Received 6 June 2020; revised 10 July 2020; accepted 17 July 2020. Date of publication 28 July 2020; date of current version 17 August 2020.

Digital Object Identifier 10.1109/OJCOMS.2020.3012466

Large-Scale Wireless-Powered Networks With Backscatter Communications—A Comprehensive Survey

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ABSTRACT Massive and ubiquitous deployment of devices in networks of fifth generation (5G) and beyond wireless has necessitated the development of ultra-low-power wireless communication paradigms. Recently, wireless-powered networks with backscatter communications (WPN-BCs) has been emerged as a most prominent technology for enabling large-scale self-sustainable wireless networks with the capabilities of RF energy harvesting (EH) and of extreme low power consumption. Therefore, we provide a comprehensive literature review on the fundamentals, challenges and the on-going research efforts in the domain of WPN-BCs. Our emphasis is on large-scale networks. In particular, we discuss signal processing aspects, network design issues and efficient communication techniques. Moreover, we review emerging technologies for WPN-BCs to bring about the best use of resources. Some applications of this innovative technology are also highlighted. Finally, we address some open research problems and future research directions.

INDEX TERMS Backscatter communication systems, wireless-powered networks, large-scale communication systems, IoT networks, and massive machine type communications.

I. INTRODUCTION

THE PERVASIVE application of Internet-of-Things (IoT) and massive machine type communications to connect a large number of small computing devices (associated with people, vehicles, environment and other factors) embedded in the environment and implanted in bodies, have attracted tremendous attention in the 5G mobile communication networks. In order to keep a massive number of energy-constrained IoT sensors alive for tasks such as continuous monitoring and controlling, uninterrupted supply of energy is essential for the sensors and controlling/computing devices. This issue poses key design challenges for IoT, i.e., batteries increase the devices' form factors and their recharging and replacement cause high cost. Moreover, it is sometimes hazardous or even impossible to recharge/replace the batteries, since a large number of sensors may be hidden or deployed in a perilous environment [1]–[4]. To resolve these issues and also due to the size and the design constraints of sensors and devices, equipping nodes with distinct power sources is one promising solution. Thus, radio frequency (RF) energy harvesting (EH) methods have been proposed as a cost-effective solution to mitigate the energy issue in energy-constrained wireless networks by exploiting alternative forms of energy resources [5]. However, the power consumption of RF-powered active communication is relatively high and is challenging specially for large-scale IoT deployments. Tackling these major challenges has initiated increasing research interests on the design of large-scale self-sustainable wireless networks with the capabilities of EH and of extreme low power consumption.

Recently, significant interest in backscatter communications systems (BCSs) for low-power wireless communications has emerged. BCSs are simply based on passive reflection and modulation of incident signals from external

RF sources by adapting the level of antenna mismatch to vary the reflection coefficient and harvest energy from the signal for operating the circuit [2], [6]. A backscatter node has no active energy hungry RF components such as oscillators and analog-to-digital converters (ADCs) and hence it can be miniaturized with extremely low power consumption; a backscatter node consumes power orders-of-magnitude less than a conventional radio (in the order of 10 μW) [7]. Therefore, the integration of EH methods and low-power backscattering communication enables passive IoT deployment at a flexible location or even an in-body implantation [8].

A. ENERGY HARVESTING

To extend the lifetime of network devices, EH has attracted an upsurge of research interests due to its numerous new opportunities and promising features for energy-constrained wireless networks (e.g., wireless sensor networks (WSN) and IoT); no wire, no contacts, no batteries, genuine mobility and predictable, dedicated and reliable energy supply [9], [10]. As shown in Fig. 1, EH can be categorized into three different types:

- Wireless power transfer (WPT)
  In this scheme, a dedicated power transmitter transmits energy to the users and it does not transmit information simultaneously. Thus, the emphasis of the system design is to exclusively deliver energy over the wireless channel Fig. 1(a). Some practical applications of such designs include home electronics, medical implants and electric vehicles [11].
- Wireless-powered communication networks (WPCNs)
  In this scheme, energy is transferred in the downlink and information is transferred in the uplink – Fig. 1(b). A protocol to enable this process is named harvest-then-transmit (HTT) [12]; the low-power users harvest energy in the downlink from the power transmitter, and actively transmit data in the uplink using their harvested energy. With the help of this protocol, wireless devices can be developed for applications such as IoT and WSNs [13], [14].
- Simultaneous wireless information and power transfer (SWIPT)
  In this scheme, energy and information are transferred simultaneously via a common signal in the downlink to user devices [15], [16] – Fig. 1(c). The power transmitter transmits a modulated waveform, from which a target user device harvests energy and demodulates information bits. The energy receivers and the information receivers can be co-located or separated. In SWIPT with co-located receivers, each low-power user device receives information and energy, simultaneously.

The integration of wireless power and information transfers, as a powerful means for powering energy-constrained wireless devices, spawn new challenges and opportunities. Extensive research efforts have thus been expended on various aspects of EH-enabled communication systems from both technical and theoretical perspectives including fundamental limits, design challenges, transmission techniques, network architecture, hardware impairments, scheduling and medium access control (MAC) [9], [16]–[18].

Despite its rapid advancement from both theoretical and technical perspectives and also its numerous and undeniable advantages, EH technology still faces many realization hurdles in large-scale low-cost and low-power networks, e.g., WSNs and IoT. For instance, with the HTT protocol, by wireless energy transfer in the downlink and wireless information transmission in the uplink, we find the doubly near-far problem; i.e., the user located near the hybrid access point (H-AP) can gain more energy than the far users, hence the far users suffer from less amount of harvested energy and uplink throughput degradation than near users due to doubly distance-dependent signal attenuation [19]. The problem of the double near-far phenomenon has been attacked in [12], [20], [21]. For instance, [12] proposes a common throughput maximization scheme, which allocates equal rates to all users regardless of their distances from the H-AP by allocating the transmission time to users inversely proportional to their distances to the H-AP. However, this scheme severely degrades the overall network performance in terms of fairness. Besides, the methods given in [20], [21], which study user cooperation to alleviate the doubly-near far problem, are not applicable for large-scale wireless networks due to their undue complexity. The doubly-near far problem also limits the far users when they want to send urgent data, as those users may require a long time to harvest enough energy to transmit data [22]. SWIPT enabled device-to-device (D2D) communication and its scheduling also need to be further addressed [17], [18]. Moreover, active RF transmission architecture contains power-hungry RF chain having oscillators, mixers, ADC, which results in non-compacts form factors and high power consumption. This issue is challenging specially for large-scale wireless networks, e.g., massive IoT devices.

BCSs, low complexity and low-power devices without active RF component, is a promising solution to sustain massive IoT devices and to tackle the above challenges [7], [19]. Since BCSs operate in passive mode by reflecting the carrier signal rather than active transmission, it can resolve the doubly near-far problem in HTT by enabling a long-range communication with low power consumption. Moreover, since it depends on instantaneous excitation energy, it does not require a dedicated time for EH, thereby, making urgent transmission possible even for far users from the H-AP [8]. Therefore, backscatter communication is a key facilitator for low-rate, low-power and large-scale wireless communication systems with EH.

B. BACKSCATTER COMMUNICATIONS

In this system, a sending device - a backscatter transmitter - modulates and reflects received RF signals in order to transmit data instead of generating RF signals by itself [24]–[26]. The backscatter transmitter, also called a

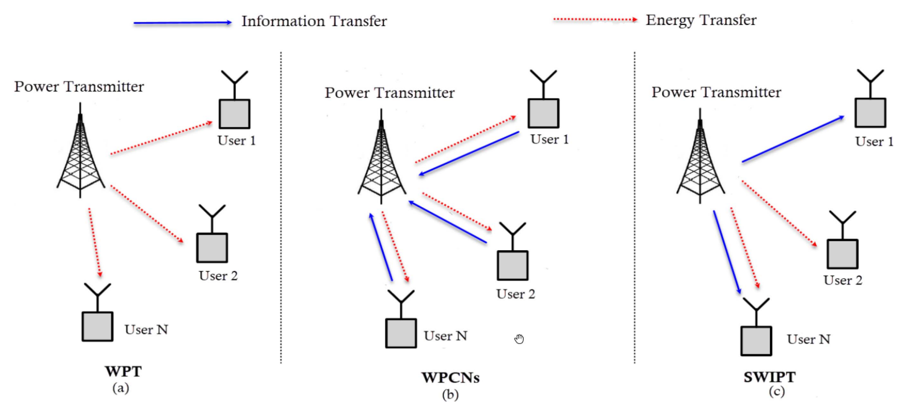

FIGURE 1. **Paradigms for EH systems [7].**

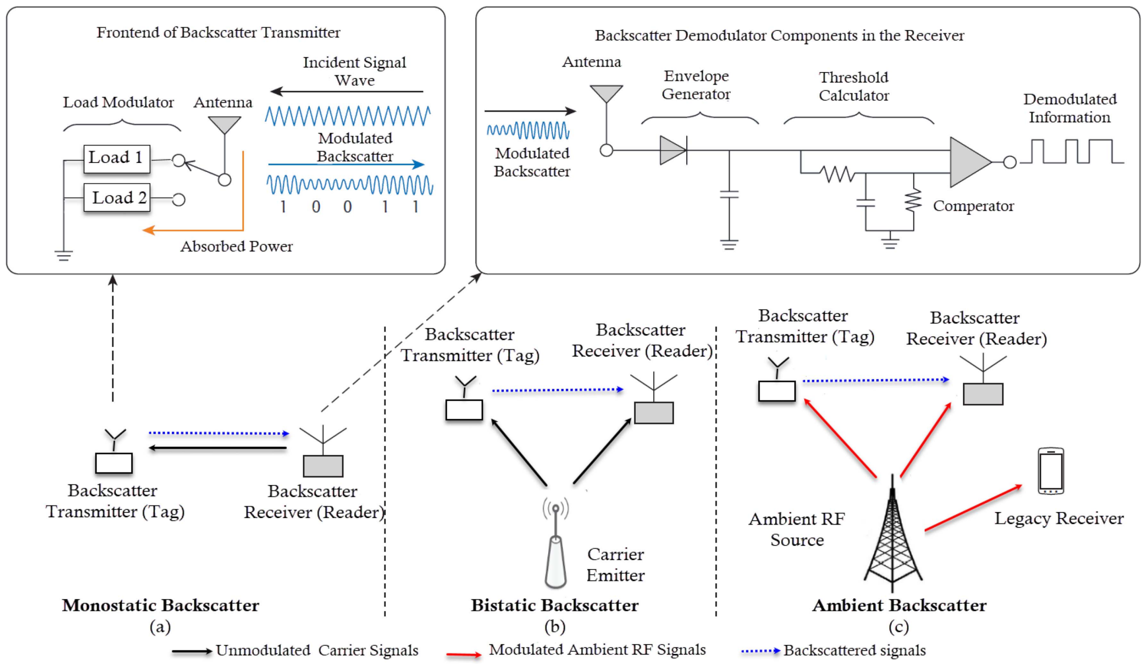

FIGURE 2. **Paradigms for backscatter communications [23].**

tag, maps a sequence of digital symbols on to the RF backscattered waveform. In particular, initiating their own RF transmissions as conventional wireless systems, a tag is a passive node that harvests energy from an incident RF signal to support its operation and send data to a backscatter receiver, i.e., reader, just by adjusting its antenna impedance to reflect the received RF signals. This process is known as load modulation [8], [23], [27], [28]. A diagram of a tag with binary load modulation is given in Fig. 2. The tag has two loads with the impedance intentionally matching and mismatching with the antenna impedance, respectively. The tag transmits its binary symbols to the reader through choosing whether to backscatter the RF incident signal or not by adjusting the load impedance of its antenna, where symbol "0" and "1" correspond to a non-backscattering (absorbing state) and a backscattering (reflecting state), respectively [29]. The reader, with its own power supply and a full set of conventional RF components, will then decode tag's transmit symbols. In the reflecting state, the reader will observe a superposition of the original RF incident signal and the tag backscattered signal. Whereas, in the absorbing state, the reader will only observe the original RF signal. These states are then interpreted as information bits. The diagram of a binary amplitude demodulation based on envelope detection at the receiver is given in Fig. 2.

In general, BCSs can be classified into monostatic backscatter communications systems (MBCSs), Bistatic backscatter Communication systems (BBCSs), and Ambient backscatter Communication systems (ABCSs) – Fig. 2. Among these, ABCSs have recently drawn much interest due to their ease of implementation.

- Monostatic Backscatter communications systems: An MBCS consists of a backscatter transmitter and a reader

– Fig. 2 (a) [23], [30]. The reader has co-located an RF source and a backscatter receiver. The RF source generates RF signals to activate the tag. The backscatter transmitter (tag) modulates and reflects these RF signals to transmit its data to the backscatter receiver. As the RF source and the backscatter receiver are co-located (reader), the backscattered signals incur a round-trip path loss [31]. Thus, MBCSs suffer from doubly near-far problem. That is, due to the signal loss from the RF source to the backscatter transmitter, and vice versa, if a backscatter transmitter is located far from the reader, it can experience a higher energy outage probability and a lower modulated backscatter signal strength [19]. However, MBCSs are mainly adopted for short-range applications, e.g., radio frequency identification (RFID) [32], [33], which is the prominent commercial application of backscatter radio. In a typical RFID system, an RFID reader interrogates the RFID tag for the desired information such as an identification number. Generally, RFID tags can be passive, active of semipassive. Of these, passive tags have received more emphasis due to their battery-less structure. They rely on the RF signal transmitted by the RFID reader and backscattering for EH and information transmission, respectively [32], [33]. This traditional setup however may not be suitable for massive IoT devices, since typical nodes are power-constrained and may fail to wirelessly power other nodes for communication over long distances [2].

- Bistatic Backscatter Communications Systems: In a BBCS, proposed in [31], the RF source, i.e., the carrier emitter, and the backscatter receiver are separated - Fig. 2 (b). The carrier emitter generates the carrier signal which is detached from the reader to overcome the limited range of power-up link of a MBCS (e.g., RFID tag). This configuration can also avoid the round-trip path loss experienced in MBCSs. Additionally, the performance of the BBCS can be improved dramatically by placing carrier emitters at optimal locations. Specifically, one centralized backscatter receiver can be located in the field while multiple carrier emitters are well placed around backscatter transmitters. Consequently, the overall field coverage can be expanded. Moreover, the doubly near-far problem can be mitigated as backscatter transmitters can derive unmodulated RF signals sent from nearby carrier emitters to harvest energy and backscatter data [19]. Although bulky and deployment costly, carrier emitters and backscatter receivers of BBCSs can be cheaper than that of MBCSs due to the simple design of the components [23].
- Ambient Backscatter Communications Systems: ABCS is an idea based on BBCSs philosophy which was developed to communicate with wireless devices nearby without using any energy supply or storage device [34], [35]. In an ABCS, the tag utilizes modulated ambient RF signals, e.g., signals from TV towers, cellular base stations (BSs), and Wi-Fi APs instead of using unmodulated dedicated RF signals (e.g., BBCSs) - Fig. 2 (c). Ambient RF sources can be classified into static and dynamic types [36], [37]. Static ambient RF sources constantly transmit high-power signals, e.g., TV towers and FM radio BSs, whereas, dynamic ambient RF sources such as Wi-Fi APs operate periodically or randomly with typically low transmit powers. The use of existing RF sources confers ABCSs with some advantages [35]. First, it eliminates the need to deploy and maintain dedicated RF sources, which inevitably reduces the cost and energy consumption. Second, it also means that ABCSs do not need new frequency spectrum allocation, and thus the spectrum resource utilization improves. However, the use of modulated ambient RF signals has some disadvantages. First, they are unpredictable and dynamic, and act as direct interference to backscatter receivers, which limits the performance of an ABCS, unlike unmodulated ones of the BBCS, which can easily be eliminated before backscattered signal detection. Second, since the parameters of ambient RF sources (e.g., transmission power and locations) are not controllable, the design and deployment of an ABCS to achieve optimal performance can be challenging. In particular, although static RF sources may provide predictable RF energy, long-term and short-term fluctuations due to service scheduling are possible [36]. On the other hand, dynamic ambient RF sources operate periodically and their power may change over time. Moreover, since an ABCS can not function when RF sources are far off, searching for available opportunities in a certain frequency range is required to utilize ambient RF sources [23]. Therefore, this setup is not scalable due to its dependence on other networks as energy resources and thus may fail to meet the requirements of massive IoT devices. ABCSs are mainly categorized into three types based on their configurations. The first category is the traditional ABCSs (TABCSs) with detached backscatter receiver and ambient transmitter (and its legacy receiver) [8], [29], [38]–[45]. Strong direct interference from the ambient transmitter received at the backscatter receiver is the most challenging issue in this setup. This direct-link interference can be avoided with the help of frequency shift methods to isolate the spectrum of the backscattered signal from the spectrum of the direct-link signal [38]. However, the frequency shift operation imposes higher requirements on device hardware. Maximum-likelihood (ML) based detection methods are also employed to detect the tag's information and the direct-link interference is treated as a part of noise [29], [46]. These methods, however, works well when the backscattered signal strength is comparable to that of direct-link interference. Some studies also assume that the legacy system employs orthogonal

frequency division multiplexing (OFDM) and mitigates the direct-link interference by exploiting some structural properties of the modulation format [39]. In [41], the noncoherent ML detection problem is formulated and solved for a general Q-ary backscatter signal over ambient OFDM modulation, where the direct-link interference is treated as an unwanted signal and modeled as a random process that is correlated to the useful backscatter signal. Furthermore, a multi-antenna receiver can mitigate the direct link-interference by employing receive beamforming and also by constellation learning based methods [40], [43]. The second category of ABCSs is the cooperative ABCSs (CABCSs) where the backscatter receiver and the legacy receiver are co-located [60]–[65]. In this setup, despite TABCSs, the signals from the ambient transmitter are recovered and decoded at the backscatter receiver. In [60], the achievable rate region of such setup is analyzed and it is shown that the rate region is strictly larger than that of the conventional time-division-multiple access (TDMA) scheme, i.e., in each time slot, either the information from the ambient transmitter or the tag is received. Moreover, the optimal ML detector, sub-optimal linear detectors and the successive interference cancellation (SIC) based detectors are derived in [61]. In [62], the sum rate of the backscatter communication and the legacy communication is investigated with perfect and imperfect channel knowledge, where a linear minimum mean square error receiver with SIC is utilized for joint decoding. In this configuration, the nodes are equipped with multiple antennas. In [63], the sum rate is analyzed for SIC based decoding, and a problem is formulated to maximize the sum rate by optimizing the beamforming vector at the multi-antenna ambient transmitter. In addition, in [64], upper bounds of the ergodic rates for both links, i.e., backscatter communication and the legacy communication, are derived considering a multi-antenna cooperative receiver which separately decodes the signals from a multi-antenna ambient transmitter and a single-antenna tag. Recently, [65] has investigated resource allocation for the CABCSs with a finite block-length backscatter link. The average achievable rate of the direct and backscatter links are derived and transmit power minimization and the energy efficiency maximization problems are formulated and solved to design the transmit beamforming vector. The third category of ABCS is full-duplex ABCSs (FABCSs) where the backscatter receiver and the ambient transmitter are co-located; therefore, the signals from the ambient transmitter can be cancelled out [3], [44], [66]–[68]. In [44], the capacity performances of both the backscatter communication and the legacy communication over OFDM carriers are investigated and the asymptotic capacity bounds are derived in closed-form for the case of sufficiently large number of subcarriers. Moreover, in [3], a FABCS is designed where a Wi-Fi AP can receive the backscattered signal while simultaneously transmitting Wi-Fi packets to its legacy client. A general FABCS is considered in [66], where unlike [3], [44], multiple tags backscatter information to the full-duplex AP. Specifically, the full-duplex AP transmits downlink signal which consists of not only information to the legacy user but also energy to multiple tags; while all the tags simultaneously backscatter information to the full-duplex AP using the TDMA protocol. Moreover, in [67], the throughput maximization of a full-duplex-enabled cognitive backscatter network is investigated via joint time scheduling, transmit power allocation, and reflection coefficient adjustment, such that the minimum rate requirements of the primary system is guaranteed. In this configuration, an ABCS underlays a primary cellular system, and the primary AP can transmit primary signals and receive backscatter signals simultaneously via full-duplex communications. The authors in [68] further focused on MAC-layer in addition to physical-layer and investigated cross-layer outage capacity for FABCSs where multiple full-duplex mobile users attempt to send packets to the AP according to the carrier sense multiple access/collision avoidance (CSMA/CA) protocol while receiving the information from their respective associated backscatter devices.

C. CONTRIBUTION AND ORGANIZATION

EH and backscatter communications enable self-sustainable, large-scale, low-power and low-cost wireless networks, e.g., WSN and IoT. Although, each technology has its own pros and cons, neither of them can separately meet all the requirements of large-scale communication systems. The integration of these two technologies effectively inherits the advantages of both techniques and can actually be the solution to build up totally passive massive WSNs [69]. They complement each other to overcome the challenges of each technology, thereby leading to considerable improvements in the performance of large-scale dense IoT deployments, i.e., increased range and throughput, low-power design, scalability, reuse of ambient signals, low-cost, low-complexity and easy-to implement communications, as the key requirements of massive IoT devices. Wireless-powered networks with backscatter communications (WPN-BCs) have attracted tremendous attention from both academia and industry as the key facilitator for IoT deployment, an important part of the new generation of information technology.

Significant research efforts have been expended on the field of WPN-BCs, with the discovery of practical advantages and solutions to many problems and research potentials. Along the way, there have been several outstanding surveys and tutorials that review wireless-powered networks and backscatter communications separately with very limited discussions on their integration [7], [13], [14]. To the best of our knowledge, no contributions have been reported

TABLE 1. Some of the literature reviews on the related domains of EH and backscatter communications.

Article	Focus	Contribution
Energy Harvesting		
[14], [16], [36], [47]–[49]	EH systems	- Information theoretical aspects, protocol design - Network model and the transceiver structures - Hardware implementation, resource allocation - Beamforming for multi-antenna EH systems - Exploiting interference for wireless EH - Promising trends for performance enhancement - Applications to wireless communications
[13], [50]	WPCNs	- Basic components and network models - Performance-enhancing techniques - Application, architecture, and standards
[9], [17], [18], [51]–[55]	SWIPT	- Physical layer security - Integral aspects of SWIPT and Cooperative relay - Hardware realization of rectenna circuits - Potential emerging technologies for 5G - Energy harvester models and technical issues - Smart antenna technologies - Receiver structures
[56]	EH-IoTs	- Commercial and standard activities - Emerging communication techniques - Context sensing from EH patterns - Intermittent computing
Backscatter Communications		
[32]	RFID	- Types of tags and their operation - Regulations and frequency ranges
[8], [57]	BCSs	- Basic principles - Existing BCSs and network architectures - Emerging advanced techniques - Applications with the emphasis on IoT
[7], [58], [59]	ABCSs	- Fundamentals of backscatter communications - Signal processing and signal detection schemes - Communication techniques - Applications and challenges

in the direction of providing a comprehensive review of the integral aspects of wireless-powered networks and backscatter communications. Our survey thus aims to fill this gap and add to the current literature. Motivated by this aspect, unlike the existing surveys on backscatter communications, we will also thoroughly address the deployment issues, waveform and energy harvester design, distributed MAC protocols, artificial intelligence based approaches and security issues in the domain of WPN-BCs, as the key features aimed at fostering 5G and beyond networks. Table 1 shows some of the literature reviews on the related domains of EH and backscatter communications.

This paper mainly focuses on the integral aspects of wireless-powered networks and backscatter communications with the emphasis on large-scale analysis. A comprehensive overview of the research and technological development on the architecture, protocols and applications of WPN-BCs is provided (Fig. 3).

Some of the contributions of this paper are as follows:

- The focus is not only given to wireless-powered networks and backscatter communications individually, but also emphasizes their integrated usages and applications.
- Basic principles and advanced design and communication techniques related to WPN-BCs are discussed with the emphasis on large-scale networks.

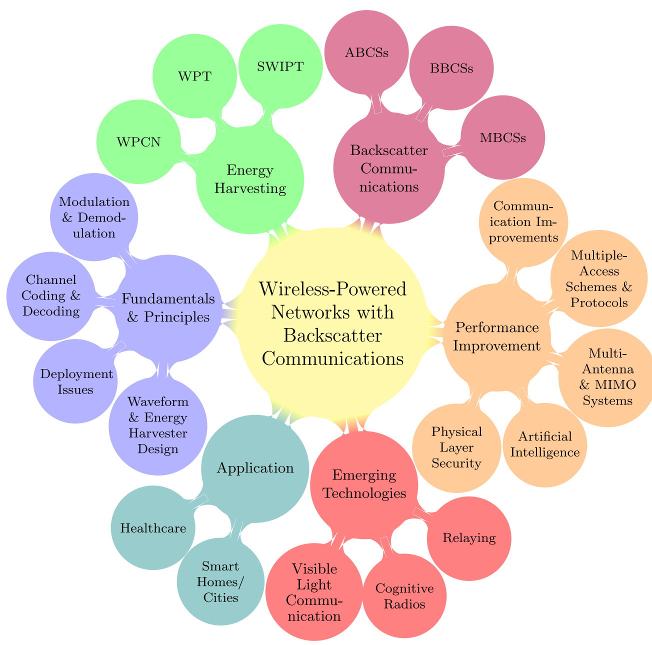

FIGURE 3. Outline of the main contributions of this survey.

- Open issues, challenges, and future research directions for WPN-BCs are mentioned.

The rest of the paper is organized as follows. We first discuss the fundamentals of WPN-BCs, including both

TABLE 2. List of abbreviations.

Abbr.	Content	Abbr.	Content
ABCSs	Ambient backscatter Communication systems	NOMA	Nonorthogonal multiple access
ASK	Amplitude shift keying	NRZ	Non-return-to-zero
BBCSs	Bistatic backscatter Communication systems	OFDM	Orthogonal frequency division multiplexing
BCSs	Backscatter communications systems	OMA	Orthogonal multiple access
BS	Base station	OOK	On-off keying
CABCSs	Cooperative ambient backscatter communication systems	PB	Power beacon
CRNs	Cognitive radio networks	PSK	Phase shift keying
CSI	Channel state information	PT	Primary transmitter
CSMA/CA	Carrier sense multiple access/collision avoidance	QAM	Quadrature amplitude modulation
D2D	Device-to-device	QoS	Quality of service
EH	Energy harvesting	RFID	Radio frequency identification
FABCSs	Full-duplex ambient backscatter communication systems	SIC	Successive interference cancellation
FSK	Frequency shift keying	SINR	Signal-to-interference-plus-noise ratio
5G/6G	Fifth/Sixth generation	SNR	Signal-to-noise ratio
H-AP	Hybrid access point	ST	Secondary transmitter
HTT	Harvest-then-transmit	SWIPT	Simultaneous wireless information and power transfer
IoT	Internet-of-Things	TABCSs	Traditional ambient backscatter communication systems
MAC	Medium access control	TDMA	Time-division-multiple access
MBCSs	Monostatic backscatter communications systems	WPCNs	Wireless-powered communication networks
MIMO	Multiple-input multiple-output	WPN-BCs	Wireless-powered networks with backscatter communications
ML	Maximum-likelihood	WSN	Wireless sensor networks

backscatter communications and wireless-powered networks in Section II. It discusses signal processing aspects including modulation, signal detection schemes and channel coding. Network design issues, i.e., deployment of WPN-BCs and waveform and energy harvester design are also outlined. In Section III, a summary of the research works aiming to address the challenges of such networks and improve their performance is provided. Efficient communication techniques including performance optimization, scheduling and resource allocation along with multiple-antenna systems, multi-access, artificial intelligence techniques and security issues are explained and discussed. Emerging wireless-powered backscatter systems are reviewed in Section IV. Some applications of WPN-BCs are shown in Section V. Section VI addresses the open issues and future research directions of WPN-BCs. Finally, we conclude the paper in Section VII. The abbreviations used in this article are summarized in Table 2.

II. PRINCIPLES OF WIRELESS-POWERED BACKSCATTER SYSTEMS

WPN-BCs inherit the fundamental and operational mechanisms of wireless-powered networks and backscatter communications. Comprehensive literature reviews on the fundamentals of these two emerging technologies can be found in [7]–[9], [13], [16], [36], [58]. In this section, we thus mainly focus on modulation and channel coding techniques, as the two important aspects of wireless communication systems, applicable to WPN-BCs. In addition, network design issues, i.e., deployment of WPN-BCs and waveform and energy harvester design are discussed in detail. The key features of designing large-scale WPN-BCs are also emphasized.

A. MODULATION AND DEMODULATION

For efficient data transmission in BCSs, different modulation techniques including amplitude modulation, i.e., amplitude shift keying (ASK) [31], [70], [71], differential modulation [72], quadrature amplitude modulation (QAM) [73]–[76], and frequency modulation, i.e., frequency shift keying (FSK) [31], [71], [77], Gaussian frequency shift keying (GFSK) [79], minimum-shift keying (MSK) [78], have been used. Phase modulation, i.e., phase shift keying (PSK), has also been adopted in BCSs [3], [73], [80]. A good summary of these modulation schemes and their applications is provided in [7], [58].

Table 3 briefly summaries the advantages and disadvantages of popular modulation schemes in backscatter communications systems. In general, ASK provides continuous power to backscatter transmitters and the receiver design is simple [81]. However, it is sensitive to noise and interference [82]. On-off keying (OOK) is the simplest type of amplitude modulation based on ASK, which is used to increase the range in backscatter communications [31], [71]. Coherent demodulation of requires channel estimation, but it will add complexity to the receiver and also results in overheads in terms of pilot/ training sequence transmissions. Thus, resources such as bandwidth and power can be consumed excessively in the process of demodulation. To mitigate these issues, differential modulation techniques conveys the information in the difference between two consecutive symbols. This assumes a quasi-static channel, which remains constant over two symbol periods. Thus, differential modulation is used to address the signal detection problem in ABCSs [72].

In order to increase the spectral efficiency of data transmission, QAM can be used, which combines two amplitude-modulated signals to double the effective bandwidth [71], [73], [74]. It maintains data throughput equal to ASK or PSK by using a frequency equal to the symbol rate. However, QAM is susceptible to the noise which results in normalized power loss [3]. FSK is resilient to the noise and signal strength variation but the spectrum of this modulation type doubles that of the ASK modulation [7]. FSK modulation is mainly used for BBCSs to extend the

TABLE 3. Summary of modulation schemes.

Modulation		Advantages/Disadvantages
Amplitude Modulation	ASK [31], [70], [71]	- Provide continuous power to backscatter transmitter and the receiver design is simple. - Sensitive to noise and interference. - OOK is based on ASK, which is used to increase the range in backscatter communications.
	Differential Modulation [72]	- Noncoherent detection can be deployed to bypass the requirement of channel information. - Bit-error-rate may be increased. - It is used to address the signal detection problem in ABCSs.
	QAM [71], [73]–[76]	- It maintains data throughput equal to ASK or PSK by using a frequency equal to the symbol rate. - It is susceptible to the noise which results in normalized power loss. - It is used to double the effective bandwidth.
Frequency Modulation	FSK [31], [77]	- It is resilient to the noise and signal strength variation. -The spectrum of this modulation type doubles that of the ASK modulation. - It is mainly used for BBCSs to extend the communication range and coverage.
	MSK [78]	- A special case of FSK with less occupied bandwidth. - It is used to minimize the interference at the backscatter receiver.
	GFSK [79]	- It provides a better spectral efficiency compared to FSK. - It is used in a monostatic full-duplex Bluetooth low energy compatible BCSs, for mobile devices.
Phase Modulation	PSK [3], [80]	- Higher data rate can be achieved. - Its demodulation process is complicated. - It is mainly adopted in ABCSs.

communication range and coverage [31], [77]. Moreover, GFSK uses the Gaussian-shaped frequency shifting technique to convey information. It is used for modulation, in a monostatic full-duplex Bluetooth low energy compatible BCSs, for mobile devices [79]. MSK, i.e., a special case of FSK, is also used to minimize the interference at the backscatter receiver [78]. For PSK, higher data rate can be achieved, but its demodulation process is more complicated than that of the other schemes. PSK is mainly adopted in ABCSs [80].

Binary modulation formats result in low data rate due to their low spectral efficiency, e.g., up to 640 kbps for FM0 and Miller coding [23]. Higher-order modulation techniques have thus been used to increase the data rate, thereby leading to reduced on-chip power consumption and extended read range, i.e., M-array QAM, e.g., 16-QAM [75], 32-QAM [76], as well as N-PSK, e.g., 16-PSK [3]. Another open possibility is to use adaptive modulation [83].

In conventional backscatter communication, the tag needs to harvest enough energy from the reader to activate and modulate data. The reader in turn must receive a strong backscattered signal to be able to recover data. Therefore, in order to obtain a fully passive system with the modulator, a combination of backscatter modulation with wireless power transfer is proposed for RFID-enabled sensors [69], [84]–[86]. In this scheme, a backscatter modulator and a dual band rectifier are designed such that two different frequencies are used for different purposes, one is used to continuously power the wireless sensor and the other to transfer data through suitable modulation techniques, e.g., ASK and QAM [84]–[86]. In [86], a 16-QAM backscatter modulator with wireless power transfer capabilities is developed with of a power consumption of 59 μW and a data rate of 960 Mbps.

Signal detection is the process of recovering the transmit data by using the received signal. This task must be done by the reader and is challenging for two reasons: (1) channel estimation is difficult due to the simple fact that ABCS networks exploit existing signals (e.g., LTE and WiFi), which are unknown to the reader. Such signals cannot be used as pilot or training sequences. Thus, the reader lacks the training symbols to estimate the channel parameters; (2) the difficulty of separating the backscattered signal from existing modulated signals (e.g., LTE and WiFi). Thus, in order to detect the modulated signals sent by the tag, different detection techniques have been proposed. Among these, non-coherent detection is commonly adopted due to its simplicity because it can be used without the knowledge of channel state information. It is suitable for ASK and FSK [28], [44], [87], [88]. A diagram of binary amplitude demodulation based on envelope detection is shown in Fig. 2 [34]. The envelope generator extracts the envelope of the instantaneous signal by smoothing the incoming waves at the antenna. The threshold calculator, then takes the mean of the long-term averaged envelope and generates a threshold. The threshold and the smoothed instantaneous envelope of the received modulated backscatter are then compared to decide the value of the information bits. However, this energy detector generally works well at high signal-to-noise ratio (SNR), but produces high detection errors at the low SNR regime. A detection algorithm based on statistical covariances is suggested in [89] for ABCSs, which outperforms the energy detector at low SNR regions.

Although it is simple, non-coherent detection offers low bit rates only and is not suitable for PSK modulation. Therefore, more complicated detection techniques, i.e., coherent detection, which requires channel state information (CSI), have been used [77]. Some general information regarding CSI acquisition can be found in [90]. A coherent and a partly coherent detector is proposed in [91] for ABCSs, where the backscatter device uses a frequency-shifted form of OOK, i.e., pseudo-FSK, to remodulate the FM signals, and the RF transmitter and the backscatter device transmit pilot sequences to estimate CSI. Such requirements and the difficulty of channel estimation may limit the use case scenarios that may allow coherent reception in practice [59]. The channel estimation problem for an ABCS has been investigated in [92], which develops an expectation maximization estimator for the modulus values of the ambient backscatter channel parameters. This paper obtains the estimates for absolute values of: (a) channel coefficient for the RF source to tag link, and (b) the composite channel coefficient involving the sum of direct and backscattered (which is the scaled product of forward and backward coefficients) channels.

ML based detection methods can also be employed to detect modulated signals at the backscatter receiver [29], [46], [80], [93]. Specifically, [46] focuses on the problem of signal detection and bit-error-rate performance analysis at the reader. Minimum-bit-error-rate detector, the optimal detection threshold, expressions and both upper and lower closed-form bit-error-rate bounds are derived. Non-coherent signal detection for ABCSs, including optimal/suboptimal detectors, bit-error-rate computation, outage analysis, threshold derivation, blind parameter acquisition are further investigated in [29]. Moreover, [93] studies semi-coherent detection for a typical ABCS. Semi-coherent alludes to the fact that a few training symbols are sent to acquire only the parameters necessary for signal detection rather than full channel states themselves.

Detection algorithms can also be designed to take advantage of spatial diversity available in multiple-antenna ABCSs to overcome channel fading and to increase the communication range. For instance, a ratio detector and antenna selection for ABCSs with multiple receive antennas have been developed [94]. Moreover, [95] considers ABCSs with multiple-antenna tags and focuses on the signal detection problem. A maximum-eigenvalue based detector is also developed in [96] with multiple-antenna reader. The problem of blind detection of ambient backscatter signals from a multi-antenna tag has been addressed via the generalized likelihood ratio test [97]. Finally, [98] develops three detectors for ABCSs with multiple-antenna tags which require neither CSI nor the RF signal power and the noise variance at the reader. An antenna selection scheme is also proposed.

B. CHANNEL CODING AND DECODING

The purpose of coding is to support the recovery of data across noisy channels. It ensures the reliability of data transmissions by protecting the message from interference, collision, and intentional modification of certain signal characteristics. At the backscatter receiver, the encoded baseband signals are decoded to recover the original message and detect any transmission errors. Thus, line coding techniques can be adopted such as non-return-to-zero (NRZ), Manchester, Miller, and bi-phase space (FM0) [99], [101]. Of these, NRZ and Manchester have been widely adopted in RFID [81]. However, the NRZ code is poor in handling long runs of "0" or "1" and the Manchester code effectively doubles the bandwidth usage. Thus, Miller and FM0 channel coding techniques (with the maximum rate of one half) are usually adopted in existing backscatter communication systems due to their advantages such as enhanced signal reliability, reduced noise, and simplicity [34], [100], [112]. But energy consumption differs widely between transmitting/receiving bit "0" and bit "1" under FM0 and Miller codes, i.e., the transmitting bit "0" consumes much greater energy than that for bit "0" [102]. To alleviate this energy consumption disparity, the energy-efficient data delivery scheme (EEDDS) is proposed in [102] that reduces energy consumption by using a codebook shared by the sender and the receiver. Specifically, the sender breaks original bit stream into multiple *m*-bit data blocks, finds the corresponding codewords of the blocks, and then transmits the codewords from which the receiver recovers the original data. This scheme however suffers from large codebook size and long delays, which poses implementation challenges. Reference [103] thus developed an energy-efficient and easy-implementation coding scheme used for WPN-BCs. An energy consumption minimization problem is formulated to derive the codebook, where only the blocks with the number of energy-consuming bits being equal to or greater than an encoding threshold, are encoded, thereby leading to a smaller codebook size. The proposed code based backscatter communication (CBBC) is energy-efficient and can be effectively applied in the nodes with restricted memory.

As more advanced BCSs are being developed, the low rate channel coding techniques, i.e., FM0 and Miller, may not meet the emerging requirements such as high data rates, long communication range, and robustness. Thus, [104] introduces an orthogonal space-time block code (OSTBC) to improve the data rate and reliability of RFID systems. The key idea of the OSTBC is to transmit data through multiple orthogonal antennas, which is referred to as multiple-input multiple-output (MIMO) wireless. Through this channel coding scheme, several symbols are transmitted simultaneously which are spread into block codes over space and time. It was shown that, OSTBC achieves the maximum diversity order equal to the number of RFID tag antennas, with linear decoding complexity. Reference [105] further investigated the joint design of reader and tag signals as well as modified OSTBC for MIMO backscatter RFID systems and showed that, the diversity order can be much greater than the number of RFID tag antennas.

Moreover, [106] highlights that the FM0 coding used in ISO 18000-6C standard for RFID tags is simple, but may not achieve maximum throughput. Thus an improved-rate 6/8 channel block codes for ABCSs have been suggested to address the need for high data rates in limited bandwidth scenarios. The experimental results demonstrate that the balanced block code increases the throughput by 50% compared to the conventional channel coding techniques, e.g., FM0. Short length cyclic error-correcting codes are also employed in BBCSs to improve transmission rates [77]. This scheme can effectively improve throughput when the carrier emitter is far from the reader. Short block length channel codes, with very low encoding complexity, are also considered for BBCSs [107].

On the other hand, [108] introduces a low-power encoding technique, to increase the communication range and ensure

TABLE 4. Summary of coding schemes.

Coding Schemes	Advantages/Disadvantages
Line coding techniques • NRZ [81], [99] • Manchester [81], [99] • Miller [81], [100] • FM0 [100], [101]	• NRZ is extremely simple but this code is poor in handling long runs of “0” or “1”. • Manchester code is simple but this code effectively doubles the bandwidth usage. • Miller and FM0 enhance signal reliability and reduce noise. • Disparity of energy consumptions between transmitting bit “0” and bit “1” under Miller and FM0 [102].
EEDDS [102]	• This scheme reduces energy consumption by using a codebook shared by the sender and the receiver. • This scheme suffers from large codebook size and long delays.
CBBC [103]	• This scheme resolves the difficulties of EEDDS [102]. • Only the blocks with the number of energy-consuming bits being equal to or greater than an encoding threshold, are encoded.
OSTBC [104]	• This scheme improves data rate and reliability of RFID systems. • This scheme achieves maximum diversity order equal to the number of RFID tag antennas, with linear decoding complexity.
Modified OSTBC [105]	• Unlike [104], the diversity order can be much greater than the number of RFID tag antennas.
Improved-rate $6/8$ channel block codes [106]	• This technique encodes data by associating the code with polynomials. • This scheme can be performed efficiently by using a simple shift register. • This scheme can support tag-to-reader ranges up to 150 meters in BBCSs.
Short length cyclic error-correcting codes [107]	• For small block length channel codes, errors usually occur in long bursts, when the channel is in deep fade. • To resolve long error bursts, the interleaving technique is also employed. • This scheme suffers from delays at both transmitter and receiver side.
μcode [108]	• This code reduces the energy consumption as well as the complexity of the backscatter receiver. • This code enables long communication ranges and supports multiple concurrent transmissions in ABCSs.
Simple 2×2 space-time code [109]	• This scheme achieves almost the same performance as the Alamouti code in backscatter channels with lower complexity.
Polar codes [110]	• This scheme automatically adopts itself to different channel quality. • Accurate channel estimates is not needed and it reduces storage overhead of the coding matrix. • Energy consumption is reduced by orders of magnitudes. • The range limit extends by $1.8\times$ compared with PLoRa [111].

concurrent transmissions for ABCSs. Without requiring synchronization operations at the receiver, this code reduces the energy consumption as well as the complexity of the backscatter receiver . Rather than a pseudorandom sequence, this code uses a periodic signal to represent the information. Since the backscatter transmitter supports only two states, i.e., absorbing and reflecting states, a periodic alternating sequence of bits “0” and “1” is adopted. This code enables long communication ranges, (40 times than that of conventional backscatter), and also supports multiple concurrent transmissions.

Recently, [109] has proposed a 2×2 space-time code for backscatter communications which achieves almost the same performance as the Alamouti code in backscatter channels with considerably lower complexity. This code however performs worse than the Alamouti code in conventional MIMO wireless channels. This issue necessitate further investigation of the existing simple codes, which do not perform well in the conventional channels, but do well in the backscatter channel.

Moreover, [110] has investigated polar codes for reliable long-range backscatter communications by leveraging the concept of channel polarization. This concept is realized by dividing the physical channel into multiple subchannels, each of which could be either extremely reliable or very unreliable. This paper gives a new polar code that automatically adopts itself to different channel quality. This polar code does not require accurate channel estimates and it reduces storage overhead of the coding matrix and energy consumption by orders of magnitudes, thereby making it feasible on battery-less backscatter tags. In particular, the backscatter tags initially encode information bits with a high code rate, and then add redundant bits in an extra transmission according to the decoding requirement of the receiver. Thus, this scheme achieves up to $10\times$ throughput gain, or extends the range limit by $1.8\times$ compared with PLoRa [111], which is the state-of-the-art long-range backscatter with tag-receiver distances up to 1.1 km.

Table 4 shows the summary of coding schemes for backscatter communications systems.

C. DEPLOYMENTS OF WPN-BCS

In massive machine-type communication and IoT networks, due to the dynamic changes of the network topology, flexibility of analysis is of great importance in the evaluation of such networks, which enables the pervasive and ubiquitous deployment of sensors. It is necessary to have scalable and efficient wireless power transfer and communication connectivity.

In addition, the spatial distribution of wireless nodes plays a critical role in the overall energy consumption and spectral efficiency. Thus, stochastic geometry, which is the study of random spatial patterns, has been recognized as a powerful tool to capture and model dynamic spatial positions of nodes [113]. Thus, the use of tools from stochastic geometry makes the performance evaluation of random large-scale networks feasible [114]–[116]. The foundations of stochastic geometry are based upon several spatial point processes, with the Poisson point process (PPP) being the most notable one due to its tractability [117]–[119]. There are also cluster process models, e.g., Poisson cluster process (PCP), where daughter points form random clusters centered at points from a parent point process [120]. PPP abstracts each randomly located point according to a uniform distribution in the Euclidean space. However, because of the assumption of independence, the spatial points in a PPP may be arbitrarily close to each other. Performance values based on the PPP only serve as lower bounds to the coverage probability and mean rate of real-world deployment [121]. Consequently, more sophisticated and general geometric approaches, e.g., Ginibre point process (GPP) and its variants, have been proposed to model the correlation among spatial points. Recent research works have adopted GPPs, e.g., the α-GPP and β-GPP, to model the distribution of cellular stations [122]–[125]. The family of α-GPPs and β-GPPs also includes the PPP as a limiting case, i.e., when $\alpha \longrightarrow 0$ and $\beta \longrightarrow 0$, respectively. These point processes can model random spatial distributions arising from geographical and other factors. These more sophisticated theoretical models can provide an accurate approximation for the network performance in real-world applications [115], [116].

Due to these reasons, stochastic geometry has been widely employed to investigate the performance of wireless-powered networks [47], [120], [124], [126]–[129]. In particular, in [126], the deployment of power beacons (PBs) is investigated for powering a cellular network by microwave power transfer based on a stochastic geometry network model. In [127], using a stochastic geometry model, the spatial throughput of a mobile ad hoc network powered by EH is analyzed. In [128], a stochastic geometry model is used for a large-scale wireless powered communication network to analyze the wireless nodes' performance tradeoff between EH and information transmission. Moreover, in [120], a PB deployment strategy is proposed where the spatial distribution of PBs follows a truncated PCP. Furthermore, [124] investigates the point-to-point uplink transmission of a wireless sensor in a network, where ambient RF sources are distributed as a α-GPP. The performance of random EH D2D networks is also analyzed [130], [131].

The above techniques mainly focus on pure wireless-powered networks and may not be directly adapted to wireless-powered backscatter communications. The reason is that backscatter communication introduces other practical factors, e.g., circuit power consumption, backscatter duty cycle (the fraction of time used for transmission), reflection coefficient (the fraction of backscattered incident energy), which may impose new challenges on network performance analysis. Recently, some works have adopted stochastic geometry tools to design and analyze WPN-BCs [2], [114], [132]–[134]. For instance, in [2], a large-scale WPN-BC is modeled using the PCP and the coverage and network capacities are analyzed with respect to the duty cycle, reflection coefficient and density of the PBs. In this setup, each PB serves only a single node. Reference [132] extends the network model of [2] to a more generic case where energy from multiple nearby PBs is considered and the effects of the densities of PBs and backscatter nodes on the coverage and network capacities are investigated. In [133], for a single-cell WPN-BC with a massive number of randomly deployed sensors, the combined implementation of three collision resolution techniques, i.e., directional antennas, ultra-narrow band transmissions and SIC, is investigated to boost the performance. Moreover, [125] analyzes the performance of hybrid D2D communications based on α-GPP.

More importantly, [114] studies the performance of a decentralized large-scale WPN-BC ad hac network with sporadic short packets. Exploiting time-space PPP model, this work captures the behavior of the network with decentralized and asynchronous transmissions. In [134], a traffic-aware backscatter communication for wireless-powered heterogeneous networks is investigated. A large-scale secondary network whose distribution follows α-GPP is investigated where multiple secondary transmitters (STs) employ ambient backscatter communications in the presence of a primary network, comprising of Wi-Fi APs or cellular BSs and mobile users with the same distribution. ST nodes communicate with a dedicated secondary receiver (reader) with the TDMA protocol by utilizing the traffic sources of the primary network.

D. WAVEFORM AND ENERGY HARVESTER DESIGN

Wireless power transfer may help to energize massive numbers of power-limited devices in large-scale wireless networks. To reach this goal, a critical component is the energy harvester circuit. Thus, increasing the RF-to-DC conversion efficiency of energy harvesters has been heavily researched [135]–[142]. The basic structure of an energy harvester is rather simple. It integrates an antenna and a rectifier and harvests energy from an RF signal and then rectifies and filters it by using a diode and a low pass filter. The recovered DC power then either directly powers a low power device, or is stored in a super capacitor for higher power low duty-cycle operation [143]–[145]. The RF-to-DC conversion efficiency of the energy harvester is a function of both its design and its input waveform [137]. Therefore, some works have investigated the design of the energy harvester [135]–[140], [146], while some others have focused on the effect of transmit signal designs [137], [141], [142].

In order to develop resource allocation schemes in wireless-powered networks, most works adopt linear EH models. As the name implies, according to these models, in the harvested power (p_h) at the user is linearly dependent on the input RF power (p_{in}) collected by the users' antenna , i,e., $p_h = \eta p_{in}$, where $0 < \eta \leq 1$ is the energy conversion efficiency [147]. Some empirical works show that, at 2.45 GHz, η is measured as from 31.8% to 61.4%, when the receive power level, p_{in}, is between -15 dBm and -5 dBm [148]. However, in practice, the energy harvester characteristics (p_{in} vs. p_h) of typical RF energy harvester circuits is nonlinear [135]. Motivated by this empirical fact, a nonlinear EH model is developed based on the logistic function [136]. This model, however, does not satisfy the sensitivity property; namely that the EH output falls to zero when the input power at the EH receiver device is smaller than the sensitivity threshold. Reference [149] thus modifies the logistic EH model to address the sensitivity issue. In [137], a tractable non-linear EH model is developed through the second and high order terms in the Taylor expansion of the diode characteristics. Besides, a piece-wise linear EH model is adopted in [140], [150], where the harvested power linearly increases with the received RF power, but the maximum power that can be harvested by each user is limited. Various energy harvester models, i.e., linear model, diode non-linear model and saturation non-linear model, and the corresponding signal and system design, i.e., transmitter and receiver architecture, waveform design, modulation, beamforming and resource allocation strategies, are investigated in [9]. The work mainly focuses on SWIPT systems, however the analysis can be well adapted to other types of WPCNs and also their integration with backscatter communications.

To improve the efficiency and DC output power in WPCNs, special designed waveforms, i.e., OFDM, white noise, chaotic and multisine waveforms, have been proposed [137], [141], [142], [151]. Multisine waveforms can significantly enhance the DC power and RF-to-DC conversion efficiency over a single sinewave signal [137], [151]. Recently, multisine waveform methods have attracted great attention due to their ability to improve read reliability and read range in RFID tags (by increasing RFID tag RF to DC power conversion efficiency) [141], [142]. It is shown that, with perfect CSI at the RF transmitter (CSIT), significant gain can be achieved with optimized multisine waveforms by exploiting the energy harvester non-linearity and the frequency selectivity of the channel [137].

In BCSs, dedicated RF transmitter typically transmits sinusoidal continuous waveform. However, the waveform design techniques, which were used for WPCNs, can be well adapted to backscatter communication systems, i.e., WPN-BCs, to improve their performance. Besides, nonlinear EH models can be further considered which are directly applicable to practical systems [118], [152]. For WPN-BCs, since a tradeoff exists between the harvested energy at the tag and the SNR at the backscatter receiver, the waveform design might be different from that for pure WPCNs. In [153], with perfect CSIT and employing the nonlinear energy harvester model in [137], a systematic design of multisine transmit waveform is designed to enlarge the tradeoff region, thereby leading to performance improvement of point-to-point backscatter communication system. Besides, in [154], the work in [153] is extended to a multi-user backscatter system. An optimization problem is formulated and solved to jointly optimize the phases and the magnitudes of the multisine waveform for multiple-tags system. Different from the design for pure WPCNs, the authors also optimize the receive combiners at the backscatter receiver such that the signal-to-interference-plus-noise ratio (SINR) with respect to a tag can be higher than a threshold. It is shown that, waveform design based on the non-linear energy harvester model can gain a larger SINR-energy region than those obtained based on the linear model. Besides, power allocation across multiple sinewaves can effectively enlarge the tradeoff region by exploiting the frequency selectivity of the channel and the non-linearity of the energy harvester. Moreover, with the increasing number of tags, the performance gap between waveform optimized based on the non-linear and the linear model increases, however, the average amount of energy harvested at each tag decreases. In [155], resource allocation problem in a backscatter-assisted WPCN is investigated under the piece-wise linear EH model at a dual-mode operating single-antenna users, i.e., the users communicate with a single-antenna AP using two modes of operation, active communication and passive backscattering. In this setup, a multi-antenna RF source transmits either an energy-carrying signal or an energy-information-bearing signal to the users via beamforming. Optimal beamforming vectors are designed at the RF source as well as the optimal time allocation for EH, backscatter communication and active wireless-powered communication of the users.

III. PERFORMANCE IMPROVEMENT OF WPN-BCS

In this section, we focus on the general architecture of WPN-BCs and review the existing approaches for performance improvement of them. Multiple access techniques, multi-antenna and MIMO systems which are critically important to meet the requirements of large-scale communication networks, are mainly discussed in this section. Moreover, we review the research works that employ artificial intelligence techniques, as powerful tools for signal processing and communications, to enhance the performance of the large-scale WPN-BCs. Physical security of WPN-BCs as a key components of 5G and beyond networks is also addressed in this section.

A. COMMUNICATION IMPROVEMENTS

Backscatter communications integrated with a WPCN can effectively increase the coverage and diminish the SNR

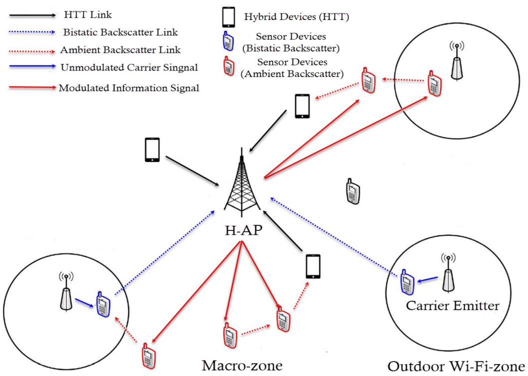

FIGURE 4. **The wireless-powered heterogeneous network model with hybrid backscatter communication [156].**

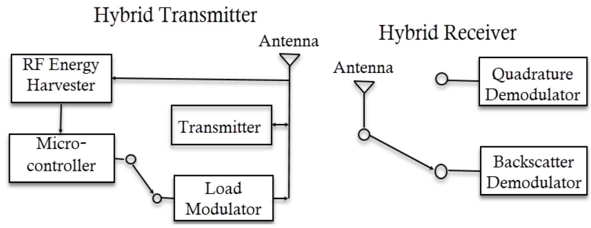

FIGURE 5. **The structure of the hybrid transmitter and hybrid receiver [125].**

outage zone compared to an active radio based WPCN [19]. In order to improve the network flexibility and to achieve performance improvements, the hybrid of passive backscatter communication and RF-powered active communication has been investigated for data transmission [125], [156]–[160]. This architecture enables the user devices to operate in different modes, i.e., active mode or passive mode via backscattering, according to the energy supply and channel conditions. For instance, when the user device has sufficient energy supply, it actively transmits information with a higher data rate and enhanced reliability against channel variation, otherwise, it switches to the power-saving passive mode and transmits its information via backscattering. The architecture of hybrid radio communication and several example scenarios are studied in [157]. In particular, in [156], to increase the range and also to ensure an uniform rate distribution, hybrid of short-range ABCS and long-range BBCS for wireless-powered heterogeneous networks is proposed. Dual mode operation is adopted which utilizes ABCS and BBCS as the secondary access on top of the primary HTT protocol, as shown in Fig. 4. A throughput maximization problem is formulated and solved to optimize the dual mode operation.

Reference [158] investigates three time-division based RF EH protocols to optimize the sum-throughput of a two-way WPCN comprising a H-AP and multiple sensors. The first protocol is the reference time-switching protocol, which is a sum-throughput optimized method that harvests energy, decodes data and transmits data using orthogonal time slots, τ_{EH}, $\tau_{DL}$and τ_{UL}, respectively. The second one is a hybrid protocol, which combines the time-switching and power splitting receiver structure. The downlink data decoding phase τ_{DL} is also used for EH and the received power during τ_{DL} is split by a power splitting ratio λ, the proportion used for energy harvesting, and $(1-\lambda)$ for data decoding. The third one is the combination protocol, which integrates hybrid protocol with backscatter communication. In this setup, the sensors that operate in backscatter mode will backscatter data to the H-AP during τ_{EH}, harvest energy and decode data during τ_{DL} and remain off during τ_{UL}. Whereas, sensors operating in the non-backscatter mode will work the same as the hybrid one. It is shown that, the combination protocol is the most appropriate for wireless-powered networks with a large sensor population. The authors further extend their work to the case where there are multiple multi-antenna H-APs, which are connected to a global controller [159]. They consider the combination protocol for the sensors and investigated the sum-throughput and fairness maximization problem with blind adaptive beamforming at the H-APs. They found that, that the proposed scheme delivered up to approximately 296% increase in the sum-throughput compared to the reference time-switching protocol in a dynamic environment, achieved a dropout rate of 0% instead of 28.5% by the reference time-switching protocol at 10mW H-AP transmission power, and increased Jain's fairness index from $J = 0.76$ to up to 0.90 and 0.80 with and without sensors operating in the backscatter mode, respectively.

In [125], a hybrid D2D system is introduced that combines both ambient backscattering and WPCN capabilities. The authors design a hybrid transmitter and a hybrid receiver, as shown in Fig. 5. The hybrid receiver can receive and decode data from both the modulated backscatter and active RF transmission. For the hybrid transmitter to choose the mode of operation, i.e., HTT or backscattering, two mode selection protocols, namely, a power threshold based protocol and an SNR threshold-based protocol are proposed. The authors then adopt stochastic geometry to analyze the hybrid D2D communications in terms of energy outage probability, coverage probability, and average throughput.

In [160], a transmission scheduling problem is investigated for a backscatter-assisted wirelessly powered IoT system to maximize the minimum system throughput where devices can backscatter when other nearby devices are actively transmitting via RF. As shown in Fig. 6, each device is equipped with an RF energy harvester, which it uses to harvest incident RF energy. It then uses the harvested energy to power the RF transmitter when sending data directly to the HAP. It can also communicate with other devices via backscattering. In this setup, first a H-AP charges all devices using an HTT protocol and each device then transmits its data directly to the H-AP using the harvested RF energy, or it backscatters its data to some neighboring devices to be forwarded to the H-AP. There are no dedicated RF sources and a device can backscatter signals emitted by any device within a certain range. The groups of devices that can simultaneously backscatter without causing interference are identified and it is shown that,

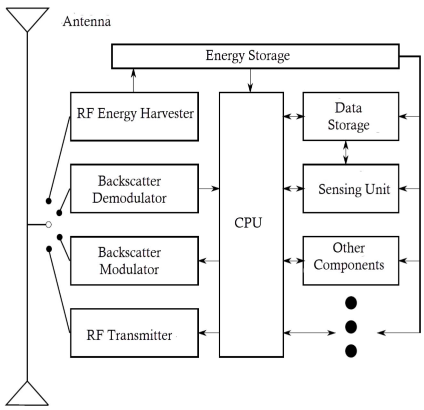

FIGURE 6. Hybrid backscatter device [160].

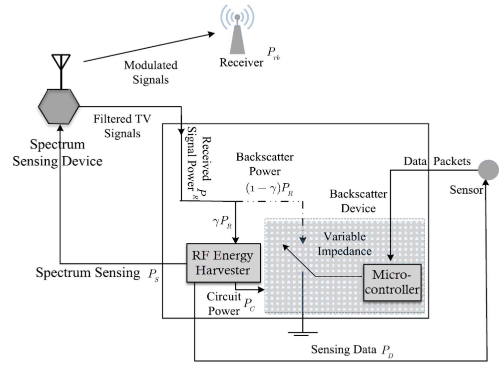

FIGURE 8. The block diagram of different modules at the IoT node [163].

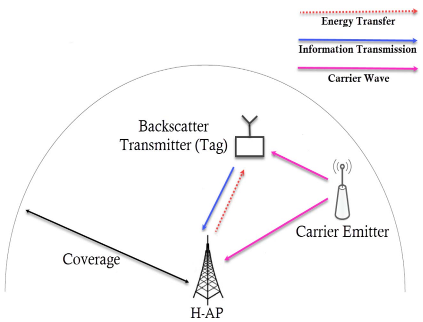

FIGURE 7. A backscatter radio based wireless powered communication network [19].

the max–min throughput can be increased by 46 and 180 times for linear and random networks, respectively, compared with TDMA.

Different from backscatter-assisted HTT transmission, the backscatter-assisted communication systems considered in [161] support battery-free backscatter transmission and the battery-assisted transmission (active radio mode with RF chain). Two adaptive mode selection schemes, i.e., power maximization-oriented and outage minimization-oriented adaptive mode selection schemes, are investigated with opportunistic SIC. In power maximization-oriented adaptive mode selection, based on the comparison of the backscatter power in the passive mode and the transmit power in the active mode, the mode corresponding to the maximum one is selected. While in outage minimization-oriented adaptive mode selection, the passive/active mode corresponding to the minimum outage probability is selected. The authors further derived the lower bounds for the outage performance in the proposed schemes in closed-form expressions.

This assumption that the devices can support two modes of operation may not be suitable for hardware-constrained IoT devices in practice [19]. Thus, the authors in [19] proposed a WPN-BC design aiming to achieve long-range coverage, compared to the active radio based WPCN with a short-range coverage due to the doubly round-trip attenuation. In this scheme, the user not only harvests energy from the RF signal broadcast by the H-AP but also the carrier signal from the carrier emitter deployed close by the tag, as shown in Fig. 7. The user first harvests energy in the downlink and then transmits its own information in a passive way by reflecting the carrier signal while performing binary FSK modulation. It is shown that, the proposed scheme can effectively resolve the problem of short coverage and wide SNR outage zone in WPCNs due to the doubly near-far problem.

In [162], to ensure that the instantaneous receive power at the device (located far from the RF source) is enough for operation, the authors consider a two-state duty cycle involving both the sleep and the active states in an RF-powered communication network with ambient backscatter. In the sleep state, the device performs dedicated energy harvesting only, where the harvested energy from the received RF signal is stored in its battery for further use. In the active state, the device backscatters a part of the received RF signal, and simultaneously absorbs the remaining part energy of the received RF signal to power its circuit. The authors derive both the optimal reflection coefficient and the optimal tradeoff between the EH time and the backscatter time, to maximize the network throughput.

Reference [163] further investigates a optimal time scheduling scheme based on compressive spectrum sensing techniques in IoT networks with a large number of IoT nodes. Each node is equipped with three modules, i.e., spectrum sensing device to detect ambient RF signals, RF energy harvester and backscatter device to transmit data to the gateway, as shown in Fig. 8. The authors first employed compressive sensing to detect ambient RF signals with high signal power, transmitted in wideband spectrum. The detected signals are then used to perform RF EH (partial signals) and ambient backscatter communication (the rest of signals), simultaneously. An optimal scheme is designed to manage the time scheduling of different modules. It is shown that larger transmission rates can be achieved via compressive sensing. The authors also analyze the outage probability of the backscatter communication and obtain the detection threshold of spectrum sensing for enabling backscatter communication.

User cooperation has also been investigated to improve the performance of WPN-BCs [164]. The considered WPN-BC

TABLE 5. Summary of communication improvements for WPN-BCs.

Article	Network model	Design goal	Key ideas
[156]	A wireless-powered heterogeneous network; a H-AP, multiple dedicated RF sources and dual mode operating users	Improving transmission range and uniform rate distribution, Throughput maximization and optimal time allocation for the hybrid operation	The users utilize ABCS and BBCS as the secondary access on top of the primary HTT protocol.
[158]	A H-AP and multiple sensors	Maximizing the sum-throughput by optimizing the system timings for EH, downlink data decoding and uplink data transmission	Three time-division based RF EH protocols are proposed and analyzed.
[159]	Multiple H-APs and multiple sensors	Sum-throughput and fairness maximization by using multiple beamforming H-APs	A multi-source, multi-sensor blind adaptive beamforming with combination sensors protocol is proposed.
[125]	Hybrid D2D communications with ambient RF transmitters	Characterizing the energy outage probability, coverage probability, and average throughput	Ambient backscattering is integrated with wireless-powered communications, a hybrid transmitter and a hybrid receiver are designed.
[160]	A H-AP and multiple hybrid backscatter devices	Transmission schedules to maximize the minimum throughput	There is no dedicated RF sources and each device transmits its data directly to the H-AP using HTT protocol or, it backscatters its data to some neighboring devices to be forwarded to the H-AP.
[161]	An RF source, one transmitter and one receiver	Analyzing adaptive passive and active radio mode selection schemes with opportunistic SIC	The transmitter can switch between backscattering mode and the battery-assisted transmission mode.
[19]	A H-AP, a dedicated RF source and a passive user	Achieving long-range coverage, characterizing the SNR outage zone	The passive user harvests energy from both the RF signal broadcast by the H-AP and the carrier emitter located in its vicinity.
[162]	An RF source, a passive user and a receiver	Throughput maximization by studying the optimal control policy	A two-state duty cycle involving both the sleep and the active states is considered.
[163]	Ambient RF sources, multiple IoT nodes and a gateway	Obtaining optimal time scheduling schemes by maximizing the transmission rate	Each node is equipped with three modules, i.e., spectrum sensing device, energy harvester and backscatter device. Compressive sensing technique is used to detect the ambient RF signals.
[164]	An AP, a dedicated RF source, an active device and a passive device	Weighted sum-rate maximization by jointly optimizing time schedule, power allocation and energy beamforming	Two user cooperation schemes are introduced.
[114]	An ad hoc network comprising multiple RFID reader-tag pairs	Maximizing the network-wide spatial throughput, analyzing energy and information outage probabilities	The behavior of the network with sporadic short packets is captured in a decentralized and asynchronous transmission way.
[165]	A single backscatter link with one dedicated RF source	Energy efficiency maximization by jointly optimizing time allocation, reflection coefficient, and transmit power of the RF source	An efficient Dinkelbach-based iterative algorithm is developed to obtain the optimal resource allocation scheme.
[166]	Two co-channel backscatter links with one dedicated RF source	Energy efficiency based max-min fairness by jointly optimizing backscatter reflection coefficients and transmit power of the RF source	An iterative algorithm is proposed for resource allocation.

consists of a PB, an AP and two devices with two different operation modes, i.e., one in HTT and one in backscattering mode. The devices can cooperate to deliver the information to the AP, i.e., the one located nearer to the AP can serve as a relay node to assist the far device to transmit information due to the low channel quality. A weighted sum rate maximization problem is formulated and solved to jointly optimize the time schedule, power allocation and energy beamforming deployed at the PB.

Asynchronous transmission and sporadic short packets, the main important features of IoT and massive machine type communications, are investigated in [114]. In particular, the authors consider a stochastic WPN-BC ad hoc network consisting of multiple RFID reader-tag pairs where each reader-tag pair randomly accesses the same frequency for ad hoc transmission asynchronously. The multi-antenna RFID reader works in the full-duplex mode to simultaneously transmit query signal and receive information signal from its corresponding RFID tag. The authors then analyze the information and outage performance during the energy harvest and backscatter modulation phases. The spatial throughput maximization is also investigated and it is shown that there exists the optimal tradeoff between the duration of two phases for spatial throughput maximization.

Energy efficiency of WPN-BCs is also investigated [165]–[167]. In [165], the energy efficiency of a single backscatter link is maximized via jointly optimizing time allocation, reflection coefficient and transmit power of the dedicated RF energy source. Moreover, the authors in [166], consider a WPCN with two backscatter links and maximize the minimum link energy efficiency by jointly optimizing the PB transmission power and the backscatter reflection coefficient.

Table 5 shows the summary of communication improvements for WPN-BCs.

B. MULTIPLE-ACCESS SCHEMES AND PROTOCOLS

Developing multiple access techniques for WPN-BCs is crucially important. The problem is to figure out how a single reader may be utilized to serve multiple tags. In this case, the reader will receive multiple uplink backscattered signals. For instance, in a warehouse, a single reader may be deployed to collect data simultaneously from a massive number of items equipped with RFID tags. This causes collisions/interference at the receiver. Due to the resulting data loss, re-transmissions may be needed, which negatively affects both energy efficiency and spectral efficiency [168]. Thus, this again emphasizes the need for efficient multiple access techniques for backscatter systems, i.e., WPN-BCs. Common multiple access techniques are orthogonal multiple access (OMA) where each user can exploit orthogonal communication resources within either a specific spatial direction, time slot, frequency band, or code in order to avoid multiple access collisions/interference [8].

A simple solution to avoid collisions between multi-tag transmissions are OMA schemes such as spatial division multiple access (SDMA) [133], frequency division multiple access (FDMA) [133], TDMA [19], [169], code division multiple access (CDMA) [170]–[172], and orthogonal frequency division multiple access (OFDMA) [173], among which TDMA is mostly adopted in backscatter communications due to its simplicity. In particular, in [66], a FABCS over ambient OFDM carrier is considered where a full-duplex AP with two antennas, transmits downlink signal which not only carries information for the legacy user but also transfers energy to the multiple backscatter devices, while at the same time, the backscatter devices transmit uplink information via backscattering similar to the TDMA protocol. The minimum throughput of the backscatter devices is maximized by the joint optimization of backscatter time allocation, power reflection coefficients, and full-duplex APs' subcarrier power allocation. In addition, [22] proposes a backscatter-assisted WPCN that includes a full-duplex H-AP and multiple users. The full-duplex H-AP uses one antenna for transferring energy to the users in the downlink, and one antenna for receiving signals from the users in the uplink, simultaneously. The users switch between HTT and backscatter modes adaptively and transmit or backscatter information to the HAP in TDMA. In this set up, the authors maximize the sum-throughput by studying the optimal transmission policy, including both the optimal working mode permutation and time allocation.

The main problem with OMA techniques is that the number of orthogonal channels has an upper bound. Consequently, the number of users that can be served simultaneously will hit this bound, especially for massive IoT devices. Nonorthogonal multiple access (NOMA) has thus been developed as an effective solution to overcome this hard limitation, where multiple users are served in each orthogonal resource block, e.g., a time slot, a frequency channel, a spreading code, or an orthogonal spatial degree of freedom [174], [175]. Thus, power-domain and code-domain NOMA schemes have been developed. The code-domain NOMA utilizes user-specific spreading sequences to enable the concurrent use of the same resource, while power-domain NOMA exploits channel-gain disparities among users to achieve the same goal and has the advantages of low latency and high spectral efficiency [175]. Therefore, backscatter communication with NOMA has recently been recognized as a promising spectrum-, energy- and cost efficient technology for enabling low-power IoT networks [176]–[180]. A hybrid channel access scheme by combining TDMA with power-domain NOMA for multiplexing the backscatter nodes in different regions or with different power levels, has been proposed [176], [180] to enhance the spectrum efficiency, outage probability and throughput of MBCSs. Reference [177] considers a NOMA-enhanced ABCS comprising four nodes, namely, the BS, the backscatter device, the nearby cellular user, and the far-away cellular user. The BS transmits the superposition message to the users at the same resource block with different powers. The backscatter device also transmits its information to nearby cellular user, over the signal received from BS. The nearby cellular user first decodes the information of the far-away cellular user, then its own information, and finally the backscatter device information. The far user, however, only decodes its own information. The authors then analyze the outage and ergodic rate performance of the system.

On the other hand, [178] considers the NOMA-enhanced BBCS with dynamic TDMA and maximized the minimum throughput of multiple backscatter nodes by jointly optimizing backscatter time allocation, power reflection coefficient while ensuring sufficient harvested energy and SINR for NOMA decoding. Moreover, [179] investigates a NOMA-enhanced dynamic TDMA transmission scheme for full-duplex symbiotic radios, where a full-duplex AP transmits downlink OFDM signals to a legacy user and simultaneously receives signals backscattered from multiple passive backscatter devices. The minimum throughput among multiple backscatter nodes is maximized by jointly optimizing the full-duplex APs' subcarrier power allocation, the nodes' backscatter time and power reflection coefficients subject to the legacy user's throughput requirement and the harvested energy requirements of the backscatter nodes. In [169], the hybrid of NOMA and TDMA is considered in a backscatter-assisted WPCN comprising a PB, an information receiver and multiple users that can work in either backscattering mode or HTT mode. The authors also derive optimal time allocation policies to maximized the system throughput.

For simultaneous transmissions from multiple devices in large-scale backscatter networks, the NetScatter protocol is suggested [181] which adopts the combination of chirp spread spectrum modulation and OOK to enable hundreds of backscatter devices to simultaneously backscatter their information to an AP. It is shown that, the NetScatter protocol can support concurrent transmission from 256 backscatter devices with the data rate of 500 kbps and communication range of 2 meters. Reference [172] further analyzes the coded-backscatter multiple access (CBMA) scheme for backscatter communication where multiple tags simultaneously transmit data to the receiver in the same frequency. The authors investigate the correlation-based detector and power control at the tag to respectively reduce the negative effects caused by the asynchronous problem and improve the performance against the significant power difference among tags. It is shown that, the proposed scheme can achieve a

10-tag bit rate up to 8 Mbps with tag-receiver distances up to 10 meters.

For large-scale networks, it may not be efficient to deploy the centralized MAC protocols, e.g., TDMA, FDMA, only for sporadic backscatter communications requirement due to the complexity, the energy consumption and the dynamic change of network topology, i.e., backscatter devices frequently join or leave from the network. Moreover, some critical data messages with high quality of service (QoS) requirements can hardly be transmitted in time and the frequency spectrum resources could be wasted due to the inflexibility of the centralized schemes. To overcome these challenges, distributed MAC protocols have been investigated and MAC-layer performance has been also analyzed in addition to physical-layer performance [182]–[184]. For these reasons, [182] proposes a modified coordination based the dominant channel occupancy (DCO) protocol, where backscatter tags use the RF signals of the Wi-Fi helper to communicate with the reader. The backscatter tags contends for the transmission together with the Wi-Fi station for a shared channel. Reference [183] further proposed a Distributed and Demand-Based (DDB) protocol for a heterogeneous network, where backscatter tags use the Wi-Fi signals to transmit information to the AP. Unlike [182], the authors considered the AP's demand for the information of backscatter device, and let the Wi-Fi device and backscatter device perform the distributed contention in a separate manner. When the AP has a demand to collect the tag information, it contends with the wireless devices and sends the *CTS_to_self* packet upon success to suspend their transmissions and reserve the channel. Then, it sends preambles to excite the backscatter tags and all the tags will adopt CSMA/CA protocol to contend for transmission within this reserved time period. The authors then analyze the MAC-layer performance in terms of per-node throughput.

Reference [184] investigates an opportunistic MAC protocol for backscatter communications in a heterogeneous wireless powered IoT network consisting of EH devices coexisting with backscatter tags, a backscatter reader and an H-AP. In this network, the wireless devices communicate with the H-AP based via HTT and the backscatter tags utilize H-AP's RF energy signal to operate and transmit information to the backscatter reader. The EH devices contend for the channel and use a handshaking method to reserve the channel to harvest and/or transmit data. The reader listens to the channel and excites the backscatter tags for contention and communication when it finds the RF energy signal of the H-AP. The authors further compare the performance of the proposed MAC protocol with DCO protocol [182] and DDB protocol [183], in terms of throughout, i.e., the successful data transmission over total time which depends on the idle slots, success, and collision of the transmissions. It is shown that, unlike DCO and DBB protocols for which throughput significantly decreases with the increase of nodes, the proposed protocol shows a steady throughput performance and it is also more collision-resilient due to its contention and channel reservation mechanism.

In [185], a distributed MAC protocol for ABCS is proposed where the backscatter devices achieve power-efficient channel access via the RF signals according to their traffic requirements in a distributed way. The authors consider the coexistence of the traditional RF communications (consisting of a continuous RF source and the legacy users) and ABCSs (consisting of a large number of backscattter devices). The proposed MAC protocol also support the backscatter communications among backscatter devices, and each backscatter device can switch among backscatter transmission, receiving and EH in a distributed fashion by combining an analog channel sensing strategy with the dual-backoff mechanism. This mechanism contains two dimensions where the first-dimension backoff is to achieve collision avoidance (CSMA/CA scheme), and the second-dimension backoff aims to reduce the channel waste during the energy harvesting. The authors develop a three-dimensional Markov model with the consideration of the false alarm and the miss detection problems occurring while sensing, to analyze the normalized throughput of the proposed MAC protocol. It is shown that, the proposed MAC protocol operates well under the strict-low power consumption for IoT networks.

In [186], in order to provide seamless wireless communications to massively deployed IoT nodes with few or no collisions in WPCNs, coordinating channel access among a large number of sensor nodes in a distributed manner is investigated. The authors proposed a group-based MAC protocol to distribute the sensor nodes into groups based on their co-location. The group head, a H-AP, uses a coordinating mechanism to send collected data from sensor nodes to the BS. The sensor nodes harvest energy or transmit data to the H-AP in their active time and are sleep during the inactive time. The nodes with sufficient energy concurrently access the medium and transmit data by using a frame slotted ALOHA to reduce collisions; if more than one node simultaneously transmit data during a slot, the outcome may result in collision and re-transmission is needed by the nodes in the active time of the next frame. It is shown that, the proposed distributed group-coordination mechanism can effectively mitigate the inter-group and intra-group collisions, thereby achieving significant performance in terms of network throughput and energy efficiency.

C. MULTI-ANTENNA AND MIMO SYSTEMS

Exploiting multiple antennas at tags/readers provide several benefits for backscatter communications [187], [188]: 1) A multiple-antenna tag can perform EH and backscattering simultaneously, unlike a single antenna tag [34], [97], [98], 2) Multiple antennas at the reader are essential for both downlink excitation and uplink detection [114], [189]–[191], 3) Increasing the number of tag/reader antennas may enlarge the communication range between the tag and the reader in conventional radio backscatter systems [40], [189],

[192], and 4) Multiple-antenna tags/readers increase diversity gain and thus enhance communication reliability and lower the bit-error-rate of conventional radio backscatter systems [104], [193].

In order to improve throughout, RFID MIMO systems have been investigated for backscatter communications [28]. Reference [187] propose a unitary query at the reader query end in the $M \times L \times N$ MIMO backscatter RFID comprising three components: the query end (with M reader transmitting antennas), the tag end (with L tag antennas) and the receiving end (with N reader receiving antennas). The proposed unitary query can provide time diversity within each channel coherent interval, and improve the performance by 5-10 dB in the mid-range SNR regimes. The authors further extended the unitary query to block-level unitary query with the corresponding modified STBC in [105]. It is shown that, the proposed scheme can achieve full diversity of classical OSTBC.

Multiple antennas indicate multiple channel parameters between the tag and the reader, which significantly challenges signal detection because the tag has limited power and can transmit few training symbols only. Thus, efficient signal detection and channel estimation techniques for MIMO backscatter communications have also gained much interest [66], [97], [98], [189]–[191], [193], [194]. In particular, [189] investigates the efficacy of a full-duplex MIMO reader for enhancing the limited communication range of MBCSs. A novel least-squares estimator for the forward and backward links between the reader and the tag and also corresponding linear minimum-mean square-error estimate for the backscattered channel are derived in a single-tag BSC setting. The authors further consider multi-tag backscatter setting in [190], as shown in Fig. 9. A novel channel estimation algorithm is presented by considering practical constraints like unintended ambient reflections (UAR), preamble design for the tags. Optimal transceiver designs are then obtained for the multi-antenna reader to maximize common backscattered throughput among the single-antenna semi-passive tags. As well, [191] maximizes the achievable sum backscattered-throughput by jointly optimizing the transceiver design at the multi-antenna reader and backscattering coefficients at the single-antenna tags. Furthermore, the authors in [193] propose an ML-based backscattering detection protocol for MBCSs with the multi-antenna reader and derive closed-form expressions for the optimal detection threshold and bit-error-rate. Channel estimation and signal detection in an ABCS with a multiple-antenna tag are also investigated [97], [98]. Fig. 10 shows an ABCS with a multi-antenna tag where the tag can perform energy harvesting and backscatter modulation, simultaneously. For backscatter-assisted wireless-powered networks, two-antenna H-AP working in full-duplex mode is also considered [22].

Energy beamforming is also investigated for WPN-BCs where a multiple-antenna system focuses the transmitted energy to the direction of the receiver [14], [164], [195].

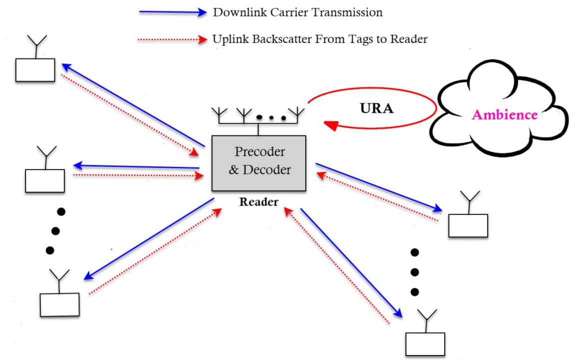

FIGURE 9. A MBCS with a full-duplex multi-antenna reader and multiple semi-passive single-antenna tags, with optimal transceiver design for reader [190].

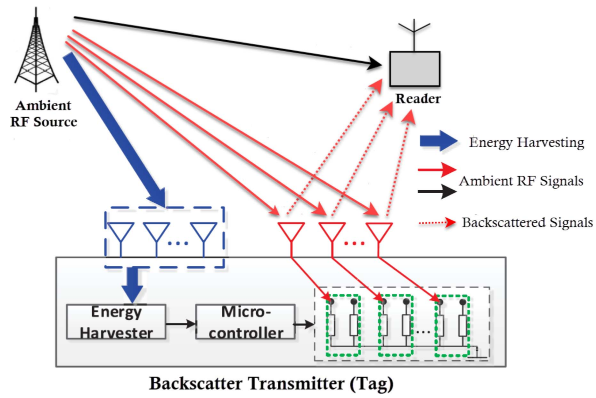

FIGURE 10. The multi-antenna-tag ambient backscatter system [98].

A combination of backscatter communication and retro-directive beamforming for energy beamforming is introduced in [14]. Retro-directive beamforming is a simple technology, which requires neither knowledge of the user location nor any complex beamforming algorithm; a multi-antenna BS automatically steer a radio beam toward a target user based on the signal transmitted by the user and received at the BS. The authors in [195] investigate a simple energy beamforming technique for a multi-user networks that combines large antenna retro-directivity with signal backscattering. In particular, the energy beamforming technique consists of two phases. In the first phase, the energy transmitter (PB) generates and broadcasts an unmodulated single-tone waveform and each energy receiver (backscatter device) reflects back a part of the received signal without further processing. In the second phase, the PB performs matching filtering on the received signal to detect the phase of the signal and transmit energy signal by using phase conjugation. The impact of reflection coefficient on the performance is also investigated. Moreover, in [164], energy beamforming is deployed at the PB to improve energy transmission for the nodes in WPN-BCs. Reference [159] also investigates the performance of a wireless-powered network using multiple blind adaptive beamforming H-APs and backscatter communication-enabled combination sensors [158]. In this setup, The impact of the number of antennas and H-APs on the sum-throughput, throughput fairness and sum-throughput and fairness tradeoff is investigated.

On the other hand, the authors in [196] design transmit beamforming at a mutli-antenna primary transmitter (PT), which transmits its primary information to a single-antenna primary receiver, and at the same time enables a single-antenna backscatter device to transmit its own information to the primary receiver. The transmit beamforming is designed such that either the weighted sum rate of the primary and backscatter device transmissions is maximized or the PT's transmit power is minimized under rate constraints. The complexity of these schemes however increases exponentially as the number of antennas at the PT increases. Thus, the authors further propose a low-complexity beamforming structure, which can be well adopted in the case of the large-scale antenna array at the PT.

D. ARTIFICIAL INTELLIGENCE

Artificial intelligence techniques are capable of solving complex problems without explicit programming and have recently been vigorously considered for signal processing and communications [197]–[202]. In particular, machine learning can be used for ultra-dense communications, e.g., massive machine type communication [202], large-scale MIMO [203] networks, to answer the challenge of supporting a huge number of devices in cellular network including QoS provisioning, handling highly dynamic and sporadic traffic flows of massive machine type communication and IoT networks and large signalling overheads [204]. It is shown that, machine learning algorithms can improve channel estimation and signal detection [205]. For example, signal detection for ABCSs by using unsupervised learning and other machine learning approaches has been studied [43], [206]. By exploring the received signal constellation information, these works have proposed a modulation-constrained expectation maximization algorithm. Interestingly, their constellation learning methods achieve comparable performance as the optimal detector with perfect channel-state information.

Moreover, in [207], a reinforcement learning approach is proposed to maximize the long term average throughput for ABCSs when the distribution of the ambient RF signal strength is unknown. It is shown that, the proposed learning method produces a close-to-optimal throughput performance, and significantly outperforms the greedy policy (where the tag chooses signal backscattering mode if it has sufficient energy to transmit information, or energy-harvesting mode otherwise). The authors in [208] also consider the data scheduling and admission control problem of a backscatter sensor network. The authors formulate the problem as a Markov decision process, and a reinforcement learning algorithm is applied to obtain the optimal policy that minimizes the weighted sum of delay of different types of data, e.g., urgent or normal.

Recently, deep reinforcement learning techniques have shown tremendous potential in the field of distributed dynamic spectrum access [199], [209]. Motivated by this, a distributed deep reinforcement learning based MAC protocol is proposed in [210] to assist the backscatter communications for IoT networks by leveraging Wi-Fi signals. With this protocol, the Wi-Fi AP can dynamically learn the served backscatter devices and the reserved step of the served backsatter devices, which allows the AP to determine the action and thus achieve the optimal throughput performance.

Reinforcement learning algorithms have also gained much interest in order to optimize the performance of the RF-powered cognitive radio networks (CRNs). In particular, the authors in [211] leverage reinforcement learning algorithms to investigate optimal sensing, channel probing, i.e., CSI estimation process, and transmission power control for an ST operating in a fading channel with harvested energy from ambient sources. Learning algorithms have been further investigated for backscatter-assisted wireless-powered CRNs for time scheduling and optimal policies [134], [212], [213] (Section IV-A).

E. PHYSICAL LAYER SECURITY

The widespread deployment of wireless-powered backscatter communications and the lack of strong protection schemes makes these systems vulnerable to security attacks such as eavesdropping and jamming [214]–[216]. WPN-BCs with simple coding and modulation schemes may suffer from potential security attacks which adversely impact the performance and reliability of the systems. Securing backscatter communication systems is challenging due to its passive nature and also practical limitations, in terms of cost, size and computation. Moreover, typical security solutions such as encryption, which provide an acceptable level of security against a number of attacks, cannot fully satisfy all the requirements of resource-constrained backscatter systems and exhibit several limitations in such systems [214], [217].

Developing physical-layer security (PLS) mechanisms, as an alternative or complement to cryptography, is a promising direction to overcome the above limitations and strengthen the security of backscatter systems [214]. PLS techniques fundamentally enhance wireless communication security at the physical layer. They exploit wireless channel characteristics, e.g., noise, fading, interference, dispersion and diversity, to construct equivalent channels via signal design and power allocation such that the superiority of the equivalent legitimate channel to the equivalent wiretap link is established [214], [218], [219].

One promising approach to deteriorate the channel condition of the eavesdropper is to inject an artificially generated noise [218]. Following this idea, [214] investigates the secrecy rate of a single-reader and single-tag model for an RFID system, where terminals employ a single antenna. The reader injects a randomly generated noise signal that is added to the standard continuous wave signal to interfere with an eavesdropper. To maximize the secrecy rate, this approach necessitates the power allocation between the continuous wave signal and the artificial noise. It is shown that the proposed approach can significantly improve the secrecy performance. This work is extended to a more general MIMO RFID system in [219] and the secrecy rate maximization is investigated by optimizing the supply energy and precoding matrix of artificial noise at the reader. To further improve the security of RFID systems, [220] deploys beam steering using a one-dimensional antenna array at the tag in addition to the noise injection from the reader side. Secrecy rate of the relay-assisted RFID systems is also investigated [221], [222]. Moreover, in [223], secrecy outage probability is investigated for an RFID system with multi-tag selection.

On the other hand, [215] investigates the PLS performance of a multi-antenna RFID system with practical binary inputs at the single-antenna tag. In order to improve the secrecy energy efficiency of the system, instead of direct using artificial noise, one randomized continuous wave signal is used at the reader for security enhancement. The secrecy rate is maximized by optimizing the parameters related to the continuous wave signal to tackle the stability-variance tradeoff between balancing legitimate signal reception and eavesdropper mitigation.

Compared to passive eavesdroppers, the proactive eavesdropper, which broadcast its own continuous wave signal, can extract the on-tag messages more confidently and interfere with the information detection at the reader simultaneously [216]. This type of attacks can cause severe security threat for RFID systems [216], [224]. In particular, [216] investigates security issues in an RFID system in the presence of a proactive eavesdropper. The authors propose a secure transmission scheme at the reader in which the wiretap channel is estimated and the artificial noise-aided continuous wave signal is designed for secrecy transmission.

Very few works have investigated PLS in ABCSs [225]–[227]. Securing ABCSs faces several challenges because the backscatter transmitters are simple devices and the RF sources are not controllable. The authors in [226] study an artificial noise-aided tag scheduling scheme in an ABCS comprising multiple tag, a reader and an eavesdropper. In the proposed scheme, a tag is selected for information transmission and another tag for artificial noise generation at the same time. It is shown that the proposed method with SIC at the reader can improve the average secrecy rate. The authors then propose a cooperation-based multi-tag scheduling method in [227], which selects a tag for data transmission and another tag for cooperative transmission (the same data) to assist a receiver. These two strategies are evaluated in terms of bit error rate and secrecy rate.

IV. EMERGING WIRELESS-POWERED BACKSCATTER SYSTEMS

Sixth generation (6G) communications are expected to raise features currently set by 5G communications with the provision of enhanced services from the perspectives of network data availability, mobile data rate, and seamless ubiquitous connection. Attaining a cost-effective approach toward rapid network deployment, reduction in the price of mobile communications' utilization, approaches to network devices battery life longevity are some critical challenges associated with the next generation communications [228]. A fundamental goal of 6G communication is to perform whenever and wherever possible with battery-free communications, aiming at 1 pico-Joules per bit communication efficiency [229]. These requirements necessitate the incorporation and accumulation of innovative and divergent technologies. Due to the undeniable advantages of WPN-BCs, this prominent technology can be further integrated with other emerging technologies to realize 6G visions.

Cognitive radio and wireless relaying are two technologies that can overcome energy and spectrum limitations and coverage of wireless networks [230], [231]. These technologies have also been adapted for large-scale IoT networks and power-constrained IoT networks. Moreover, using light as the transmission medium, visible light communication (VLC) has been identified as a promising technology in RF limited environments that can revolutionise the future of wireless communication [228], [232]. It possess certain compelling merits, such as minimal deployment overhead in terms of hardware replacement and high-speed data communication with the added advantage of improved energy efficiency and communication security/privacy [232]. Motivated by this, visible light backscatter Communication (VLBC) has been developed for battery-free IoT applications to tackle the challenges of directional communication and low optical coupling for wideband VLC [233]–[236].

Therefore, in this section, we address the integration of WPN-BCs with these emerging technologies. In particular, backscatter-assisted wireless-powered CRNs and backscatter-assisted wireless-powered relaying, for wireless-powered backscatter systems are reviewed to bring about the best use of resources and to enhance the coverage of such networks. Moreover, we review the recent research efforts that have been expended on the field of practical backscatter communication using visible light for battery-free IoT applications.

A. HYBRID BACKSCATTER-ASSISTED COGNITIVE WIRELESS-POWERED RADIO NETWORKS

Due to the tremendous growth of wireless communications, the spectrum bands become scarce. Thus, allocating spectrum bands to a large number of devices is another challenge for large-scale IoT networks. Cognitive radio by using various spectrum sensing methods [237], [238] facilitates the efficient usage of the wireless spectrum [239]. Considering both energy and spectrum limitations in large-scale IoT networks, RF-powered CRNs have been introduced and extensively investigated in the literature [12], [240]. By enabling RF EH on the cognitive radio devices, not only the devices exploit the underutilized spectrum but also opportunistically harness the free energy from primary signals. However, since the transmission used in a typical RF-powered CRN is usually based on HTT manner, the performance of the secondary network is highly dependent on the PTs; a PT with high frequent data transmission will leave little time for the STs to transmit over the idle channel, while a PT with low frequent data transmission will result in shortage of the harvested energy [241]. To tackle these challenges and to achieve the best performance for the secondary system, equipping the existing RF-powered CR devices with ambient backscattering module, has been introduced as an alternative solution [23], [71], [241], [242]. Following this idea, [241] investigated a CRN in which a wireless-powered ST is equipped with ambient backscattering module. In this setup, when the PT is active, the ST can select to perform EH or ambient backscattering. When the PT is idle, the ST can perform active transmission with the harvested energy. The optimal transmission policies is then obtained to maximize the throughput of the ST in two scenarios, i.e., overlay and underlay CRNs. The authors proved that there always exists the globally optimal time tradeoff. This implies that the integration of the ambient backscatter technique into RF-powered CRN always achieves the overall transmission rate higher than that of using either the ambient backscatter communication or the HTT scheme, individually. Besides, in [71], a CRN with multiple STs operating in HTT and backscatteing modes is considered where during the busy state, the STs transmit information via ambient backscattering or harvest energy for the future information transmission, while during the idle state, the STs adopt the bistatic backscattering mode or the HTT mode for information transmission. The authors maximized throughput by finding the optimal time allocation between modes in busy and idle states.

In [242], an overlay CRN is considered with multiple STs which switch among HTT mode and ambient backscattering mode, to communicate with a secondary gateway. The authors developed a distributed stackelberg game model of the interaction between the secondary gateway and the STs for the optimization of time switching between two modes and interference management with imperfect channel condition. Considering the variety of demand requirements from STs, the authors in [243] employed the auction approach to assign the time resource for the STs in a backscatter-assisted RF-powered network where the secondary gateway acts as the seller as well as the auctioneer, and the STs act as the buyers to bid for the time resource. Moreover, [244] investigated the dynamic AP and service selection in such networks where a group of dual mode STs are within a coverage of multiple APs. The authors formulated the AP and service selection as an evolutionary game where the STs act as players and adjust their selections of the APs and services based on their utilities.

Energy efficiency of a backscatter-assisted RF-powered network comprising a single secondary link is further investigated in [245] in the presence of sensing errors and without assuming knowledge of the PT activity. Energy detection-based spectrum sensing is employed and analytic expressions for the average achievable throughput, the average energy consumption and the energy efficiency are derived. The authors further maximized energy efficiency of the proposed network, and evaluate the optimal detection threshold, the optimal energy harvesting time and the optimal data transmission time, subject to PT interference and energy harvesting constraints.

Reinforcement learning algorithms have been also investigated in backscatter-assisted RF-powered CRN to deal with dynamics of the ambient signals. In particular, [212] investigated a learning algorithm with incomplete environment parameters, e.g., channel state, the successful data transmission probabilities, that helps the ST to obtain the optimal policy through learning from its decisions. It is shown that, the proposed learning algorithm with incomplete environment parameters can closely attain the performance of the Markov decision process [246] optimization with complete information. Besides, reference [213] adopted a deep reinforcement learning algorithm for time scheduling in an RF-powered backscatter CRN with multiple STs, where the information about the network is incomplete. The proposed algorithm allows the network to assign backscattering time, EH time, and transmission time to the STs to maximize the network throughput. Moreover, for a large-scale RF-powered backscatter CRN, the authors in [134] developed an unsupervised Bayesian non-parametric learning algorithm to obtain the information from the primary network such as traffic application and popularity, which help to improve the performance of the secondary network.

B. BACKSCATTER-ASSISTED WIRELESS-POWERED RELAYING

Relaying has been considered as an effective solution to enhance the communication ranges of power-constrained IoT networks. Backscatter communication devices have been regularly used as relays to assist the transmission by backscattering the received signals from the source node to the destination node, where they can effectively improve the signal diversity [156], [157], [247], [248]. Following this idea, [247] studied a relay network with multiple backscatter devices which are wirelessly powered by a PB. The backscatter devices work cooperatively to help as wireless relays for data transmission. The authors investigate the joint design of reflection coefficients of the backscatter devices to improve the signal reception with imperfect channel knowledge. Short-range backscatter communications may not guarantee the network coverage as the critical issue for relay networks. To overcome this limitation and to use the advantages of both active RF communication ad backscatter communications, it is considered that, the relay nodes have a dual mode transceiver structure and can flexibly switch between two operating modes, i.e., active and passive modes, to assist the information delivery [157], [248]. This way, the passive devices serve as passive relays to improve the performance of the active RF communications with proper reflection coefficients. In particular, in [248], a wireless-powered D2D network is studied where each user equipment can operate in either active mode or passive backscatter communications. The users are wirelessly powered by a multi-antenna PB via RF signal beamforming. When there are active communications, e.g., cellular network, the users can leverage the existing RF signals for low-rate backscatter communication. While, the channels are idle, the PB can beamform dedicated RF signals for the users and they can switch to active mode to use the idle channels, opportunistically. Cooperation among the users is also considered to further improve the performance. When a user actively transmit information, the other users can either harvest energy or switch into passive mode to assist the active user. The authors first investigated the sum throughput maximization by jointly optimizing the energy beamforming strategy, the power control and transmission scheduling in two radio modes and then consider the cooperation among the users to further improve the performance gain. Besides, in [249], a game-theoretic approach is proposed for the nodes to optimize the relaying strategy in a distributed manner. Moreover, the authors in [250], investigated ambient backscatter-assisted wireless-powered relaying for IoT networks where the relays use the ambient RF resources for dual mode operation. The end-to-end success probabilities and ergodic capacity under different mode selection protocols are derived based on stochastic geometry analysis. Furthermore, in [251], ambient backscatter-assisted cooperation method is investigated to improve the fairness in a two-user wireless-powered communication network.

Dual mode operation extensively used in backscatter-assisted relay networks requires complex integration circuits for switching modes and consume much more power. These requirements may limit their application in large-scale hardware- and power-constrained IoT networks in practice. Thus, [252], [253] proposed a relaying scheme for IoT networks where energy-constrained gateways are deployed close to the user devices to assist them for information transmission to the H-AP, as relay nodes. In [252], multiple backscatter devices, each with one gateway which is located near the device, are powered by an H-AP. While a user device transmits data to its gateway by backscattering the signals from the H-AP, other gateways harvest energy from the H-AP. Then, the gateways use the harvested energy to actively forward the received signals to the H-AP in a round-robin fashion. The authors maximized the achievable sum rate by optimizing the time allocation between data backscattering, EH and data forwarding. The authors in [253] further considered multi-antenna H-AP with energy beamforming techniques. Three successive working phases were considered for data transmission. In the first phase, the H-AP beamforms energy signals to the gateways via a known sequence with unit power to the gateways, while all backscatter devices keep idle. In the second phase, the sensors employ the signals form the H-AP to backscatter data to the gateways in TDMA manner. In this phase, in the duration of each backscatter device, the H-AP focuses its signals toward the device via beamforming to enhance energy efficiency. In the third phase, the gateways forward the receive backscatter signals from the devices to the H-AP, sequentially. The authors investigated the joint design of energy beamforming vectors, time scheduling and power allocation. However, the assumption that each gateway just assists one user device for transmission may not be efficient for large-scale IoT networks. In [37], multi-hop relaying with power splitting is considered for massive tags/sensors. The authors investigated ABCSs based on Wi-Fi architecture and designed multi-hop and massive tag/sensors backscatter transmission mechanism.

C. VISIBLE LIGHT BACKSCATTER COMMUNICATION (VLBC)

VLBC has been identified as a practical solution for indoor IoT applications [233]–[236] . The VLC backscatter device harvests energy from the existing indoor lighting infrastructure and modulates the reflected light beam as long as the illumination is available [233]. Unlike RF backscatter, VLC backscatter enjoys minimal deployment overheads in terms of hardware replacements [234]. A bi-directional VLC system, RetroVLC, is designed in [233], which uses the retroreflector fabric to backscatter the encoded information modulated by a liquid crystal display (LCD) shutter. RetroVLC achieves 10 kbps downlink rate and 0.5 kbps uplink rate over a distance up to 2.4 meters using OOK modulation and Manchester coding. The authors in [234] extend the idea of RetroVLC and use a plural of retroreflectors and LCD shutters to form numbers of pixels, each pixel can be switched on/off independently to produce multi-level signals. Experimental results show that by using 8-pulse amplitude modulation (8-PAM), a bitrate of 600 bps can be achieved at a distance of 2 meters compared to 200 bps when using the OOK scheme.

Reference [235] further upgrades the RetroVLC design from coding and modulation perspectives to increase the data rate. Specifically, Manchester coding is replaced with a Miller code, which doubles the bandwidth utilization. Besides, a trend-based modulation and code-assisted demodulation scheme is designed. The proposed approach can reduce the modulation time from 4 ms to 1 ms and achieves 1 Kbps (8× over RetroVLC) using the same LCD shutter. This scheme however frees up the potential to further improve the data rate by adding more pixels.

It is observed that, the response time of LCD's different charging states is highly asymmetric; that is, charging is much faster than discharging, i.e., sub-ms and 4 ms. Reference [236] thus exploits the LCD asymmetric response and proposes a delayed superimposed modulation scheme that pushes the rate limit to 4 Kbps with an array of LCD pixels, which is 4× the rate over the proposed method in [235].

V. WPN-BCS APPLICATIONS

Miniature and low-powered WPN-BCs may provide pervasive connectivity for a myriad of applications. Some of the potential areas that can leverage the capabilities of low-powered WPN-BCs are smart homes/cities, industrial IoT, bio-medical field and environmental monitoring systems. In the following, we briefly review the applications of WPN-BCs in healthcare and smart homes/cities.

A. WPN-BCS FOR HEALTHCARE

Communication systems used in modern medical applications consume comparatively excess energy because of the need to generate their own radio signals. For instance, wireless capsules used for endoscopy consume up to 10 times more power than the sensors [254]. Such excessive power consumption is a drawback, and thus new solutions for tiny and low heat-radiation in-body and on-body devices are needed and they should be capable of battery-free operation with smart networking. WPN-BCs, without any active RF components, can be regarded as an innovative communication modality to meet these requirements [255]. The low-powered architecture of WPN-BCs can be well-suited for not only capturing sensory data but also transmitting it over short distances. Some further applications in healthcare are information registry, emergency evaluation, health monitoring and lab analysis [255]. Moreover, wireless-powered backscatter-based localization systems can also be a potential technology to facilitate social distancing, which may be necessary due to COVID-19 [256]. In the context of healthcare applications, WPN-BCs may help with energy management, latency minimization, mobility management and cost optimization, which are some of the critical system-level objectives.

B. WPN-BCS FOR SMART HOMES/CITIES

In a smart home, a large number of passive backscatter tags sensors can be deployed at flexible locations (e.g., embedded in walls, roof, and furniture). These passive tags can be powered by either multiple in-house deployed PBs or ambient sources such as Wi-Fi access points, TV towers, or cellular BSs. These tags can perform a wide range of activities such as gas leakage/smoke detection, monitoring movements, indoor positioning, and surveillance. On the other hand, in a smart city, a large number of passive tags, energized with the ambient sources, can be deployed in buildings, streets, bridges, and parking spaces to improve the quality of life. Passive tags can also monitor air/noise pollution, traffic, and parking availability [257].

VI. OPEN ISSUES AND FUTURE RESEARCH DIRECTIONS

Based on our review of recent efforts and publications in the field of WPN-BCs, herein, we discuss some open problems that require further research attention and specifically ones pertaining to large-scale WPN-BCs.

A. INTERFERENCE MANAGEMENT

A critical system issue is the interference resulting from wireless-powered networks with ambient backscatter on licensed users, especially when there are high-rate users. Moreover, for large-scale WPN-BCs, massive numbers of devices in close proximity may result in mutual interference among them. Therefore, one can investigate sophisticated interference avoidance and suppression techniques to not only take care of the communication needs of licensed users but also to manage the interference issues in large-scale WPN-BCs to guarantee reliable communications with sufficiently high rates.

B. CHANNEL CODING SCHEMES

As discussed before, backscatter communications could be integrated with emerging technologies, e.g., full-duplex, MIMO, CRNs, relays and others. Therefore, this integration needs coding and decoding schemes. New OSTBC schemes should thus be developed for MIMO backscatter links and their performances should be analyzed and quantified. Moreover, well-known error correcting codes, e.g., low density parity check (LDPC) codes and low complexity polar codes, which are primarily designed for high-end devices with active radios, may be used with WPN-BCs to enable reliable transmission with high data rates [110]. The adoption of these codes in power-constrained and low-complexity backscatter tags, the encoder and decoder, entails several practical challenges that needs further investigations.

C. ARTIFICIAL INTELLIGENCE BASED APPROACHES

Artificial intelligence techniques have recently been vigorously considered for signal processing and communications. For instance, deep learning is a powerful tool to extract key features of communication systems, e.g., signals, channels, modulation/demodulation schemes and hence it can be effectively employed to address many problems in large-scale wireless communication systems [199]–[201], [205]. Deep learning approaches to address the challenge of CSI sensing and recovery in large dimensional WPN-BCs need further investigations. Besides, channel coding algorithms based on deep learning can be well adopted in large-scale WPN-BCs. Moreover, in multi-antenna systems, the optimal antenna subset selection (e.g., see [258], [259]) problem can be interpreted as a multi-class classification and/or decision-making task, which is readily solvable via machine learning. Multi-class classifier algorithms are the k-nearest neighbours (k-NN) and support vector machine (SVM), Naive–Bayes (NB) and others [260], [261]. These may improve the design and optimization of complex and dynamic wireless communication systems.

D. MULTIPLE-ACCESS SCHEMES AND PROTOCOLS

In WPN-BCs with a large number of devices, high capacity should be offered to not just a single node but as many nodes as possible, simultaneously. Through efficient multiple access techniques, a large number of devices could be served and at the same time, the interference between the devices could be handled and suppressed. Moreover, WPN-BCs require new communication protocols to coordinate RF energy and backscatter communications together. In particular, decentralized MAC protocols where the nodes are communicating in a distributed way need further investigations. To this end, cooperation among devices, tag-selection [30], and scheduling algorithms guaranteeing fairness are important issues to be addressed.

E. PHYSICAL LAYER SECURITY

Provision of network security is one of key components of 6G communication networks. Therefore, enabling secure WPN-BCs, as an innovative technology to realize 6G visions, is of great importance. However, the security aspects of such systems are only marginally studied in the existing works. Thus, we must identify effective strategies to implement physical security to prevent the vulnerability of different types of attacks, e.g., interference attack, denial of service attack, and eavesdropping attacks.

F. UAV-AIDED LARGE-SCALE WPN-BCS

Unmanned aerial vehicles (UAVs) [262] have the potential to provide wireless connectivity to remote locations due to their mobility, and hence, UAV-enabled backscatter communications have been recently investigated [263], [264]. For large-scale backscatter sensors, UAVs can help to ease the channel estimation process and also to assist data transmission. It is shown that, UAVs can act not only as data aggregators but also RF signal emitters enabling fast data aggregation and energy transfer at remote locations [262]. Therefore, the integration of UAVs with WPN-BCs is a worthy future research direction to facilitate large-scale communication networks. Joint optimization of UAV location, time allocation and reflection coefficient, subject to the UAV mobility and practical harvest-backscatter constraints need to be investigated to enhance the performance of the large-scale WPN-BCs.

VII. CONCLUSION

In this paper, we have presented a comprehensive literature survey on wireless-powered networks with backscatter communications, as a key enabler for large-scale low-power and low-cost wireless communications. First, we introduced the concepts of wireless-powered communication networks and backscatter communication systems. We next focused on their integrated usage and applications with the emphasis on large-scale wireless communication networks. We have reviewed the fundamentals and design issues of WPN-BCs including modulation, channel coding, waveform and energy harvester design and deployment of such networks. We have also reviewed recent efforts and existing approaches to enhance the performance of WPN-BCs. Furthermore, the emerging technologies for wireless-powered backscatter systems have been discussed. We have also highlighted some applications of this innovative technology. Finally, we have addressed some practical open research problems and future research directions.

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