An Overview on Backscatter Communications

Jin-Ping Niu, Geoffrey Ye Li

***Abstract*—As a key low-power communication technique, backscatter communications exploits the reflected or backscattered signals to transmit data, where the backscattered signals can be the reflection of ambient radio frequency (RF) signals, the RF signals from the dedicated carrier emitter or the signal photons in the non-classical quantum entangled pairs, etc. In the past 70 years, various kinds of backscatter communication systems have been developed, which will enable the low-power communications as required in the Internet of things (IoTs) and green communications. This article provides a historical view on the development and the research achievements on backscatter communications, including the fundamental principles, the applications, the challenges, and the potential research topics. This article will benefit the researchers and engineers concerning the area of backscatter communications, especially for applications in IoTs.**

***Keywords*—backscatter, backscatter communications, energy harvesting, IoTs**

I. Introduction

Backscatter communications can be dated back to the Second World War when it was used to identify whether an airplane was from a friend or an enemy[1]. The first academic article on backscatter communications was published in 1948 in Ref. [2]. It has been continuously investigated since then.

A typical backscatter communication system includes three components: the signal source, the backscatter transmitter equipped with antennas, and the backscatter receiver, as illustrated in Fig. 1. The signal source is to generate the incident signal, which can be a dedicated signal generator or an ambient radio signal (RF) source, such as a cellular base station or a TV tower. After arriving at the backscatter transmitter, the signal will be remodulated and reflected by the backscatter antenna to deliver information. The receiver detects the information from the backscatter transmitter after receiving the reflected signal. Different from the traditional communications, which transmits data via generating RF signal itself at the transmitter, the backscatter communications conveys information by remodulating and reflecting signals from other signal sources instead of generating carrier signal at its transmitter.

As shown in Fig. 1, in backscatter communications, two-way pathloss is involved: the pathloss from the signal source to the backscatter transmitter and the one from the backscatter transmitter to the backscatter receiver, which limits its transmission range. Improved configurations at the signal source, the backscatter transmitter, and the backscatter receiver can help to decrease or compensate for the pathloss and improve the communication performance.

The backscatter communication system with a dedicated signal resource, such as a radio frequency identification (RFID) system, was extensively investigated in the first few decades after backscatter communications was invented[3,4]. With a dedicated signal source, the backscatter transmitter can be placed close to the signal source, thus decreasing the corresponding pathloss. Various kinds of methods have been proposed to reduce the pathloss between the backscatter transmitter and the backscatter receiver and to improve the system performance, including the coding schemes[5,6], multi-antenna techniques[7], anti-collision schemes[8], channel modeling[9], etc. In general, backscatter communications with a dedicated source has many practical applications, such as in retail, positioning, etc. With a dedicated signal source, the cost and size of the system can be improved. However, backscatter communications with dedicated signal source is still hard to satisfy the requirement of data-intensive communications[10].

Over the past decade, the research focus on backscatter communications has been shifted to the system utilizing ambient signal sources or further considering energy harvesting at the backscatter transmitter, which is more energy-efficient and enables ubiquitous communications and applications. Instead

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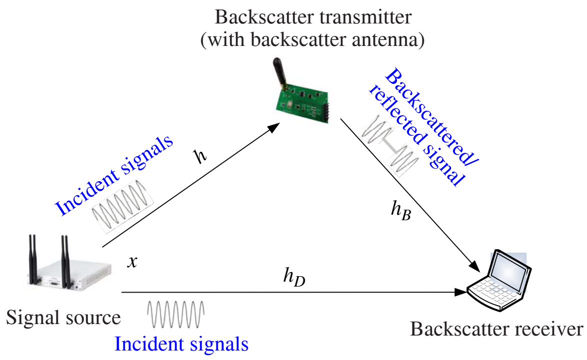

Figure 1 An example of signal transmission in backscatter communication system

of using a dedicated signal source, the ambient backscatter communication system utilizes the ambient RF, such as TV or cellular signals, as the signal source, decreasing the cost of the system. To further facilitate battery-free operation, energy harvesting[11] can be utilized at the backscatter transmitter to collect energy from the ambient signal sources and improve the system flexibility. Lots of works on ambient backscatter communications have been proposed, including system design[12-17], coherent, semi-coherent, or non-coherent signal detection[18-21], coding[22], and modulation[23-28]. Energy harvesting in backscatter has also been studied extensively, including the energy harvesting module design[29], the overall system design[30-33], the system analysis and reviews[11,34-37]. Due to its low-cost and flexibility, the ambient backscatter with energy harvesting is a promising solution for future low-power and ubiquitous communications, such Internet of things (IoTs).

This article provides an overview on different kinds of techniques and various design issues in the backscatter communications. Specifically, we introduce the achievements of backscatter communications over the past 70 years. Furthermore, we also discuss the emerging backscatter techniques, such as quantum backscatter, which has been ignored in the existing surveys. This article will benefit for the researchers and engineers concerning the area of backscatter communications.

The rest of this article is organized as follows. Section II first describes the concept of the backscatter communications, including the basic principle, the categories of backscatter communications, and some common features for different systems, and then discusses the milestones in the history of backscatter communications. Section III reviews the research on the traditional dedicated backscatter communications. Section IV introduces the advanced ambient backscatter communications and the energy harvesting in the backscatter systems. Section V discusses the requirements of future backscatter communications and identifies potential topics for future research. Conclusions are presented in section VI.

Table 1 Typical theoretical and experimental works on backscatter communications

Works on backscatter communications	References
Theoretical works	[18,19,38-42]
Experimental works	[12-15,30,43-46]

II. Overview of Backscatter Communications

In this section, we will first introduce the principle of backscatter communication systems and divide them into several categories, then analyze their key features, and finally discuss some milestones in the history of backscatter communications.

A. Basic Principle of Backscatter Communications

In the backscatter communications in Fig. 1, the radiation or incident signal is reflected by the backscatter antennas and then the transmit information at the backscatter transmitter is remodulated to the reflected signal and delivered to the backscatter receiver. Signal reflection by the backscatter antennas is involved in the backscatter communications. This is different from the traditional communications, where the transmit information is included in the radiation signal and delivered to the receiver directly. Different kinds of backscatter communication systems have been proposed, including theoretical and experimental works, where the typical works have been summarized in Tab. 1. The general principle behind these systems is similar. We will demonstrate the signal transmission in the backscatter communications in the following by using the simple example in Fig. 1.

In the backscatter communications, by regulating the impedance of the backscatter antennas at the transmitter, the incident signal from the signal source can be reflected by the antennas, as illustrated in Fig. 1. Assume there are two states for the backscatter antenna at the transmitter, the reflecting or non-reflecting states. Using simple on-off-keying (OOK) modulation, bits ‘0’ and ‘1’ at the backscatter transmitter can be modulated onto the reflecting signal. For example, if the data bit to be transmitted is ‘1’, switch the backscatter antenna to the reflecting mode; otherwise, switch the backscatter antenna to the non-reflecting mode. In this way, the data at the backscatter transmitter can be modulated to the reflection signal and delivered to the receiver. Then the receiver can decode the data transmitted according to the power variations of the received signal.

As in Fig. 1, the received signal at the backscatter transmitter from the signal source can be expressed as

$$y = h\sqrt{p}x + n, \tag{1}$$

where h is the channel gain from the signal source to the backscatter transmitter, p and x are the transmit power and the transmit signal at the signal source, respectively, and n is the White Gaussian noise at the backscatter transmitter.

By regulating the working state of the backscatter antenna, the received RF signal at the backscatter transmitter can be remodulated and reflected. Specifically, the received signal, y, will be reflected at the backscatter antenna as

$$z = \alpha_d y, \tag{2}$$

where α_d is the complex reflection coefficient caused by regulating the antenna's working state, and d is the transmit data. For backscatter antennas with two working states, Eq. (2) can be realized by switching the antenna to reflecting mode if $d = 1$ or switching to non-reflecting mode if $d = 0$. Note that d has a much lower data rate than x and thus z will keep relatively stable for some time period[19].

The received signal at the backscatter receiver includes the signals from the signal source and the backscatter transmitter and can be expressed as

$$\begin{aligned} z_B = h_D\sqrt{p}x + h_B\sqrt{p_B}z + n_B = \\ h_D\sqrt{p}x + h_B\sqrt{p_B}\alpha_d h\sqrt{p}x + n_B', \end{aligned} \tag{3}$$

where h_D is the channel gain from the signal source to the backscatter receiver, the h_B and p_B are the channel gain from the backscatter transmitter to the backscatter receiver and the transmit power of the backscatter transmitter, respectively, n_B is the noise at the backscatter receiver, and $n_B' = h_B\sqrt{p_B}\alpha_d n + n_B$. Through the power changes of z_B, the transmit data, d, can be detected at the backscatter receiver.

Additionally, backscatter antennas can be designed to have several reflecting states by varying the antenna impedance[47] and thus may support higher order modulation schemes. Specifically, depending on the number of antenna's working states, i.e. the number of feasible values of α_d, the transmit data, d, can be a binary bit or a symbol including several binary bits. For example, if there are two antenna working states, reflecting or non-reflecting modes, then d can be the bit '0' or '1', while if there are four antenna working states, then d can be a symbol related with bits '00', '01', '10' or '11'.

B. Categories

According to the system architectures, the backscatter communication systems can be classified into two major categories: the monostatic and the bistatic backscatter communication systems, as in Figures 2 and 3, respectively.

For the monostatic backscatter communications in Fig. 2, the signal source and the backscatter receiver are in the same device, as illustrated in Fig. 2. In the monostatic backscatter communications, the incident signal from the signal source propagates to the backscatter transmitter as an excitation signal and then the transmitter modulates the transmit information and reflects it to the backscatter receiver. One of the most popular application of the monostatic backscatter is the RFID, where the backscatter transmitter and the receiver in Figure 3 are called RFID tag and the RFID reader, respectively.

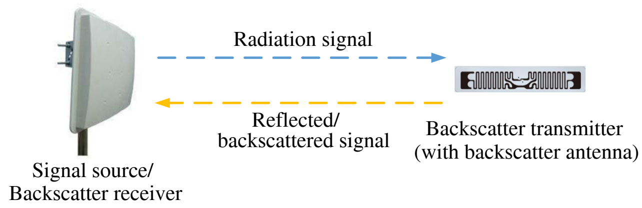

Figure 2 Monostatic backscatter communication system

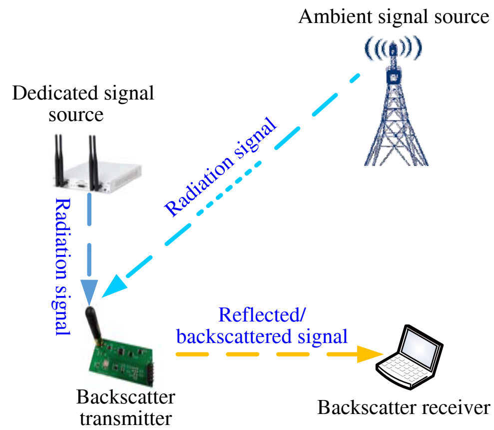

Figure 3 Bistatic backscatter communication systems

Table 2 Types of backscatter transmitters in RFID

Backscatter transmitters	Features
Active	With internal power supply and transceiver, be able to transmit data actively, long communication range
Passive	Without internal power supply, power excitation and operation via energy harvesting, with simple structure, small size, and low cost
Semi-passive	With internal power supply, usually transmit data only when being excited with the advantages of both active and passive transmitters

In the typical monostatic backscatter system, RFID, there are three types of backscatter transmitters: active, passive, and semi-passive ones[3,48]. The active RFID tag has the internal power supply and transceiver implemented, which can send information to the reader actively as well as backscatter the RF signal from the RFID reader. On the other hand, the passive tag does not have the internal power supply configured and transmits data only if the harvested energy from the

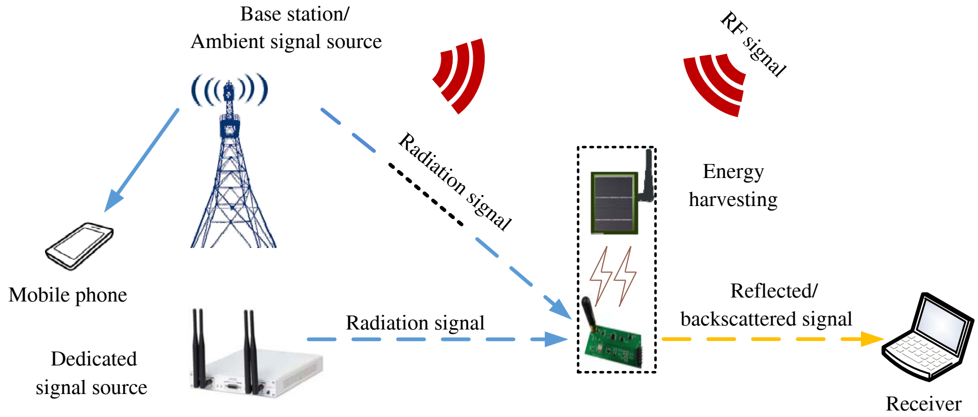

Figure 4 Bistatic backscatter communication system with energy harvesting

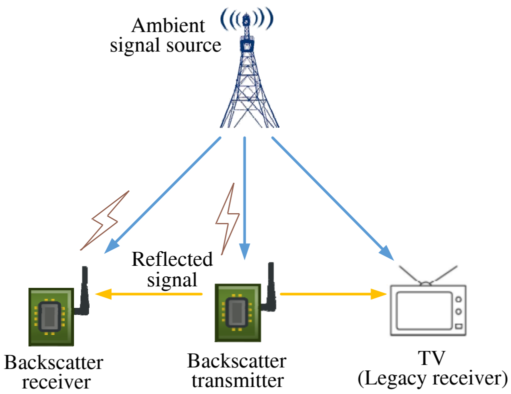

Figure 5 Bistatic backscatter communication system with both passive transmitter and receiver[12]

reader satisfies its working requirement. The semi-passive tag has the compromise functions of the active and passive tags, where it has both limited power supply and energy harvesting. To save the power, the semi-passive tag does not transmit data actively and only transmits data when being excited. After being excited, it can use the internal power for data transmission. The features of these three kinds of backscatter transmitters in RFID systems are summarized in Tab. 2.

To avoid self-interference (SI) at the receiver side, the incident and the reflected signal can use different carrier frequencies. Thus, besides the backscatter antenna to reflect incident signal, the backscatter transmitter can also perform frequency conversion in the monostatic backscatter communication system. In addition, two-way pathloss, including the incident and reflected pathloss, are involved, which limits the communication range.

For the bistatic backscatter communications, the signal source and the receiver are at different terminals as in Fig. 3, where the signal source can be a dedicated signal generator or an ambient signal source. In the traditional bistatic backscatter communication system, the special carrier emitter is utilized as the signal source, which can be placed near the backscatter transmitter. Therefore, it avoids the two-way pathloss problem in the monostatic backscatter communication system and improves the system performance due to the flexibility of the special carrier emitter. In the recent ambient backscatter system, the ambient signal sources, such as cellular signals, Wi-Fi signals, TV tower signals, etc., are exploited. No dedicated signal source, such as special carrier emitter, is needed for the system. Besides, bistatic backscatter communications with energy harvesting at the backscatter transmitter side has been proposed as in Fig. 4. By further implementing the energy harvesting into the backscatter transmitter, high energy efficient system can be obtained. In addition, the recent backscatter communication system[12] with both passive backscatter transmitter and receiver enables the low-power device-to-device communications, as illustrated in Fig. 5.

Different categories of backscatter communication systems and their features are summarized in Tab. 3, where the backscatter transmitters are divided into passive, semi-passive, and active ones, similar to the transmitter types in RFID systems.

C. Common Features

Different backscatter communication systems have different configurations and performance. But they have some common features in general. We will introduce some common features in this section.

1) Backscatter Antenna at the Transmitter: Although there are different kinds of backscatter communication techniques, such as Wi-Fi backscatter, RFID backscatter, and long range (LoRa) backscatter, the basic principle is similar. They all need a antenna configured to support the signal backscattering. The signal backscattering is realized by varying the antenna impedance, which will changes the value of reflection coefficient correspondingly. More specifically, the complex reflection coefficient, α_d, in Eq. (2) can be expressed as[3]

$$\alpha_d = \frac{Z_d - Z_a^*}{Z_d + Z_a}, \tag{4}$$

Table 3 Categories of backscatter communication systems

Backscatter systems	Signal source	Backscatter transmitter	Features	Reference system
Monostatic backscatter systems	Dedicated signals	Passive	Two-way pathloss compact and cheap transmitter high energy efficiency downlink limited	[3]
		Semi-passive	Two-way pathloss downlink limited	[3]
		Active	Two-way pathloss	[49]
	Ambient signals	Passive	Two-way pathloss dynamic signal source compact and cheap transmitter high energy efficiency	-
		Semi-passive	Two-way pathloss dynamic signal source	-
		Active	Two-way pathloss dynamic signal source	[44]
Bistatic backscatter systems	Dedicated signals	Passive	Low-cost system high energy efficiency	[50]
		Semi-passive	Longer communication range	[51]
		Active	Longer communication range	[15]
	Ambient signals	Passive	Two-way pathloss dynamic signal source low-cost system high energy efficiency	[12]
		Semi-passive	Two-way pathloss dynamic signal source	-
		Active	Two-way pathloss dynamic signal source	[13]

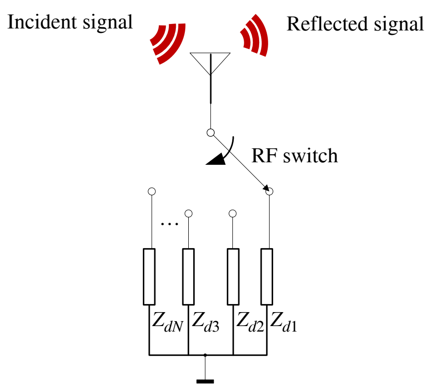

Figure 6 An example of the backscatter antenna with N reflecting states

where Z_d and Z_a is the load impedance and the antenna impedance, respectively. By switching the antenna modes, the transmit data, d, can map to the reflection coefficient, α_d, for data transmission and decoding, as illustrated in Fig. 6.

The backscatter antenna should have at least two states: the reflecting or non-reflecting states. When switching between these two modes, OOK modulation can be realized to include the transmit data to the reflected signal to facilitate information transmission for the backscatter system. Advanced backscatter antenna with multiple reflecting states can facilitate higher-order modulation and thus improve the data transmission rate of the system.

2) Low Power Consumption: The data transmission in backscatter communications utilizes signal reflection instead of signal radiation. Thus low power is consumed at the backscatter transmitter. Moreover, the passive RF module is implemented at the backscatter transmitter, further reducing its cost and power consumption.

3) Weak Backscatter Signal at the Receiver: The backscatter signal is usually very weak due to energy loss during the backscatter process. Thus it is vulnerable to noise and fading. Therefore, many schemes have been proposed to improve system performance, which will be discussed subsequently.

Generally, there has been a huge achievement in backscatter communications over the past 70 years. Some important milestones of backscatter communications are summarized in Tab. 4.

III. Traditional Backscatter Communications with Dedicated Signal Source

The backscatter communications in the first sixty years is mainly based on the dedicated signal source for short-range communications. By utilizing a special carrier generator, the backscatter transmitter can be located near the signal source, thus reducing the two-way pathloss involved in the system and improving the communication performance. Depending on the specific implementation of the signal source, monostatic and bistatic backscatter communication systems may be involved. According to whether the power supply is implemented at the backscatter transmitter or not, the systems can be further classified into active, semi-passive, or passive ones. The battery-free passive backscatter is with low-cost and compact structure. To support sustainable communications, espe-

Table 4 List of milestones for the backscatter communications during the past 70 years

Year	Contributions	Reference
The Second World War	Backscatter communications has been used to identify enemy or friend	[1]
1948	Backscatter communications has been first published	[2]
1952	RFID with dedicated signal resource has been explored	[52,53]
1960's	Field trials and commercialization on RFID have emerged	[53]
1980's	The first widespread commercial RFID systems has been developed	[53]
2012	The bistatic backscatter with dedicated signal resource has been examined	[54]
2013	Ambient backscatter has been proposed	[12]
2014	Full-duplex backscatter has been proposed	[55]
2015	Ambient backscatter with energy harvesting has been designed	[43]
2015	Inter-technology backscatter has been proposed	[16]
2017	Hybrid backscatter has been proposed	[31]
2017	Quantum backscatter has been proposed	[16]

cially for the passive backscatter systems, energy harvesting has been introduced into the backscatter communication later on.

A. Traditional Monostatic Backscatter: RFID

The most typical application of the monostatic backscatter communications is the RFID system, which has been proposed to substitute the bar code scanning technology because of the low-cost for the RFID tags[3]. The reason behind it is that the intelligence can be embed into each object and uniquely identify the object in a low-cost way using the RFID technique[4].

The RFID reader is served as the backscatter receiver and the signal source while the RFID tag is the backscatter transmitter without RF components. Generally, the reader generates the RF signal and sends out, the tag within the communication range of the reader then scatters the RF signal back to the reader for data detection. By regulating the tag's antenna impedance, modulation is performed during the signal backscattering process to help data delivering at the tag to the reader.

RFID has been investigated extensively for a long period. More details on the basic principle, field trials, and commercializing can be found in Refs. [52,53]. The schemes to improve the uplink performance of RFID can be found in Refs. [56,57]. The coded modulation and signal detection for RFID can refer to Refs. [3,58]. Because of the communication range limitation of the RFID technique, especially for passive RFID, the system is uplink limited[59]. Multiple-input multiple-output (MIMO) has been introduced into the RFID to deal with the uplink limitation[60]. The discussion on the channels, diversity, and multiplexing trade-off for RFID MIMO systems can be found in Ref. [3]. The effect of channel correlation on the RFID MIMO system performance has been investigated in Ref. [61], where the single-input multiple-output (SIMO) and MIMO systems with maximum ratio combining reception are considered.

B. Traditional Bistatic Backscatter with Dedicated Carrier Emitter

In bistatic backscatter communication systems with dedicated carrier emitters[51,54,62], the signal source and the receiver are implemented separately, which improves the flexibility and the performance of the system. In such a system, multiple signal sources can be placed in a field, where a large coverage area can be obtained with up to 50 times of power decreasing from the carrier emitters[62].

However, compared with its monostatic counterpart, the bistatic introduces the new problem of carrier frequency offset (CFO) between the signal source and the receiver in the systems, which severely affects the system performance, especially for low-data rate transmission. Besides studying the system performance, the signal detection technique and its applications[62-64], the new CFO challenge has been addressed in Ref. [54].

C. Dedicated-Signal-Source Backscatter Communication with Energy Harvesting

The passive tag is battery-free and can harvest energy from the reader to support sustainable communications, where the energy harvesting efficiency depends on the working state of the tag, i.e. idle or backscattering. From Refs. [65,66], the energy harvesting efficiency is no more than 20% when the tag is idle. When the tag is scattering signals back, its energy harvesting efficiency depends on the coding schemes[6].

In general, despite the benefits of the backscatter communications with the dedicated source, it is still hard to satisfy the requirement of data-intensive and ubiquitous communications due to the limitations of the cost and the size of the system.

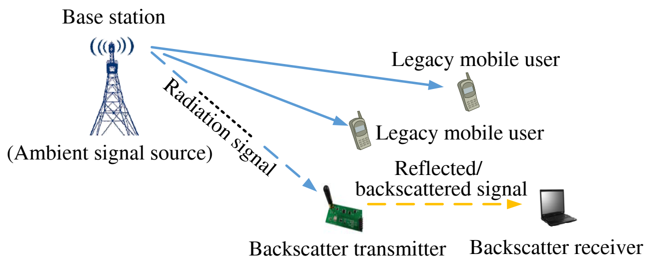

Figure 7 An example of an ambient backscatter communication system utilizing cellular signal as the signal source

IV. Advanced Ambient Backscatter Communications

For the traditional dedicated-signal source backscatter, generating carrier signals by utilizing special devices is expensive and not energy-efficient. To enable the energy-efficient and ubiquitous communications and applications, ambient signal sources have been utilized in the last decade. Various kinds of ambient backscatter systems have been developed and energy harvesting is further utilized to improve the system performance. Fig. 7 illustrates a typical ambient backscatter communication system.

A. Ambient Backscatter Communications

Ambient backscatter communications is first proposed in Ref. [12]. It exploits the ambient RF, such as TV or cellular communications, as the signal source. Afterwards, various kinds of ambient backscatter communication systems have been developed[13-15,30,45,46,50,67]. Compared with the RFID backscatter and the traditional bistatic backscatter communications, ambient backscatter communications requires no dedicated device to generate RF signals and is with low cost. It is also more energy-efficient than the traditional communications and thus enables ubiquitous communications. Some typical ambient communication systems with different kinds of signal sources and their features are summarized in Tab. 5, where $d_{S\rightarrow Tx}$ and $d_{Tx\rightarrow Rx}$ are the incident path distance from the signal source to the backscatter transmitter and the reflected path distance from the transmitter to the receiver, respectively. In Tab. 5, the uplink represents the communication from the device configured with backscatter antennas to the receiver and the downlink is the reverse link for the uplink.

On the other hand, the ambient backscatter communications exploits the surrounding RF signals as the source to facilitate signal reflection, where the surrounding RF signals, usually unpredictable and uncontrollable, carry information encoded for their original systems. As a result, the information extraction for the backscatter systems from the reflected ambient signals is more difficult. Therefore, most of the research on the ambient backscatter communications focuses on how to effectively extract the transmit information. Besides, the reflected signal is usually relatively weak, which limits the communication range. There are lots of works on improving the communication performance and designing new ambient backscatter communication systems.

The work in Ref. [12] prototypes an ambient backscatter communication system, which can modulate and reflect the TV or cellular RF signals to the transmit data. Low power analog operations are used to decode the transmit information of the backscatter communication system based on the transmission rate difference of the backscatter and ambient RF signals. The ambient backscatter transceiver designed in Ref. [12] is battery-free, and thus energy harvesting module to collect the power from the TV signal is also prototyped to provide the power for the backscatter data transmission. Nevertheless, the system is with very limited data rate of 1 kbit/s and communication ranges of 0.5 m indoor and 0.75 m outdoor communications. The work in Ref. [43] exploits multi-antenna cancelation to encode in the backscatter communication system to improve the communication rate and range. Instead of using analog-to-digital converters (ADCs) and digital computation as in traditional communication systems, the analog components with low power consumption are utilized in the backscatter system to facilitate these mutli-antenna and coding techniques in the battery-free backscatter transceiver. Energy harvesting is utilized to power the multi-antenna receiver for the backscatter system. The above technique can improve communication rate and range by 100 and 40 times, respectively, compared with the ambient backscatter communication system in Ref. [12].

To enable the internet connectivity for the RF-power devices, such as the one used in ambient backscatter communications, the Wi-Fi backscatter in Ref. [14] supports the communication between the RF-powered devices and the commercial Wi-Fi devices without deploying new infrastructure. This is realized by modulating the Wi-Fi channel using a dedicated Wi-Fi backscatter antenna or tag via the existing Wi-Fi infrastructure. The performance of Wi-Fi backscatter is further improved by the BackFi system in Ref. [44], utilizing the full-duplex technique. Nevertheless, the ambient backscatter communication systems discussed in Refs. [12,14,15,30,43,67] requires the dedicated backscatter antenna to reflect RF signals. The NICScatter proposed in Ref. [13] uses the Wi-Fi network-interface-card (NIC) as the backscatter antenna to transmit information instead of designing specialized backscatter antennas.

Besides system design, theoretical works, such as signal processing schemes, detection schemes, coding schemes, performance analysis, and scheduling scheme, etc., have also been investigated to further improve the system performance. It has been shown in Ref. [38] that the overall system data rate can be improved by introducing backscatter communication into the traditional network. In Ref. [19], signal detec-

Table 5 Typical ambient backscatter communication systems

Signal source	Backscatter system	Communication range		Data rate	Energy consumption	Other features
		$d_{S\to Tx}$	$d_{Tx\to Rx}$			
Ambient Wi-Fi signal	Wi-Fi backscatter[14] (*uplink and downlink*)	3 m	65 cm	30 packets/bit	0.65 μW for transmit circuit; 9.0 μW for receiver circuit	Uplink
		-	2.13 m	20 kbit/s		Downlink
		-	2.90 m	10 kbit/s		
	NIC backscatter[13] (*uplink*)	1.64 m	1.90 m	1.60 bit/s	-	Laptop as the receiver
		1.64 m	0.30 m	1.60 bit/s		USRP as the receiver
	HitchHike[45] (*uplink*)	1 m	54 m	200 kbit/s	33 μW	Line-of-sight
		1 m	34 m	300 kbit/s		Line-of-sight
Wi-Fi signal	BackFi[44] (*uplink*)	1 m	1 m	5 Mbit/s	-	Wi-Fi from the dedicated device
		5 m	5 m	1 Mbit/s	-	
Ambient TV signal	Backscatter in Ref. [12] (*uplink*)	-	0.90 m	3 kbit/s	0.79 μW	Outdoors
			1.50 m	1 kbit/s		Indoors
Ambient FM signal	FM backscatter[46] (*uplink*)	-	1.50 m	3.20 kbit/s	11.07 μW	Uplink
LoRa signal	PloRa[30] (*uplink*)	20 cm	300 m	6.25 kbit/s	220 μW	Passive backscatter transmitter
	NetScatter[15] (*uplink*)	-	-	249.86 kbit/s	45.2 μW	Concurrent transmission for 256 backscatter transmitters

tion and bit-error-rate analysis have been performed, where differential encoders have been considered at the backscatter transmitter. The scheduling and resource allocation schemes for ambient backscatter systems can be found in Refs. [39,40]. The backscatter communications over ambient orthogonal frequency division multiplexing (OFDM) signals has been investigated in Refs. [18,41,42]. In Ref. [42], mathematical modeling and performance analysis of the ambient backscatter communications based on OFDM have been performed. The work in Ref. [41] considers the direct-link interference cancelation. Besides, the work in Ref. [18] has studied the non-coherent detection scheme for ambient OFDM signals exploiting null subcarriers.

B. Ambient Backscatter Communication with Energy Harvesting

To support the self-sustainable and independent communications, energy can be harvested from the surrounding signals for the ambient backscatter communication systems, as illustrated Fig. 4. Compared with the traditional dedicated-source-backscatter with energy harvesting, the energy-harvested ambient backscatter has more limited communication range due to the dynamic feature of the surrounding signals[10,44]. The recent development of the RF energy harvesting circuit will enable the ambient backscatter communication with energy harvesting.

V. Future Backscatter Communications

Although there have been lots of research achievements in backscatter communications, it still has a long way to go to meet the practical requirements for future green and ubiquitous communications, especially in IoTs applications. Generally, there are four main concerns on the backscatter communications[47]: data transmission rate, coverage, energy efficiency, and deployment cost. To satisfy these requirements, future backscatter communications systems should incorporate some critical techniques, such as energy harvesting, backscatter relay, full-duplex, millimeter wave communications, hybrid backscatter, and quantum communications, etc. We will discuss in detail on the requirements of the future backscatter communications, the potential techniques to fulfill the requirements, and some typical future backscatter communication systems in the following.

A. Basic Requirements for Future Backscatter Communications

High-bit rate, for example over several kbit/s in most IoTs applications[47], is a fundamental need for general communication systems. Traditional schemes, such as increasing the bandwidth, modulation order, or the transmit power, may not be feasible or enough for the backscatter systems to improve the data rate significantly, due to the low-power and low-cost requirements and the system architecture. Additionally, the two-way pathloss involved in the backscatter communication systems, such as ambient backscatter, has an adverse impact on the system data rate. Advanced schemes to improve data rate should be investigated considering the architecture and the characteristics of the backscatter systems.

Long communication distance is desired in many applications. Two distances, the incident path distance $d_{S\to Tx}$ from the signal source to the backscatter transmitter and the reflected path distance $d_{Tx\to Rx}$ from the transmitter to the receiver as illustrated in Fig. 1, are involved in the backscatter communications. They relate with each other and directly determine the pathloss of the system. Specifically, a larger $d_{S\to Tx}$ leads to smaller signal power for the reflected signal and accordingly causes shorter $d_{Tx\to Rx}$. Different applications have different requirements on $d_{S\to Tx}$ and $d_{Tx\to Rx}$. In general, a larger $d_{S\to Tx}$ will causes a smaller $d_{Tx\to Rx}$. Instead of using the traditional power increasing scheme that is not feasible for the backscatter system, further schemes need to be taken into account for enlarging the communication distance while considering the low-power nature of the backscatter.

Besides, high energy efficiency is also an important factor and should be taken into account in future backscatter communications. The backscatter communications has ultra-low power consumption, enabling the pervasive communications in IoTs and green communications, especially in a battery-free manner[18,47]. To support such applications, the RF-powered backscatter communications with high-efficiency energy harvesting needs to be investigated. Nevertheless, currently the typical energy harvesting efficiency in backscatter communications is usually less than 20%[30,68,69].

Low deployment cost is another critical concern for the utilization of backscatter communications in the future. For the three components involved in a backscatter communication system, the receiver generally accounts for a large proportion of the cost. More specifically, instead of designing dedicated carrier emitters, the existing surrounding RF signals can be used as the signal source and thus lowers the cost for the ambient backscatter. A transmitter with backscatter antennas is usually compact and cheap. The receiver needs to detect information from weak signals and is usually expensive. For example, if the RFID reader is used as the signal source, the receiver in the RFID backscatter communications costs much more than the tag. To make the backscatter communications more practical so that it can be commonly used, especially in IoTs applications, low-cost receivers are desired.

B. Potential Techniques to Meet the Requirements

1) Energy Harvesting: A battery-free or passive backscatter communication system has low deployment cost and can be widely applied to enable ubiquitous communication in the future. To facilitate its practical applications, the energy harvesting[44] can be utilized to improve the system performance. Future schemes should jointly optimize the energy harvesting and data rate.

2) Relay Technique: Generally, backscatter communication transmits information based on signal reflection instead of signal radiation. Thus the communication distance for such a system is relatively limited. For the applications with communication distance requirements, relay technique[70] can be introduced to help increase the communication range.

3) Full-Duplex (FD) Technique: FD technique can benefits the backscatter communication by supporting simultaneous transmitting and receiving at the same device at the same frequency[71]. One example is to simultaneously transmit the data and receive the control information from the backscatter transmitter. Another example is to transmit data while perform energy harvesting at the backscatter transmitter. By configuring the system appropriately with the consideration of the effective self-interference cancelation, the benefit of FD can be obtained for the backscatter communications.

4) MIMO Scheme: Generally, channel fading, including small-scale fading and large-scale fading, is involved in the two-way transmission in backscatter communications, which will affect the communication reliability. MIMO technique can potentially enhance the system reliability in such a circumstance[60]. The spatial diversity or multiplexing gain can be obtained if MIMO schemes are applied appropriately.

5) Quantum Communication: According to the principle of the backscatter communications, the received signal is usually weak thus limits the system performance. Besides the effective signal detection schemes, the quantum communication[72] can potentially enhance the detection of noise-contaminated weak microwave backscatter signals according to quantum entanglement.

C. Future Backscatter Communication Systems

1) Battery-Free Backscatter Communications: Many IoT applications are expected to operate in a battery-free manner[55,73-76]. Battery-free backscatter communications[55,75,76] consumes ultra-low power and thus enables these battery-free IoT applications. The battery-free RFID system for gas detection is proposed in Ref. [73]. It integrates the battery-free tag with Carbon Nanotubes. Its electrical conductivity is sensitive to the gas quantities and leads to backscattered signal power variations. In Ref. [55], a backscatter system with both battery-free transmitter and receiver is designed, where fully-passive analog components almost consume no power is implemented in the system. It can deal with the packet collision detection, the rate adaptation, and the retransmission with very low power.

2) FD Backscatter: Recently, FD communications[55,71,71,77-81] has been introduced into the backscatter systems to improve the spectrum efficiency. With the FD function, the device can transmit and receive data at the same time and frequency. One critical problem faced by the FD system is SI. In the backscatter communication systems, a FD scheme can be exploited at the transmitter or the receiver, where the scheme to deal with the SI depends on the specific backscatter system. When the FD is utilized at the receiver with powerful functionality, such as the access point (AP) in Ref. [79], the SI cancelation methods for the traditional communication system can be used directly. Nevertheless, the SI issue becomes challenging in the backscatter system with battery-free devices because of the power limitation. If the FD scheme is utilized at the backscatter transmitter[77], which is usually compact, battery-free, and with simple architecture, the SI cancelation will become difficult. In Ref. [71], a FD backscatter systems with battery-free transmitter and receiver has been developed, where the SI can be canceled down to the noise level by using passive analog components. FD is an effective approach to simultaneously support data transmission and control information receiving in the backscatter systems, where SI cancelation schemes with low-power consumption should be further developed, especially for systems with passive backscatter devices at the transmitters.

3) Inter-Technology Backscatter: Inter-technology backscatter means that the wireless transmission using one technique can be transformed to another[16,82] by using backscatter technique. By modulating and reflecting one type of incident signals, the other type of signals, for example Bluetooth or Wi-Fi signals, can be generated and then transmitted to decode by devices supporting these wireless transmissions. The inter-technology backscatter communications can benefit the devices using multiple wireless techniques. In Ref. [16], Bluetooth transmission can be generated by backscattering a fixed-frequency continuous wave source. Commercial devices with Bluetooth function can be utilized to detect the generated Bluetooth signals. A inter-technology backscatter system has been proposed in Ref. [82], which can generating Wi-Fi signals by backscattering the Bluetooth signals using commodity devices. 2∼11 Mbit/s Wi-Fi signals can be generated by such a system. The technique can potentially facilitate ubiquitous communications for commercial devices in IoTs by benefiting from multiple techniques.

4) Hybrid Backscatter Communication: In hybrid backscatter communication systems, different backscatter techniques can co-exist to improve the system performance. If the energy harvested from one type of signal source is unable to trigger the backscatter transmitter to operate, the secondary signal source can be utilized to facilitate energy harvesting for the backscatter[31,83]. It thus can improve the system robustness. Further investigation on hybrid backscatter communications should balance data transmission, energy harvesting, coding, etc.

5) Backscatter Relay: For the ambient backscatter with energy harvesting, the energy for the transmitter is harvested from the surrounding RF signals, the power of which is conformed to strict regulations by the authorities[70]. This may limit the harvested energy for the backscatter transmitter and thus decrease the communication distance. For the application of backscatter communications with distance requirements, relay technique can be introduced to help increase the communication range[70]. Further research on backscatter relay should jointly consider the features of the backscatter systems and the energy harvesting schemes.

6) Millimeter Wave Backscatter: In millimeter wave band, the antennas with a high directional gain and miniaturized size can be designed, which can be implemented into the devices with limited size and facilitates the system application. Gbps data transmission can be supported in millimeter wave backscatter systems[84-87]. For the applications of backscatter communications with high-data-rate requirement, millimeter wave backscatter can be utilized.

7) Quantum Backscatter Communication: Different from the conventional backscatter communication techniques, the quantum backscatter communications[88-90] is based on microwave quantum illumination[72] and utilizes the non-classical quantum resources. It has been proposed to enhance the detection of noise-contaminated weak microwave backscatter signals by using quantum entanglement, where the detection is limited by the shot noise classically. The signal and the idler entangled photon pairs are involved in the quantum backscatter communications, where the signal photon is transmitted and then backscattered to the receiver while the idler photon is delivered to the receiver directly. Higher detection performance can be obtained by using the non-classical quantum correlation characteristics between the entangled photon pairs[72,91].

One practical limitation of the quantum backscatter communications is that the limited number of the independent entangled photon mode pairs generated by the microwave illumination devices restricts the detection performance. To improve the system performance, potential schemes as exploiting multiple microwave illumination devices to generate entangled photon pairs considering mutual interference cancelation, can be investigated. Other schemes, such as the non-classical receiver design, and MIMO assisted quantum backscatter communications can also be studied.

8) Other Systems: Recently, machine learning approaches, have been utilized in the wireless communications, which can improve the system performance extensively[92,93]. Machine learning is also an effective approach to improve the performance of backscatter communication systems. In Ref. [94], machine learning and backscattering approach have been utilized together to facilitate handwriting input system and about 90% recognition accuracy can be obtained. To estimate the channel parameters in the ambient backscatter system, a machine learning approach is utilized to design semi-blind channel estimation in Ref. [95]. Further research by utilizing machine learning in the backscatter communication can be performed to improve the communication performance of the backscatter systems.

Besides, the heterogeneous network is promising for future communications[96]. Backscatter communications in heterogeneous networks needs to be investigated by taking into account the particular network structure and performance requirement.

Moreover, the channel estimation in the ambient backscatter communications is different from that in the tradition systems. The first paper on channel estimation for battery-less backscatter communications has been proposed in Ref. [97]. Machine learning based semi-blind channel estimation approach has been proposed in Ref. [95]. Channel estimation on ambient backscatter communications can be further investigated to improve the system performance.

Additionally, due to the broadcast feature of the backscatter system, it is vulnerable to interfere[98,99]. Backscatter communications that has better interference cancelation function can be further utilized for robust data transmission.

VI. Conclusion

This article has summarized the development and research achievements on the backscatter communications in the past 70 years. More specifically, we first provide the fundamental principle, features, and categories of the backscatter communications and then the basic, advanced, and future backscatter communication techniques are discussed. Considering the ubiquitous communication demands nowadays and the low-power requirement in the green radio communications and IoTs applications, we believe that the backscatter communications will continue to develop in the following years.

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