RIS-Assisted Integrated Sensing and Backscatter Communications for Future IoT Networks

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***Abstract*—Reconfigurable intelligent surface (RIS), by intelligently manipulating the incident waveform, offers a spectral and energy efficient capability for improving sensing and communication performance. In this article, we introduce a novel concept of RIS-assisted integrated sensing and backscatter communication (ISABC) system, by introducing RIS as either helper or transceiver to resolve the energy constraint of devices in internet of things (IoT) network and enable non line-of-sight (NLoS) sensing. We first introduce the RIS-assisted ISABC framework, including the system architecture and realization of RIS. Three potential applications are then discussed, with the analysis on their requirements. The research on several critical techniques for the RIS-assisted ISABC system is then discussed. Finally, we provide our vision of the challenges and future research directions to facilitate the development of the RIS-assisted ISABC systems.**

I. Introduction

To realize the vision of "Intelligent Internet of Everything", next-generation wireless networks, e.g., beyond 5G (B5G) and 6G, are expected to provide ultra-broadband, ubiquitous sensing, and connected intelligence [1], thereby supporting massive machine type communication (mMTC). One critical issue in deploying such massive internet of things (IoT) networks is the limited battery storage of IoT devices, which is even required to be lower than 1 mW. In view of this, developing low-power communication technique to extend the battery life for IoT devices is of vital importance.

Among the various low-power communication techniques, backscatter communication stands out as the most promising one. It enables information delivery by modulating and reflecting the incident signals from an external radio frequency (RF) emitter. The receiver, in turn, performs demodulation by detecting the reflection coefficients. Additionally, backscatter devices have the capability to harvest energy from the incident signals, supporting their other activities. This passive communication approach eliminates the need for IoT devices to actively transmit signals, resulting in significant benefits. One of the key advantages of backscatter communication is the conservation of RF chains. Consequently, valuable space can be saved, facilitating the miniaturization of IoT devices and reducing their power consumption.

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Despite the potential of enabling power and cost efficient signal transmission, the conventional backscatter communication technique suffers from low data rate due to the severe round-trip signal propagation. As another representative energy-efficient technique [2], reconfigurable intelligent surface (RIS) provides opportunities to improve the spectral efficiency of backscatter communication systems from two perspectives. On one hand, RIS can reconfigure the propagation environment to mitigate inter-device interference. On the other hand, by deploying RIS as the backscatter component, more spatial degrees of freedom (DoFs) can be obtained, thereby enhancing the backscatter link and improving the signal quality.

While deploying backscatter communication networks, one critical issue is the deployment of RF sources. To cover widely distributed IoT devices, RF sources also need to be widely deployed, potentially causing severe interference to other systems. One efficient way to address this challenge is to employ the ambient backscatter communication technique by utilizing the ambient RF signals as RF sources. In view of this, we propose to employ the sensing nodes in future integrated sensing and communication (ISAC) networks [3] as the RF source. Notably, in conventional active sensing systems, e.g. radar systems, target sensing is also based on the reflecting principle. Therefore, compared with conventional ambient RF sources, e.g., cellular base stations or digital video broadcasting (DVB) base stations, the signal power of sensing systems, is typically much higher, supporting wide-area high-precision sensing and more suitable to support backscatter communication. Furthermore, the sensing node can shape sharp beams towards edge IoT devices.

On the other hand, the IoT devices equipped with RIS can also help improve sensing performance by reflecting sensing signals towards targets or acting as distributed sensors. Consequently, the integration of sensing nodes and RIS-assisted IoT devices forms the concept of an integrated sensing and backscatter communication (ISABC) system. In this integrated system, the sensing nodes serve as the RF sources for backscatter communication, while the IoT devices equipped with RIS play a dual role by enhancing communication performance and contributing to the sensing process.

Through the interaction between the IoT devices and ISAC systems, the RIS-assisted ISABC system is expected to play an important role in both civilian and military applications. Although significant progress has been made in advancing the RIS-assisted backscatter communication technique as well as ISAC technique, addressing the distinctive features and

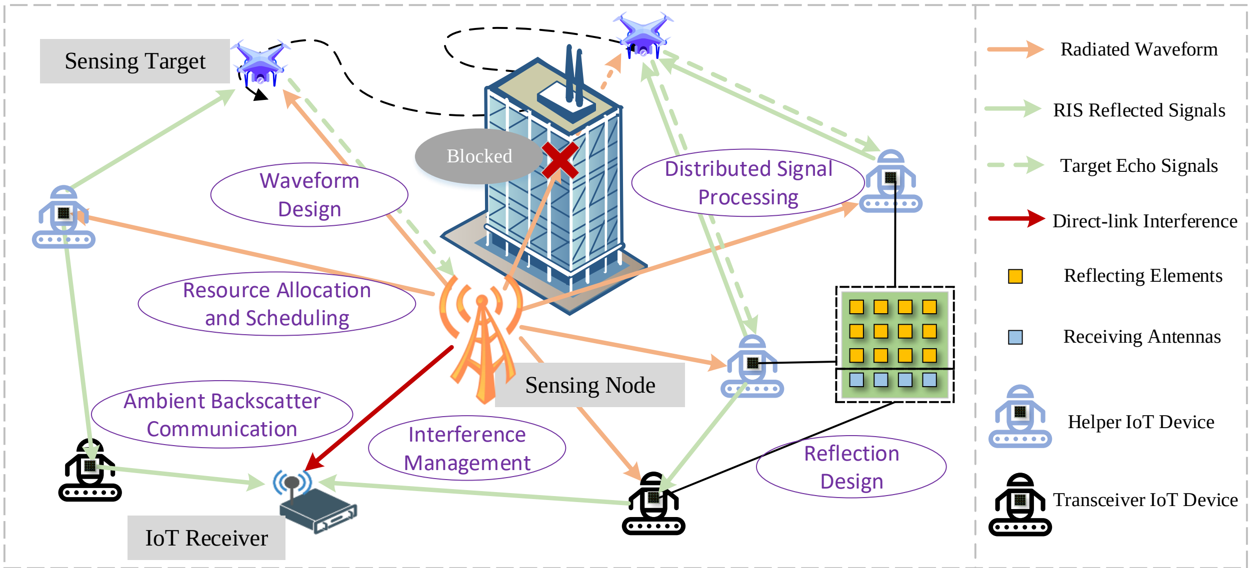

Fig. 1. An illustration of the RIS-assisted ISABC system for future IoT networks.

critical challenges in RIS-assisted ISABC systems requires special techniques. In this article, we aim to introduce the RIS-assisted ISABC framework for future IoT networks and shed lights on its future development. We will begin by presenting the system architecture for RIS-assisted ISABC systems, with several potential applications discussed. Subsequently, several critical techniques are elaborated, with potential solutions illustrated. Finally, challenges and future research directions are highlighted to pave the way for its further advancements.

II. System Architecture and Typical Applications

Fig. 1 depicts the system model of the RIS-assisted ISABC system, where multiple IoT devices are activated by the waveform radiated from a sensing node and passively backscatter their data signals to an IoT receiver. Concurrently, the sensing node endeavors to detect or track illegal targets based on the received echo signals. As depicted, each IoT device is equipped with an RIS and a receiving antenna array, which are employed to execute backscatter communication and sensing tasks, respectively.

Basically, RIS can be realized using either antenna elements or metamaterial. In the case of antenna-based RIS, a 2-D antenna array is typically employed, where each element first receives the incident signals and then reflects them with a reflection coefficient, achieved by adjusting its load impedance [1]. In this case, each antenna element is similar to a tag in conventional backscatter communication systems. Although each element has a limited effect on the propagated waveform, when a sufficient large number of elements work cooperatively, they can effectively manipulate the waveform. To enable this cooperation, an RIS controller is typically required, which can be implemented with the field-programmable gate array (FPGA).

In comparison, the metamaterial-based RIS comprises a huge number of periodic metamaterial units capable of directly reflecting the incident waveform, eliminating the need for reception. In this way, the reflection occurs at the boundary of the metamaterial units, and the equivalent impedance of each unit is influenced by various factors. Similar to the antenna-based RIS, the metamaterial-based RIS also requires a controller for adaptive adjustment.

A comparison between the antenna-based RIS and metamaterial-based RIS is presented in Table II. Compared with the antenna-based RIS, the spacing of the elements in metamaterial-based RIS is much smaller, enabling the deployment of a large number of metamaterial units on the spacing-limited IoT devices. As a result, the metamaterial-based RIS can provide a higher number of DoFs to manipulate the waveform effectively.

Due to the large amount of IoT devices in future networks, it is impractical to simultaneously communicate with all devices. One common solution is to divide the devices into different groups, with each group being served in one time slot. Although this orthogonal allocation scheme may result in a slight loss in spectral efficiency compared with non-orthogonal multiple access (NOMA) schemes, it offers benefits such as low implementation complexity and efficient protocol design, making it more suitable for low-complexity IoT system deployments. Furthermore, by controlling the reflection coefficients of the IoT devices that are not performing backscatter communications, the electromagnetic waveform can be focused towards the IoT devices served in current time slot, compensating for the high path-loss in signal propagation and improving the spectral efficiency. Based on the above analysis, in the RIS-assisted ISABC systems, the RIS equipped on IoT devices can play two different roles. On one hand, they can help improve the DoFs in carrying backscatter information. On the other hand, they can be utilized to reconfigure the propagation environment and enhance the signal received by IoT receiver. Consequently, the corresponding IoT devices are named *Transceiver* or *Helper*, respectively, which are denoted with the same icon with different colors in Fig. 1. Note that

TABLE I
COMPARISONS BETWEEN THE ANTENNA-BASED RIS AND METAMATERIAL-BASED RIS

Categories	Antenna-based RIS	Metamaterial-based RIS
Element Spacing	Half of the wavelength	Much smaller than the wavelength, resulting in mutual coupling
Component Size	Large, not compatible for spacing-limited devices	Thin and small, thus more flexible for IoT devices
Impedance Controlling	Switching the states or structures of the load circuit	Varying the relative permittivity for the functional materials Changing the physical structure of the metamaterial unit Varying the external biasing voltage for the tunable electronic devices
Analytical Tools	Conventional antenna theory and antenna array model	Field theory, Floquet theory, and full-wave simulator

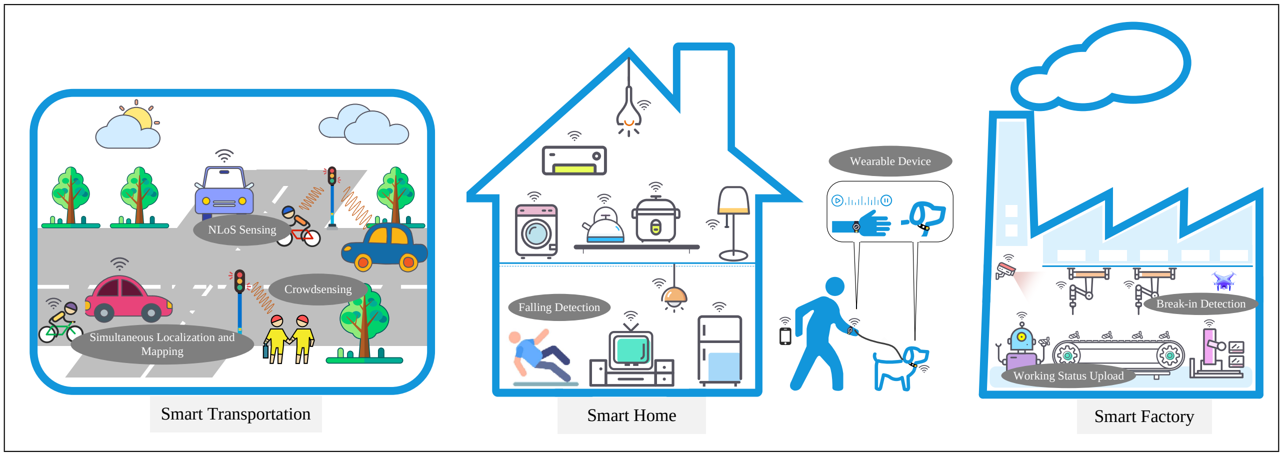

Fig. 2. Potential applications of the RIS-assisted ISABC system.

the role of each IoT device is not fixed. Instead, their roles depend on the scheduling of the whole network.

Compared with conventional mono-static backscatter communication systems, the ISABC systems eliminate the need for a dedicated RF emitter to activate the IoT devices. Instead, IoT devices can leverage the strong electromagnetic waveform radiated by the sensing node. In this way, inter-system interference, i.e., the interference between the signals transmitted by sensing node and dedicated electromagnetic waveform transmitter in backscatter communication systems, can be avoided, and the energy efficiency can be improved. Moreover, in return, IoT devices, especially while working in helper mode, can help enhance the sensing capability by focusing the waveform towards the target or sensing blocked targets. In particular, by cascading the reflecting elements with several receiving antennas, as illustrated in Fig. 1, the IoT devices can also act as distributed radar receivers, providing angle-domain diversity gain.

Several potential applications of the RIS-assisted ISABC system are shown in Fig. 2 and listed as follows:

- **Smart Transportation:** In vehicular communication systems, the sensing functionality can be deployed at the roadside units (RSUs) to help extend the sensing range of vehicles beyond their line-of-sight (LoS) regions. By exploiting ambient sensing signals, the distributed IoT devices can act as extended sensors for crowdsensing and upload environmental information in an energy efficient way, based on which, the ISABC system is able to support simultaneous localization and mapping, thereby facilitating safe driving.
- **Smart Home:** Through deploying ISABC systems at home, the sensing node can recognize and analyse human daily activities and activate the wearable devices to upload health information via backscatter communication. Since the millimeter-wave systems are broadly employed indoors, both antenna-based and material-based RIS can be made tiny. Therefore, leveraging the backscatter communication technique, wearable device can become more portable, and their endurance can be prolonged.
- **Smart Factory:** Two major concerns in smart factories are device status acquisition and break-in detection. The ISABC system can periodically sweep the environment to execute break-in detection. Furthermore, each device can upload its status without actively transmitting signals; thus, the RF chains can be saved, and the cost can be significantly decreased.

III. CRITICAL TECHNIQUES IN RIS-ASSISTED ISABC SYSTEMS

In this section, we discuss some critical techniques in the RIS-assisted ISABC systems, as presented in the ellipses in Fig. 1.

A. Resource Allocation and Scheduling

One critical issue in ISAC systems is to strike a balance between the sensing and communication performance, which is typically achieved through resource allocation. In conventional ISAC systems, communication signals undergo single-trip propagation, while sensing signals compensate for high

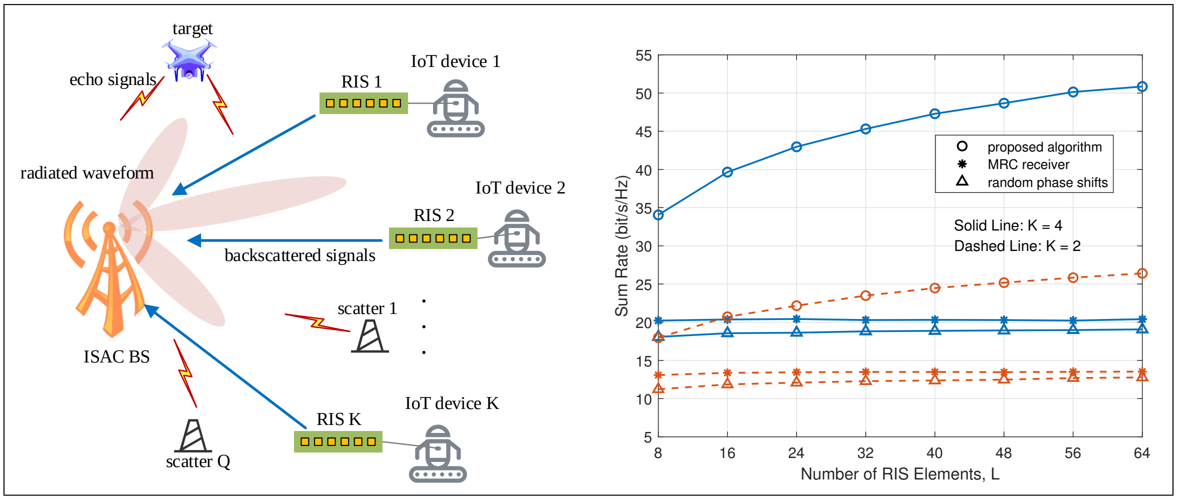

Fig. 3. RIS-assisted integrated sensing and monostatic backscatter communications: System model and sum-rate performance [5].

path-loss due to round-trip propagation. This allows for more power allocation to the sensing functionality. However, the situation changes in the ISABC systems, since the backscatter communication signals also experience round-trip propagation. Therefore, the resource allocation between sensing and communication functionalities need to be adaptively adjusted.

Furthermore, the signal bandwidth required for high-accuracy sensing is typically much larger than that needed for backscatter communications. To support a large number of IoT devices simultaneously with constrained interference, a potential approach is to divide the entire band into several sub-bands and apply the multi-beam technique introduced in [4] to shape beams towards the target and IoT devices respectively. In particular, the fixed beam of all sub-bands can be tuned to the target enabling continuous high-precision parameter estimation. Meanwhile, the dynamic beams of different sub-bands can be adjusted towards different IoT devices, eliminating inter-device interference and improving spectral efficiency.

On the other hand, artificial intelligence provides an efficient method to deal with the issue of resource allocation for a large IoT network. In particular, graph neural networks (GNNs), by modelling communication nodes and channels as graph nodes and edges, has shown its advancements in resource allocation.

Besides the resource allocation, the scheduling among different IoT devices is also of great importance, especially when there exist urgent messages to be uploaded. To address this issue, it is necessary to take both priority and the age of information (AoI) into consideration.

B. *Interference Management*

In IoT networks, one crucial challenge is to deal with the interference among massive IoT devices. Although serving different sets of IoT devices in a time division multiple access (TDMA) manner can reduce interference, serving only one device per time slot is impractical due to low spectral efficiency and high delay. As a result, inter-device interference becomes a concern. Fortunately, with the introduction of RIS as the backscatter device, backscatter communication will benefit from the spatial DoFs. Specifically, in backscatter communication, the mapping between backscatter symbols and the reflecting coefficient matrix allows each symbol to be encoded as a complex sequence of length L. By designing the reflecting coefficients appropriately, orthogonality among different sequences can be achieved, enhancing the detection performance at the receiver.

To show the superiority of employing RIS as the backscatter device in improving the backscatter communication, we take the RIS-assisted ISABC system in [5] as an example, where the ISAC base station simultaneously senses the target and activate IoT devices for backscatter communication, as shown in Fig. 3. To support multi-device transmission, the BS applies different linear receive beamforming vectors to extract each device's signals from the received superimposed signals before demodulation. As can be seen, through jointly designing radiated waveform, reflecting coefficients and receive beamforming vector, the system sum rate can be dramatically improved.

However, in backscatter communication and radar-based active sensing, large round-trip path-loss requires the sensing node's transmit power to be sufficiently high for wide coverage and high accuracy. By viewing one sensing node as well as its activated IoT devices as one "cell", the inter-cell interference in ISABC system would be much larger than that in conventional downlink cellular systems, especially for the "cell-edge" IoT receivers. One potential and efficient way to address this issue is to adaptively adjust the reflecting coefficients of the helper IoT devices to simultaneously improve the desired signal power and suppress the interference, creating a "signal hotpot" and "interference-free zone" in the vicinity of the IoT receivers [6].

C. *Waveform and Reflection Design*

In ISABC systems, while activating the IoT devices to perform backscatter communication, the sensing node also executes sensing tasks based on the received echo signals. However, the high-accuracy sensing requirements may impose strong constraints on the system, reducing the DoFs available for waveform design and potentially degrading communication performance. Focusing on this issue, the authors in [7], [8]

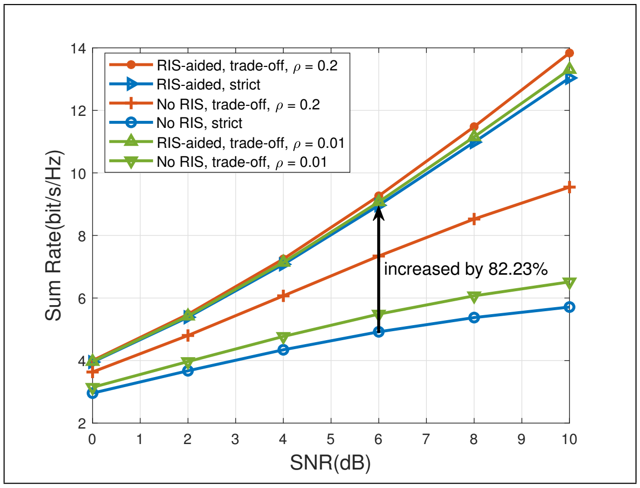

Fig. 4. Sum-rate performance of the RIS-assisted ISAC systems [7].

explored the utility of RIS in enhancing the signal strength at the receiver in a downlink ISAC system. As shown in Fig. 4, through jointly designing the transmit waveform and reflecting coefficients, stronger signals can be forwarded to the users, leading to a sum-rate improvement of over 80%. Similarly, in RIS-assisted ISABC systems, although the sensing node may not form strong beams towards the IoT devices, the reflecting coefficients of helper IoT devices can be adjusted to improve the signal strength at the transceiver IoT devices.

While employing the waveform radiated by sensing nodes as the backscattering carrier, the IoT devices, especially working in helper mode, can also assist in detecting or tracking targets in non-line-of-sight (NLoS) area of the sensing node. Note that the severe path-loss over multiple hops, i.e., sensing node (SN)-RIS-target-RIS-SN, may lead to extremely low echo signal-to-noise ratio (SNR) and poor sensing performance. To address this issue, a dedicated receive array can be deployed along with the RIS, such that distributed IoT devices can assist in handling the sensing tasks based on the received echo signals. This approach is often referred to as the *self-sensing* RIS architecture, and we refer readers to [9] for more details.

D. Distributed Signal Processing

Restricted by limited hardware cost and resources, the computing capability of a single IoT device may not be sufficient to support high-accuracy NLoS target localization. Therefore, one critical technique is to exploit the massive IoT devices to boost distributed signal processing. For example, distributed IoT devices may receive the echo signals, and execute low-complexity local pre-processing. The processing results can then be uploaded via RIS-assisted backscatter communications. Subsequently, more efficient artificial intelligence (AI) based techniques can be introduced to achieve sensing information fusion. One promising approach is to employ the federated learning (FL) framework to train intelligent learning models for IoT devices in a distributed manner [10].

In the FL framework, the IoT devices can firstly train their local sensing models, which include neural network weights, based on the pre-processed results of the received echo signals. Thereafter, these local sensing models can be uploaded to the sensing node through backscatter communications. The sensing node can then compute a global sensing model by aggregating and processing the uploaded local models from multiple IoT devices. This global sensing model is then used to update the local sensing models for each IoT device. Through iteratively updating the global and local sensing models, an efficient distributed sensing model can be established, benefiting from the collective intelligence of the IoT devices. Compared with the conventional distributed wireless sensor network, the size of information to be shared can be significantly reduced, improving the network efficiency.

E. Ambient Backscatter Communication Transceiver Design

In the ISABC systems, the IoT devices exploit the ambient sensing signals from sensing nodes as the RF carrier for backscatter transmission. Consequently, the IoT receiver receives two types of signals: the direct-link signals from the sensing node and the backscattered signals from the IoT devices. Although the direct-link signals do not contain any backscattered information, they are essential for demodulating the backscattered information from the received backscattered signals. On the other hand, the backscattered signals are weaker due to two-hop fading, making it possible to extract the direct-link RF carrier from the received superimposed signals and perform interference cancellation to obtain a clean version of backscattered signals for demodulation. The direct-link interference cancellation mechanism was investigated in [11] with digital video broadcasting (DVB) signals as the RF carrier, demonstrating successful recovery of the direct-link interference with an interference cancellation ratio of up to 50 dB.

In contrast to communication systems, radar based sensing systems aim at extract the target's information from the echo signals. Therefore, the sensing waveform typically contains no information, making it simple to estimate and reconstruct the RF carrier. However, in some cases, multiple-input multiple-output (MIMO) radar may adopt phase-coded sequences to constitute the transmit waveform, achieving orthogonality among the signals transmitted by different antennas and higher DoFs. In this case, fast changing radar waveform may not be perfectly estimated and reconstructed, leading to residual interference after interference cancellation, which can affect the demodulation performance of backscattered signals. To address this issue, the reflecting coefficients can be appropriately designed to enhance the backscatter link or suppress the direct-link interference. Nevertheless, it is crucial to find a balance between the power of backscattered signals and direct-link signals. Overly suppressing the direct-link signals may degrade their estimation and reconstruction performance, leading to a negative impact on demodulation.

IV. Challenges and Future Research Directions

Implementing the proposed RIS-assisted ISABC system for future IoT networks faces several major challenges, which also mean great research opportunities. We briefly discuss these challenges and potential solutions in the following.

A. Network Synchronization

In plenty of existing works, the RIS is assumed to be deployed at the surface of the building or roadside unit to help enhance the signal quality. In this case, the synchronization between the RIS and transmitter can be achieved via cables. However, in ISABC systems, employing IoT devices equipped with RIS as helpers poses challenges related to synchronization, as these devices are not directly connected to the transmitter. Accurate synchronization among distributed IoT devices is crucial to exploit the diversity gain in cooperative target sensing. To achieve centimeter-level resolution accuracy, the synchronization errors among different clocks need to be less than tens of picoseconds, as specified in [12]. Imperfect synchronization can result in timing offset and carrier frequency errors, leading to ambiguity in delay and Doppler estimation.

B. Security Issue

While the IoT devices execute backscatter communications, there is a concern about potential eavesdropping of the backscattered signals. In conventional cellular communication systems, encryption techniques are often used to secure the communication link. However, due to the cost-effectiveness of IoT devices and the large number of devices in the network, applying complex encryption operations and sharing secret keys might not be practical.

To address this issue, the sensing-assisted secure communication technique proposed in [13], [14] can be employed, where the extended Kalman filtering technique is utilized to capture the motion characteristics of the aerial eavesdropper. With the help of the IoT devices acting as helpers, the sensing node can efficiently detect and track any illegal nodes or eavesdroppers in the ISABC system. To protect the backscattered messages, especially those containing confidential information, from being eavesdropped, the sensing node can transmit artificial noise towards the potential eavesdroppers. Nevertheless, it is important to design the transmitted artificial noise carefully to avoid affecting the legitimate reception of backscattered signals at the intended IoT receiver. Since the signal power received at the IoT receiver is much weaker than that at the eavesdropper, the artificial noise should be adjusted to provide a secure communication link while ensuring that the legitimate IoT receiver can still reliably demodulate the backscattered signals.

C. Symbiotic Sensing and Communication

In the ISABC systems, the helper IoT devices can play a crucial role in sensing the targets located in NLoS regions by reflecting the incident signals towards them. However, such sensing-oriented design may lead to destructive superposition of the direct link and reflective link at the transceiver IoT devices. Facing this issue, One may ask if the IoT devices can help execute NLoS sensing while backscattering information signals towards the IoT receiver over the sensing signals, resulting in a symbiotic sensing and backscatter communication system, as shown in Fig. 5.

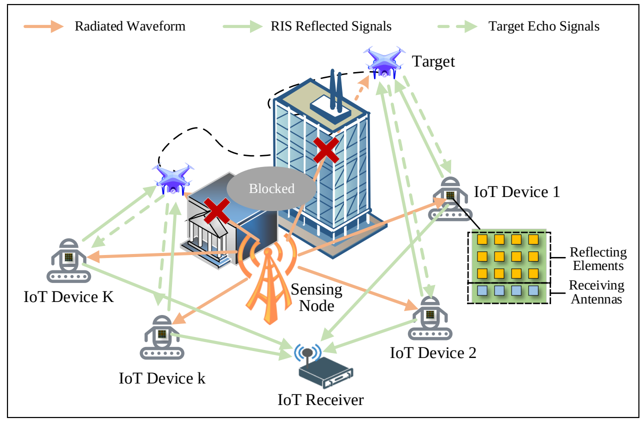

Fig. 5. An illustration of the symbiotic sensing and backscatter communication systems.

In this symbiotic system, there exists a trade-off between the sensing and communication signals in reflecting coefficients design. Compared with the symbiotic communication systems in [15], where the IoT device simultaneously acts as transceiver and helper, the implementation complexity of the symbiotic sensing and communication system is lower. This is because the sensing signals contain no information, and the aim of the primary system, i.e., the sensing system, is to execute target parameter estimation based on the echo signals. However, implementing a distributed sensor network using IoT devices does pose some challenges. The IoT devices need to extract the weak echo signals from the strong direct-link incident signals via advanced interference cancellation techniques. This requires robust signal processing and interference mitigation algorithms to effectively separate and extract the desired sensing signals from the received mixed signals.

D. Energy Harvesting

Facing the limited battery storage of IoT devices, radio frequency energy harvesting has been considered as a promising technique to extend their battery life. However, compared with the information receivers, the sensitivity required for the energy harvesting circuit is higher, and the changes of environment as well as the mobility of IoT devices may lead to fluctuations in energy transfer. Moreover, a low energy transferring efficiency may further degrade the harvesting performance. To address this issue, the energy source, i.e., the sensing node, can make use of its sensing capability and strong radiated power, to capture these changes, and shape sharp beams towards the IoT devices. Nevertheless, note that the sensing node cannot simultaneously transfer energy to all of the massive IoT devices. Therefore, an efficient scheduling scheme should be designed with the priority as well as the dump energy of each IoT device.

V. Conclusion

In this article, we provided a new concept of the RIS-assisted ISABC system for future IoT networks. By employing RIS as either helper or transceiver, we aim to enhance sensing and communication performance and facilitate distributed

NLoS sensing. We introduced the RIS-assisted ISABC framework by presenting the system architecture and discussing three potential applications in future IoT networks. We also discussed the research progress on several critical techniques, including resource allocation, interference management, waveform and reflection design, distributed signal processing, and ambient backscatter communication transceiver design. Finally, we analyzed potential challenges and future research directions. With its capability and feasibility to support energy-efficient communications and seamless sensing, the RIS-assisted ISABC system is expected to become one of the key enabling techniques for future IoT networks.

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