Wireless Energy Transfer in RIS-Aided Cell-Free Massive MIMO Systems: Opportunities and Challenges

Enyu Shi, Jiayi Zhang, Shuaifei Chen, Jiakang Zheng, Yan Zhang, Derrick Wing Kwan Ng, and Bo Ai

The authors propose the paradigm of reconfigurable intelligent surface (RIS)-aided CF massive MIMO systems for WET, including its potential application scenarios and system architecture. The four-stage transmission procedure is discussed and analyzed to illustrate the practicality of the architecture.

Abstract

In future 6G mobile networks, the Internet-of-Everything (IoE) is expected to provide extremely massive connectivity for small battery-powered devices. Indeed, massive devices with limited energy storage capacity impose persistent energy demand hindering the lifetime of communication networks. As a remedy, wireless energy transfer (WET) is a key technology to address these critical energy supply issues. On the other hand, cell-free (CF) massive multiple-input multiple-output (MIMO) systems offer an efficient network architecture to realize the rollout of IoE. In this article, we first propose the paradigm of reconfigurable intelligent surface (RIS)-aided CF massive MIMO systems for WET, including its potential application scenarios and system architecture. The four-stage transmission procedure is discussed and analyzed to illustrate the practicality of the architecture. Then we put forward and analyze the hardware design of RIS. In particular, we discuss the three corresponding operating modes and the amalgamation of WET technology and RIS-aided CF massive MIMO. Representative simulation results are given to confirm the superior performance achieved by our proposed schemes. Also, we investigate the optimal location of deploying multiple RISs to achieve the best system performance. Finally, several important research directions of RIS-aided CF massive MIMO systems with WET are presented to inspire further potential investigation.

Introduction

The fifth generation (5G) wireless network has targeted a 1000-fold increase in network capacity offering ubiquitous wireless connection for at least 100 billion devices worldwide compared to the previous generations of networks. Recently, with the large-scale commercialization of 5G worldwide, the global industry has begun initial research on the next-generation mobile communication technology, that is, the sixth generation (6G). One of the key performance indicators for 6G is its extremely massive connectivity for small devices to enable the so-called Internet of Everything (IoE) [1]. In practice, most of these IoE devices will be either battery-powered or battery-less due to the associated high cost of applying conventional power-grid-based solutions. Unfortunately, the use of limited battery power shortens the lifetime of networks, degrading the quality of service. Although frequent battery replacement offers an intermediate solution to this problem, a large number of devices in IoE would further lead to exceedingly high labor and material costs. Therefore, advanced energy replenishing solutions are urgently needed to improve the energy supply challenges of future networks.

Wireless energy transfer (WET) has been proposed to address various practical scenarios where adopting electrical grid is not possible, such as unmanned aerial vehicle (UAV) communications, wireless sensor networks with sensors embedded in challenging environment structures, and inside a human body [2]. By exploiting the far-field radiation properties of electromagnetic (EM) waves, the radio frequency (RF) energy signal radiated by the transmitter can be harvested at the receiver, which converts it into electrical energy for future use. However, WET technologies face various technical problems such as large path loss attenuation, challenging energy beam alignment, and inefficient resource allocation. Hence, to fully unlock the potential of WET, it must be combined with other advanced communication technologies and architectures to fully unlock the potential of practical IoE networks.

The cellular concept was introduced over half a century ago for handling a small number of users in a large area. Recently, cell-free (CF) massive multiple-input multiple-output (MIMO) systems have been proposed [3], which advocates the removal of cellular boundaries for supporting the massive number of users. In practice, this paradigm can effectively shorten the distance between communication devices and access points (APs) through distributed deployment, thereby improving communication performance. Specifically, all the APs are connected to a central processing unit (CPU) with high-speed fronthaul links. Different from conventional centralized massive MIMO systems, APs are deployed in a certain range in a distributed manner and cooperate among themselves, which offers rich spatial diversity to improve the system spectral efficiency (SE). On the other hand, the use of high-frequency bands, such as terahertz (THz), is expected for 6G networks to cope with the aggressive

Enyu Shi, Jiayi Zhang, Shuaifei Chen, Jiakang Zheng, Yan Zhang, and Bo Ai are with Beijing Jiaotong University, China, as well as the Frontiers Science Center for Smart High-Speed Railway System, China;
Derrick Wing Kwan Ng is with the University of New South Wales, Australia.

needs required in massive access [4]. Indeed, by further considering the path loss in high-frequency bands, super-dense APs have to be deployed for reducing communication distances and for ensuring line of sight (LoS) between APs and IoE devices. In general, to support such large-scale multiple access networks, a large amount of energy would be radiated, while the increased interference imposed by super-dense APs has to be carefully managed and controlled. Therefore, it is imperative to study an innovative, spectral- and energy-efficient, but low-cost 6G wireless network solution.

Recently, reconfigurable intelligent surface (RIS) has been proposed as a promising new technology for reconfiguring the wireless propagation environment through software-controlled signal reflection [5–7]. Specifically, RIS requires only low power consumption and low cost. Undoubtedly, RIS can address the shortcomings of CF architecture in future communications, and these two technologies complement each other. On the other hand, although RIS was initially proposed as a passive component, the coordination of a large number of elements still requires a certain amount of electrical energy [7]. When there are a large number of RISs, configuring a physical link for each RIS would cause huge resource consumption. Therefore, WET technology is an excellent solution to replace the grid energy-based approach. The energy supply of RISs through WET technology is expected to realize passive deployment of RISs, reduce hardware overhead, and improve the system energy efficiency. Despite its great potential, there is relatively little research on RIS-aided CF massive MIMO systems at present. In fact, some authors have studied the system performance of a single-RIS system, or optimized communication problems in multiple-RIS systems [8]. Also, the authors have studied the combination of RIS and WET, and the corresponding optimization through advanced optimization [9]. The results unveiled the nontrivial trade-off between achieving RIS self-sustainability and the system sum-rate. Others have studied the system performance of a single RIS-aided CF massive MIMO systems under idealistic conditions such as with sufficient energy storage and Rayleigh fading channels [10]. Furthermore, the authors introduced a precoding framework for RIS-aided CF networks [11]. Nevertheless, there is a lack of thorough research on the study of RIS-aided CF massive MIMO systems and their applications with WET technology.

In this article, we try to answer the question: *How can we apply WET technology in RIS-aided CF massive MIMO systems?* To fully exploit the RIS benefits and the WET technology, we design the system architecture applying the WET technology to RIS and discuss its potential future application scenarios. In addition, we design the transmission procedures of the considered system and analyze each procedure. Based on this, we design different hardware architectures of RIS with WET technology for different practical scenarios. Meanwhile, we propose and compare different operation modes of this system, which provide useful insights for the implication of RIS-aided CF massive MIMO systems. With the novel system architecture, we also discuss how to deploy RIS to achieve better system performance. Finally, we highlight potential research directions
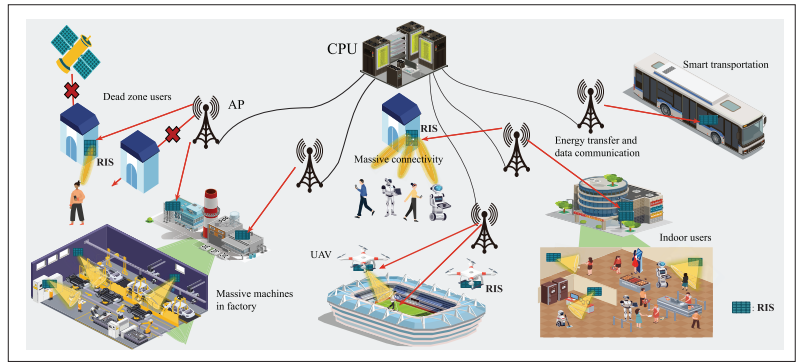

FIGURE 1. Application scenarios of RIS-aided CF massive MIMO systems with WET.

that deserve further study.

MAIN APPLICATION SCENARIOS AND SYSTEM ARCHITECTURE

In this section, we introduce the main application scenarios of RIS-aided CF massive MIMO systems in future wireless networks and analyze the characteristics of different scenarios. Meanwhile, we provide a detailed introduction to the architecture of the considered system and the corresponding transmission procedure.

MAIN APPLICATION SCENARIOS

In the current research (e.g., [6, 7]) as a passive device, RIS can be flexibly deployed in communication systems for improving the coverage area and providing wireless services for dead spots.

In future 6G network architecture, RIS should be combined with other technologies to achieve better communication performance. Our proposed RIS-aided CF massive MIMO communication architecture serves as an excellent candidate for better exploiting the advantages of WET technology and realizing the vision of IoE. The future wireless networks are expected to make full use of the low, medium, and high full-spectrum resources to achieve seamless global coverage of space, sky, and Earth trinity, such that they can satisfy the stringent demand for establishing unlimited safe and reliable "human-machine-object" connections anytime and anywhere. Indeed, the success of this desired vision relies on the support of massive access required by IoE, requiring higher transmission rates, lower delays, and higher reliability [12]. The main scenes include two categories, densely populated spaces and large-scale factories with densely deployed equipment. As shown in Fig. 1, crowded spaces include large indoor shopping malls, basketball courts, restaurants, stadiums, and so on. In contrast, the scene of a large-scale factory with densely deployed equipment is relatively static, and the only main challenge is to facilitate energy harvesting at potential equipment. Note that in the factory scenario, CPUs and APs are internal devices rather than external additional devices. The main feature of the former is that the mobility of personnel is relatively high and the wireless equipment in the latter has only limited mobility. For the former scenes, there is generally more uncertainty in wireless communication channels. For example, for the indoor scenario, under the original CF system architecture, we can deploy multiple RISs in some communication
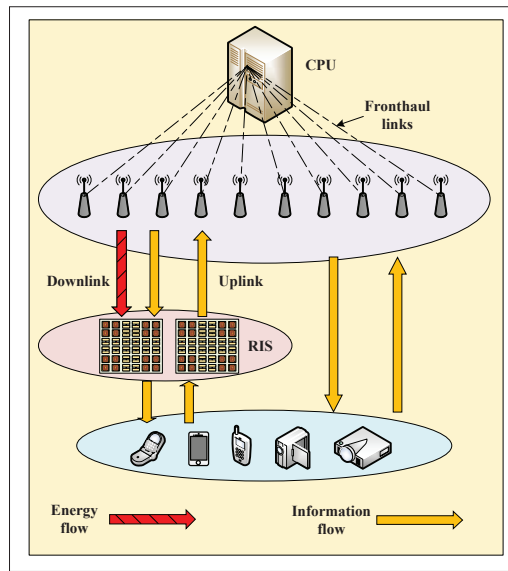
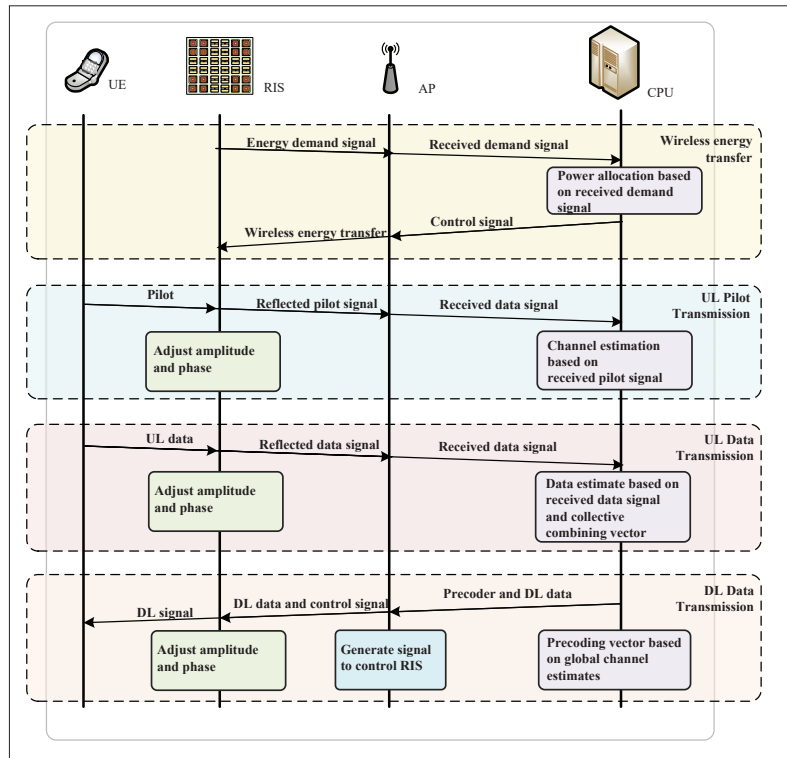FIGURE 2. System architecture of RIS-aided CF massive MIMO systems with WET.

FIGURE 3. Four-stage transmission procedure of RIS-aided CF massive MIMO systems with WET.

gent design of the track. On the other hand, for the latter scenes that equipment is not mobile, we only need to deploy the RIS in a fixed location in advance to improve the system performance.

SYSTEM ARCHITECTURE

As shown in Fig. 2, the system is based on the CF architecture with an "additional" RIS layer between the user equipments (UEs) and the APs. The existing CF massive MIMO system is a three-tier structure composed of the CPU, APs, and UEs. Our proposed system architecture realizes a 3.5-layer architecture, which adds a cascading link through RIS. When there is a direct path, the APs can receive the signal from the UEs via two uplink paths: the direct link and the aggregated link through the RIS. As such, we treat the channels through the RIS with an additional 0.5 layer. In particular, when the direct path is blocked, this proposed structure can still guarantee stable user communication.

A CPU has an extremely high computational capability, which not only can receive or transmit a large amount of information but also process the large number of APs receiving data [13]. In contrast, an AP has limited computing resources that are equipped with a simple RF antenna. In the considered system, the difference between the proposed RIS and the traditional one is that our proposed one allows RIS to be equipped with a wireless energy harvesting module, which replaces the original wired-power circuit. By adopting WET technology, an AP is considered as an energy source to charge the RIS module wirelessly to ensure the normal operation of RIS.

To realize this paradigm, we introduce the flow of the four-stage transmission procedure of the system in Fig. 3.

Stage 1: Downlink energy transmission: The CPU collects the information transmitted by the AP via the fronthaul and sends control commands to the AP after signal processing. Based on the received signal, the AP decides whether to transmit wireless energy signals to the RIS for energy harvesting. Especially when the stored energy level in the RIS exceeds a threshold value, the RIS controller transmits a feedback signal to the AP for terminating the energy transmission.

Stage 2: Data transmission: In the uplink, the UE first sends a pilot signal to the APs that reaches the APs directly or through the RISs cascaded channel. Then the APs receive the pilot signal and convey it to the CPU via dedicated fronthaul for channel estimation. Subsequently, the UE sends their uplink data, and the APs receive the signal via a direct path as well as the reflected signal arriving through RISs beamforming. Furthermore, the APs send their received data to the CPU, which performs joint signal processing for data detection. Finally, the CPU obtains the uplink decoded signal based on the global channel estimation. Then the downlink data signal is generated by the downlink precoder and transmitted to the AP, which finally reaches the user equipments (UEs) through the RIS. Meanwhile, the AP generates the signal to control the RIS for phase adaptation. Note that if the AP desires to realize dynamic control of the RIS, it is necessary to modify the frame structure and to insert some control time slots. Correspondingly, deploying sig-

dead zones and improve the quality of communication by increasing the number of RISs. Since WET technology is exploited to supply the necessary energy to RISs, there is no need to deploy physical power lines for charging which is more flexible in practical implementation. Moreover, in the indoor environment, there is an upsurge in the demand for temporary communication such as large-scale activities in which the role of flexible RIS deployment is particularly prominent. As for outdoor environments such as the gymnasium, we can deploy an unmanned aerial vehicle (UAV) on-demand as a carrier of RIS to offer signal coverage and enhancement through intelli-
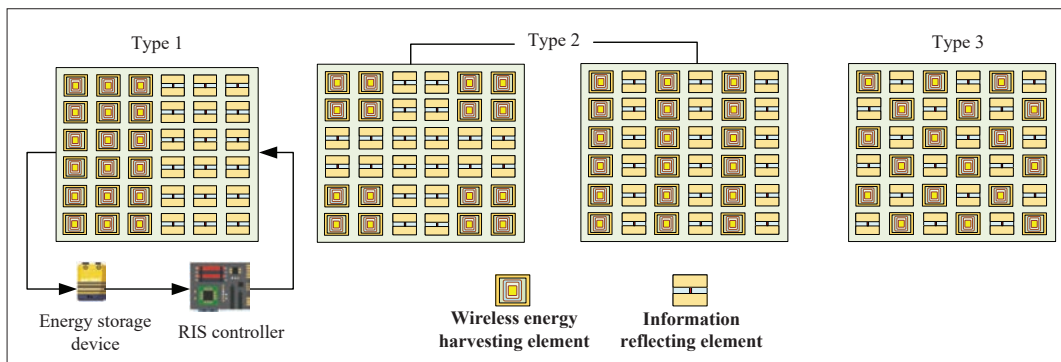
FIGURE 4. Hardware designs for information and energy transmission in an RIS. Type 1: energy harvesting and information reflecting elements are completely separated and distributed in blocks; type 2: block structure with incomplete separation of energy harvesting and information reflection elements; type 3: energy harvesting and information reflecting elements alternate with each other in a scattered distribution.

nal processing modules at the RIS may be needed to respond to the control signals.

DEPLOYMENT DESIGN

In this section, we propose an RIS hardware design scheme supported by WET technology. On this basis, we explore different system operation modes and compare their advantages and disadvantages. Finally, we discuss various practical scenarios on how to effectively determine the location of RIS deployments in practice.

HARDWARE DESIGN

The hardware implementation of RISs is based on the concept of "metasurface," each element of which is a programmable sub-wavelength structural unit composed of two-dimensional metamaterials [14]. In practice, the field-programmable gate array (FPGA) can be used as a controller to achieve flexible control of the RIS, which usually communicates and coordinates with other network components (e.g., base station [BS], APs, and UEs) through dedicated links. Although FPGA consumes a small amount of energy, it still needs some electrical power source to support its operation. As shown in Fig. 4, we introduce the wireless energy scavenging module to the original RIS panel and exploit some elements for energy reception and other elements for signal reflection. The energy harvesting elements are connected with a piece of energy storage hardware (e.g., a rechargeable battery), which can store the harvested energy and support the energy consumption of other elements performing reflection.

An RIS is generally assembled by hundreds of elements [6], so it is worth exploring which elements are selected for serving as energy receiving modules. Here, we have designed and compared three types of hardware structures in Fig. 4. The first type consists of complete separation of the energy harvesting elements and the information reflecting elements, which are easy to implement in hardware. However, when the RIS panel is large, there aree some energy reception dead spots in this design due to non-uniform energy flux created by impinging signals. Based on this, we further propose an improved block structure, that is, deployment of energy harvesting elements at the four corners of the RIS (i.e., type 2), which can alleviate the impact of dead spots but introduces moderate hardware implementation difficulty. Finally, we also design a scattered structure

aimed at reducing the impacts of dead zones on energy harvesting or signal reflection, but at the cost of higher hardware complexity. In practice, the energy consumption of the centralized and distributed element designs mainly depends on the number of elements used for information reflection. Indeed, in addition to considering the balance between the system performance and the implementation complexity, the ratio between the number of RIS elements in energy harvesting mode and that in reflecting mode is another key issue. This is determined by various factors, such as distance, energy conversion efficiency, and the channel environment. In practice, the information and energy elements' ratios can be adaptively adjusted according to the feedback of the actual parameters to realize dynamic assignment [9].

OPERATION MODES

In practice, there are different ways of deploying RISs leading to different system operation modes. They affect the hardware design complexity and signal processing methods, as well as the synergy between individual communication devices, which inevitably brings different system performance. In this section, we discuss several different operation modes of RISs for WET and information reflection.

Centralized RIS: As shown in Fig. 6, we first consider that there is only a single large-scale centralized RIS with massive elements. It is configured with high computational power and signal processing capability at the RIS controller, which can reduce the processing burden of the APs. Meanwhile, the centralized RIS has high beamforming capability that can assist the APs to service massive UEs via excellent interference management [9]. Moreover, the centralized design facilitates highly efficient wireless energy focusing, while it is easier to deploy and maintain the equipment. However, due to the architecture of the centralized RIS, the path loss of long-distance devices can be severe as UEs are randomly deployed. Also, the ability of WET to keep such a sophisticated controller functioning properly still needs to be explored. Furthermore, the requirements for hardware design are also demanding, resulting in high cost.

Non-Cooperative Distributed RIS: In this case, we assume that multiple RISs are non-cooperatively deployed in a service area. This distributed deployment is more flexible and can avoid dead
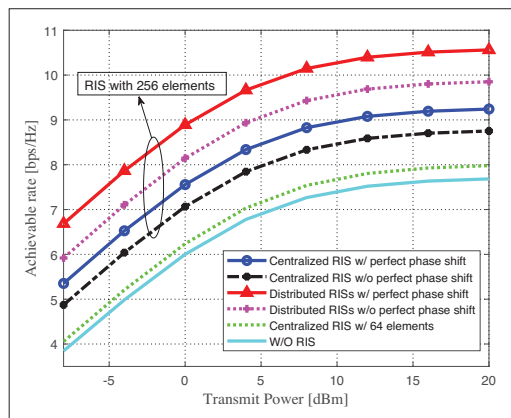
FIGURE 5. Achievable rate of different RIS operation modes and elements with phase errors.

spots in WET as much as possible. Meanwhile, the distance between RIS-AP and RIS-UE is shortened, which reduces the path loss of WET. As such, significant improvements in energy efficiency and communication quality can be achieved. In practice, the hardware design of each RIS is still relatively simple since it only expects to implement simple signal reflection. Also, since multiple non-cooperative RISs are distributed in the service area, the signals between different RISs may interfere with each other, which degrades the communication performance of UEs.

Cooperative Distributed RIS: Similar to the last operation mode, we consider that there are multiple RISs in a service area. The difference is that there is some intelligent cooperation among RISs through physical links or dedicated wireless communication, as shown in Fig. 6. Note that when there is a physical link connected to the RIS, WET is regarded as supplementary electric energy to reduce the required energy consumption. This operation mode not only reduces the path loss of WET and information communication, but also enables better beam management among multiple RISs through cooperation, thus reducing interference. However, it also places additional requirements on the hardware design of RISs, such as how to implement physical connections between multiple RISs and the design of the controller. As such, RISs will generate additional energy consumption for channel estimation and cooperation. However, due to the stable characteristics of the channel, frequent communication between RISs is not required, so the required energy consumption is still reasonable. In practice, a high computational requirement at the CPU and advanced optimization algorithms are needed to achieve efficient and intelligent cooperation of RISs. In practice, centralized RIS is more suitable for small-scale networks with dense users. In contrast, distributed RIS has better performance in large-scale networks due to its inherent ability in exploiting spatial diversities.

In Fig. 5, we compare different RIS operation modes for different element numbers within an area of 1000 m² and consider the effect of phase errors. The achievable rate (bits per second per Hertz) and the transmit power (dBm) are the two main performance metrics for information communication. It shows that RIS can significantly improve the system performance, and compared

to centralized RIS, distributed deployment can obtain higher system achievable rate. Moreover, phase errors reduce the performance of the system and the influence of phase errors is more significant with the increase of the RIS element numbers.

RIS Deployment

How to judiciously deploy multiple RISs in a hybrid wireless network containing passive RISs, active CPUs, and APs to optimize the system performance is a critical problem that needs to be solved. Previous studies have provided some solutions for RIS location deployment, such as deploying an RIS close to the UE, or the AP side can obtain higher system performance [15]. Unfortunately, the considered system is not a single point-to-point communication, and the RIS needs support from WET technology. In the considered network, energy and information transmission are two equally important performance metrics.

First, from the perspective of optimizing the system communication performance, the RIS should be intuitively deployed in a location with a clear LoS from the AP to maximize its received signal power for passive beamforming and WET. Although this deployment scheme enjoys good performance for the case of a single UE, it does not work well when the number of UEs increases, due to the lack of enough non-LoS paths to achieve high-rank MIMO channels. To enhance the experience of UEs with poor communication quality, we should also deploy some RISs in dedicated areas with weak signal coverage and communication dead zones caused by blockages. On the other hand, from the perspective of WET, RIS should be deployed in scenarios where it is difficult to install power lines for emergencies, such as unmanned aerial vehicle (UAV) communication and temporary placement sites. In practice, ensuring proper system operation first requires that the RIS can effectively receive wireless energy signals to support its operation. As such, an RIS should be reasonably deployed near an AP to facilitate the establishment of an LoS path.

In practice, the dynamic of propagation environment and user mobility lead to channel variations over time, and each RIS may also be associated with multiple APs and UEs, while multiple RISs may be interconnected. In such cases, heuristic solutions to the design of RIS deployment may be ineffective. In particular, it is generally intractable to acquire accurate globally channel state information (CSI) at low cost in large systems. Therefore, how to determine a precise location deployment scheme of multiple RISs based on partial system information is a new problem with high practical significance. A promising approach to solve this problem is to utilize machine learning techniques, such as deep learning (DL). For example, in the training phase, we can empirically deploy multiple RISs at reasonable reference locations and collect key performance metrics, such as the received signal strength and the corresponding energy efficiency measured at different UE locations. The collected key metrics and the location of the RIS are then exploited to train the DL-based neural network as input and output, respectively. However, during the training process, it is generally not possible to change
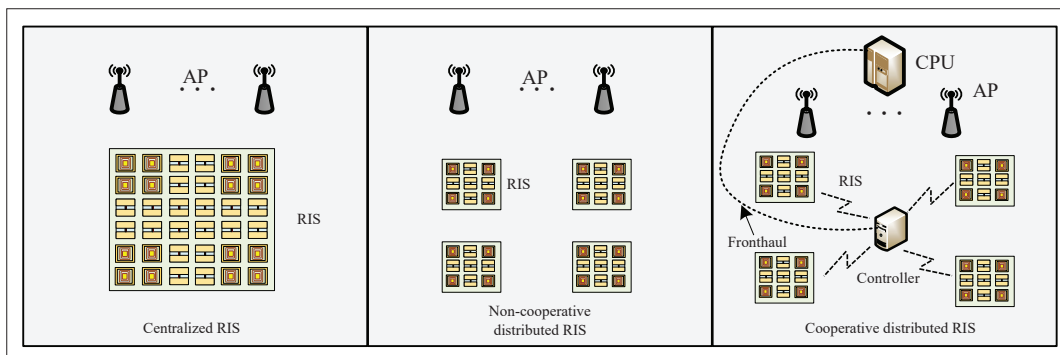
FIGURE 6. Comparison of different RIS operation modes.

the locations of RISs, and additional installation costs will be incurred. In fact, the obtained results serve as a performance upper bound for a fixed RIS deployment location. As for more practical implementation, one may consider statical long-term optimization. Furthermore, we can adopt convex optimization methods such as the gradient descent and Newton methods to optimize RIS location and system power allocation to improve the system performance.

FUTURE DIRECTIONS

In addition to the system architecture and deployment schemes discussed above, there are still some other research directions worth future investigation for the systems.

CONTROL SCHEME

For a single RIS, how to control the activation of energy harvesting and information reflection elements is an important problem to be solved with the following aspects. For instance, stringent requirements are imposed for the hardware design of RIS, while higher information receiving and processing capabilities are also required. Furthermore, the massive elements in RIS incur new challenges to the optimization algorithm of high-dimensional matrices [9]. As for the systems, the traditional analysis results in the literature do not consider the cooperation among RISs, which may lead to UE unfairness and communication quality degradation due to signal interference among multiple RISs. To fully utilize the advantage of the strong directivity of the RIS reflected beam, the RIS phase shift matrix is designed according to the AP and UE positions to achieve precise control of the beam direction, thereby avoiding interference as much as possible. For example, with a large number of APs and RISs, computationally efficient distributed machine learning algorithms serve as appealing solutions as they have been successfully applied to address large-scale optimization problems. However, a rigorous control protocol must be designed to ensure orderly communication and harness the interference among devices.

RESOURCE ALLOCATION

Large and complex systems inevitably face the problem of resource allocation. In traditional CF systems, pilot assignment is an important research direction that is also inherent to our system. Furthermore, for the consideration of supporting WET technology, power allocation is another key issue worthy of attention. Specifically, we need to control the energy supply offered by APs to optimize the system energy efficiency. If all the APs adopt a uniform power allocation to supply energy to RISs, it is generally suboptimal, which can cause energy waste. As such, certain optimization mechanisms are needed to maximize power utilization. For instance, for imperfect CSI, we can exploit the large-scale channel information and solve the related resource allocation problem through optimization algorithms such as geometric programming. In practice, formulating design optimization problems to realize accurate and efficient power allocation is an ideal solution. However, most of the practical problems are non-convex and intractable in complex networks. Hence, finding an optimal power control scheme within a reasonable timescale is an urgent future research direction. It is worth mentioning that using the WET technology to supply energy to UEs is also worth considering in resource allocation.

HARDWARE

To achieve ubiquitous deployment of RIS-aided CF massive MIMO systems, the cost and quality of hardware for receivers and transmitters as well as RIS naturally swing a nontrivial trade-off in system design. However, to overcome the associated high cost, we typically utilize low-cost components at APs. Unfortunately, the use of low-cost hardware at RISs affects the hardware accuracy, including the limited phase shift resolution and the mutual coupling of phase and incidence angles in each RIS element. In practice, the nonlinear amplitude and phase response of RIS would affect the accuracy of reflected signals, resulting in unsatisfactory system performance. As a result, a pragmatic system design taking into account the potential imperfect hardware is necessary. Furthermore, the hardware design of energy reception introduces extra hardware complexity in fabricating RIS. Indeed, designing WET elements at the wavelength level is challenging. In addition, how to avoid the coupling interference between the WET elements and the reflecting elements is also a problem that needs to be considered. On the other hand, the fronthaul capacity limitation reduces the availability of converging control signals between the APs and the CPU. As such, the above hardware impairment problems would definitely degrade the communication and energy transmission performance of the system, which are important issues for investigation.

CONCLUSIONS

In this article, we investigate the promising RIS-aided CF massive MIMO system with WET technology for realizing IoE in future wireless networks. First, we discuss several potential application scenarios of the system and the proposed system architecture. Furthermore, we propose different operation modes and shed light on the suitable RIS hardware design for WET. In addition, we investigate feasible solutions for the possible deployment of RISs in the system. Finally, to offer useful guidance for future research, we indicate the critical challenges and promising research directions for realizing RIS-aided CF massive MIMO systems with WET.

REFERENCES

[1] H. Tataria *et al.*, "6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities," *Proc. IEEE*, vol. 109, no. 7, July 2021, pp. 1166–99.
[2] J. Hu, Q. Wang, and K. Yang, "Energy Self-Sustainability in Full-Spectrum 6G," *IEEE Wireless Commun.*, vol. 28, no. 1, Feb. 2020, pp. 104–11.
[3] J. Zhang *et al.*, "Prospective Multiple Antenna Technologies for Beyond 5G," *IEEE JSAC*, vol. 38, no. 8, Aug. 2020, pp. 1637–60.
[4] S. Chen *et al.*, "Structured Massive Access for Scalable Cell-Free Massive MIMO Systems," *IEEE JSAC*, vol. 39, no. 4, Apr. 2020, pp. 1086–1100.
[5] W. Tang *et al.*, "Wireless Communications with Programmable Metasurface: New Paradigms, Opportunities, and Challenges on Transceiver Design," *IEEE Wireless Commun.*, vol. 27, no. 2, Feb. 2020, pp. 180–87.
[6] Q. Wu and R. Zhang, "Toward Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Network," *IEEE Commun. Mag.*, vol. 58, no. 1, Jan. 2019, pp. 106–12.
[7] M. Di Renzo *et al.*, "Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces: How It Works, State of Research, and the Road Ahead," *IEEE JSAC*, vol. 38, no. 11, Nov. 2020, pp. 2450–2525.
[8] Q. Wu and R. Zhang, "Joint Active and Passive Beamforming Optimization for Intelligent Reflecting Surface Assisted SWIPT Under QoS Constraints," *IEEE JSCA*, vol. 38, no. 8, Aug. 2020, pp. 1735–48.
[9] S. Hu *et al.*, "Robust and Secure sSum-Rate Maximization for Multiuser MISO Downlink Systems with Self-Sustainable IRS," *IEEE Trans. Commun.*, vol. 69, no. 10, Oct. 2021, pp. 7032–49.
[10] T. Van Chien *et al.*, "Reconfigurable Intelligent Surface-Assisted Cell-Free Massive MIMO Systems over Spatially-Correlated Channels," *IEEE Trans. Wireless Commun.*, early access, 2021.
[11] Z. Zhang and L. Dai, "A Joint Precoding Framework for Wideband Reconfigurable Intelligent Surface-Aided Cell-Free Network," *IEEE Trans. Signal Processing*, vol. 69, 2021, pp. 4085–4101.
[12] M. Giordani *et al.*, "Toward 6G Networks: Use Cases and Technologies," *IEEE Commun. Mag.*, vol. 58, no. 3, Mar. 2020, pp. 55–61.
[13] J. Zhang *et al.*, "Improving Sum-Rate of Cell-Free Massive MIMO with Expanded Compute-and-Forward," *IEEE Trans. Signal Processing*, vol. 70.
[14] C. Liaskos *et al.*, "A New Wireless Communication Paradigm through Software-Controlled Metasurfaces," *IEEE Commun. Mag.*, vol. 56, no. 9, Sept. 2018, pp. 162–69.
[15] X. Liu *et al.*, "RIS Enhanced Massive Nonorthogonal Multiple Access Networks: Deployment and Passive Beamforming Design," *IEEE JSAC*, vol. 39, no. 4, Apr. 2020, pp. 1057–71.

BIOGRAPHIES

ENYU SHI received his B.S. degree in communication engineering from Beijing Jiaotong University, China, in 2019, where he is currently pursuing a Ph.D. degree.

JIAYI ZHANG [SM'20] is a professor with the School of Electronic and Information Engineering, Beijing Jiaotong University. His current research interests include cell-free massive MIMO and RISs.

SHUAIFEI CHEN received his B.S. degree in communication engineering from Beijing Jiaotong University, China, in 2018, where he is currently pursuing a Ph.D. degree.

JIAKANG ZHENG received his B.S. degree in communication engineering from Beijing Jiaotong University in 2019, where he is currently pursuing a Ph.D. degree.

YAN ZHANG is currently working toward a Master's degree in communications engineering from Beijing Jiaotong University.

BO AI [F'22] is a professor with the State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University. His research interests include rail traffic mobile communications and channel modeling.

DERRICK WING KWAN NG [F'21] received his Ph.D. degree from the University of British Columbia in 2012. He is currently working as a Scientia Associate Professor at the University of New South Wales, Sydney, Australia.