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Survey paper

# A survey on ambient backscatter communications: Principles, systems, applications, and challenges☆

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ABSTRACT

Owing to the nature of ultra-low-power and extremely low deployment as well as maintenance costs, ambient backscatter technology is promising to become a prominent choice of future low-power communications systems, especially Internet of Things (IoT). Considerable studies have been reported in the emerging area of ambient backscatter communications. However, there is a lack of this kind of survey that is specific to a certain area of ambient backscatter communications and discusses some of the latest systems and the developments in the emerging area. Therefore, in this paper, we provide a comprehensive survey of the existing literature related to ambient backscatter communications. We first present the basic principles of ambient backscatter communications covering architecture, basic techniques, and primer knowledge of ambient signals. After that, we provide a new taxonomy for ambient backscatter communications systems, based on the type of ambient signals. We also review different ambient backscatter communications systems proposed in the literature for each category. Then, we describe potential applications driven by ambient backscatter communications. Finally, some open issues and challenges for future research are identified and discussed.

## 1. Introduction

In recent years, the significant advances made in modulated backscatter technology and energy harvesting (EH) technology spurred the development of backscatter communications (BackComs). In BackComs systems, the backscatter transmitter (i.e., the tag), which is a battery-free device, can harvest energy from incident signals sent from a nearby excitation source (i.e., a carrier emitter) and transmit its data just by modulating and reflecting the incoming excitation signals [1–3]. In this way, BackComs eliminate the need for wires and batteries, thereby reducing the power consumption and promising to achieve ubiquitous communication. In general, BackComs can be broadly categorized into the following three types:

(i) *Monostatic BackComs (Mon-BackComs)*: This type of BackComs uses a dedicated carrier emitter. The carrier emitter and the backscatter receiver are equipped inside the same device called the reader. Owing to the co-located configuration, the reflected signal experiences a round-trip path loss [4]. In addition, this configuration suffers from the doubly near-far problem [5]. Specifically, far tags from the reader can experience a less amount of the harvested energy and a lower signal strength than near tags [6]. As a result, the system performance is limited in terms of communication range and throughput. Moreover, Mon-BackComs inevitably incur installation and maintenance costs due to the use of a dedicated carrier emitter.

(ii) *Bistatic BackComs (Bis-BackComs)*: The carrier emitter and the backscatter receiver are separated in this type of BackComs. Thus, the round-path loss can be avoided in Bis-BackComs. Furthermore, the doubly near-far effect can be alleviated by deploying carrier emitters near backscatter tags. However, Bis-BackComs also need to deploy and maintain special excitation sources, thereby increasing the cost.

(iii) *Ambient BackComs (Amb-BackComs)*: This type of BackComs is similar to Bis-BackComs. Different from Bis-BackComs, the signals (e.g., Wi-Fi and TV) transmitted in existing systems can act as the excitation signals in Amb-BackComs. Therefore, Amb-BackComs eliminate the need to allocate a dedicated frequency spectrum and install a special carrier emitter, thereby greatly improving frequency spectrum resource utilization and reducing deployment and maintenance costs.

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**Table 1**
Abbreviations used throughout the paper.

| Abbreviation | Description | Abbreviation | Description |
|---|---|---|---|
| EH | Energy Harvesting | IoT | Internet-of-Things |
| BackComs | Backscatter Communications | CSS | Chirp Spread Spectrum |
| AC | Alternating Current | DC | Direct Current |
| BLE | Bluetooth Low Energy | GFSK | Gaussian Frequency Shift Keying |
| MAC | Medium Access Control | OQPSK | Offset Quadrature Phase-Shift Keying |
| Mon-BackComs | Monostatic Backscatter Communications | DSSS | Direct-Sequences Spread Spectrum |
| ISM | Industrial Scientific Medical | FPGA | Field-Programmable Gate Array |
| Amb-BackComs | Ambient Backscatter Communications | FFT | Fast Fourier Transform |
| DBPSK | Differential Binary Phase Shift Keying | DQPSK | Differential Quadrature Phase Shift Keying |
| OFDM | Orthogonal Frequency Division Multiplexing | MIMO | Multiple-Input Multiple-Output |
| LoRa | Long Range | Bis-BackComs | Bistatic Backscatter Communications |
| SC-FDMA | Single Carrier-Frequency Division Multiple Access | PSS | Primary Synchronization Signal |
| SSS | Secondary Synchronization Signal | BER | Bit Error Ratio |
| PER | Packet Error Ratio | ADC | Analog-to-Digital Converter |
| P-FSK | Pseudo-Frequency Shift Keying | OOK | On-Off Keying |
| S-BPSK | frequency-Shifted Binary Phase Shift Keying | BPSK | Binary Phase Shift Keying |
| DAC | Digital-to-Analog Converter | VCO | Voltage-Controlled Oscillator |
| CSI | Channel State Information | ACK | Acknowledgment |
| RS | Reed–Solomon | TV | Television |
| FM | Frequency Modulation | Wi-Fi | Wireless Fidelity |
| LTE | Long-Term Evolution | UE | User Equipment |

The remarkable advantages in Amb-BackComs technology make it possible to play a key role in future Internet-of-Things (IoT) applications [7–10]. Significant studies have been reported in the emerging area of Amb-BackComs. Therefore, a survey paper is needed to review the existing literature related to Amb-BackComs and to provide a clear sight for future research efforts in this direction. There have been several outstanding surveys and tutorials [11–16] in the field of BackComs. Huynh et al. [11] provide a detailed survey of Amb-BackComs. The paper provides a detailed discussion on the fundamentals of modulated backscatter communications. In addition, the paper also presents some backscatter systems and discusses some challenges that the Amb-BackComs systems face. Xu et al. [12] provide a survey of BackComs. The paper provides a discussion on the backscatter basics and different modulation methods, and presents some Bis-BackComs systems as well as some potential research directions. Memon et al. [13] present a detailed survey on the aspects of leveraging BackComs to solve the limited battery life problem in emerging networks. Muratkar et al. [15] provide a detailed discussion on various methodologies proposed in the literature to make battery-less wireless communication a reality. Rezaei et al. [16] present a detailed survey of the integral aspects of wireless-powered networks and BackComs.

While there exist survey articles on BackComs, these articles do not provide a discussion on the primer knowledge of ambient excitation signals. It is very important for readers to understand the operation and development of Amb-BackComs systems. In addition, these articles focus on the whole field of BackComs. There is a need for a survey paper that is specific to a certain area of Amb-BackComs and discusses some of the latest systems and the developments in the emerging area. Furthermore, most of the existing surveys discuss Amb-BackComs systems from energy efficiency, throughput, communication range angles. However, most of the existing Amb-BackComs systems are designed specifically for particular ambient signals. Therefore, a new taxonomy for Amb-BackComs systems from ambient signals angles is expected to provide readers with a clearer insight into the developments of Amb-BackComs systems.

Motivated by the aforementioned observations, we provide a new survey paper. The contributions of this survey are summarized as follows:

(1) This paper provides a discussion on the primer knowledge of different ambient signals, including Bluetooth, Wi-Fi, ZigBee, TV, FM, LTE, and LoRa. The discussed primer knowledge, not found in other papers, is of great importance for readers to have a basic understanding of the operation and development of Amb-BackComs systems.

(2) This paper provides an exhaustive discussion on different Amb-BackComs systems that have been proposed in the literature between 2013 and 2021. We provide a summary of different Amb-BackComs systems from the performance perspective, including minimum power, maximum throughput, and maximum range.

(3) This paper provides a new taxonomy for Amb-BackComs systems, based on the type of ambient signals (e.g., Bluetooth or Wi-Fi). This is because most of the existing Amb-BackComs systems are designed specifically for particular ambient signals. This new taxonomy can provide readers with deep visibility into the development of Amb-BackComs systems.

(4) This paper also discusses some practical applications empowered by Amb-BackComs, and different challenges that Amb-BackComs currently face.

The rest of this paper is organized as follows. Section 2 presents the principles of Amb-BackComs including architecture, basic techniques, and primer knowledge of ambient excitation signals. Section 3 provides a taxonomy for Amb-BackComs systems. We also provide a detailed discussion on different Amb-BackComs systems proposed in the literature for each category. Section 4 describes applications driven by Amb-BackComs. Open issues and future research directions are discussed in Section 5. Finally, Section 6 concludes this paper. The abbreviations in this article are summarized in Table 1.

## 2. Principles of Amb-BackComs

In this section, we first present a typical Amb-BackComs system architecture. Then, basic techniques used in Amb-BackComs systems are discussed. Finally, we provide a discussion on the primer knowledge of ambient signals.

### 2.1. Architecture

An Amb-BackComs system typically consists of three main components, i) ambient sources, ii) backscatter tags, and iii) backscatter receivers, as shown in Fig. 1 (a) [11,17,18]. The backscatter tag conveys its data to the backscatter receiver by backscattering ambient signals. In this paper, ambient signals include Bluetooth, Wi-Fi, ZigBee, TV, FM, LTE, and LoRa. A commodity device (e.g., a Wi-Fi device) or another backscatter tag can act as the backscatter receiver. The backscatter tag is a battery-free device, which consists of an antenna module, an energy harvester and power management module, a detector module, a processing subsystem module, and a load modulator module, as shown in Fig. 1(b).

- *Antenna*: to transmit and receive radio waves.

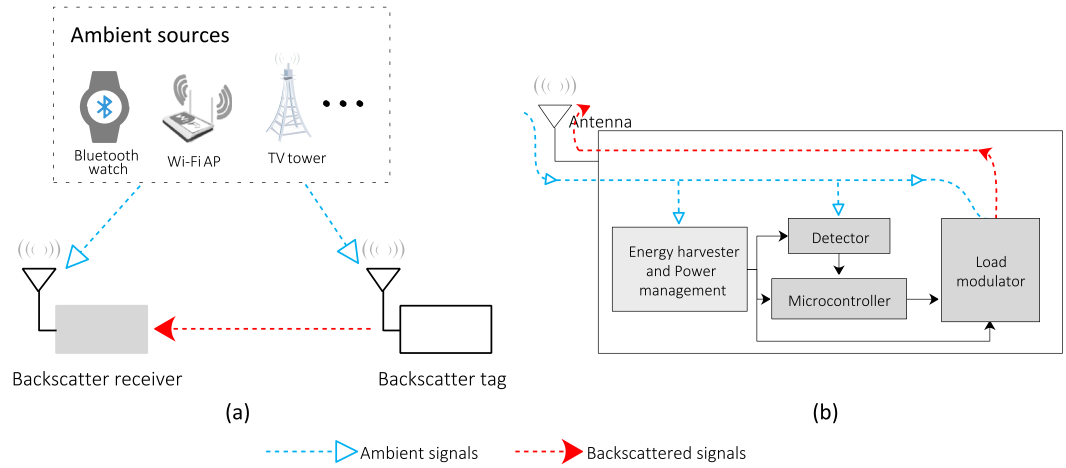


**Fig. 1.** (a) A typical Amb-BackComs system architecture. (b) A general backscatter tag architecture.

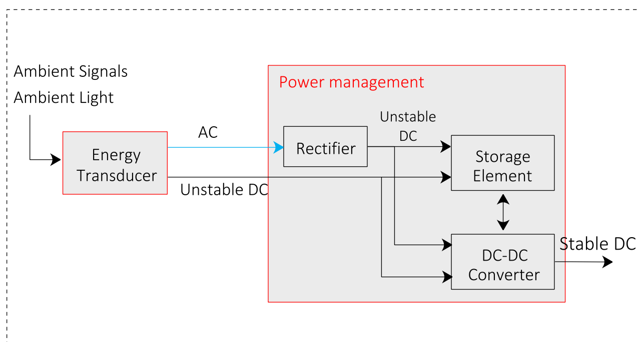


**Fig. 2.** A typical energy harvesting architecture [19], in which AC and DC are short for alternating current and direct current, respectively.

- *Energy harvester and power management*: to harvest energy from ambient signals and ambient light, and to power the device.
- *Detector*: to detect the excitation signal.
- *Processing subsystem*: to control load modulator to generate backscattered signals.
- *Load modulator*: to modify the characteristics (amplitude, frequency, and phase) of the incoming ambient signals in order to transmit data.

## 2.2. Basic techniques used in Amb-BackComs systems

### 2.2.1. Energy harvesting (EH)

The fundamental purpose of energy harvesting is to harvest energy from ambient signals and ambient light, and provide energy for the device. The energy harvesting module is very important for passive tags. A basic EH module consists of two main components: i) an energy *transducer* component and ii) a power management component, as shown in Fig. 2 [19]. The energy from ambient signals or ambient light is first converted into usable electricity through the transducer. However, the output of the transducer is highly unstable, which cannot be used directly to power the device, since conventional electronic components are designed for stable direct current (DC) supply [19]. Thus, the transducer is followed by a power management module that is used to further regulate the electricity generated by the transducer in order to provide a stable power supply for the device. In general, the power management component includes a rectifier that converts an alternating current (AC) to a direct current, a DC-to-DC converter that converts an unstable DC to a stable DC, and a storage element that stores the energy.

### 2.2.2. Detector

The detector is a key component on the backscatter tag for detecting the presence of the excitation signal. Once the signal is detected, the backscatter tag will perform a series of operations to piggyback its data on the signal. Traditional detector generally requires power-hungry components, which are not feasible for low-power tags. The existing detector used on the tag can be broadly classified into two categories: i) leveraging the strength of the incoming signal and a threshold voltage to detect the presence of a specific signal, and ii) leveraging the features of a specific signal to detect the presence of the signal. Zhao et al. [20] present a design of a Wi-Fi signal detector, which falls into the first category. As shown in Fig. 3(a), the detector consists of two key modules: i) a multistage demodulating logarithmic amplifier and ii) a voltage comparator. First, on the backscatter tag side, the incoming signal is amplified and summed up by a multistage amplifier circuit. Then, a lowpass filter is used to remove unwanted noise. After that, the voltage comparator circuit compares the amplifier's output (denoted by $V_{RF}$) with a threshold voltage (denoted by $V_{ref}$). The comparator will output a high voltage if $V_{RF} > V_{ref}$, and a low voltage otherwise. This high voltage implies that a Wi-Fi signal is detected. The experiment results show that this detector can clearly identify the beginning, duration, and ending of Wi-Fi signals.

Peng et al. [21] present a design of other category of the detector, as shown in Fig. 3(b). This detector leverages the features of LoRa preamble to identify LoRa signals. Peng et al. [21] notice that the LoRa preamble consists of ten identical up chirps. Thus, we can identify the existence of LoRa signals by correlating the incoming signal with the pre-stored up chirp. The experiment results demonstrate that this detector can achieve more than 99% accuracy for LoRa signal detection over a distance of 50 m.

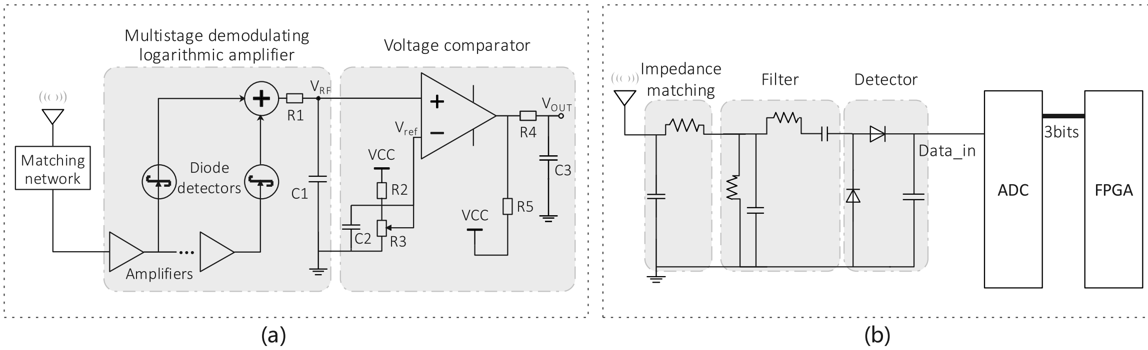


**Fig. 3.** (a) Design of a Wi-Fi signal detector circuit [20], and (b) Packet detection workflow on the PLoRa tag [21].

### 2.2.3. Modulated backscatter

Modulated backscatter technique is based on the fact that a radio wave when encountered a boundary between two media with diverse impedance or densities will be reflected back, and the amount of reflection usually depends on the variation in impedance or density values [1]. Thus, by tuning the load impedance of the antenna, a backscatter tag can piggyback its data on the backscattered signal. Specifically, let $S_{in}(t) = A_{in}e^{j(2\pi f_{in}t+\theta_{in})}$, $S_{out}(t) = A_{out}e^{j(2\pi f_{out}t+\theta_{out})}$, and $\Gamma_{tag}$ be the excitation signal, the backscattered signal, and the reflection coefficient of the antenna, respectively. Thus, the backscattered signal $S_{out}(t)$ is computed by Eq. (1) [12,22]:

$$\begin{aligned} S_{out} &= S_{in}(t) \times \Gamma_{tag} \\ &= A_{in}e^{j(2\pi f_{in}t+\theta_{in})} \times \Gamma_{tag} \end{aligned} \tag{1}$$

In Eq. (1), $\Gamma_{tag}$ can be expressed as follows [12,23]:

$$\Gamma_{tag} = \frac{Z_l - Z_a}{Z_l + Z_a} = \left|\Gamma_{tag}\right| e^{j\theta_{tag}} \tag{2}$$

In Eq. (2), $Z_a = |Z_a|e^{j\theta_a}$ and $Z_l = |Z_l|e^{j\theta_l}$ are an antenna impedance and a load impedance, respectively. $\left|\Gamma_{tag}\right|$ and $\theta_{tag}$ are computed as follows:

$$\left|\Gamma_{tag}\right| = \frac{|Z_a|^2 + |Z_l|^2 - 2|Z_a||Z_l|cos(\theta_a - \theta_l)}{|Z_a|^2 + |Z_l|^2 + 2|Z_a||Z_l|cos(\theta_a - \theta_l)} \tag{3}$$

$$\theta_{tag} = arctan(\frac{2|Z_a||Z_l|sin(\theta_a - \theta_l)}{|Z_a|^2 - |Z_l|^2}) \tag{4}$$

Based on Eq. (2), Eq. (1) can be written as:

$$\begin{aligned} S_{out} &= A_{in}e^{j(2\pi f_{in}t+\theta_{in})} \times \Gamma_{tag} \\ &= \left|\Gamma_{tag}\right| A_{in}e^{j(2\pi f_{in}t+\theta_{in}+\theta_{tag})} \end{aligned} \tag{5}$$

From Eq. (3)–(5), we can conclude that the backscattered signal $S_{out}$ can only be modified by changing the value of the load impedance $Z_l$, since the impedance of a given antenna, i.e., $Z_a$, is constant. Thus, by switching among a set of loads, we can change the amplitude and phase of the backscattered signal accordingly. To do this, the tag uses a *switch* that connects the antenna to a set of loads and toggles between different loads. The *switch* is controlled by the processing subsystem (e.g., microcontroller or *field-programmable gate array* (FPGA)). It is worth noting that the frequency of the backscattered signal can be modified by changing the frequency of toggling *switch* [22]. As a result, a tag can adjust one or more of the components, i.e., amplitude, frequency, and phase, of the backscattered signal to transmit its data to a backscatter receiver.

## 2.3. Primer knowledge of ambient signals

The selection of ambient signals is significant in designing Amb-BackComs systems and the transmission efficiency of Amb-BackComs systems usually depends on the type of ambient signals (e.g., Wi-Fi or LoRa) [11,24]. In this section, we present the primer knowledge of ambient signals including Bluetooth, ZigBee, TV, FM, LoRa, Wi-Fi, and LTE, so that readers can better understand the operation and development of Amb-BackComs systems.

### 2.3.1. Bluetooth [25]

Bluetooth is a short-range wireless technology standard, which is primarily designed for short-range, low-power, and low-cost wireless communication [26]. It consists of different versions among which Bluetooth 4.0, also known as Bluetooth Low Energy (BLE), is the most commonly encountered version.

BLE adopts Gaussian Frequency Shift Keying (GFSK) modulation with a bandwidth of 2 MHz [27]. In GFSK, bit '1' and bit '0' are represented by a positive and a negative frequency deviation, respectively. This means a single-tone signal can be generated by transmitting a stream of all zeros or ones. However, Bluetooth uses data whitening to avoid such sequences. Iyer et al. [28] have demonstrated how to generate a single-tone Bluetooth transmission and create a valid 802.11b Wi-Fi or ZigBee signal from this single-tone transmission. Most of the subsequent studies [26,29–31] on Bluetooth-based backscatter systems rely on the single-tone transmission since the single-tone signal provides a reliable carrier for backscatter. However, a fundamental limitation is that the single-tone transmission cannot be used for productive data communication, thereby greatly reducing spectrum efficiency.

### 2.3.2. ZigBee [32]

ZigBee builds upon the IEEE 802.15.4 standard [33]. The IEEE 802.15.4 standard specifies the physical and Medium Access Control (MAC) layers of ZigBee protocol stack while ZigBee defines the network and application layers. ZigBee radios adopt Direct-Sequences Spread Spectrum (DSSS) coding and Offset Quadrature Phase-Shift Keying (OQPSK) modulation. Such modulation creates the possibility for the tag to embed its data. Zhang et al. [22] have shown how a tag embeds its data in an OQPSK signal. To reduce signal interference, DSSS maps each ZigBee symbol into a corresponding pseudorandom noise (PN) code of 32 chirps. The chirps are then assigned into in-phase and quadrature series, and there exists a half-a-chip offset between in-phase and quadrature. Such offset also poses a challenge for phase-based tag-data modulation because the phase shift from the tag would damage this half-a-chip offset structure, thereby causing decoding failure on the receiver side. The challenge can be addressed by encoding one tag bit on multiple ZigBee symbols [34].

### 2.3.3. Television (TV) [35]

TV towers transmit continuous and uninterrupted signals. These signals are widely available in outdoor environments. Thus, TV signals are promising as a dependable source for backscatter. The studies of [1,36] have shown how to achieve ambient backscatter systems based on TV signals. While these systems are useful outdoors, they

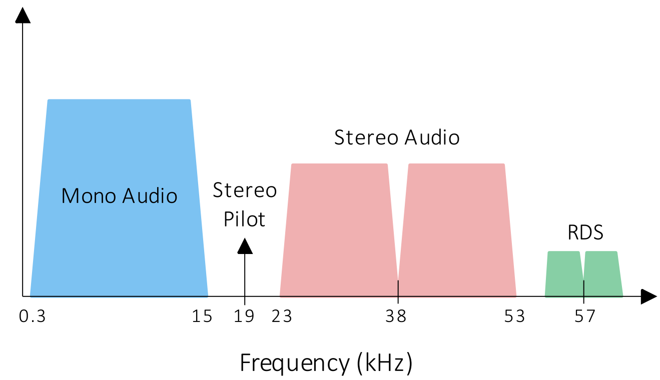


**Fig. 4.** The structure of a baseband audio signal transmitted from a typical FM station [38,39].

are unsuitable for indoor environments. This is because these systems require the power level of TV signals to be at least −10 dBm to −20 dBm, but the strength of TV signals in indoor environments is very low and usually in the range from −80 to −50 dBm [37].

*2.3.4. Frequency Modulation (FM)*

FM stations broadcast continuous signals. These signals are ubiquitous in outdoor environments. They provide a source for ambient backscatter. An FM transmission can be mathematically expressed as follows [38].

$$FM(t) = cos\left(2\pi f_c t + 2\pi \Delta f \int_0^t FM_{audio}(\tau)\, d\tau\right) \tag{6}$$

In Eq. (6), $f_c$, $\Delta f$, and $FM_{audio}(\tau)$ are the carrier frequency of the FM transmission, the deviation in frequency from $f_c$, and the baseband audio signal, respectively. The baseband audio signal consists of a mono audio stream, a stereo audio stream, a 19 kHz pilot tone, and a broadcast data system (RDS) stream, as shown in Fig. 4. Wang et al. [38] have shown how to leverage FM transmissions for Amb-BackComs.

*2.3.5. Long Range (LoRa) [40]*

LoRa is a long-range and low-power wireless communication technology standard [41,42]. It adopts Chirp Spread Spectrum (CSS) modulation. In CSS, bits ‘0’ and ‘1’ are encoded respectively as a continuous chirp that increases linearly with frequency and a chirp that is cyclically shifted in time [11,43,44]. Fig. 5 shows a chirp ‘0’ and chirp ‘1’ in the time domain. As the chirp-modulated signal occupies the whole allocated bandwidth, it is less susceptible to channel noise, Doppler, and multi-path effects. Thus, it provides a reliable source for ambient backscatter. In addition, chirp-modulated signals can be decoded at very low signal-to-noise ratio (SNR). Thus, it is expected to enable long-range backscatter communication. LoRa uses packetized protocols to transmit data. A LoRa frame begins with a preamble. The preamble is composed of ten consecutive up-chirps with zero initial frequency offset. Guo et al. [45] have shown how to leverage the unique features in the LoRa preamble to detect the appearance of LoRa signals.

To demodulate the LoRa signal, the receiver first multiplies an incoming LoRa chirp with a down-chirp and then performs a Fast Fourier transform (FFT) on the resulting multiplication. This FFT operation will yield a peak in an FFT frequency bin. By tracking FFT peaks, the receiver finally demodulates the incoming LoRa symbol.

*2.3.6. Wireless Fidelity (Wi-Fi) [46]*

Wi-Fi usually refers to the wireless local area networking technique based on the IEEE 802.11 family of standards [47]. It is a short-range wireless communication technique, which is primarily used for providing network communication capabilities to different devices in private, public, and commercial environments [48,49]. As most devices

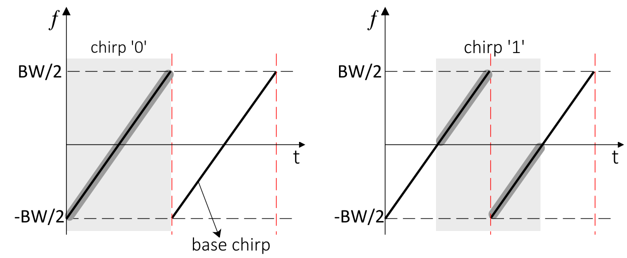


**Fig. 5.** LoRa chirp signal ‘0’ and chirp signal ‘1’, in which $BW$ is the LoRa chirp bandwidth [21].

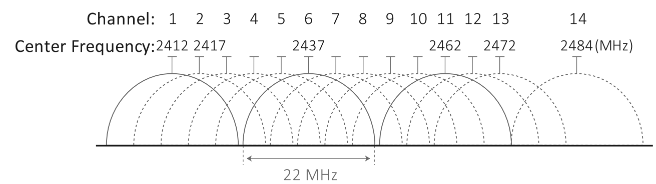


**Fig. 6.** The 2.4 GHz Wi-Fi channels.

(e.g., Wi-Fi access points, smartphones, laptops, and watches) are Wi-Fi enabled, this makes Wi-Fi signals a natural choice for ambient backscatter and one of the most widely studied excitation signals in the literature. IEEE 802.11 supports various frequencies, such as 2.4 GHz and 5 GHz frequency bands. Regarding 2.4 GHz band, it is divided into 14 channels with a bandwidth of 22 MHz and spaced 5 MHz apart from each other except for a 12 MHz space before channel 14, as shown in Fig. 6. The channels labeled as 1, 6, and 11 are a set of non-overlapping channels. Thus, the backscatter tag in Wi-Fi backscatter systems usually uses a frequency phase of 20 MHz to avoid interference to the original signal.

There are many different versions of Wi-Fi, such as 802.11a [50], 802.11b [51], 802.11 g [52], and 802.11n [53]. Different versions of Wi-Fi use different techniques. In terms of 802.11n Wi-Fi, it supports Multiple-Input Multiple-Output (MIMO) technology. The technology can significantly improve the communication performance of wireless systems in terms of reliability and capacity [54]. Thus, if it is possible to acquire the benefits of the MIMO technology on low-power tags. Recent study [55] has implemented a MIMO backscatter system with a low bit error ratio and high throughput.

*2.3.7. Long-Term Evolution (LTE) [56]*

LTE radio transmits continuous signals. It adopts Orthogonal Frequency Division Multiplexing (OFDM) for downlink and Single Carrier-Frequency Division Multiple Access (SC-FDMA) for uplink transmission [57]. One LTE frame consists of ten 1 ms sub-frames. Each sub-frame consists of two 0.5 ms slots, and each slot consists of seven OFDM symbols. Each OFDM symbol consists of two main components: i) the useful symbol and ii) the cyclic prefix (CP). The useful symbol can be represented by multiplying the baseband signal with the carrier wave and the CP will be removed on the User Equipment (UE) side to avoid inter symbol interference (ISI). The LTE signal periodically embeds Primary Synchronization Signal (PSS) and Secondary Synchronization Signal (SSS) messages. These messages appear every five sub-frames and play a key role on the UE side. A key challenge in designing an LTE-based backscatter system is how to avoid changes to PSS and SSS messages. Chi et al. [58] have shown how to address this challenge and leverage LTE signals for Amb-BackComs.

## 3. Amb-BackComs systems

The Amb-BackComs paradigm first appeared in 2013, with the design of the first Amb-BackComs system, *Ambient backscatter* [1],

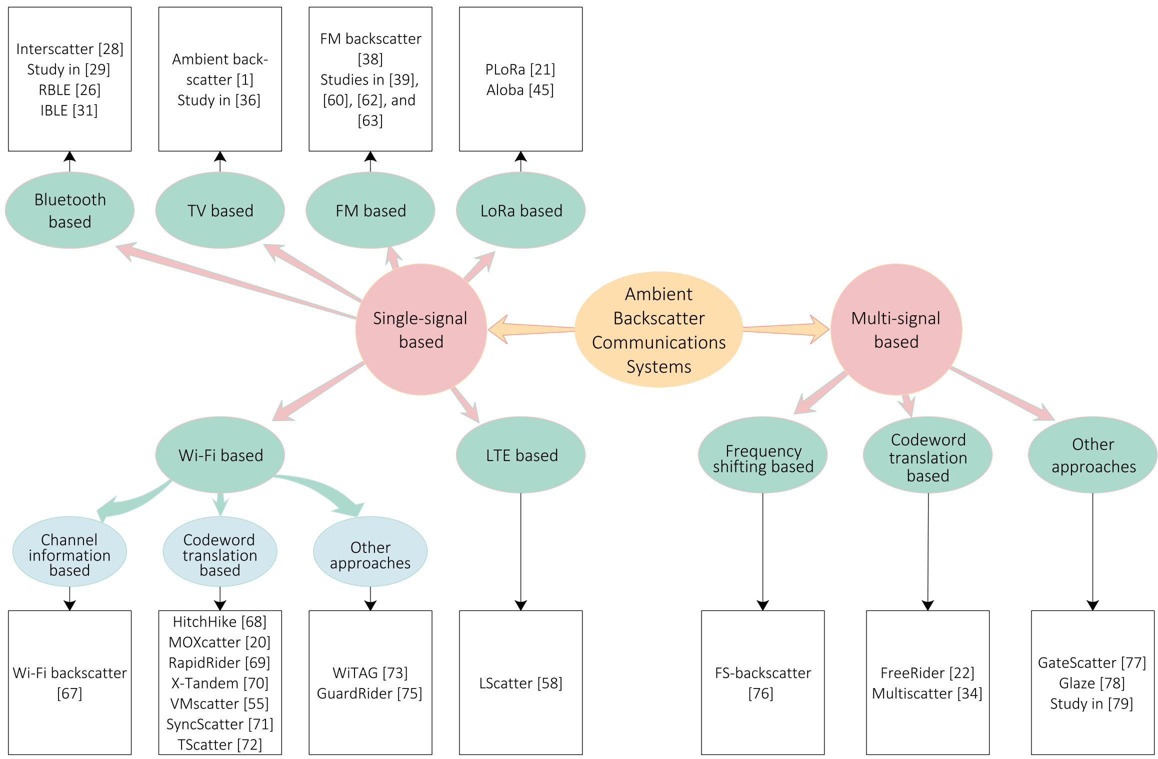


**Fig. 7.** Taxonomy of Amb-BackComs systems.

which allows two battery-free devices to communicate by using existing TV transmissions as the source of carrier and power. This eliminates the need for a new spectrum allocation, batteries, and a dedicated carrier source, thereby increasing spectrum efficiency and reducing the deployment as well as maintenance costs. In the last few years, Amb-BackComs systems have gained great attention within the research community owing to their remarkable advantages.

The available Amb-BackComs systems proposed in the literature support either one ambient signal or multiple ambient signals. Thus, these systems can be broadly categorized into two major groups, i) single-signal based Amb-BackComs systems and ii) multi-signal based Amb-BackComs systems. The systems that only work with a particular ambient signal are listed in the first group. The other group covers the systems that are compatible with multiple ambient signals. According to the type of ambient signals, the single-signal based Amb-BackComs systems can be further divided into the following six categories[1]: i) Bluetooth based BackComs systems, ii) TV based BackComs systems, iii) FM based BackComs systems, iv) LoRa based BackComs systems, v) Wi-Fi based BackComs systems, and vi) LTE based BackComs systems. In addition, we primarily classify the multi-signal based Amb-BackComs systems based on the technique used. Considering that Wi-Fi is one of the most widely explored excitation signals in the area of Amb-BackComs, we further classify the Wi-Fi based BackComs systems based on the technique adopted. In the following sections, we review the existing literature based on the proposed taxonomy, which is schematically depicted in Fig. 7.

### 3.1. Single-signal based Amb-BackComs systems

#### 3.1.1. Bluetooth based BackComs systems

Iyer et al. [28] introduce *Interscatter*, a BLE based backscatter system. The highlight of this system is that *Interscatter* tags can generate valid Wi-Fi 802.11b or ZigBee signals by backscattering the incoming Bluetooth signals. As a result, a commodity Wi-Fi or ZigBee device can act as the backscatter receiver. The main idea of *Interscatter* is that by setting the appropriate bits on the payload part of the Bluetooth packet, a commodity Bluetooth device can transmit a single-tone signal (i.e., single-frequency), which can then be used to generate a valid Wi-Fi or ZigBee signal. Because Bluetooth adopts GFSK modulation, a single-tone signal can be created by transmitting a continuous stream of zeros or ones. However, a key challenge is how to create long sequences of either zeros or ones, since Bluetooth uses data whitening to avoid such sequences. The authors note that by setting bits in the payload section to be the same as the whitening sequence or their bit complement, we can generate long sequences of zeros or ones, respectively. To create Wi-Fi signals, the backscatter tag first shifts the signal from the Bluetooth channel to the Wi-Fi channel. However, existing sideband modulation techniques create the desired frequency shifts as well as the copy on the opposite side of the signal. This not only wastes bandwidth but causes interference. To address this, the authors design a *single-sideband backscatter* technique that only creates frequency shifts on a single side of the carrier. Then, the backscatter tag performs the modulation of DBPSK and DQPSK on the resulting signal-tone signal. By doing this, the backscatter tag can generate standards-compliant Wi-Fi packets on a single side of the resulting single-tone Bluetooth signal. The same procedure can also be applied to create ZigBee signals. Through experiments, the results show that *Interscatter* can achieve a range of around 90 ft when generating Wi-Fi signals, and a range of up to 15 ft when generating ZigBee signals.

Zhang et al. [29] present a novel BLE based backscatter system to enable multi-channel backscatter communication. In this system, a Bluetooth radio transmits BLE signals on one channel, while the backscatter tag reflects these BLE signals on multiple channels in a channel-hopping manner. To achieve this, the authors design a novel multi-channel backscatter tag. The key technique behind the tag is the *dynamic reconfiguration* technique. The dynamic reconfiguration provides multiple sets of different clocks. Each set of clocks can be used to shift BLE signals from one channel to another channel. Thus, multiple

[1] Existing ambient backscatter systems that support ZigBee radio also work with other ambient signals (e.g., Wi-Fi), and thus this group does not include ZigBee based backscatter systems.

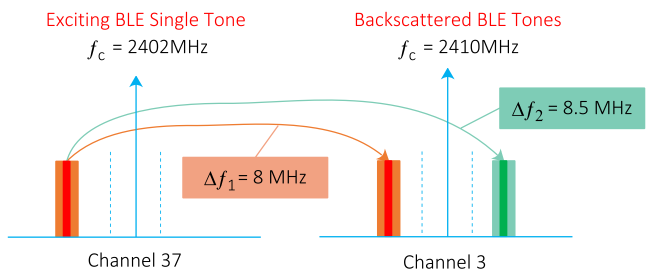


**Fig. 8.** An example of direct frequency shift modulation [26].

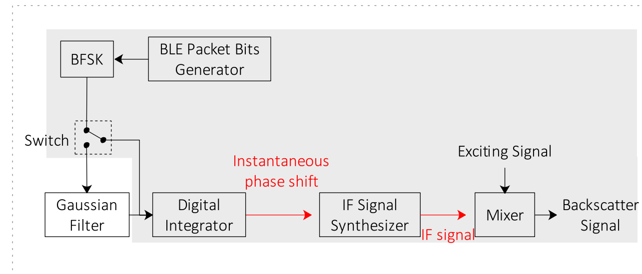


**Fig. 9.** The architecture of IPS (the gray part) and GFSK (the whole part) modulations used in IBLE [31].

sets of different clocks achieve multi-channel backscatter communication. The experimental results demonstrate that the proposed system can achieve a throughput of up to 2.8 Kbps.

Zhang et al. propose *RBLE* [26,30], a BLE backscatter system that tries to enable reliable backscatter communication. *RBLE* is built on the studies [22,28,29]. To do this, *RBLE* first presents a *direct frequency shift modulation* scheme that uses the single-tones part of BLE signals as the modulation carrier. The single-tone signal is generated by using the same technique as *Interscatter* [28]. Next, *RBLE* directly applies frequency shift to modulate symbols '0' or '1'. Specifically, suppose that the excitation signal is in the advertising channel 37, the single-tone part of this excitation signal is symbol '0', and the target channel is data channel 3. If we want to modulate a symbol '0' to the target channel, we only need to apply a frequency shift of 8 MHz. Otherwise, a frequency shift of 8.5 MHz is applied to modulate a symbol '1' into the target channel, as shown in Fig. 8. After that, *RBLE* introduces a *dynamic channel configuration* scheme. Similar to their previous work [29], the dynamic channel configuration scheme allows the backscatter tag to perform channel hopping, thereby reducing the interference to original signals and improving the reliability of backscatter communication. Then, *RBLE* presents a novel *packet regeneration* scheme. As such, the backscatter tag can regenerate an advertising packet or a data packet by modulating the incoming BLE advertising signal. This allows *RBLE* to communicate across all BLE channels, thereby further enhancing backscatter reliability. Finally, the authors evaluate the performance of *RBLE* in various real-world scenarios. The experimental results show that *RBLE* can achieve a throughput of 11.8 Kbps at 15 m.

Zhang et al. [31] test the Bit Error Ratio (BER) and Packet Error Ratio (PER) of *RBLE* [26] in an indoor scenario and find a huge performance gap between *RBLE* and commodity-level devices. In other words, *RBLE* cannot meet the BER and PER requirements (BER$<0.1\%$ and PER$<17.5\%$) of the BLE specification [25,59]. Through analysis, the authors find that the backscatter reliability of *RBLE* is limited owing to its modulation scheme (i.e., BFSK modulation), since commodity BLE receivers are designed to receive and demodulate GFSK modulated BLE signals. Zhang et al. [31] thus design *IBLE* that tries to improve the reliability of BLE backscatter communication to the commodity level. The authors notice that the phase shift can be obtained by integrating the frequency over time. This means that digital frequency modulated signals can be transformed into digital phase-modulated signals. Based on this insight, two novel modulation schemes, i.e., *Instantaneous Phase Shift* (IPS) and GFSK modulations, are designed to improve the reliability of backscatter communication. Fig. 9 shows the architecture of IPS and GFSK modulations. At a high level, the IPS modulation can be viewed as the GFSK modulation without *Gaussian Filter*. On the *IBLE* tag side, the highlight is the design of a novel intermediate frequency (IF) signal synthesizer. This synthesizer leverages the output of the digital integrator module as the input and directly outputs a GFSK modulated IF signal or an IPS modulated IF signal. The generated IF signal will be used to modulate the excitation signal, thereby achieving BLE backscatter using IPS or GFSK modulation. Furthermore, a *Forward Error Correction* (FEC) coding is used to further enhance communication reliability. The experimental results show that *IBLE* can achieve a throughput of up to 8.275 Kbps and an effective uplink range of up to 20 m.

#### 3.1.2. TV based BackComs systems

Liu et al. [1] design the first TV based BackComs system, in which two backscatter tags can communicate with each other by reflecting TV signals in the environment. In fact, this system is also the first Amb-BackComs system. In [1], the backscatter tag can serve as both a backscatter transmitter and a backscatter receiver. To do this, each tag is composed of three main components, i) a backscatter transmitter, ii) a backscatter receiver, and iii) a harvester. All components are connected to the same antenna and use the same ambient signals, as shown in Fig. 10(a). To transmit information, a switch is adopted at the transmitter, whose input is a stream of bits '0' and '1'. When the input is bit '0', the switch is in the non-reflecting state. Otherwise, if the input is bit '1', the switch is in the reflecting state. As such, a backscatter device can convey its data to another backscatter device, thereby allowing a backscatter tag to act as a backscatter transmitter. To extract backscattered information from ambient TV signals, a key insight is that the backscatter receiver can separate the backscattered signals and the ambient TV signals if the backscattered information is transmitted at a lower rate than that of ambient TV transmissions. This is possible because the difference in the bitrates of the two signals will result in adjacent samples in TV signals to be more uncorrelated than the adjacent samples in the backscattered signals. Thus, by averaging the received signals across multiple samples, the variations can be removed by the backscatter receiver in the ambient TV signals while remaining in the backscattered signals, thereby allowing the backscattered information to be decoded. Based on this insight, a low-power demodulator is designed on the receiver, which consists of an average envelope circuit, a compute-threshold circuit, and a comparator circuit, as shown in Fig. 10 (b). The received signals are first smoothed by the averaging circuit while yielding two voltage levels, $V_0$ and $V_1$, corresponding to the power levels for zero and one bits, respectively. Then, a threshold value (i.e., $\frac{V_0+V_1}{2}$) is computed by the compute-threshold circuit. Finally, the comparator circuit compares the average envelope signals with the threshold value to generate desired bits. The experimental results show that the backscatter receiver can achieve a bit rate of 10 Kbps over distances of less than 2 ft.

While the work of [1] achieves tag-to-tag communication by reflecting TV signals, its communication range and throughput are limited to 2 ft and 10 Kbps, respectively. This significantly limits its applicability. Parks et al. [36] thus propose another TV based backscatter system. In this system, a multi-antenna backscatter receiver (i.e., $\mu$mo) and a low-power coding mechanism (i.e., $\mu$code) are proposed to improve communication range and throughput. Through the experiments, the authors demonstrate that $\mu$mo increases the throughput from 10 Kbps to 1 Mbps and $\mu$code increases the communication range from 2 ft to up to 80 ft.

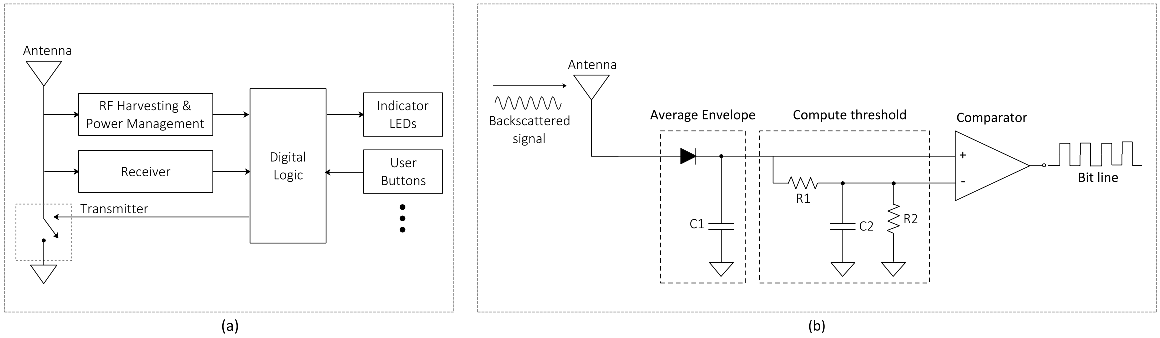


**Fig. 10.** (a) Block diagram of a backscatter device and (b) The demodulator [1].

### 3.1.3. FM based BackComs systems

Wang et al. propose *FM Backscatter* [38], the first FM based BackComs system. In this system, the backscatter tag can convey its data on top of ambient FM transmissions and any commodity FM receiver can act as the backscatter receiver. The highlight of this system is the design of the *overlay backscatter* modulation. It can transform the multiplicative nature of backscatter into an addition operation on the audio signals. Specifically, by picking the appropriate baseband signal $B(t)$, such as $B(t) = cos\left(2\pi f_{back}t + 2\pi\Delta f \int_0^t FM_{back}(\tau)\, d\tau\right)$, in which $f_{back}$ and $FM_{back}(\tau)$ are the center frequency of the baseband signal and the audio signal respectively, the backscattered signal $B(t)\times FM(t)$ can become:

$$cos\left(2\pi f_{back}t + 2\pi\Delta f \int_0^t FM_{back}(\tau)\, d\tau\right) \times cos\left(2\pi f_c t + 2\pi\Delta f \int_0^t FM_{audio}(\tau)\, d\tau\right) \quad (7)$$

Next, by applying the trigonometric identity, $2cos(A) \times cos(B) = cos(A+B) + cos(A-B)$, and using a single-sideband modulation technique [28], we can remove the term $cos(A-B)$ and thus yield the Eq. (8), thereby achieving the conversion from a multiplication operation to an addition operation. In essence, Eq. (8) remains a valid FM signal, thereby allowing any FM receiver (e.g., a smartphone) to decode the tag information. The experimental results demonstrate that *FM backscatter* can achieve a throughput of up to 3.2 Kbps and a communication range of up to 60 ft.

$$cos\left(2\pi\left[\left(f_c + f_{back}\right) + \Delta f \int_0^t \left(FM_{audio}(\tau) + FM_{back}\right) d\tau\right]\right) \quad (8)$$

Daskalakis et al. [60] propose a novel FM based backscatter system for smart agricultural monitoring, in which the backscatter tag can measure the moisture level in plants and transmit its data to a backscatter receiver by reflecting ambient FM broadcasting signals. To measure the moisture level in plants, an efficient solution is to measure the temperature difference between the leaf and the air [61]. To do this, the backscatter tag contains two analog temperature sensors, which measure the air temperature ($T_{air}$) and the leaf temperature ($T_{leaf}$), respectively. By subtracting $T_{air}$ from $T_{leaf}$, we can obtain moisture level in plants. On the backscatter transmitter side, the backscatter tag adopts AM modulation and FM0 encoding on the FM transmissions to transmit its data. The experimental results show that the proposed system can achieve a bit rate of 500 bps and a communication range of 2 m.

Daskalakis et al. [39] extend the work of [60]. In [39], the backscatter tag can read four analog inputs by using a 16-channel 12-bit analog-to-digital converter (ADC), thereby enabling a wide range of applications. In addition, a novel *receiver algorithm* is designed at the backscatter receiver to improve throughput and communication range. The key idea of this algorithm is to reduce the frequency difference between the backscatter tag and the backscatter receiver. A matched filter is then employed to reduce noise and interference and maximize the SNR of the received signals, thereby improving the throughput and communication range of the system. The experimental results show that the proposed system can achieve a bit rate of 2.5 Kbps at a tag-to-reader distance of 5 m.

Vougioukas et al. [62] present a novel design that can achieve a Tag-to-FM receiver distance of 26 m and 15 m, outdoors and indoors, respectively, when reflecting FM transmissions, and work with any off-the-shelf FM receiver (e.g., a smartphone). To achieve this, two pivotal techniques, i.e., *FM Remodulation* and *Selection Diversity*, are proposed. The FM remodulation technique uses the same ideas as the overlay backscatter technique used in [38]. Specifically, the tag signal is designed with the same structure as the FM radio transmissions. Thus, the reflected signal is still a valid FM signal, thereby allowing any off-the-shelf FM receiver to decode the tag data. Selection diversity leverages the fact that modulation from the tag signal occurs at passband, not at baseband, and thus the tag signal can be modulated on multiple FM radio signals at the same time. By selecting the FM station with the strongest received power, we can increase the value of the amplitude of the backscattered signal, which in turn reduces the impact of thermal noise at the receiver's output, thereby achieving a longer communication range from the tag to the receiver.

Another FM based backscatter system is introduced by Vougioukas et al. in [63]. In this system, the backscatter tag can use both analog and digital modulation schemes. As a result, the system can benefit from different modulations. In terms of the digital modulation scheme, the backscatter tag uses Pseudo-Frequency Shift Keying (P-FSK) [64], a frequency-shifted form of On-Off Keying (OOK), and frequency-shifted Binary Phase Shift Keying (S-BPSK), a frequency-shifted form of Binary Phase Shift Keying (BPSK). Unlike P-FSK, the S-BPSK does not require information about the ambient carrier. In addition, the short packet error correction coding can be utilized for the S-BPSK. The analog modulation scheme is designed based on *FM Remodulation* principles [62]. The experimental results show that the proposed system can achieve a tag-to-receiver distance of 26 m in an outdoor environment while consuming the power of 24 $\mu W$.

### 3.1.4. LoRa based BackComs systems

Peng et al. propose *PLoRa* [21], a novel LoRa based backscatter system that tries to enable long-range backscatter communication. In this system, the tag can transmit its data by backscattering incoming LoRa signals and the backscattered signal remains a valid LoRa signal. On the backscatter tag side, to implement *PLoRa*, a challenge is how to detect an incoming LoRa packet and synchronize with its LoRa symbols on the low-power tag without requiring power-hungry components (e.g., *digital to analog converter* (DAC) and *voltage-controlled oscillator* (VCO)). Peng et al. [21] note that the power consumption of packet detection decreases monotonically with the increase of sampling rate [65], and thus propose to reduce the sampling rate for packet detection. Regarding synchronization, the *PLoRa* tag first performs the correlation between incoming signals and pre-stored preambles. After detecting the whole preamble of the incoming signal and waiting for a specific time, the *PLoRa* tag begins to backscatter. Another challenge is how to generate a standard LoRa signal in the backscattering process. To address this, a novel *blind chirp modulation* scheme is designed. The main idea underlying scheme is that the incoming LoRa chirp can be shifted by an amount of $\frac{BW}{2}$ and $\frac{-BW}{2}$, in which $BW$ denotes the LoRa chirp bandwidth, by multiplying an FSK-modulated baseband signal with the incoming LoRa chirp, and these two shifted LoRa chips can be spliced together into a valid LoRa chirp. To reduce interference, moreover, *PLoRa* shifts the backscattered signal into a different channel. On the backscatter receiver side, a novel *backscatter signal demodulation* scheme is proposed to demodulate the tag data. The main principle of this scheme is to examine the location consistency of FFT peaks. Specifically, the backscatter receiver will perform two FFT operations, one on the product of the excitation LoRa chirp and the backscattered LoRa chirp, and the other on the product of the excitation LoRa chirp and the LoRa down chirp. These two FFT operations will lead to two peaks in FFT bins. If the location difference of the two peaks is greater than a pre-defined threshold, this means a bit '1' is transmitted. Otherwise, a bit '0' is transmitted. Moreover, an energy management circuit is designed to efficiently manage node energy. Through the experiments, the authors demonstrate that *PLoRa* can achieve a communication range of up to 1.1 km and a bit rate of 6.25 Kbps at 300 m.

Another LoRa based BackComs system, *Aloba*, is introduced by Guo et al. in [45,66]. In *Aloba*, the tag can detect LoRa transmissions even if there exist interfering signals (e.g., noise and other legacy signals). Guo et al. notice that the LoRa preamble consists of ten consecutive up-chirps with zero initial frequency offset. When the incoming signal passes through a low-pass filter, the LoRa preamble will show ten equally spaced RSS pulses, while the interfering signals will not. Therefore, *Aloba* can detect LoRa transmissions by leveraging this unique feature. After detecting the LoRa preamble as well as waiting for a specific time, the *Aloba* tag begins to perform modulation using OOK. Unlike *PLoRa* [21], the backscattered signal in *Aloba* works in the same frequency band of the carrier signal. On the backscatter receiver side, hence, the received signals are the superposition of the backscattered signal and the carrier signal. To decode the tag data, *Aloba* first converts the received LoRa signals into a sinusoidal tone. As a result, the variation of the sinusoidal tone is affected by the backscatter signal. Then, *Aloba* leverages the variations to demodulate the tag data. The experimental results show that *Aloba* can achieve a throughput of 199.4 Kbps at 50 m.

### 3.1.5. Wi-Fi based BackComs systems

Most of the existing Wi-Fi based BackComs systems leverage the principle of *codeword translation*, while others use channel information, MAC-layer features, or optimization code. In the following, we provide a brief overview of these systems. We primarily classify them based on the technique used.

***(1) Channel information based:*** Kellogg et al. [67] design *Wi-Fi Backscatter*, which is the first Wi-Fi based BackComs system that enables the communication between backscatter tags and off-the-shelf Wi-Fi devices. This system supports both uplink and downlink communications. In [67], the backscatter tag transmits bit '1' or bit '0' by reflecting or absorbing the Wi-Fi packets, respectively. As a result, the channel information, such as received signal strength indicator (RSSI) and channel state information (CSI), will be changed on the backscatter receiver side. Thus, by measuring the changes in RSSI or CSI, the backscatter receiver can decode the tag data. The experimental results demonstrate that the proposed system can achieve a data rate of up to 1 Kbps and a range of up to 2.1 m.

***(2) Codeword translation based:*** The *codeword translation* technique is first introduced in *HitchHike* [68]. This system can work completely with commodity 802.11b Wi-Fi devices thanks to the technique. The authors [68] note that every 802.11b Wi-Fi packet can be viewed as a sequence of codewords from the same codebook. Thus, the backscatter tag can embed its data by transforming the received codeword into another valid codeword in the 802.11b codebook. In this way, the backscattered packet remains a valid 802.11b Wi-Fi packet and thus can be decoded by commodity 802.11b devices. To decode the tag information, *HitchHike* uses two receivers, one for receiving Wi-Fi signals being transmitted and the other for backscattered signals. The tag data can be extracted by XORing the data from the two receivers. To avoid self-interference, moreover, *HitchHike* shifts the backscattered signal into a non-overlapping Wi-Fi channel. The experimental results show that *HitchHike* can achieve an uplink throughput of up to 300 Kbps at 34 m in a line-of-sight scenario and an uplink throughput of around 100 Kbps at 25 m in a non-line-of-sight scenario.

Zhao et al. introduce *MOXcatter* [20], a novel Wi-Fi based BackComs system that tries to enable spatial stream backscatter using commodity multi-antenna Wi-Fi. *MOXcatter* is built on the work of *HitchHike* [68]. In *MOXcatter*, the backscatter tag uses phase change (similar to the *codeword translation* method in *HitchHike* [68]) to embed its data on incoming Wi-Fi signals. In particular, when backscattering 802.11n signal-stream signals, the backscatter tag applies a phase shift (e.g., 0 or 180 degrees) to symbols in a Wi-Fi packet to embed desired data. When backscattering 802.11n multi-stream signals, the backscatter tag applies a phase shift to the whole data payload of a packet. In other words, the antennas on the tag transmit the same data. To decode the tag data, like *HitchHike* [68], *MOXcatter* also requires two receivers. The experimental results demonstrate that *MOXcatter* can reach a bitrate of up to 50 Kbps for 802.11n signal-stream signals and up to 1 Kbps for 802.11n double-stream signals with a range up to 14 m.

Wang et al. design *RapidRider* [69], a Wi-Fi based BackComs system that enables single-symbol modulation. This system is built on the studies of *HitchHike* [68] and *MOXcatter* [68]. Unlike *HitchHike* and *MOXcatter*, *RapidRider* modulates one bit in each symbol and requires one receiver only. The authors note that by using a reference symbol, both productive and tag data can be combined into the same packet. Thus, one receiver is able to decode the tag data. To enable single-symbol modulation, Wang et al. [69] first analyze the reasons of the failure of the single-symbol modulation in existing Wi-Fi based backscatter systems and find that the root cause is the incompatibility between symbol-wide and payload-wide operations. Based on this insight, *RapidRider* performs the decoding on the deinterleaved-data level instead of the payload level. On the backscatter receiver side, a novel *deinterleaving-twins decoding* scheme is proposed, which leverages backward deinterleaved data and forward deinterleaved data to recover the tag data. The experimental results show that *RapidRider* can achieve a throughput of 237.8 Kbps with ambient OFDM signals.

Zhao et al. [70] present a multi-hop Wi-Fi based backscatter system, namely *X-Tandem*. In this system, the backscatter tag can not only work as relays for each other but also modulate their data simultaneously in a single backscatter packet. On the backscatter tag, the employed modulation is similar to the *codeword translation* method in [68]. Thus, the backscatter packet remains a valid Wi-Fi packet that can be decoded by commodity Wi-Fi devices. The main principle of *X-Tandem* is shown in Fig. 11(a). Assume there is an ongoing Wi-Fi signal, the first tag uses this original Wi-Fi signal as an excitation, modulates its data onto a specific part of this excitation (see Fig. 11(b)), and shifts backscattered signal into a new channel to reduce interference. The second tag, when receiving the original packet, performs the same procedure. As a result, it embeds its data in the same backscattered packet and relays the first tag's data. The experimental results show that, for a two-hop implementation, X-Tandem can achieve a throughput of up to 200 bps when the distance between the two tags is 0.05 m and a communication range of up to 8 m.

Liu et al. [55] design and implement another Wi-Fi MIMO backscatter system, namely *VMscatter*. Unlike *MOXcatter* [20], the antennas on the *VMscatter* tag transmit different data. In addition, *VMscatter* can achieve the same full diversity gain as the traditional MIMO system and work with massive MIMO. The diversity features of MIMO can be leveraged in *VMscatter* by operating the space–time coding scheme.

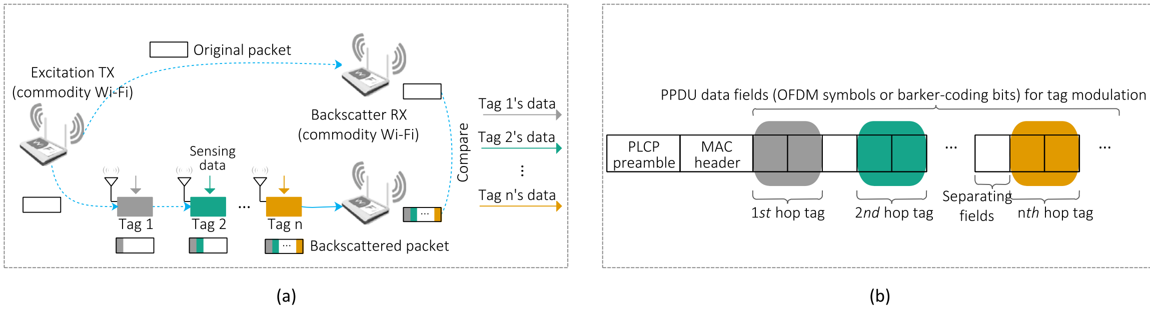


**Fig. 11.** (a) X-Tandem communication and (b) The data field allocation in the original packet for multiple backscatter tags [70].

A highlight of this system is that the *VMscatter* tag implements the space–time coding by using a *two-states* (on and off) switch since the space–time coding encodes data into four states. Moreover, to successfully demodulate the tag data, *VMscatter* deals with the frequency mismatch between the tag and the receiver, and evaluates the channels among the sender, tag, and receiver. The experimental results show that *VMscatter* can achieve a bit error rate of around 0.000011 and the data rates of 239.7 Kbps and 245.9 Kbps for single data stream and multi-data stream, respectively.

Dunna et al. [71] notice that many existing studies in the area of Wi-Fi based BackComs overlook the importance of synchronization, thereby leading to limited downlink range and reduced throughput. Dunna et al. [71] thus present *SyncScatter* that tries to achieve synchronized backscatter communication with incident Wi-Fi signals. To implement *SyncScatter*, the authors first analyze the synchronization requirement for Wi-Fi based BackComs and the sensitivity requirement needed at the tag, and conclude that the sensitivity of −35 dBm would provide the maximum range benefit and the minimum required synchronization accuracy is 150 nanoseconds for 802.11b Wi-Fi signals. However, achieving these requirements typically consumes significant power, which is not feasible for the passive tag. To address this problem, a novel hierarchical wake-up scheme is designed at the tag. The key idea behind this scheme is to set wake-up functionality apart from synchronization functionality. Specifically, a low-power wake-up receiver is used to detect the appearance of the excitation signal and wake up the synchronization receiver. After that, the synchronization receiver leverages high-power *radio frequency* amplification to provide the required synchronization accuracy and desired sensitivity. By periodically turning the amplification on and off, the power consumption of the overall system can be reduced significantly. The experimental results demonstrate that *SyncScatter* can achieve a communication range of up to 30 m and a bit rate of 500 Kbps, with an average power consumption of 30 $\mu W$.

Liu et al. [72] note that existing OFDM-based Wi-Fi backscatter systems [20,68,70] leverage the principle of *codeword translation* at the OFDM symbol-level to send the tag data. To make *codeword translation* work, these systems require specific Wi-Fi receivers that cannot enable the phase error correction. This is because the phase error correction in Wi-Fi receivers can eliminate the phase offset created by a tag, which results in the decoding error. Liu et al. [72] thus propose *TScatter*. The highlight of this system is the design of a sample-level modulation scheme. In this scheme, the phase offsets on the pilot subcarriers and the data subcarriers are very different. Therefore, the phase offsets on the data subcarriers cannot be eliminated by the phase error correction, since the phase error correction leverages pilot subcarriers to correct the phase offset. On the backscatter receiver side, a novel demodulation model is proposed and the tag data is estimated by using a minimization function that is derived from the proposed demodulation model. Liu et al. [72] evaluate the performance of *TScatter* in various real-world scenarios. The results show that, with 4-phase modulation scheme, *TScatter* can achieve a throughput of around 10.61 Mbps over a range of 120 ft in a hallway scenario.

***(3) Other approaches:*** Abedi et al. propose *WiTAG* [73,74], which leverages MAC-layer features to enable communication between backscatter tags and Wi-Fi devices. Specifically, the IEEE 802.11n/ac standards support a MAC-layer frame aggregation mechanism to reduce communication overhead. In this mechanism, multiple *MAC Protocol DATA Units* (MPDUs) are integrated into a larger aggregated frame (A-MPDU). After receiving the A-MPDU, the receiver will transmit a *block* acknowledgment (ACK) back to the sender to report the state of each MPDU in the A-MPDU. Therefore, during the transmission of each MPDU, a *WiTAG* tag can transmit bits ‘0’ or ‘1’ by corrupting (e.g., changing the phase of a signal) or not corrupting the transmission, respectively. The experimental results show that, with a distance of 8 m between the sender and the receiver, *WiTAG* can achieve a throughput of 40 Kbps when the tag operates anywhere between them.

He et al. [75] note that most Wi-Fi based backscatter systems suffer from low reliability owing to the intermittent characteristic of the Wi-Fi signals. Thus, a novel Wi-Fi based BackComs system, namely *GuardRider*, is proposed, which tries to achieve reliable communication between backscatter tags and backscatter receivers. A highlight of this system is the design of an *optimized Reed–Solomon (RS) code* scheme. The main principle of this scheme is to adaptively add some redundancy in a given information sequence, so that the tag data and redundant bits will be respectively transmitted during the “on” (i.e., presence) and “off” (i.e., absence) states of Wi-Fi signals. To implement *GuardRider*, a key problem is to evaluate the “on” and “off” states of Wi-Fi signals. Considering the limited resources of the tag, the authors shift the estimating process from the tag to the receiver. On the backscatter receiver side, the receiver first listens on the desired channel. After that, the duration of the “on” and “off” states of Wi-Fi signals is measured based on the received signals. Then, the optimal RS code parameters are obtained based on both the duration and a novel heuristic algorithm. Finally, the receiver feeds back the parameters to the tag. Through simulations and experiments, the results show that *GuardRider* can achieve a throughput of around 700 Kbps.

### *3.1.6. LTE based BackComs systems*

Chi et al. [58] design the first LTE based BackComs system called *LScatter*. It enables ubiquitous, high throughput, and low latency BackComs by reflecting the continuous and ubiquitous LTE signals. To achieve this, on the backscatter tag, a challenge is to avoid modification of the *primary synchronization signal* (PSS) and *secondary synchronization signal* (SSS) messages, because these messages are important for decoding the LTE signal. The authors thus design an ambient LTE signal synchronization circuit to detect the PSS signals. The basic idea underlying the circuit is that the signal strength of PSS in LTE signal is higher than that of other parts in LTE signal. Therefore, by comparing the average envelope signals with the incoming envelope signals, we can determine whether the PSS appears. Once the PSS signals are detected, the backscatter tag can avoid modulating the PSS and SSS by transmitting square waves. Another challenge is how to modulate the LTE signal to achieve higher throughput. The authors note that the LTE signal in time-domain is constructed by the basic-timing units. The basic-timing units provide a much higher granularity than a symbol duration. The authors thus design a novel phase modulation scheme. It embeds tag data by changing the phases of the LTE signals in different basic-timing units, thereby achieving high throughput. On the backscatter receiver side, the reference signals on different subcarriers in the original LTE physical layer are used to eliminate the effect from the phase offset. The experimental results demonstrate that *LScatter* can achieve a throughput of up to 13.63 Mbps.

***Discussion:*** In this section, we have reviewed single-signal based BackComs systems. Table 2 provides a summary of different Amb-BackComs systems from the performance perspective, including minimum power, maximum throughput, and maximum range. From the table, we observe that *LScatter* [58] achieves a maximum throughput. However, it is not compatible with existing infrastructures owing to the need for a dedicated receiver. This limits its application in the real world. In general, Bluetooth, ZigBee, and Wi-Fi signals would be a more appropriate choice for indoor applications while outdoor applications can be implemented by leveraging TV, FM, LoRa, and LTE signals. In terms of single-signal based BackComs systems, some open issues are summarized as follows:

- As Amb-BackComs leverage signals from existing systems, it is important to ensure that backscattering will not cause any performance degradation to existing systems. Therefore, the evaluation and analysis of the interference to existing systems is a hot research direction.
- Many current studies in this area mainly focus on uplink communication. Performance improvement in downlink communication is less studied. Some techniques (e.g., full-duplex) can be exploited to improve the overall throughput.
- The existing studies in this area mainly consider the communication between one tag and one receiver. However, practical applications involve multiple tags. Thus, the coordination between multiple tags needs to be further studied.
- In terms of Bluetooth based BackComs systems, many existing studies are built on the work of *Interscatter* [28]. These studies leverage a single-tone transmission for backscatter. As a result, the excitation signals cannot be used for productive data communication and carriers simultaneously, thereby greatly reducing spectral efficiency. Thus, more studies need to be done to improve spectral efficiency.
- For Wi-Fi based BackComs systems, many current studies in this area leverage the principle of *codeword translation*. While *codeword translation* works well in single-stream excitation, it has a low throughput in multi-stream excitation. Thus, new modulation schemes are needed to be studied.

### 3.2. Multi-signal based Amb-BackComs systems

We primarily classify the multi-signal based Amb-BackComs systems based on the technique used.

***(1) Frequency shifting based:*** The *frequency shifting* technique is first introduced in *FS-Backscatter* [76]. In this system, the backscatter tag is able to shift an incoming Bluetooth or Wi-Fi signal into an adjacent Bluetooth or Wi-Fi band. This leads to a reduction in interference between the backscattered signal and the original signal. As such, the tag can transmit its information by using on-off keying (OOK) modulation. Shifting the carrier by 20 MHz, however, typically needs to consume milliwatts of power, which is not feasible for low-power tags. To address this, a novel ring oscillator is designed on the backscatter tag, which can consume tens of micro-watts while shifting the carrier by such a substantial amount. The experimental results show that *FS-Backscatter* can achieve a throughput of 627.7 bps and an operational distance of up to 4.8 m when reflecting Wi-Fi signals, and a throughput of up to 50 Kbps at 36 m when reflecting BLE signals.

***(2) Codeword translation based:*** Zhang et al. [22] notice that any wireless signal on the ISM band can be viewed as a sequence of codewords from a codebook to represent different bits that are being transmitted. This means that the *codeword translation* technique originated in [68] can be extended to support other various commodity radios, such as Bluetooth and ZigBee. Zhang et al. [22] thus propose *FreeRider*, a multi-signal based BackComs system that works with Bluetooth, 802.11g/n Wi-Fi, and ZigBee radios. In this system, the excitation signal can carry productive data and serve as the carrier at the same time. In addition, this system requires two receivers to decode the tag information. The authors evaluate the performance of *FreeRider* in various scenarios. The experimental results show that *FreeRider* can achieve a data rate of around 60 Kbps at 18 m when reflecting 802.11g/n Wi-Fi signals, a throughput of 12 Kbps at a distance of 20 m when reflecting ZigBee signals, and a data rate of around 50 Kbps at 10 m when reflecting Bluetooth signals.

Gong et al. propose *Multiscatter* [34], a novel multi-signal based BackComs system. Like *FreeRider* [22], *Multiscatter* also supports multiple radios (e.g., ZigBee, Bluetooth, and Wi-Fi) and these radios are simultaneously used for productive data communication and carriers. Different from *FreeRider*, *Multiscatter* tags can distinguish those excitation signals and leverage excitation diversity to improve throughput gains. In addition, *Multiscatter* uses a single receiver to decode the tag data. To achieve the goal of identifying different signals, a key insight is that every packet has a unique preamble field. Thus, by identifying such preambles, different signals can be distinguished. Doing so first requires obtaining high-bandwidth baseband signals, like ZigBee. However, acquiring such signals usually requires power-hungry components, which are infeasible for low-power tags. The authors thus propose a *high-bandwidth rectifier*, which can acquire high-bandwidth input signals by using simple low-power hardware elements, such as diodes, capacitors, and resistors. In addition, a *low-power protocol identification* scheme is designed to further reduce computation and power overhead while keeping identification results accurate. After identifying the excitation signals, the tag embeds its data on those signals by using a novel *overlay modulation* scheme. The overlay modulation is based on *codeword translation* [22]. The highlight of overlay modulation is using the reference symbol in the carrier. The reference symbol plays the same role as the original Wi-Fi signal used in the decoding process of the *codeword translation*. As a result, a backscatter receiver is able to complete decoding. The experimental results show that *Multiscatter* can achieve maximum backscatter communication ranges of 28 m, 22 m, and 20 m for Bluetooth, 802.11b/n Wi-Fi, and ZigBee, respectively.

***(3) Other approaches:*** Jung et al. [77] propose *GateScatter*, a multi-signal based BackComs system that works with Bluetooth and ZigBee signals. In this system, the *GateScatter* tag is able to transform an incoming ZigBee or Bluetooth signal into a valid 802.11b Wi-Fi signal while maintaining the original data. In short, the *GateScatter* tag can be viewed as a gateway. To implement *GateScatter*, the authors note that, with an appropriate tag signal, the incoming ZigBee's positive (negative) half-sine signal after backscattering approximates 802.11b Wi-Fi's non-inverted (inverted) Barker code. This means a ZigBee signal can be reshaped into an 802.11b Wi-Fi signal on the backscatter tag. However, the tag signal has to be carefully selected because both in-phase and quadrature signals of ZigBee can correlate to 802.11b Wi-Fi Barker code, which results in false decoding. The authors notice that the original ZigBee symbols can be uniquely identified with only the quadrature portion of ZigBee. Hence, an optimization method is proposed to select the optimal tag signal, so that only the quadrature component correlates to the Wi-Fi Backer code. On the receiver side, after the received signal has been decoded into Wi-Fi bits, a mapping from Wi-Fi bits to ZigBee symbols is performed to retrieve the original ZigBee symbols. Furthermore, the authors demonstrate that *GateScatter* works with BLE. The experimental results show that *GateScatter* can achieve a data rate of up to 662 Kbps and a communication distance at most 27 m when backscattering Bluetooth signals, and a throughput

**Table 2**
Summary of Amb-BackComs systems.

| Article | Year | Signal source | Performance | | | | |
|---|---|---|---|---|---|---|---|
| | | | Minimum Power | Maximum Throughput | | Range | |
| | | | | Throughput | Distance | TX to Tag | Tag to RX |
| *Interscatter* [28] | 2016 | BLE | 28 μW (IC) | 11 Mbps | N/A | 0.9 m | 27.4 m |
| [29] | 2020 | BLE | N/A | 2.8 Kbps | 1 m | 0.5 m | 23 m |
| *RBLE* [26] | 2020 | BLE | 37 μW (IC) | 16.6 Kbps | 1 m | N/A | 56 m |
| *IBLE* [31] | 2021 | BLE | 53.528 mW | 8.275 Kbps | 2 m | 0.5 m | 20 m |
| *Ambient backscatter* [1] | 2013 | TV | 0.79 μW | 10 Kbps | 0.4 m | N/A | 2.5 m |
| [36] | 2014 | TV | 430.9 μW | 1 Mbps | 2.1 m | N/A | N/A |
| *FM backscatter* [38] | 2017 | FM | 11.07 μW (IC) | 3.2 Kbps | 4.9 m | N/A | 18.3 m |
| [60] | 2017 | FM | N/A | 500 bps | 0.5 m | N/A | 2 m |
| [39] | 2017 | FM | 0.677 mW | 2.5 Kbps | 5 m | 34 km | 5 m |
| [62] | 2017 | FM | 24 μW | N/A | N/A | N/A | 26 m |
| [63] | 2018 | FM | 24 μW | N/A | N/A | N/A | 26 m |
| *PLoRa* [21] | 2018 | LoRa | 2.591 mW | 6.25 Kbps | 300 m | N/A | 1.1 km |
| *Aloba* [45] | 2020 | LoRa | 0.3 mW | 199.4 Kbps | 50 m | 1 m | 250 m |
| *Wi-Fi backscatter* [67] | 2014 | Wi-Fi | 9.65 μW | 1 Kbps | N/A | N/A | 2.1 m |
| *HitchHike* [68] | 2016 | 802.11b Wi-Fi | 33μW (IC) | 300 Kbps | 34 m | 1 m | 54 m |
| *MOXcatter* [20] | 2018 | 802.11n Wi-Fi | N/A | 50 Kbps | 3 m | 0.3 m | 14 m |
| *RapidRider* [69] | 2021 | 802.11a/g/n Wi-Fi | N/A | 239.1 Kbps | 1 m | N/A | 16 m |
| *X-Tandem* [70] | 2018 | 802.11b/g/n Wi-Fi | 14.2 mW | 200 bps | 0.5 m | 0.3 m | 8 m |
| *VMscatter* [55] | 2020 | 802.11n Wi-Fi | 32 μW (IC) | 500 Kbps | 1.5 m | 0.9 m | 34.6 m |
| *SyncScatter* [71] | 2021 | 802.11b Wi-Fi | 30 μW (IC) | N/A | N/A | N/A | 30 m |
| *TScatter* [72] | 2021 | 802.11 g Wi-Fi | 30.2 μW (IC) | 10.61 Mbps | N/A | N/A | 48.8 m |
| *WiTAG* [73] | 2018 | 802.11n/ac Wi-Fi | N/A | 40 Kbps | 7 m | 1 m | 17 m |
| *GuardRider* [75] | 2019 | Wi-Fi | N/A | 700 Kbps | N/A | N/A | N/A |
| *LScatter* [58] | 2021 | LTE | 153 μW (IC) | 13.63 Mbps | N/A | 0.6 m | 97.5 m |
| *FS-backscatter* [76] | 2016 | Wi-Fi | 45 μW | 627.7 bps | N/A | N/A | 4.8 m |
| | | BLE | | 50 Kbps | 3.6 m | N/A | 4.4 m |
| *FreeRider* [22] | 2017 | 802.11g/n Wi-Fi | 32 μW (IC) | 60 Kbps | 18 m | 1 m | 42 m |
| | | Bluetooth | | 50 Kbps | 10 m | 1 m | 12 m |
| | | ZigBee | | 14 Kbps | 12 m | 1 m | 22 m |
| *Multiscatter* [34] | 2020 | 802.11b/n Wi-Fi | 279.5 mW | 219.8 Kbps | 2 m | 0.8 m | 28 m |
| | | BLE | | 278.4 Kbps | 2 m | 0.8 m | 22 m |
| | | ZigBee | | 26.2 Kbps | 2 m | 0.8 m | 20 m |
| *GateScatter* [77] | 2020 | BLE | 77.4 μW (IC) | 662 Kbps | 1 m | 0.5 m | 23 m |
| | | ZigBee | | 222 Kbps | 1 m | 0.5 m | 27 m |
| *Glaze* [78] | 2019 | Wi-Fi | 850 μW | 10 Kbps | 3.5 m | N/A | 3.5 m |
| | | FM | | 10 Kbps | 3.5 m | N/A | 10 m |
| | | TV | | 10 Kbps | 3.5 m | N/A | 9 m |
| [79] | 2017 | FM | N/A | 1 Kbps | 15.3 m | N/A | 22 m |
| | | TV | | 1 Kbps | 9 m | N/A | 12.4 m |

Note: Under "Range", we provide the maximum operating distance between tag and receiver (denoted by *Tag to RX*) and the corresponding distance between ambient source and tag (denoted by *TX to Tag*). In the "Maximum Bit Rate" column, the "Distance" is the distance between tag and receiver when obtaining the maximum throughput. For all numbers marked "IC" in the "Minimum Power" column, the number is the simulation result of an integrated circuit (IC) design.

of up to 222 Kbps and a communication range of up to 27 m when backscattering ZigBee signals.

Kapetanovic et al. [78] propose *Glaze*, which tries to overlay additional data on existing ambient signals (e.g., Wi-Fi and Bluetooth) to enable downlink communication while those signals are still being received by legacy receivers. Kapetanovic et al. [78] notice that most wireless receivers are able to tolerate a small amount of noise in the wireless signal. Thus, we can transmit additional data on existing ambient signals by introducing small amounts of attenuation. Based on this insight, a novel *Glaze* module is designed, which can overlay data on existing signals by changing the amplitude of those signals. The *Glaze* module is connected to the antenna ports of existing wireless transmitters, as shown in Fig. 12. The input of the Glaze module is a wireless signal and the output is a composite signal that is composed of original information and additional data. On the *Glaze* receiver side, the composite signal passes through the matching network circuit, envelop detector circuit, threshold compute circuit, and comparator circuit, and finally is decoded. The experimental results demonstrate that *Glaze* can achieve downlink ranges of 3.5 m, 10 m, and 9 m by overlaying data on Wi-Fi, FM, and TV signals, respectively.

Another multi-signal based BackComs system is introduced by Yang et al. in [79] to enable the backscatter system to operate on ambient carriers as low as −80 dBm. A highlight of this system is the design of an ultra-wideband backscatter tag. This tag can reflect any ambient signal from 80 MHz to 900 MHz, including TV, FM, and cellular

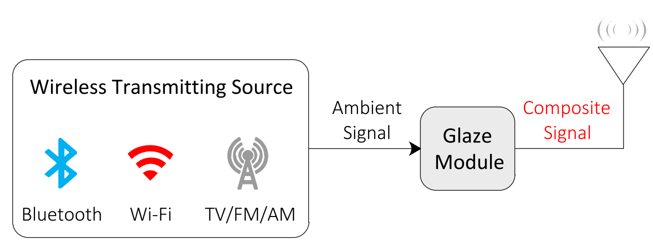


**Fig. 12.** The Glaze module connects to the antenna port of wireless transmitters [78].

signals, to transmit its information. By combining multiple backscatter carriers, the signal-to-noise ratio can be enhanced, thereby improving the sensitivity of a backscatter receiver. To decode the backscattered data, a novel signal processing module is designed, as shown in Fig. 13. First, on the receiver side, the received signals are digitally sampled by an analog-to-digital converter. Then, each signal from different channels is separated using an appropriate band pass filter. After that, the backscattered signals embedded in different channels are individually extracted by down-conversion and signal processing operations. Finally, a *maximal ratio combining with interference* technique is used to decode the backscattered data. The experiment results show that the proposed system can achieve a communication range of up to 22 m at

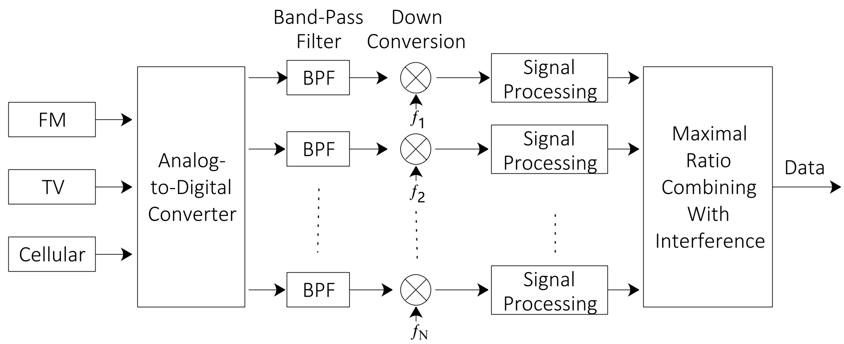


**Fig. 13.** The block diagram of the receiver signal chain used in [79].

data rates of 158 bps when reflecting FM signals, and a distance of 9 m at 1 Kbps when reflecting TV signals.

***Discussion:*** In this section, multi-signal based Amb-BackComs systems are reviewed and summarized in Table 2. Compared to single-signal based Amb-BackComs systems, multi-signal based Amb-BackComs systems have advantages in scenarios where a particular type of ambient signals is not available or the signal quality is poor. However, the design of multi-signal based Amb-BackComs systems is more complicated and the performance is limited in terms of the communication range and throughput. Thus, we should choose Amb-BackComs systems based on the actual requirements. Similar to the issues in single-signal based Amb-BackComs systems, some critical problems (e.g., multiple access, downlink communication, and interference to existing systems) are less studied in multi-signal based Amb-BackComs systems. Therefore, there is a need for further studies to address these problems.

## 4. Applications

Ambient backscatter technology is expected to be widely adopted in various practical applications (e.g., smart homes [20,70], environment monitoring [60], and health care [28]) by virtue of its characteristics of ultra-low-power, efficient spectrum utilization, low cost and easy deployment. In this section, we provide a brief discussion on the practical applications empowered by Amb-BackComs.

### 4.1. Smart homes and smart cities

In a smart home, massive passive tags can be flexibly deployed at any location, such as embedded in walls and furniture. These devices are powered by collecting energy from ambient signals (e.g., Wi-Fi, Bluetooth) and can collaborate to monitor the indoor environment. The environmental data (e.g., temperature, humidity) collected by the tag can be reported to smart home devices. By analyzing those data, smart home devices can intelligently adjust the temperature or humidity of the room, thereby providing a comfortable living condition for us. The studies in [20,70] have demonstrated the applicability of smart home design using Wi-Fi backscatter.

Similarly, in a smart city, massive passive tags can be deployed in buildings, streets, and parking spaces to help improve the quality of life by providing users with helpful information (e.g., parking availability). Wang et al. [38] have demonstrated that smart posters are able to convey information (e.g., audio and notifications) to nearby users by backscattering FM radio signals. Waghmare et al. [80] have shown that posters can be used to collect user feedback (e.g., shopping experience) and transmit the collected information to a nearby smartphone using FM backscatter.

### 4.2. Universal localization

Localization is a process that finds a device or user location in any arbitrary environment such as a home or office. Obtaining the location of devices or users is becoming a fundamental requirement in our daily life. A person may desire to easily obtain the location of his or her items such as keys, smartphone, pill bottle, or books. By attaching a passive tag to these objects of interest, we can find them by leveraging the ambient backscatter communication technique. *WiTag* [81] can achieve a median localization error of 0.92 m in a line-of-sight scenario and 1.48 m in a non-line-of-sight scenario, in an office building with Wi-Fi access points. *TagFi* [82] can achieve a median localization accuracy of 0.2 m over a range of up to 8 m in an office building with Wi-Fi infrastructure.

### 4.3. Environmental monitoring

Environmental monitoring is increasingly important for tackling global climate change and improving the environment. Ambient backscatter communication promises to play a key role in environmental monitoring owing to low deployment and maintenance costs. Backscatter tags can be placed in any arbitrary environment to assist in monitoring environmental parameters such as humidity and temperature. Temperature and humidity data measured by the tag can be collected and further analyzed so that a corresponding plan is implemented. Daskalakis et al. [60] have shown an ambient FM backscattering scheme for smart agricultural monitoring.

### 4.4. Health care

Health care is vitally important for preventing or treating illness and injuries. Traditional health care is carried out in hospitals or clinics, with the help of medical apparatus and instruments. It is inconvenient for the elderly and office workers, since they may desire to diagnose their health even without going to the hospital. Ambient backscatter communication promises to achieve this vision. In particular, the backscatter tags can combine a variety of biosensors and collect physiological signs such as body temperature and heart rate. By backscattering ambient signals (e.g., Wi-Fi), these tags can report the collected physiological information to a receiver (e.g., a smartphone). In this way, users can easily know their health conditions. In addition, these physiological data can be transmitted to their family members, so that families can take better care of them. Iyer et al. [28] have demonstrated that a smart contact lens can leverage ambient backscatter communication to help diabetic patients sense their condition.

### 4.5. Smart card

Owing to the small size, backscatter tags can be embedded inside the cards. In this way, these cards are able to communicate with each other by leveraging ambient backscatter technology. A typical application scenario is the money transfer between smart cards. In [1], the authors present a proof-of-concept of the smart card application. Specifically, the authors let a smart card send the message "Hello World" to another smart card with the help of Amb-BackComs. The experimental results demonstrate that the message can be transmitted with 94% of successful ratio when the two cards are 4 inches apart and communicate at a bit rate of 1 Kbps.

### 4.6. Logistics

Logistics applications can greatly benefit from ambient backscatter technology as it can help to manage the logistics items. In particular, backscatter tags can be attached to the surface of the goods to assist in reading their information. The information collected by the tag can be reported to the logistics administrator by leveraging nearby ambient signals. In this way, the logistics administrator can manage the items conveniently, thereby improving the management efficiency of logistics items. The work [1] has demonstrated that Amb-BackComs can be adopted to help monitor the items on a shelf.

### 4.7. Vision applications

Amb-BackComs can also be applied in real-time vision applications such as face detection and recognition. In [83], ambient backscatter technology is implemented to assist in the face detection and recognition process. Specifically, the authors design a novel camera board. The camera board is able to transmit the collected image streaming message to a backscatter receiver (e.g., a laptop) by backscattering Wi-Fi signals. After authenticating the received images, a corresponding action can be performed, such as opening the door for users. The experimental results present a face detection accuracy of 90.1% and a face recognition accuracy of 98.5%.

## 5. Open issues and challenges

In this section, we discuss some remaining open issues and challenges that are to be addressed to motivate further research efforts in the area of Amb-BackComs.

### 5.1. Full compatibility with existing infrastructures

Most of the exiting Amb-BackComs systems are not fully compatible with existing infrastructures. Either a specific sequence of excitation signals is required, or deployment of a dedicated receiver is required. The studies in [26,28–31] require single-tone Bluetooth transmissions for backscatter. As a result, excitation signals in these studies cannot be used for productive data communication and the carrier at the same time, thereby greatly reducing spectrum efficiency. The studies in [36,39,60,62,63,79] require modifications to commodity devices or deployment of a dedicated receiver, thereby limiting the commodity device usage and causing more cost. Designing an Amb-BackComs system that is fully compatible with existing infrastructures is challenging since existing devices are specifically designed to receive signals from a specific source. It is unclear how these devices would decode other types of signals from the backscatter tag. The studies in [22,67,68] show full compatibility with existing Wi-Fi infrastructures and the work in [1] show full compatibility with existing TV infrastructures. However, communication performance is limited in terms of throughput and communication range. Thus, further efforts are needed to improve throughput and communication range.

### 5.2. Interference to existing systems

Ambient backscatter leverages signals transmitted in existing systems. As a result, the reflected signals can cause interference to existing systems. In [1], the authors evaluated the effect of the backscatter on the existing TV receiver and showed that, for the backscatter rates less than 10 Kbps, the backscattering does not lead to a noticeable interference to the TV receiver unless its distance to the tag is less than 7.2 inches. In addition, recent studies in [22,68,69] have demonstrated that backscattering does not cause any noticeable interference to Wi-Fi networks. However, this may not be the case for other systems. Thus, more studies need to be done to evaluate the impact of Amb-BackComs on existing systems.

### 5.3. Downlink communication

Almost all the ambient backscatter researches focus on uplink transmission (i.e., the transmission from the backscatter tag to the backscatter receiver). There exists a huge gap in the exploration of downlink transmission (i.e., the transmission from ambient sources to backscatter tags). Existing backscatter downlink designs leverage the presence and duration time of the excitation signal to encode information, and use a low-power energy detector to identify the presence of a packet and demodulate data. This inevitably leads to low throughput. In addition, the low-power requirement also restricts the use of power-hungry components on the backscatter tag, thereby further degrading the performance of downlink transmission. Therefore, in-depth research in this direction is necessary.

### 5.4. Enabling multi-hop backscatter networks

Ambient backscatter research remains in its infancy with primary focus on single-hop design. The robustness and scalability of Amb-BackComs can be severely limited by single-hop design owing to poor channel and its restricted connectivity. Recent work [70] has demonstrated that a multi-hop backscatter can provide path diversity and robustness for tag data transmission. However, its performance is limited to two hops, achieving a throughput of only 200 bps with tag-to-tag distances of 40 cm. There is significant research to be done on multi-hop design to extend the coverage of Amb-BackComs systems as well as achieve higher data rates and longer communication ranges.

### 5.5. Medium access control protocol

The practical application of Amb-BackComs involves the communication of numerous tags. These tags are deployed in our surrounding environment to perform a wide range of activities (e.g., gas leakage detection) and could collaborate to send the collected data to the receiver employing a single-hop or multi-hop mechanism. An efficient MAC protocol is needed to coordinate multiple tags or support concurrent transmission. Through efficient MAC schemes, the wireless medium between multiple tags can be efficiently shared. Thus, the interference and collision between multi-tag transmission could be handled and suppressed, thereby achieving significant performance gain. *FreeRider* [22] achieves an aggregate throughput of 15 Kbps when communicating with 20 tags by implementing a MAC scheme. *$P^2$LoRa* [84] achieves the parallel transmission of up to 101 tags with ambient LoRa as the excitation signal. *NetScatter* [85] provides a throughput of about 250 Kbps when communicating with up to 256 concurrent tags using *distributed chirp spread spectrum coding*, but only works with LoRa signals. Therefore, further efforts are needed to support large-scale deployment regardless of ambient signals.

*5.6. Full-duplex technique*

Amb-BackComs can benefit from the full-duplex technique. With the full-duplex operation, the backscatter tag can transmit and receive data at the same time and frequency. Thus, the performance of Amb-BackComs systems can be improved including, but not limited to transmission latency, spectral efficiency, and throughput. Achieving full-duplex communication on the low-power tag is challenging since traditional full-duplex techniques usually require complex hardware design, which is power-intensive. Prior studies [86,87] have demonstrated the full-duplex communication on the low-power tag. However, these methods suffer from interference and spectrum efficiency. Therefore, further researches in this direction are needed to solve these problems.

*5.7. Channel capacity and coverage analysis*

Channel capacity and coverage are important indicators of system performance. Owing to the low-power nature of the backscatter tag as well as the unpredictability and burstiness of ambient signals, traditional models of coverage and capacity analysis cannot be directly applied into ambient backscatter systems. Recent studies [88,89] have taken a step forward in this paradigm. Zhao et al. [88] investigated the capacity problem of an ambient backscatter system by using the Gaussian channel model. Wei et al. [89] performed the capacity analysis of an 802.11b-based ambient backscatter system. These studies open the door for further efforts in this direction.

## 6. Conclusion

Ambient backscatter technology is promising to play a vital role in future low-power communications systems, such as IoT. Further efforts in this direction are needed to enable a practical ambient backscatter system that is sufficiently effective for real-world IoT applications. In this paper, we have provided a detailed discussion on different Amb-BackComs systems that have been reported in the literature between 2013 and 2021. We believe that new Amb-BackComs systems with full compatibility with existing infrastructures and higher performance will be an interesting topic in the following years. The evaluation and analysis of the interference to existing systems is also an important research topic. Also, the solutions for enhancing the performance of downlink communication in Amb-BackComs systems will be a hot direction. Another interesting future topic is the design of a practical multi-hop backscatter system. Considering that future IoT applications comprise numerous backscatter tags, the design of an efficient MAC protocol is also a hot research direction. Apart from this, full-duplex communication on the tag is still a challenging topic, because traditional full-duplex communication generally requires power-hungry components, which are not feasible for low-power tags. In addition, coverage and capacity analysis in Amb-BackComs systems will be good directions.

Furthermore, this paper provided a detailed discussion on basic principles and potential applications. We believe that this paper is able to provide readers, interested in Amb-BackComs, with a comprehensive and detailed insight into different aspects of Amb-BackComs, and that this paper is expected to act as a starting point for future research.

## CRediT authorship contribution statement

**Weiqi Wu:** Writing – original draft. **Xingfu Wang:** Supervision, Writing – review and editing, Resources. **Ammar Hawbani:** Supervision, Writing – review and editing, Resources. **Longzhi Yuan:** Resources. **Wei Gong:** Supervision, Writing – review and editing, Resources.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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