducing the burden of CPU. However, since these distributed signal processing techniques only exploit their local CSI, they perform badly for anti-interference. To reduce the inter-user interference and further improve the system performance, some centralized precoding techniques, e.g., zero-forcing (ZF) precoding and MMSE precoding, are advocated at the cost of an increased fronthaul burden[6, 21]. This is because the prerequisite to implementing centralized precoding is the availability of all related channels at the CPU. In general, the optimal transmit precoding scheme should strike a balance between the fronthaul traffic and the network.

Different from the above precoding techniques in TDD systems, angle-based precoding schemes are more commonly used in FDD protocols. Specifically, these angle-based precoding techniques use the estimated multi-path components such as the large-scale fading factors and Angel-of-Arrival (AoA), along with the angle reciprocity principle, to determine the transmit vectors according to different precoding options, e.g., the angle-based MMSE precoding, the angle-based conjugate precoding, and the angle-based ZF precoding[21, 25].

Advanced power control is pivotal for enhancing the network capacity or QoS and simple equal power allocation may result in poor system performance. A simple but efficient way to perform power control is to allocate power to different users at each AP proportional to the corresponding channel gain, which has been used by many papers that aim at improving achievable data rates[13, 26]. On the other hand, to provide uniformly good service for different users, the max-min power control technique is suggested[27–28]. By maximizing the minimum spectral efficiency of all users under the constraints of per-AP transmit power, all users have almost equal spectral efficiency with max-min power control. In FDD systems, the above power control techniques, namely equal power, water-filling power, and max-min power allocation techniques, can also be utilized under angle-based precoding according to different requirements[21].

While the above precoding techniques can achieve optimal antenna gain, they demand the same number of radio frequency (RF) chains as that of the transmit antennas. This causes high hardware cost and power consumption, especially in CF MIMO systems equipped with a vast number of APs. To this end, hybrid analog and digital precoding, for which multiple antennas are connected to the same RF chain, is a more attractive alternative[29]. However, due to the unit-modulus constraint of the analog phase shifters, it is hard to obtain the optimal solution of the hybrid precoding. Up to now, the existing studies on the design of hybrid precoding schemes in CF MIMO systems are mainly divided into two kinds. One exploits the block coordinate descent (BCD) algorithm to alternatively optimize the analog and digital domain precodings[30], and the other resorts to heuristic solutions, where analog precoding is designed by maximizing the received signal power and traditional digital precoding schemes such as ZF can be utilized based on the equivalent channel for multiuser interference cancellation. Besides, advanced machine learning-based solutions have also shown great potential in the design of hybrid precoding[31].

2.3 Synchronization and Phase Calibration

In CF MIMO systems with massive geographically distributed APs and users, the signals from different APs generally experience different propagation delays, leading to timing synchronization among the received signals. To realize coherent transmission, the APs need to maintain relative signal time synchronization and phase calibration[32]. Furthermore, the synchronization accuracy requirement of CF MIMO networks becomes more demanding as more users become time-sensitive. To address this issue, many time synchronization schemes are proposed, such as one-way message dissemination, two-way message exchange, and receiver-only synchronization. Generally, after the clock offset and clock skew are estimated, the above timing misalignment management schemes are adopted[33]. Besides, to ensure accurate CSI at the APs, phase calibration should be performed on the uplink transmitted signals. To this end, a reference signal is needed to obtain the over-the-air reciprocity calibration[34].

3 Two Performance Metrics For RIS-Assisted Cell-Free MIMO

With the help of RISs, CF MIMO can enable better communication to user terminals than typical massive MIMO and pure CF MIMO. To harvest the promised performance gains provided by the RIS-assisted CF MIMO technique, it is necessary to optimize the resource allocation of the distributed network. The optimization objective can be different QoS metrics based on the actual need. In this section, we investigate the interplay between the RIS-assisted MIMO technique and wireless resource allocation optimization in terms of various communication metrics.

3.1 Energy Efficiency

RISs are highly recommended in CF MIMO systems due to their low cost and energy consumption. Various studies have been devoted to deeply investigating how RIS acts as an energy-efficient technique in CF MIMO systems. By iteratively optimizing the digital beamforming at the APs and the RIS-based analog beamforming, the energy efficiency of the RIS-assisted CF MIMO system can beat that of the conventional distributed antenna system and the no-RIS case by orders of magnitude in Ref. [35]. Furthermore, it is observed that by replacing some of the APs with RISs, a two-fold performance gain in terms of energy efficiency can be harvested compared with the conventional CF MIMO scheme without RIS, which indicates the validity of RISs. Similarly, the authors in Ref. [36] proposed an iterative alternating algorithm based on a fractional programming method and successive lower-bound maximization to maximize the energy efficiency. The simulation also illustrates that with the default settings, the proposed design can offer an improvement of at least 168% higher energy efficiency than traditional user-centric CF MIMO systems without RIS assistance.

However, the above research has not considered practical constraints such as limited backhaul capacity. As a remedy, Ref. [37] devised an energy efficiency maximization design for RIS-aided CF MIMO networks under the constraints of per-AP transmit power, limited backhaul capacity, nonconvexity of RIS reflection, and minimum achievable rate requirement. As expected, the performance of the proposed RIS-aided CF MIMO system outperforms that of the co-located network with or without RIS.

3.2 Spectral Efficiency

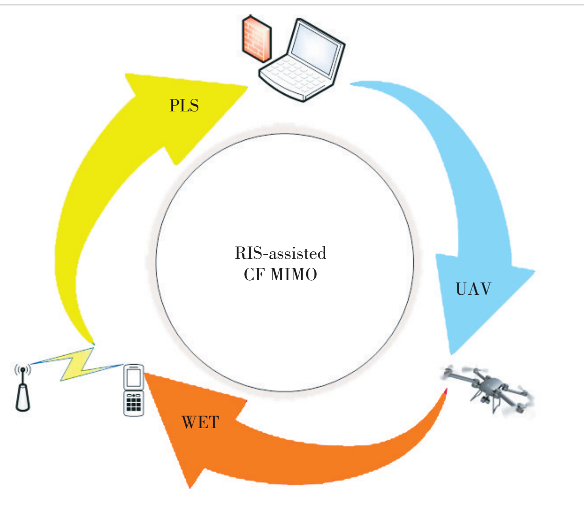
As a counterpart of energy efficiency, spectral efficiency is also a main communication metric. Since RIS can construct a favorable propagation environment by artificially creating a virtual line-of-sight (LoS) link, the signals of users at a dead zone or cell edge can be improved, thus bringing about spectral efficiency enhancement to the CF MIMO system.

As the first attempt, the authors in Ref. [38] proposed the concept of RIS-assisted CF MIMO to improve the network capacity or the spectral efficiency of the distributed MIMO system. Specifically, the authors considered a general framework with multiple antennas, multiple APs, multiple users, multiple RISs and multiple carriers. At the beginning of a large coherent timescale, each user is matched with specified RISs by the proposed linear conic relaxation-based matching method. In the rest of the coherent timescale, only the channels of the matched user-RIS pairs are estimated and exploited for joint active and passive precoding design, and those of the unmatched RISs are modeled as random noise. This process is repeated in the next coherent timescale until the end of data transmission. Once the RIS-UE association is fixed, the joint optimization problem is decoupled into two sub-problems through Lagrangian dual reformulation and multidimensional complex quadratic transform. The two decoupled sub-problems, i. e., the active transmit precoding at the APs and the passive reflection precoding at the RISs, are converted to two quadratically constrained quadratic program problems again, which can be solved by existing optimization tools. By iteratively optimizing the two sub-problems alternatively until converge, a sub-optimal solution to the weighted spectral efficiency of the system is obtained.

The authors in Ref. [39] also considered the burden on the fronthaul network, and proposed a decentralized cooperative joint active and passive precoding framework for RIS-assisted CF MIMO systems based on the alternating direction method of multipliers to maximize the weighted downlink spectral efficiency. Since only a few variables are incrementally updated and transmitted to the next AP, the backhaul overhead can be significantly reduced compared to the case with the whole CSI exchange among APs.

4 Applications of RIS-Assisted Cell-Free MIMO

This section presents various novel applications of the RIS-assisted CF MIMO technique, e. g., physical layer security (PLS), unmanned aerial vehicle (UAV) networks, and wireless energy transmission (WET), as depicted in Fig. 4. In fact, integrating RIS and CF MIMO with these emerging technologies can offer opportunities for beyond 5G networks. In particular, we provide an overview of state-of-the-art contributions on integrating each technology with RIS-assisted CF MIMO to pinpoint the main techniques that can be adopted for developing future wireless network services and novel applications in the following section.



CF: cell-free
MIMO: multiple-input multiple-output
PLS: physical layer security
RIS: reconfigurable intelligent surface
UAV: unmanned aerial vehicle
WET: wireless energy transmission

▲**Figure 4. Applications of RIS-assisted CF MIMO**

4.1 Physical Layer Security

With the development of wireless communication and the internet of everything (IoE), handheld devices such as mobile phones have carried more and more important/private information such as identity information, credit card passwords, ehealth data, and chat history. However, these devices are more vulnerable to security threats or attacks due to their limited memory capacity, battery life, computational power, and network bandwidth. Hence, physical layer security has become one of the top concerns of future wireless communication systems, especially for CF MIMO systems.

RIS-assisted secure issues have gained great attention recently and a large number of works have shown that by deploying RISs in the vicinity of the user and the eavesdropper, the physical layer security of the CF MIMO systems can be improved. Specifically, in Ref. [38], the maximum weight sum secrecy rate problem is considered by jointly optimizing the active cooperating precodings at multiple APs and the passive cooperating precodings at multiple RISs. The non-convex problem is decomposed into two separate sub-problems, and each sub-problem is solved by semi-definite relaxation and successive convex approximation techniques. With the aim of reducing channel estimation and feedback overhead, the authors further proposed a two-timescale transmission, where only partial CSI of the corresponding RISs that are selected by the assigning scheme is needed in each small coherence time, and the whole CSI is needed only at the beginning of the large coherence time.

Similarly, the work in Ref. [40] also studied the role of RISs in CF MIMO secure issues in the presence of active eavesdroppers. Channel estimation errors caused by pilot contamination, spoofing attacks and reuse are considered. To manage the inter-user interference, ZF precoding is applied to the CPU. Then by iteratively optimizing the RIS phase shifts and the downlink power allocation, the information leakage to active eavesdroppers is minimized while the legitimate user's performance is guaranteed.

4.2 Unmanned Aerial Vehicle

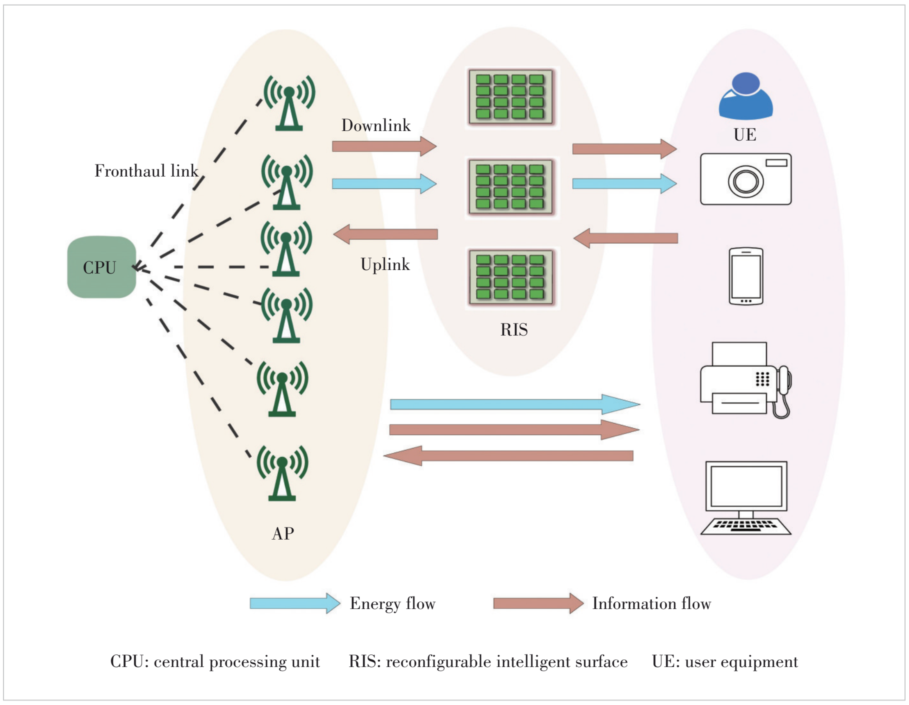
Due to their immense potential in logistics transportation, agricultural cultivation, delivery of medical supplies and telecommunications, UAVs have been recommended as a key enabling technology in both commercial and civilian fields. Specifically, a UAV acts as a flying AP that can dynamically change its location to enhance the network coverage and thus improve the network capacity. Since there are fewer obstacles in the airspace, it is easier to establish an air LoS link by deploying UAVs rather than a ground LoS link by deploying APs.

In traditional CF MIMO systems, a UAV usually serves as an active relay to assist the transmission from APs to users. However, since the AP antennas are generally tilted downwards to serve the ground users, communication with UAV usually suffers from poor signal strength. One way to deal with this problem is by tilting the AP antenna upwards or allocating more transmit power to the UAV. However, this would weaken the communication with ground users. Motivated by the emerging RIS technology, some researchers proposed to utilize RIS to strengthen the UAV communication while maintaining or even improving the downlink rate at the ground users[41]. By judiciously designing the reflection coefficients of the RIS and the power allocation, the achievable rate of both the UAV and the ground users can be improved without changing the AP antenna tilt.

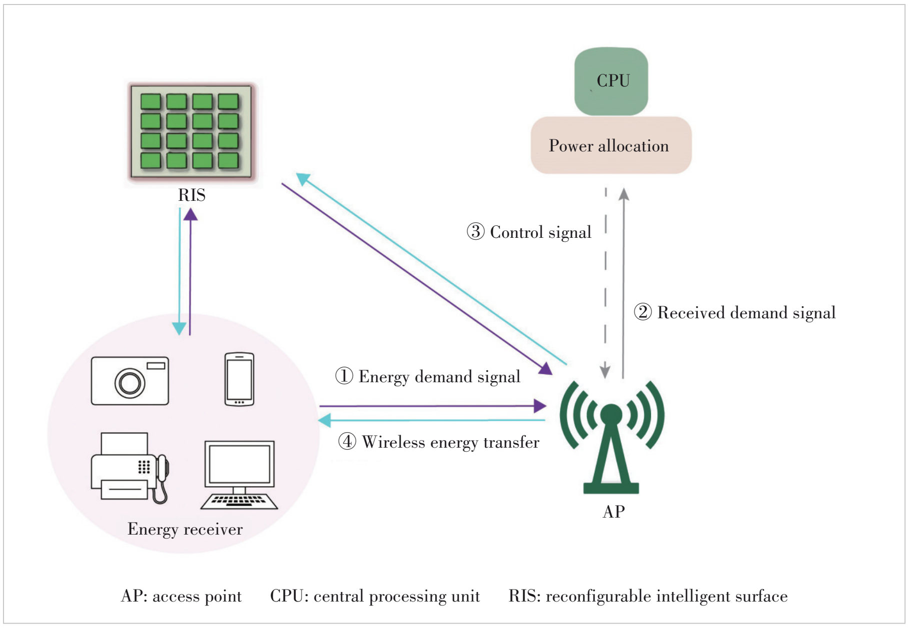
4.3 Wireless Energy Transfer

In practice, most IoE devices will be battery- or energy-constrained due to their limited sizes. Although frequent battery replacement and replenishing may offer a temporary solution to this problem, in future communication systems with multitudinous ubiquitous mobile access devices such as CF MIMO, this comes with dramatically high labor and material costs. As such, advanced energy supplement techniques are urgently needed to improve the energy shortage challenges.

Among various candidates, wireless energy transfer has been regarded as a promising technology to address these critical energy replenishing problems. Specifically, the radio frequency (RF) energy signal radiated by the AP can be acquired at the energy receiver by utilizing the far-field radiation properties of electromagnetic waves. After that, the AP transforms the received energy signal into energy for potential use. Unfortunately, despite the appealing merits of WET, it still faces some practical problems such as severe loss attenuation and signal obstruction. As a remedy, RIS has exactly the ability to smartly enhance the channel conditions via software-controlled signal reflection. Figs. 5 and 6 illustrate the specific transmission flow and the system architecture of the RIS-assisted CF MIMO system with WET respectively. As shown in Fig. 5, for the proposed RIS-assisted CF MIMO systems, multiple cooperative APs transmit both information signals and energy-carrying signals to multiple energy receivers and information receivers, where RISs are deployed to enhance the corresponding communication links. In Fig. 6, the system architecture can be divided into four parts. In the first part, the energy receivers transmit the energy demand signal to the APs through direct and RIS-



▲Figure 5. Transmission flow of RIS-assisted cell-free (CF) multiple-input multiple-output (MIMO) system with wireless energy transmission (WET)



▲Figure 6. Architecture of RIS-assisted cell-free multiple-input multiple-output (CF MIMO) system with wireless energy transmission (WET) assisted cascaded channels. Second, the APs transmit the demand signal received to the CPU. Then, the CPU allocates power and transmits a control signal to APs based on the signal transmitted by APs. Finally, APs transmit wireless energy signals to the energy receiver via downlink.

Recently, some works have considered the WET in RIS-assisted CF MIMO systems and analyzed its opportunities and challenges. For example, the authors of Ref. [42] answered the question of how the WET technology could be integrated into RIS-assisted CF MIMO systems from the main application scenarios, the four-stage transmission procedure, the specific deployment and hardware design, and the operation modes. The weighted sum rate maximization problem for RIS-assisted CF MIMO systems was studied in Ref. [43], under the total power constraints, the energy harvesting constraints and the unit-modulus constraints of the RISs. In Ref. [44], the authors proposed to substitute APs with UAVs to construct a CF MIMO-mount UAV assisted by RISs for RF energy transfer, which combines the benefits of CF MIMO, RISs and UAV. This framework where the distributed UAVs act as APs and operate in a cell-free fashion can provide a strong LoS signal and thus harvest more energy than other benchmarks.

5 Technical Challenges and Future Directions

Although several aspects of the RIS-assisted CF MIMO technique have been discussed in this paper, there are still some remaining challenges and unidentified areas in this field. In the following, we will point out some of the major challenges and future directions for implementing this technology in future wireless networks to realize its full potential.

5.1 Technical Challenges

To achieve the promised performance gains brought by the RIS-assisted CF MIMO technique, exact channel estimation is indispensable, which is rather difficult due to the following reasons. First, it is challenging to achieve perfect channel estimation for RISs, if not impossible. Due to their passive nature, RISs do not have any capability of signal processing, which makes it an arduous task to obtain individual channels of each hop of the links as in traditional relay systems. Second, RISs are usually composed of hundreds or even thousands of reflecting elements. Consequently, the channel coefficients that need to be estimated are tremendous, leading to an unaffordable overhead.

Due to hardware limitations of RIS elements, achieving optimal phase shift on all frequencies simultaneously in RIS-assisted MIMO systems is impractical, resulting in the so-called beam squint effect[45]. Specifically, the application of a large system bandwidth and intelligent reflecting surface causes a non-negligible propagation delay of electromagnetic waves and thus leads to a frequency-dependent antenna array response, i.e., beam pointing direction varies with frequency. However, ignoring the beam squint effects can lead to severe beam gain loss and seriously degrade system performance, especially for RIS-assisted wideband mmWave systems. Therefore, the impact of beam squint needs to be taken into consideration, and effective measures should be implemented to mitigate its impact in RIS-assisted systems.

Another critical technical challenge of the RIS-assisted CF MIMO system is low-complexity signal processing. On the one hand, to provide better QoS for future networks with massive access devices, it is necessary to deploy more APs and RISs with numerous antennas and reflecting elements. On the other hand, the problem of jointly optimizing the active precodings at APs and passive precodings at RISs is always non-convex due to the unit-modulus constraints of RISs, which always comes with a vast number of time-consuming iterations, leading to high calculation complexity and huge time latency. Meanwhile, due to the coupling between the optimization variables, the problem is hard to solve[38]. While many existing researchers have focused on and proposed various sub-optimal solutions to this problem, considering practical system implementations such as channel estimation and hardware impairments may make it even more sophisticated to solve[37]. Thus, there is an urgent need for more low-complexity signal processing techniques.

5.2 Future Directions

Learning-based techniques have attracted increasing attention from both academia and industry due to their ability to process a vast number of data in emerging wireless applications[46]. However, only a few studies have investigated the learning-enabled RIS-assisted CF MIMO networks. In fact, learning can play an essential role in channel estimation and power allocation for RIS-aided systems and CF MIMO systems. For example, some results have shown that the neural network-based estimation method can outperform the traditional estimation methods even with a few pilots, and the deep learning-based resource allocation can approximate the globally optimal performance for max-min power control. As such, more in-depth studies should be conducted in learning-enabled RIS systems and CF MIMO systems to fully exploit the potential of these techniques.

Near-field communication is an indispensable part of future 6G networks, which will bring several challenges to wireless communications. The low cost and low power consumption enable RIS to be equipped with a large number of reflective elements[47]. Meanwhile, increasing the number of antennas in the BS is also an important trend for future communication systems. However, large-scale RIS panels and large antenna arrays in the BS can lead to the near-field effect, especially in RIS-assisted CF MIMO wireless communication systems. Most traditional techniques designed for the far field suffer severe performance losses in the near-field region, such as channel estimation and beamforming[48]. Thus, it is practically important to efficiently adapt these traditional techniques to the near-field domain in IRS-aided CF MIMO systems and explore the possibilities of improving capacity by exploiting the near-field spherical wavefront.

Another emerging feature of 6G networks is the integration of sensing and communications, which enables the exploitation of dense sensing objects, computing resources and complicated communication resources to construct a perceptive network[49]. In CF MIMO systems, distributed array antennas can be used to significantly increase the effective array aperture, thus improving the sensing accuracy. Moreover, the position, speed and other information obtained from integrated sensing and communication can be utilized to optimize transmission performance and simplify computation complexity in CF MIMO systems. Therefore, the integrated design of communication and sensing based on CF MIMO systems is a potential technology for the exponentially growing demands and application requirements of 6G.

Most existing research has focused on CF MIMO systems with low-mobility users moving at a velocity of less than 10 km/h. However, in practical implementations with a large number of distributed users, there exist some users with high movement rates, although few, but vital. This is because in high mobility scenarios, the combination effect of Doppler frequency offset, timing offset and phase noise may trigger the inter-carrier interference and therefore deteriorate the system performance. Therefore, it is crucial to consider transmit precoding and power allocation algorithms under high vehicular speeds.

Besides, hardware constraints and imperfections are also an interesting topic that needs to be investigated. In the initial research on RIS-assisted CF MIMO wireless communication systems, most works have mainly assumed the ideal RIS reflection model for the ease of communication optimization design and performance analysis. However, in practice, RISs always suffer from hardware imperfections/impairments such as limited precision of reflection and phase-dependent amplitude that could seriously decrease the system performance. Hence, it is necessary to build a hardware-constrained system model that can accurately capture the hardware imperfections of RISs to cater to practical use.

The association between APs, users and RISs is also a difficult task that remains to be solved. Prior research has been conducted in a scenario where all APs jointly transmit their signals to all users through all RISs. This is however both power- and performance-inefficient since only the users near APs and RISs can benefit from the predesigned transmit precoding. A more practical and efficient way is to dynamically allocate a group of RISs and APs that have the best channel conditions to serve each individual user, and this kind of matching schemes has been verified to have better performance compared with the all-AP scheme. This AP-RIS-UE matching approach is still in its fancy and needs to be investigated especially when considering passive RISs.

Finally, the space-air-ground-sea integrated networks (SAGSIN) is a network architecture for 6G, which has been widely envisioned as a promising solution to complete, multi-angle and high-speed communication coverage worldwide[50]. SAGSIN is divided into four segments: the space network, air network, ground network, and sea network. It is a comprehensive integration of systems, technologies and applications, rather than just connecting different communication networks. Therefore, the RIS-assisted CF MIMO network is well suited for SAGSIN because of its significant network coverage capabilities and extraordinarily high data transfer speeds. However, given the heterogeneity of multi-layer networks among SAGSIN, it is significant to thoroughly investigate how to integrate the RIS-assisted CF MIMO network with other networks to satisfy user QoS and achieve complementary benefits among various networks.

6 Conclusions

In this paper, we provide a comprehensive survey of RIS-assisted CF MIMO system by reviewing the recent achievements in this area. In particular, we point out the key performance metrics, such as spectral efficiency and energy efficiency, and introduce the corresponding communication optimization techniques to achieve these metrics. Moreover, we discuss the potential applications of RIS-assisted CF MIMO in novel scenarios in B5G systems such as PLS, UAV and WET. Finally, the open problems and potential directions are studied to promote in-depth investigations and developments of RIS-assisted CF MIMO in future wireless networks.

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