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Practical Backscatter Communication Systems for Battery-Free Internet of Things

A tutorial and survey of recent research

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Backscatter presents an emerging ultralow-power wireless communication paradigm. The ability to offer submilliwatt power consumption makes it a competitive core technology for Internet of Things (IoT) applications. In this article, we provide a tutorial of backscatter communication from the signal processing perspective as well as a survey of the recent research activities in this domain, primarily focusing on bistatic backscatter systems. We also discuss the unique real-world applications empowered by backscatter communication and identify open questions in this domain. We believe this article will shed light on the low-power wireless connectivity design toward building and deploying IoT services in the wild.

Overview of backscatter communication

The vision of the IoT promises a world where sensors and actuators are ubiquitous and interconnected so that we can better understand and control the surrounding world. One critical challenge toward this vision is to build such devices that can be easily deployed and run autonomously for a lengthy duration. Backscatter communication, an emerging microwatt-level wireless communication paradigm, is gaining popularity as a suitable solution to fulfill such a need.

The principle of backscatter communication is similar to that of the heliograph shown in Figure 1. People have been using mirrors to reflect sunlight for communication for a long time, and this method is especially important when there is no source of energy like a campfire or a flashlight. By flipping the mirror, the sender can signal the remote target by controlling the presence of reflected light using Morse code. For backscatter communication, the same reflecting while manipulating process is applied on radio-frequency (RF) signals. At a high level, the system model of backscatter communication is shown in Figure 2. A special device called a *backscatter tag* reflects the incoming excitation signal emitted by a nearby (carrier) transmitter. At the same time, it selectively changes the amplitude, frequency, and/or phase of the signal for modulation. The backscattered signal is then captured by a receiver and piped through a signal processing engine to extract information

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injected by the backscatter tag. Note that the transmitter and the receiver were previously integrated in the conventional or monostatic backscatter system [e.g., RF identification (RFID) reader [1]] but are separated in bistatic backscatter system designs. Specifically, the transmitters can be available ambient RF sources [e.g., TV or frequency modulation (FM) radio towers, cellular base stations, and Wi-Fi access points (APs)] from anywhere. This new modular design introduces the following intrinsic properties for performance enhancement.

1) *Temporal flexibility*: In many sensing applications, it is important for the backscatter tag (as a sensor node) to transmit as soon as the sensory data are available. When excitation signals can potentially come from multiple sources, the tag has more time slots for data transmission instead of waiting for protocol-constrained interrogation from a single reader.
2) *Spatial flexibility*: The coverage of excitation signals is vital to the performance of backscatter communication. Being decoupled from the receiver, the transmitter(s) can be strategically placed in optimal locations to balance the scalability and performance for backscatter tags.
3) *Technology flexibility*: Bistatic backscatter system design presents a general and technology-independent communication paradigm that allows a variety of excitation signals and modulation schemes to be used in situ. Ambient RF sources, e.g., Wi-Fi signals, can be used to make the backscatter technology immediately deployable, because there are commodity Wi-Fi transmitters (e.g., APs) and receivers everywhere.

The main advantage of backscatter communication is energy efficiency. Compared with conventional wireless technologies, such as Wi-Fi (tens of milliwatts), Bluetooth/Bluetooth Low Energy (several milliwatts), and long-term evolution (LTE) (hundreds of milliwatts), the power consumption of backscatter communication is more than 1,000 times smaller. The key to realize such power reduction is that the procedure of radio signal generation, i.e., the most power-consuming block in radio communicators, is offloaded to the powered transmitter and thus is not present in a backscatter tag. In addition, signal amplification and processing are also delegated to the transmitter. This creates an asymmetric design consisting of a fat transmitter/receiver and a thin backscatter tag. The ultralow-power nature of such a design makes it feasible for backscatter tags to be battery-free by utilizing today's energy-harvesting techniques, such as solar/light, mechanical motion/vibration, thermoelectric effect, and electromagnetic radiation [2], [3] with the limited form factor (square centimeter) of common IoT devices. Apart from the benefit of energy efficiency, this asymmetric design also means simpler hardware design, smaller form factor, and lower cost of the tag. The idea of such an asymmetric design can also be extended to provide a more energy-efficient wireless link for day-to-day use of mobile devices [4]. This design is making backscatter a competitive solution for IoT devices, and it is an important step toward realizing large-scale IoT application deployment in the wild.

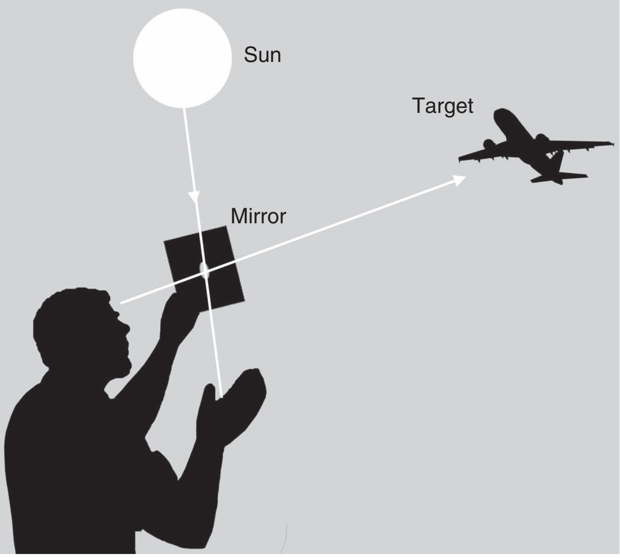

FIGURE 1. A heliograph, a simple but effective instrument that signals by flashes of sunlight reflected by a mirror for instantaneous optical communication over long distances. The flashes are modulated by momentarily pivoting the mirror or by interrupting the beam with a shutter.

Tutorial on backscatter communication

Backscatter basics

While various backscatter communication technologies are available, all of them are based on the same or similar model and techniques, which is to enable backscatter tags to reflect an incoming RF signal and at the same time modify and modulate the signal for secondary transmission, or backscatter. The core idea of modifying and reflecting the RF signal is impedance mismatching. On a backscatter tag, such discontinuity can be implemented by connecting an antenna of impedance $Z_A = |Z_A|e^{j\theta_A}$ to a load of impedance $Z_L = |Z_L|e^{j\theta_L}$. The

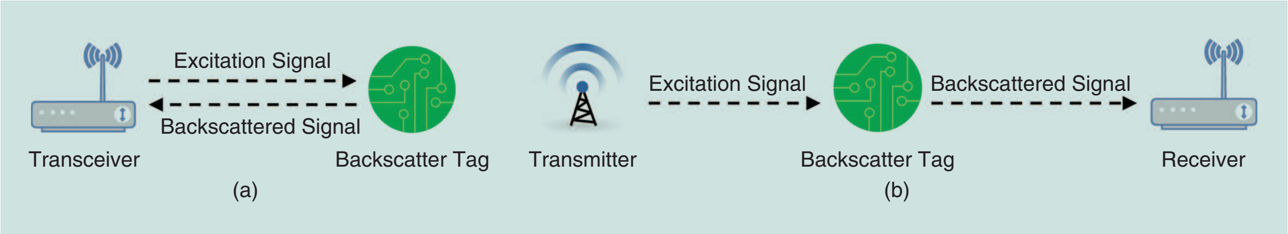

FIGURE 2. The (carrier) transmitter is separated from the receiver in the (modern) bistatic backscatter system design, in comparison to the (conventional) monostatic backscatter system model: (a) the monostatic backscatter system and (b) the bistatic backscatter system.

reflection coefficient of the backscatter tag circuit Γ_T can be calculated as (1), where $|\Gamma_T|$ and θ_T are given in (2) and (3):

$$\Gamma_T = \frac{Z_L - Z_A}{Z_L + Z_A} = 1 - \frac{2|Z_A|}{|Z_A| + |Z_L| e^{-j(\theta_A - \theta_L)}} = |\Gamma_T| e^{j\theta_T}, \quad (1)$$

$$|\Gamma_T| = \frac{|Z_A|^2 + |Z_L|^2 - 2|Z_A||Z_L|\cos(\theta_A - \theta_L)}{|Z_A|^2 + |Z_L|^2 + 2|Z_A||Z_L|\cos(\theta_A - \theta_L)}, \quad (2)$$

$$\theta_T = \arctan\left(\frac{2|Z_A||Z_L|\sin(\theta_A - \theta_L)}{|Z_A|^2 - |Z_L|^2}\right). \quad (3)$$

As the name suggests, the reflection coefficient Γ_T describes the ratio of the complex amplitudes of the incoming signal $S_{\text{in}}(t)$ and the reflected signal $S_{\text{out}}(t)$. For simplicity, we define the incoming signal $S_{\text{in}}(t)$ as a sine wave, as shown in (4):

$$S_{\text{in}}(t) = A_{\text{in}} e^{j(2\pi f_{\text{in}} t + \theta_{\text{in}})}. \quad (4)$$

Note that we do not lose generality here by replacing arbitrary $S_{\text{in}}(t)$ with a sine wave because any $S_{\text{in}}(t)$ can be regarded as a collection of sine waves using Fourier transform. Given the definition of $S_{\text{in}}(t)$ and the reflection coefficient Γ_T, the reflected signal $S_{\text{out}}(t)$ is calculated and shown in (5):

$$S_{\text{out}}(t) = \Gamma_T \cdot S_{\text{in}}(t) = |\Gamma_T| A_{\text{in}} e^{j(2\pi f_{\text{in}} t + \theta_{\text{in}} + \theta_T)}. \quad (5)$$

We can see that the backscatter tag is able to control $S_{\text{out}}(t)$ by controlling Γ_T, which is derived from the impedance of the antenna Z_A and the load Z_L. As a result, we can adjust Z_L to change the value of Γ_T for modulating $S_{\text{out}}(t)$. Unlike conventional radio communication systems that can directly change the amplitude, frequency, and phase of $S_{\text{out}}(t)$ for modulation, in backscatter systems, $S_{\text{out}}(t)$ can only be manipulated by changing Γ_T. As shown in (5), Γ_T effectively applies a phase shift of θ_T and an attenuation of $|\Gamma_T|$ to the incoming signal $S_{\text{in}}(t)$, where

$$A_{\text{out}} = |\Gamma_T| \cdot A_{\text{in}} \quad \text{and} \quad \theta_{\text{out}} = \theta_{\text{in}} + \theta_T. \quad (6)$$

By selecting between different Γ_T values, the backscatter is able to toggle the reflected signal $S_{\text{out}}(t)$ among a set of amplitudes and phases. To implement it on a backscatter tag, a commodity electronic component called an *RF switch* [5] is used. An RF switch is able to route the high-frequency signal through different transmission paths. On the backscatter tag, the RF switch is used to connect the antenna to RF loads with different impedance and switch between them. A low-power microcontroller unit (MCU) or a field-programmable gate array (FPGA) is then used as a controller to control the RF switch. As a result, the backscatter tag is able to adjust Γ_T and thus control A_{out} and θ_{out}. On top of these basic operations, we develop the backscatter tag design taxonomy based on the following two aspects: frequency shifting (FS) or not, and digital or analog modulation. The comparison of different backscatter systems surveyed in this article based on this taxonomy is summarized in Table 1.

FS

One of the major differences between backscatter tag designs is whether the tag has the ability to change the frequency of the backscattered signal.

Backscatter without FS

Because the backscatter tag is able to adjust A_{out} and θ_{out} by changing Γ_T, it can use a set of different amplitudes, phases, or their combinations to represent data. For digital data, $\Gamma_T(t)$ follows the function shown in (7):

$$\Gamma_T(t) = \begin{cases} \Gamma_0 & \text{when transmitting symbol 0} \\ \Gamma_1 & \text{when transmitting symbol 1} \\ \cdots & \\ \Gamma_n & \text{when transmitting symbol } n \end{cases}, \quad (7)$$

where $\Gamma_0, \Gamma_1, \ldots, \Gamma_n$ are discrete values producing different $S_{\text{out}}(t)$. For analog data, special circuits are designed to convert the value of the input data, such as voltage, to Γ_T, so that A_{out} and θ_{out} change accordingly. By doing so, the backscatter tag is able to perform amplitude-shift keying, amplitude modulation (AM), phase-shift keying (PSK), phase modulation (PM), or their combinations.

Non-FS backscatter tags use a simple design that maps the input data directly to the amplitude and phase of $S_{\text{out}}(t)$.

Table 1. A comparison of different backscatter tag designs.

Modulation	FS	Examples	Figure	Advantages	Disadvantages
Digital	No	BackFi [6] Ambient backscatter [7] Wi-Fi backscatter [8]	Figure 3	Simple design	May cause self-interference
	Yes	Passive Wi-Fi [9] HitchHike [10] LoRea [11] Interscatter [12]	Figure 4	More flexible in controlling the backscattered signal and supporting more modulation schemes	May generate unwanted sidebands and cause interference when $\Gamma_T(t)$ is not pure sinusoidal
Analog	No	Battery-free cell phone [13] Hybrid backscatter [5]	Figure 5	Energy efficient for analog data	Not applicable to all kinds of input data and may suffer from self-interference
	Yes	LoRa backscatter [14] FM backscatter [15]	Figure 6	Energy efficient for analog data, supports FM and CSS modulation	Not applicable to all kinds of input data and may cause interference when $\Gamma_T(t)$ is not purely sinusoidal

However, this design can cause problems on receiving $S_{\text{out}}(t)$ because $S_{\text{in}}(t)$ (emitted by the carrier transmitter) and $S_{\text{out}}(t)$ (emitted by the backscatter tag) will potentially interfere with each other at the receiver. In addition, such a design limits the usage of frequency-related modulation schemes, such as FM and FS keying (FSK).

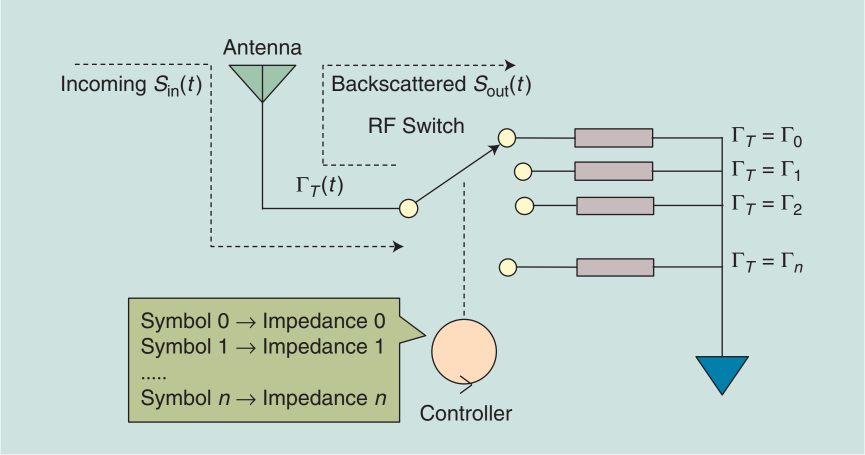

FIGURE 3. A typical backscatter tag that uses digital modulation without FS.

Backscatter with FS

To change the frequency of the reflected signal $S_{\text{out}}(t)$, the backscatter tags change Γ_T over time so that $\Gamma_T(t)$ is or approximates a sine wave $|\Gamma_T| e^{j(2\pi f_T t+\phi_T)}$. In this case, $S_{\text{out}}(T)$ can be calculated as (8):

$$S_{\text{out}}(t) = \Gamma_T(t)\cdot S_{\text{in}}(t) = |\Gamma_T|\, A_{\text{in}}\, e^{j(2\pi(f_{\text{in}}+f_T)t+(\theta_{\text{in}}+\phi_T))}. \quad (8)$$

As a result, $S_{\text{out}}(t)$ is frequency shifted by f_T, phase shifted by ϕ_T from $S_{\text{in}}(t)$, and attenuated by $|\Gamma_T|$.

While the sinusoidal $\Gamma_T(t)$ can actually be a sine wave signal, many backscatter tag systems use digital signals like a square wave to approximate a sine wave. For simplicity, here we define $\Gamma_T(t)$ as a square wave, shown in (9):

$$\Gamma_T(t) = \frac{A_T}{2}\operatorname{sgn}(\sin(2\pi f_T t+\phi_T)) + \frac{A_T}{2} = \sum_{k=0}^{\infty}\gamma_k(t). \quad (9)$$

Note that the same method that we use to analyze the square wave can be applied to other types of digital signals as well. In this case, Γ_T is toggled back and forth between 0 and A_T, with frequency f_T and phase ϕ_T. $\Gamma_T(t)$ can be expanded into a series of $\gamma_k(t)$ elements using Fourier transform. The definition of $\gamma_k(t)$ is provided in (10):

$$\gamma_k(t) = \begin{cases} \dfrac{A_T}{2} & k = 0 \\ \dfrac{A_T}{k\pi}\left(e^{j\left(-2k\pi f_T t - k\phi_T + \frac{\pi}{2}\right)} + e^{j\left(2k\pi f_T t + k\phi_T - \frac{\pi}{2}\right)}\right) & k = 1,3,5,\ldots \\ 0 & k = 2,4,6,\ldots, \end{cases} \quad (10)$$

when k is a positive odd number and γ_k is a pair of sine waves, which are desired by FS backscatter tags. In this case, γ_k is able to create a pair of sidebands in $S_{\text{out}}(t)$, as shown in (11):

$$\gamma_k(t) S_{\text{in}}(t) = \frac{A_{\text{in}} A_T}{k\pi}\left(e^{j\left(2\pi(f_{\text{in}}-kf_T)t+\theta_{\text{in}}-k\phi_T+\frac{\pi}{2}\right)} + e^{j\left(2\pi(f_{\text{in}}+kf_T)t+\theta_{\text{in}}+k\phi_T-\frac{\pi}{2}\right)}\right). \quad (11)$$

The sidebands are frequency shifted by $\pm kf_T$, phase shifted by $\pm(-k\phi_T + \pi/2)$ from S_{in}, and attenuated by $(A_T/k\pi)$. Note that, as long as $\Gamma_T(t)$ is not pure sinusoidal, the tag will produce multiple sidebands in $S_{\text{out}}(t)$, of which only one is used for transmitting data, i.e., other unsed sidebands may cause interference to surrounding wireless devices. Although there have been proposals on removing some of those sidebands [14], a solution to completely eliminate the interference in a low-power manner is yet to be developed.

To implement an FS backscatter, the tag needs to generate $\Gamma_T(t)$. As mentioned previously, many tags generate a square wave to approximate a sinusoidal. In this case, an RF switch is used to connect different RF loads to the antenna, and an FPGA or MCU toggles the RF switch between Γ_T and 0 at frequency f_T and phase ϕ_T to generate the square wave. Other types of $\Gamma_T(t)$ can also be generated in a similar way. In real-world implementations, we observe that FPGA is often preferred over an MCU as the controller because it consumes less energy when running at the same clock rate. A Freescale Kinetis low-power MCU running at 50 MHz, e.g., can use up to 23 mW, while the Microsemi IGLOO FPGA in HitchHike [10] at the same clock rate consumes fewer than 2 mW.

Digital/analog modulation

Similar to conventional communication systems, the modulation process of backscatter signals can also be digital or analog.

Digital modulation

When a backscatter tag uses digital modulation, it maps symbols to different $S_{\text{out}}(t)$ waveforms that vary in frequency, amplitude, or phase. To do so, the backscatter tag generates $\Gamma_T(t)$ that changes with the symbol to be transmitted by having a controller (e.g., an MCU or FPGA) to switch between the finite set of discrete states (see Figures 3 and 4).

Analog modulation

In analog modulation, $S_{\text{out}}(t)$ changes continuously. It is achieved by converting the input data to the frequency, amplitude, and phase of $\Gamma_T(t)$ using dedicated analog circuits. The input voltage can control the output frequency of a voltage-controlled oscillator (VCO), e.g., and, hence, the frequency of a sine wave $\Gamma_T(t)$ signal. In this case, the backscatter tag creates an $S_{\text{out}}(t)$ that is frequency modulated. Analog backscatters vary in the method to control $\Gamma_T(t)$, which depends on the source and the properties of input data. By using analog modulation, the backscatter tag is able to directly convert the analog

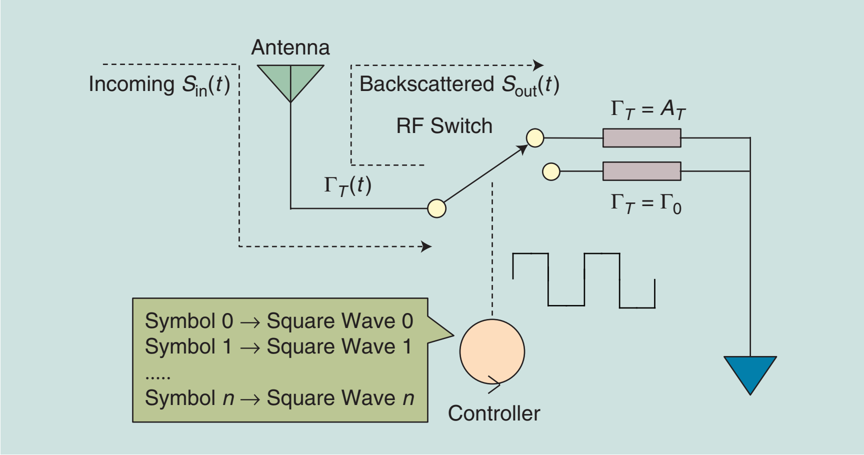

FIGURE 4. A typical backscatter tag that uses digital modulation with FS.

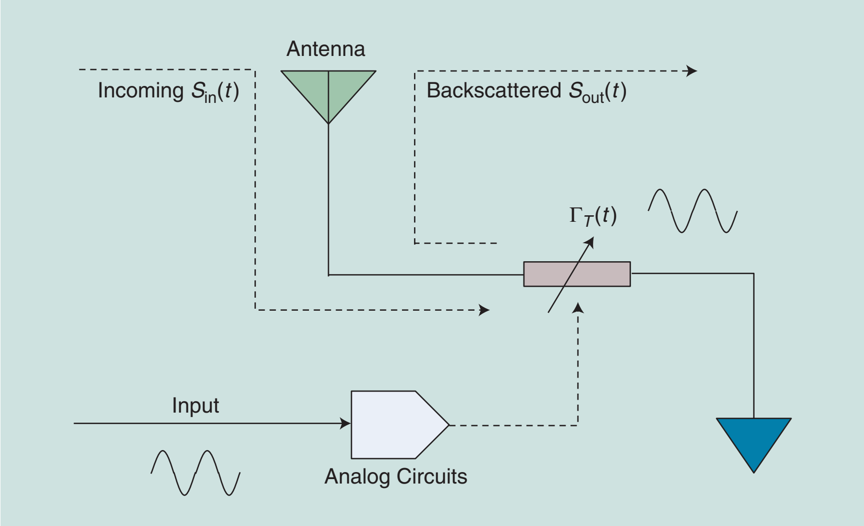

FIGURE 5. A typical backscatter tag that uses analog modulation without FS.

input to analog-modulated $S_{\text{out}}(t)$ without processing it in the digital domain, which eliminates the need for computational components, such as MCUs or FPGAs, as well as analog-to-digital converters (ADCs) (for purposes of sensing), which are power hungry especially when processing high-bandwidth data streams, such as audio and video. However, analog modulation is not able to deal with all kinds of input data, especially when the data are already in digital format. A case-by-case analog circuit design has to be developed to correlate the data source to $\Gamma_T(t)$ so that the input data modulate $S_{\text{out}}(t)$ (see Figure 5).

State-of-the-art backscatter systems

Despite the simplicity of backscatter operation in principle, there is a long way to go toward delivering a practical (bistatic) backscatter communication system good enough for real-world IoT applications. The research community has identified four main challenges of backscatter communication: energy efficiency, bit rate, communication range, and deployment cost. Motivated by the promising advantages of backscatter communication, research activities and efforts to tackle those problems have flourished in recent years. We summarize the key performance of the surveyed research projects in Table 2 and elaborate on them based on these performance metrics in the rest of this section.

Energy efficiency

The ultralow-power nature of backscatter communication makes it promising to run IoT applications in a battery-free manner. In extreme cases, applications would even be in need of always-on communication, which makes RF signals (rather than solar, vibration, and so forth) as the ambient energy source probably the only choice for energy harvesting. Consequently, there is great incentive to build backscatter communication systems that can be powered entirely by harvesting ambient RF energy. However, typical RF harvesting efficiency is as low as 18.2% when ambient RF signal strength is –20 dBm and only 0.4% at –40 dBm [16]. Such a low-energy budget poses great challenges to the hardware and system design.

Recent years have seen projects exploring the design and implementation toward this goal. Ambient backscatter [7] presents the first backscatter communication system that runs solely on energy harvested from ambient RF signals, such as TV and cellular towers. In this system, no customized carrier transmitter is deployed. The highlight of this system is that the backscatter tags have two-way communication capabilities and can talk to each other directly. Data injection on the backscatter tag is realized by controlling the RF switch to reflect or absorb the ambient RF signal. It reflects signals when transmitting 1, e.g., and absorbs signals when transmitting 0. Such operation creates a difference in the RF energy detected by a nearby backscatter tag. However, it is challenging to detect such a change on the receiving backscatter tag, because the ambient RF signal is already weak and has been modulated to convey other information, such as TV. To reliably decode data on backscatter tags, a two-step decoding circuit is designed. First, the received RF signal passes through an envelope detector and an averaging circuit to get the current RF energy level. Then it passes through a threshold comparator to decide whether or not the transmitting tag is a reflecting RF signal. The threshold here is computed by taking a long-term average of the signal. This system achieves a throughput of 1 kilobit/s over 0.76 and 0.46 m in outdoor and indoor environments, respectively.

Table 2. A performance comparison of state-of-the-art backscatter communication systems.

		Maximum Bit Rate		Range		Deployment	
Name	**Minimum Power**	**Bit Rate**	**Distance**	**Transmitter to Tag**	**Tag to Receiver**	**Transmitter**	**Receiver**
BackFi [6]	N/A	5 megabit/s	1 m	7 m	7 m	Ambient Wi-Fi	Software-defined radio
Ambient backscatter [7]	0.79 μW	10 kilobit/s	0.4 m	N/A	2.5 m	Ambient TV	Customized hardware
Wi-Fi backscatter [8]	9.65 μW	1 kilobit/s	N/A	N/A	2.1 m	Commodity Wi-Fi	Commodity Wi-Fi
Passive Wi-Fi [9]	14.5 μW (IC)	11 megabit/s	N/A	3.7 m	16.8 m	Customized hardware	Commodity Wi-Fi
HitchHike [10]	33 μW (IC)	300 kilobit/s	34 m	1 m	54 m	Commodity Wi-Fi	Commodity Wi-Fi
LoRea [11]	70 μW	197 kilobit/s	175 m	1 m	3.4 km	Patched commodity	Customized hardware
Interscatter [12]	28 μW (IC)	11 megabit/s	N/A	0.9 m	27.4 m	Commodity BLE	Commodity Wi-Fi/Zigbee
Battery-free cell phone [13]	3.48 μW	N/A	N/A	15.2 m	15.2 m	Customized hardware	Customized hardware
LoRa backscatter [14]	9.25 μW (IC)	37.5 kilobit/s	N/A	5 m	2.8 km	Customized hardware	Commodity LoRa
FM backscatter [15]	11.07 μW (IC)	3.2 kilobit/s	4.9 m	N/A	18.3 m	Ambient FM	Commodity FM

Note: In the "Range" column, the operating range of a bistatic backscatter system consists of two parts: the distance between transmitter and tag and the distance between tag and receiver. Here, we provide the maximum tag-to-receiver distance and the corresponding transmitter-to-tag distance. Under "Maximum Bit Rate," the "Distance" is the tag-to-receiver distance when achieving the maximum bit rate. For passive Wi-Fi and all numbers marked "IC", the number in the "Minimum Power" column is the simulation result of an IC design. IC: integrated circuit; BLE: Bluetooth/BLE.

The battery-free cell phone project [13] presents another battery-free backscatter system that is able to sense and transmit voice as well as receive and actuate audio. In this system, a battery-free backscatter tag works with a nearby customized base station (connected to cellular networks) to send and receive audio data. The key contribution of this system is the design and use of analog backscatter, where analog data, such as a wave signal, are directly backscattered without being converted and processed in the digital domain. This new design is even more energy efficient than the (conventional) digital backscatter design, because all of the digital computational components, such as the FPGA and ADC/digital-to-analog converter (DAC) (for converting sound to and from a digital signal), that potentially become the bottleneck of battery-free operation are eliminated to save energy. To convert the input audio to the impedance of the antenna, a special component called an *electret microphone* is used. Inside the electret microphone, there is a junction-gate field-effect transistor (JFET). In this design, the JFET is configured to work in its triode region and acts as a voltage-to-impedance converter. So the backscatter tag modifies the incoming signal according to the change of the audio voltage and eliminates the need for digital circuits. To receive and actuate downlink audio without the need for digital components, AM audio is transmitted from the base station to the backscatter tag, passes through an AM demodulator, and is directly fed into an earphone. To allow the exchange of control commands between the backscatter tag and the base station, the backscatter tag also has the ability to transmit and receive digital packets, but this functionality is only used when initiating and ending a call and thus does not use much energy overall. The device can work on RF energy harvesting when the cellular base station is 9.4 m away.

For other systems, the energy efficiency is traded for other goals. Passive Wi-Fi [13] and BackFi [6], e.g., implement differential quadrature PSK (DQPSK) and 16-PSK, respectively, to support 10+ megabits/s bit rate. Such high-speed baseband processing consumes much energy when compared to the cases where the RF switch toggles at a much lower speed [7] and the baseband processing is done in analog [13]. LoRa backscatter [14] trades power consumption for communication range, where much energy is used to generate chirp spread spectrum (CSS) modulation. HitchHike [10] and FreeRider [17] require precise synchronization with Wi-Fi packets in the air to provide compatibility with existing wireless protocols. Such synchronization needs low-delay RF energy detectors, which consume more power than the passive RF energy detectors used in other systems.

Bit rate

There are many IoT applications that require a wireless link faster than several kilobits per second. A smart speaker that continuously streams user voice to the cloud, e.g., needs a bit rate of more than 70 kilobit/s. Vision-based devices like security cameras can easily take up more than 1 megabits/s when in active operation. The bit rate requirement is even higher when considering emerging applications like augmented and virtual reality. Conventional radio technology tackles this problem by adopting advanced modulation schemes to make more efficient use of the available channel bandwidth, such as channel bonding and carrier aggregation. However, it is difficult for backscatter communication to use similar solutions. First, it is nontrivial to implement very complex modulations on a backscatter tag due to its limited capability in manipulating the RF signal and performing baseband processing. New techniques must be developed to enable more efficient use of the spectrum. Second, high throughput usually requires high-performance electronic components and fast computation, which further increases the energy consumption. As a result, it is nontrivial to support high-throughput applications atop backscatter communication systems, and a careful tradeoff must be made to balance throughput and per-bit energy consumption.

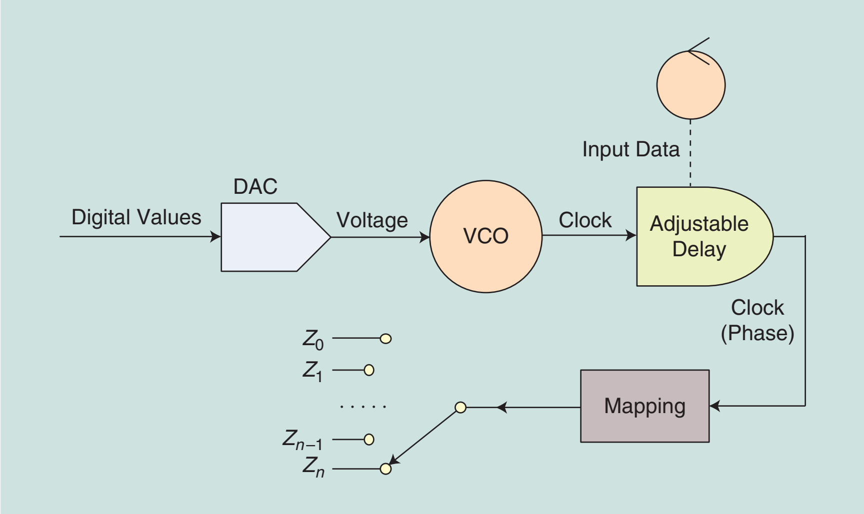

FIGURE 6. The design of the LoRa backscatter tag. The DAC and VCO are used to perform CSS modulation in a low-power manner. By replacing the SPDT RF switch in regular backscatter tags with a single-pole multithrow switch, a LoRa backscatter tag can cancel most of the sideband interference.

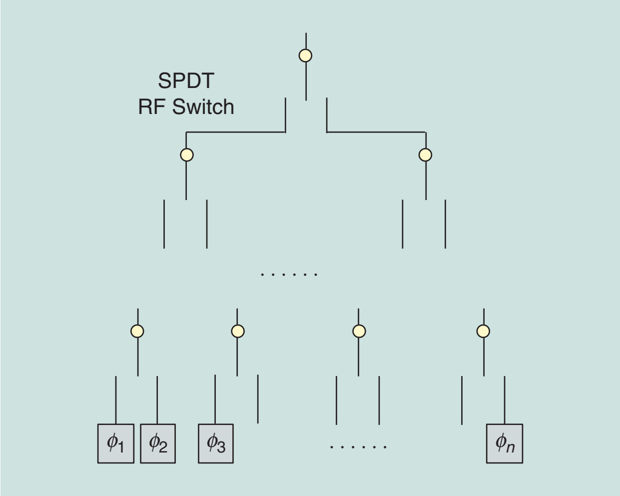

FIGURE 7. The design of a PM circuit in BackFi. Multiple SPDT switches are connected into a binary tree, and each leaf of the tree is connected to an RF delay line to provide precise phase shift of the incoming signal.

BackFi [6] presents a high-throughput Wi-Fi backscatter design that achieves 1,000 times higher throughput than the previous Wi-Fi backscatter system [8]. In this system, a customized Wi-Fi AP that is transmitting normal Wi-Fi packets to surrounding clients acts as both the backscatter transmitter and the receiver. The highlight of this system is that a novel backscatter tag is designed to provide efficient PMs, such as 16-PSK. Self-interference cancellation technology is used to allow the customized Wi-Fi AP to receive a reflected signal from backscatter tags while transmitting to surrounding Wi-Fi clients. In addition, an advanced decoder is designed to decode backscatter on wide-band signals, such as Wi-Fi. PM on backscatter tag is done by using a set of single-pole double-throw (SPDT) RF switches connected together to form a binary tree, as shown in Figure 7. RF delay lines of different length are connected at the tree leaves, providing different phase shifting, which is necessary to form the PSK constellation. Self-interference cancellation is done with the technology used in full-duplex radios. When a backscatter tag detects an incoming Wi-Fi signal, it waits for a short period of time before modulating the Wi-Fi signal, so that the self-interference cancellation circuits can use this time to estimate the channel between the backscatter tag and the receiver to avoid canceling actual backscattered data. This system is able to achieve 5 megabits/s at a range of 1 m.

Another backscatter system that provides high throughput is passive Wi-Fi [9], where the backscatter tag generates valid Wi-Fi 802.11b transmission at all bit rates, including the highest 11 megabits/s. In this system, a customized transmitter is used to transmit a single tone at a frequency out of Wi-Fi channels as the excitation signal, and a backscatter tag modulates this signal into valid Wi-Fi packets. All Wi-Fi-enabled devices can receive the transmission from the backscatter tag. One key contribution of this system is the design and implementation of a backscatter tag that performs baseband processing and modulates the incoming single-tone signal into 802.11b packets in a low-power manner. First, the backscatter tag generates a baseband of Wi-Fi packets following the specification of 802.11b. It then uses the techniques explained in the "Tutorial on Backscatter Communication" section to transform the single-tone signal. Specifically, it uses phase modification to perform differential binary PSK (DBPSK) and DQPSK, which are the two modulations used in 802.11b. It then uses frequency modification to move the signal to the center of the Wi-Fi channel. Another contribution of this system is a full network stack to enable multiple backscatter tags to share the channel and provide acknowledgment and rate adaption. Such a network stack requires a downlink from the transmitter to the backscatter tag. The downlink is encoded using on/off keying (OOK) and is decoded using a low-power RF energy detector on the backscatter tag.

Bit rate can be traded for other purposes as well. HitchHike [10] and FreeRider [17] backscatter valid Wi-Fi signals into valid Wi-Fi signals. To do so, they need to keep individual Wi-Fi symbols unbroken after being backscattered. Therefore, the smallest unit of modification is the size of a Wi-Fi symbol, which is 1 μs for HitchHike and even longer for FreeRider because of orthogonal frequency-division multiplexing (OFDM), which fundamentally limits the throughput. Ambient backscatter [7] trades throughput for power consumption. It uses the simple modulation scheme where the backscatter tag reflects the RF signal when transmitting 1 s and absorbs signal when transmitting 0 s. The bit rate is limited to enable successful decoding on the receiver. LoRa backscatter [14] trades throughput for communication distance. It uses the modulation schemes of LoRa, which is a low-rate long-range communication technology in nature.

Communication range

Outdoor IoT services often require a long communication range up to several kilometers. Although this requirement is already challenging to almost all wireless technologies, it is particularly hard to achieve in backscatter systems, primarily because of the higher path loss compared to conventional wireless communication. To be more specific, there can be significant loss when the signal is being reflected at the backscatter tag. Our experiments found that this attenuation could be up to 30 dB. In addition, radio signals experience path loss twice (from the transmitter to tag and from tag to receiver) instead of once. For conventional wireless technologies, this problem can be dealt with by either increasing the transmission power or adopting special modulation schemes, such as CSS used in LoRa. However, for backscatter, both solutions are not readily applicable. First, the transmission power may have to be increased to compensate for the extra attenuation in backscatter systems. Note that the transmission power has to be at least quadrupled when the total distance doubles, which can easily break through the limitations imposed by the electronic component, circuit design, power budget, and government regulations. Second, a backscatter tag can only perform limited processing on the incoming signal due to the power budget. As a result, special modulation schemes can be hard to implement on ordinary backscatter tags, which calls for special techniques to be developed to overcome this problem. All those issues make it challenging to build a long-range backscatter communication system.

When considering the problem of communication range, it should be noted that there are two distances involved in a backscatter communication system. The first is the distance from the transmitter to the backscatter tag (transmitter distance), which determines the range of the area where the backscatter tag can move freely while injecting data. The second is the distance from the backscatter tag to the receiver (receiver distance), which determines the range where the receiver can reliably decode data. The two distances are related to each other because the overall path loss is a combined attenuation of both paths. For the same backscatter communication system, the maximum receiver distance becomes shorter when the transmitter distance increases. However, there are different requirements of the two distances for different applications. For a wearable health sensor that backscatters data to a user's smartphone, e.g., there is no need for a long receiver distance because a phone is presumably always kept nearby. For a sensor deployed on a farm, both the transmitter and the receiver distance need to be long. The different needs of applications provide the possibility to tackle the problem of communication range in different ways.

FM backscatter [15] is an example that makes use of ambient RF signals already having good strength and coverage to solve the problem of transmitter distance. In this system, ambient FM radio is leveraged as the signal source, and the receiver is a commodity FM radio device. This setup enables backscatter tags to be deployed in outdoor environments where it is not possible to set up a dedicated transmitter. It also allows the tags to move freely within a city-scale area without worrying about getting too far from the transmitter. The key contribution of this project is that the backscatter tag can add an FM stream on top of incoming FM-modulated audio. It is achieved by using the frequency modification technique explained in the "Tutorial on Backscatter Communication" section. The backscatter tag shifts the frequency of incoming signals according to the data to be injected, which essentially performs FM on top of the existing FM signal. The receiver demodulates the signal as normal FM and gets the addition of the original FM audio and the injected data. Three operation modes are proposed based on this technique: overlay, where an audio stream is combined with existing radio program; stereo, where the underused stereo band of an FM radio station is used to accommodate reflected signal to eliminate interference to other radio stations; and cooperative, where two receivers work together to remove the original FM audio. This system is able to achieve 3.2 kilobit/s at ranges of 1.5–18 m.

The design of LoRa backscatter [14] develops advanced modulation schemes on backscatter tags to support both long transmitter distance and long receiver distance. Specifically, it is the first wide-area backscatter communication system that uses LoRa. LoRa is chosen because it demonstrates excellent sensitivity at the receiver of −149 dBm, which is key to battle significant path loss as well as attenuation at the backscatter tag. Also, it is more robust to out-of-band interference, such as the excitation signal from the transmitter. In this system, a dedicated RF power emitter transmits a continuous single-tone signal. The signal is modified into a LoRa signal by the backscatter tag and is then received by a commodity LoRa receiver device. However, it is nontrivial to use backscatter tags to generate CSS-modulated LoRa signals. Because CSS uses chirps that linearly increase in frequency, the backscatter tag has to continuously and smoothly change the frequency of the reflected signal. It could be difficult to implement such operation on backscatter tags, because the control logic is all digital. The key innovation here is a new backscatter tag design that combines analog and digital circuits to be able to perform CSS. The design of the backscatter tag is shown in Figure 6. A low-power baseband processor outputs a continuously increasing digital signal, and it is then converted to increasing voltage by a DAC. The voltage is then fed into a VCO and generates a square wave signal whose frequency continuously increases. It is then used to generate a CSS-modulated signal by the RF switch. To avoid interference between the original signal and the backscattered signal, the backscatter tag uses the frequency modification technique mentioned in the "Tutorial on Backscatter Communication" section to move the reflected signal off the original channel. In addition, this work proposes a way to cancel harmonics generated when reflecting the signal to prevent the neighboring channels from being interfered with by the backscatter tag. This is done by using a single-pole multithrow RF switch that has multiple states instead of two, so that the signal multiplied with the incoming signal is more like a sine wave, resulting in weaker sidebands. This technology achieves a range of 475 m.

LoRea [11] is another backscatter system that achieves both long transmitter and receiver distance. In this system, a Wi-Fi or IEEE 802.15.4 chip is put into a special test mode to generate a single-tone excitation signal at 2.4 GHz and 868 MHz, respectively. The receiver and backscatter tag are customized hardware. The system operates at a low bit rate of 2.9 kilobit/s to allow the use of ultrasensitive narrow-band receivers. The backscatter tag modulates data using OOK or FSK. To avoid self-interference, the backscatter tag shifts the reflected signal away from the excitation signal. A highlight of the tag design is that it uses an oscillator instead of an MCU or FPGA to generate the square wave signal used for FS and FSK. This saves power and simplifies the design of the tag. When the transmitter distance is 1 m, it can achieve 3.4 km of receiver range when operating at 868 MHz and 225 m at 2.4 GHz.

The communication range is highly relevant to receiver sensitivity and, thus, is often traded for bit rate. LoRa backscatter uses the modulation scheme of LoRa, e.g., and therefore achieves a data rate up to only 37.5 kilobit/s. Most other backscatter communication systems achieving a much higher throughput with other modulation schemes often come with a poorer sensitivity.

Deployment cost

A typical backscatter communication system includes a backscatter tag and (carrier) transmitter and receiver as supporting devices. While the backscatter tag is usually cheap and tiny, the transmitter and the receiver are often expensive and bulky, greatly increasing the cost of deployment. Unlike conventional wireless communication, such as Wi-Fi and Bluetooth, backscatter communication currently has a much smaller market, and, hence, there is little incentive for manufacturers to massively produce the supporting devices at low cost. With RFID, the most mature backscatter communication technology, e.g., a typical ultrahigh-frequency RFID reader weighs about 0.5 kg [18] and costs more than US$500, which is often beyond the space and cost budget of many IoT deployments, such as smart home applications. Most recent backscatter technology innovations rely on professional equipment like software-defined radio devices or even their own customized hardware, which can potentially discourage customers from using them due to the initial investment, especially when there is already infrastructure for conventional wireless communication like LTE and Wi-Fi. As a result, the high deployment cost challenges the practical adoption of backscatter communication.

Because building customized transmitter and receiver hardware for backscatter communication from scratch would be expensive, it is desirable to leverage the cheaper and common commodity devices and add to them the functionality as a backscatter transmitter or receiver. Such commodity devices could be conventional wireless devices, such as Wi-Fi APs or Bluetooth-enabled computers. Those devices are usually affordable and are already in many scenarios where backscatter communication is to be deployed, so making use of them can greatly reduce the deployment overhead. In addition, commodity wireless devices usually use mature technologies, and their performance has been optimized by significant engineering efforts over the years. Many Wi-Fi chips, e.g., provide excellent sensitivity as good as −80 dBm while costing only several dollars. Hence, making use of these products has a side advantage of improving the system performance.

To achieve the goal of using commodity hardware as backscatter transmitter/receiver, two main problems have to be solved. First, the backscatter tag has to be able to effectively inject data on an excitation signal transmitted by commodity devices, such as Wi-Fi or Bluetooth packets. This could be difficult because backscatter tags do not have the ability to decode the signal and must inject data blindly. Second, the commodity receiver has to be able to decode and process a signal that is modified and reflected by a backscatter tag. The challenge lies in the fact that commodity wireless devices usually allow little control over the decoding process. Packets modified by a backscatter tag may get ignored or corrupted during decoding and never reach a user-space program.

Wi-Fi backscatter [8] presents a way to inject data by modifying the received signal strength indicator (RSSI) or channel state information (CSI) of the Wi-Fi. Almost all Wi-Fi chips provide RSSI information, and many of them also provide CSI, which is a set of complex numbers representing the change of amplitude and phase of each subcarrier. In this system, a commodity Wi-Fi AP is used as the transmitter, and an Intel 5300 wireless network interface controller is used as the receiver. Normal Wi-Fi packets are being transmitted continuously from the transmitter to the receiver. A typical backscatter tag uses an RF switch to change the impedance of the antenna. When set at different states, the backscatter tag affects the Wi-Fi channel between transmitter and receiver differently, resulting in different RSSI and CSI captured at the receiver, used to represent 0 and 1. On the receiver, signal processing is used to reliably detect changes in RSSI and CSI to recover data injected by the backscatter tag. To avoid disrupting decoding packets at the receiver, the RF switch stays in the same state over the duration of multiple Wi-Fi packets. The system achieves up to 1 kilobit/s of throughput with a range of up to 2.1 m. When it is hard to access low-level information, such as RSSI or CSI, an alternative approach is proposed in FS backscatter [19]. Instead of operating on the same channel as the transmitter, the receiver listens to an adjacent channel. The backscatter tag is able to shift incoming Wi-Fi or Bluetooth packets to the adjacent channel. By toggling between shifting and not shifting, the tag is able to transmit data. FS backscatter is able to achieve up to 4.8 m of communication range.

While Wi-Fi backscatter can use commodity Wi-Fi devices as the receiver, it is not compatible with the Wi-Fi protocol itself. There are projects that are compatible with major wireless communication protocols, and both transmitter and receiver can be replaced by commodity devices. The design of intertechnology backscatter [12] proposes a way to transform a valid Bluetooth signal to valid a Wi-Fi or Zigbee signal on a backscatter tag so that a commodity Bluetooth radio can be used as the transmitter and a commodity Wi-Fi or Zigbee radio can be used as the receiver. The key idea behind this system is that, with a carefully designed payload, a commodity Bluetooth radio can transmit a single-tone signal, which can then be modulated into a valid Wi-Fi or Zigbee signal using the methods explained in the "Tutorial on Backscatter Communication" section. This is possible because Bluetooth uses Gaussian FSK, so a continuous stream of 0 s or 1 s is modulated into a single-frequency tone. To achieve the goal of modulating continuous 0 s or 1 s, however, the payload has to be carefully designed because Bluetooth uses a linear feedback shift register to perform data whitening before modulation. This process is inverted to get a payload that will result in all 0 s or 1 s after whitening. In addition, an envelope detector is used on the backscatter tag to detect the start of a Bluetooth packet and help skip the metadata part, because this part is not a single-tone signal. On the backscatter tag, the data of a valid Wi-Fi packet are generated. Methods mentioned in the "Tutorial on Backscatter Communication" section are used to perform DBPSK and DQPSK, two modulation schemes used by Wi-Fi. The tag shifts the signal from the Bluetooth channel to the Wi-Fi channel. The same procedure can also be applied to backscatter Zigbee signals from Bluetooth.

HitchHike [10] presents another project that is compatible with a commodity wireless protocol. This design proposes a way to enable backscatter tags to transform a valid Wi-Fi 802.11b packet to another valid one while modifying the content to inject data. In this system, two commodity Wi-Fi radios act as the backscatter transmitter and receiver. The key innovation is a method called *codeword translation* by which the backscatter tag can transform a valid 802.11b codeword to another valid one so that it can modify some bits in a packet while still allowing the receiver to decode the modified packet. The 0 s and 1 s are represented as a transformed codeword and an untransformed codeword, respectively. The receiver then compares the modified packet with the original one and performs an exclusive operation to recover the data injected by the backscatter tag. Codeword translation is implemented with the RF switch on the backscatter tag. Wi-Fi 802.11b 1 megabit/s uses DBPSK modulation, and there are only two valid codewords representing 0 and 1, with one codeword being the other flipped. To transform a codeword into the other, the backscatter tag needs to flip the phase of the incoming signal, which can be done by using the phase modification method explained earlier. To avoid the backscatter signal and the original signal interfering with each other, the backscatter also shifts the signal to another valid Wi-Fi channel. The system can reach a throughput of up to 300 kilobit/s at 34 m. The idea of codeword translation can also be applied to other wireless protocols, such as Zigbee and Bluetooth [17].

For those projects that are not compatible with existing technologies, they trade deployment cost for other purposes. BackFi [6], e.g., uses a customized transmitter/receiver device that supports concurrent transmission of the transmitter and the backscatter tag. This improves the spectrum efficiency but requires new hardware. LoRa backscatter [14] requires a dedicated transmitter to provide a single-tone excitation signal. This enables the backscatter tag to synthesize a CSS-modulated signal, which significantly improves the communication range. Battery-free cell phones [13] require a special base station to transmit an AM voice signal to the backscatter tag and to receive an FM voice signal from the backscatter tag, and it consumes only 3.48 μW in operation.

Applications empowered by backscatter communication

We envision the prevalence of backscatter tags featured with ultralow power or even battery free can greatly mitigate or even eliminate the existing deployment hurdles of many IoT applications, such as universal localization, ubiquitous surveillance, and invasive monitoring. In the following, we elaborate on how these applications can benefit from backscatter communication along with the research challenges to be addressed.

Universal localization

Location is becoming a fundamental service in mobile/IoT sensing. The tracking demand is extending from smartphones and wearables to universal objects, such as wallets, keys, and pill bottles. Previous research efforts can be classified into two categories: in active approaches, the object of interest needs to emit signals at the milliwatt level and, thus, often carry a battery, whereas passive methods, such as RFID, often require dedicated and costly reader deployment. With backscatter communication, it is possible to attach such battery-free tags to any objects and make them work with existing infrastructure. However, localizing a backscatter tag is not that straightforward, and a number of challenges need to be addressed, such as the RSSI or CSI obtained at the receiver (e.g., AP) being dependent on the location of both tag and transmitter. WiTag [20] presents the first design to achieve that goal—it estimates the angle of arrival from the tag to multiple APs and uses triangulation techniques to achieve 0.92- and 1.48-m median localization error in line-of-sight and nonline-of-sight deployments, respectively, in an office building with commodity Wi-Fi APs.

Ubiquitous surveillance

Wireless cameras are increasingly important and popular for security purposes in the home and office and for public safety. Unfortunately, they still need to be externally powered by outlets, which prevents them from reaching inaccessible areas, such as fabrication plants. By cutting both Internet and power cords, the deployment scale of wireless cameras can potentially reach a new milestone. However, a number of challenges need to be addressed when building a practical video surveillance system based on backscatter communication. The most obvious one can be the mismatch between the intermittent kilobits per second the state-of-the-art solutions can provide and the megabits per second streaming requirement for the application. Performing conventional codec and compression is also extremely challenging on backscatter tags with impoverished compute power. The design of WISPCam [21] opens the door in this direction. It features a battery-free camera that is able to emit a new 176 × 144 gray-scale picture captured and transmitted approximately every 15 min when it is placed 5 m away from a normal RFID reader. The most recent analog video backscatter design [22] even supports 720-p full-high-definition video streaming at 10 frames per second up to distances of 4.9 m from the reader.

Invasive monitoring

In the scenarios where sensor devices need to be instrumented in an invasive manner, the backscatter communication can be found particularly useful because it can potentially eliminate the need for replacing batteries and the accompanying extra high cost in certain applications, such as structural health monitoring (SHM) [23] and implantable health-care monitoring (IHM) [24]. To be more specific, periodic and effective SHM is vital to ensuring safe and reliable operation of large-scale structures (e.g., railways, pipelines, dams, bridges, and aircraft). Deterioration (such as corrosion and fatigue) and damage can be detected at an early stage, and action can be taken correspondingly. The huge labor cost and potential safety issues induced by human inspection today can be addressed with battery-free IoT solutions with backscatter communication. In biomedical applications, IHM poses several harsh requests in the design of implanted medical devices. They need to be tiny and long lasting and radiate low heat. Backscatter again serves as an ideal solution to fulfill all of these requirements. Nevertheless, fundamental tradeoffs existing in power consumption, communication range, bit rate, and form factor need to be fully considered and respected by experts from different domains when designing a backscatter solution dedicated for each use case.

Open areas and future directions

Advanced modulation scheme

Supporting an advanced modulation scheme (on backscatter link) is one of the keys for achieving a higher data rate. The idea of OFDM-based backscatter communication, e.g., has been exercised in both simulation [25] and implementation [17]. However, their throughput is constrained by the fact that OFDM uses much longer symbols. Specifically, the maximum throughput of FreeRider is 60 kilobit/s, in comparison to 300 kilobit/s of HitchHike [10], which uses BPSK and shorter symbols. Presently, there is no efficient design for that in the context of backscatter communication. It would be desirable if new techniques were developed for backscatter tags to modify or generate OFDM signals not only in a low-power manner but also to provide a higher data rate.

Downlink and full duplex

The current backscatter downlink design leverages the low-power RF envelope detector and uses the presence and length of the excitation signal to demodulate data, which are intrinsically low in rate because of the modulation scheme. However, the low-power requirement also poses challenges to implement complex digital signal processing on the tag and, hence, an efficient downlink solution. It would be desirable for the tag's receiver to be renovated to support both efficient and low-power modulation. However, given the limited throughput of the current downlink designs, it would be more efficient if the tag could transmit and receive at the same time (i.e., full duplex) to improve the overall throughput. The key challenge is that the uplink requires the persistent excitation signal, whereas the downlink leverages the intermittent patterns. Obviously, there is a fundamental tradeoff here. Prior work [26] has demonstrated a full-duplex design that achieves 1 kilobit/s downlink and 100 bits/s uplink between two tags, which opens the door for more efforts in this direction.

Multiple-input, multiple-output

As another essential technology extensively used in today's wireless systems for performance enhancement, multiple-input, multiple-output (MIMO) is demanding to be introduced into backscatter system design from different aspects. Beamforming, e.g., can effectively help the backscatter tag to get a strong excitation signal. As another example, the diversity technique can be used potentially in a distributed manner for improving the bit rate and robustness of the tag-to-receiver link. While the idea of MIMO backscatter has been explored in an analytical model [27], there has yet to be real-world implementation to demonstrate its practicality.

Multiple access

It is important to efficiently support multiple access as the backscatter communication technique scales to the network level. Recent work has shown that parallel decoding is an effective physical layer approach. Laissez-faire [28] demonstrated support of an aggregated throughput of 100 kilobit/s for up to 16 devices using parallel decoding, and FlipTracer [29] supports 500 kilobit/s for five tags. In the link layer, FreeRider [17] provides an aggregated throughput of 15 kilobit/s for 20 devices by implementing a basic media access control layer. However, there is yet to be a more efficient design to support large-scale deployment.

Alternative communication medium

Although the performance of radio communication is often limited by scarce spectrum resources, visible light communication (VLC) is always regarded as a complementary solution because it features sufficient spectrum and directionality and is sniff-proof. PassiveVLC [30] presents the state-of-the-art design achieving 1 kilobit/s by modulating the light retroreflection with a commercial liquid-crystal display shutter; yet it also needs to address the challenges for a higher rate, a longer range, and multiple access.

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