Ambient Backscatter Communications for Future Ultra-Low-Power Machine Type Communications: Challenges, Solutions, Opportunities, and Future Research Trends

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The authors present the development trends in AmBC prototype designs and discuss potential applications, highlight the specific features of the AmBC technology, and review AmBC receiver designs. They investigate and outline the future research challenges and trends from the practical aspects of AmBC systems.

Abstract

The widespread applications of massive MTC are limited by energy availability, spectrum congestion, and device costs. The emerging AmBC not only addresses these bottlenecks but also opens opportunities for new applications. This article aims to explore AmBC-enhanced future ultra-low-power MTC. In this context, we present the development trends in AmBC prototype designs and discuss potential applications, highlight the specific features of the AmBC technology, and review AmBC receiver designs. Finally, we investigate and outline the future research challenges and trends from the practical aspects of AmBC systems.

Introduction

Recent advances in wireless communications, and miniaturization in computing and sensing components have enabled the development of ubiquitous systems that acquire and convey information without human intervention, often referred to as the Internet of Things (IoT). For realizing pervasive connectivity among different devices, these systems aim at generating a common operational framework for different applications and services by utilizing machine-type communication (MTC). The same communication methodology is used for conveying the data among machines and MTC central servers for forming a common framework in the servers.

The scalability and flexibility of IoT deployment using MTC are mainly limited by three factors:

- The connectivity of different devices is limited by their life span, defined by energy availability.
- The cost of each device also constrains the number of devices that can be deployed for an application.
- The link availability is limited by the congestion of the communication medium.

The ambient backscatter communication (AmBC) technology provides a complete solution to these problems. Without need of a dedicated power infrastructure and a carrier emitter, AmBC enables devices to communicate by scattering ambient modulated RF signals existing in the air. For example, it can use the signals of terrestrial television broadcasts, cellular system transmissions, and WiFi or Bluetooth transmissions [1]. It provides orders of magnitude of power efficiency better than that of the traditional radio communication systems, enables ultra-low-cost manufacturing of communication devices by avoiding expensive and power-hungry radio components, and can operate in a spectrum allocated for other wireless transmissions.

An AmBC system integrates new ultra-low-power communication systems into existing IoT connectivity infrastructure seamlessly. It leads to the evolution of 5G and beyond MTC solutions by opening new applications and enriching existing ones. The commercial potential is vast, and the expectation of generating both theoretical and technological breakthroughs is high. Despite the advantages of the AmBC technology and the proposed solutions, this field of research is largely less explored, and there are various challenges arising from practical implementations.

This article aims at providing a guideline for practitioners and researchers working in this area. For this purpose, we first introduce currently available AmBC designs and their application opportunities. We then identify the common features of AmBC before presenting the most important challenges and their mitigation methods. We present future research trends, and finally draw the conclusions.

AmBC Systems

Sustainable wireless communication has been identified as one of the key enabling technologies for IoT. The cost and energy limitations of MTC-based IoT deployments have been driving the development of the IoT connectivity solutions such as IEEE 802.15.4, Bluetooth Low Energy (BLE), and more recently, low-power wide area radios such as SigFox, long-range (LoRa), and narrowband IoT. These systems can operate for extended duration with finite energy, and their cost is significantly lower than that of the tradition-

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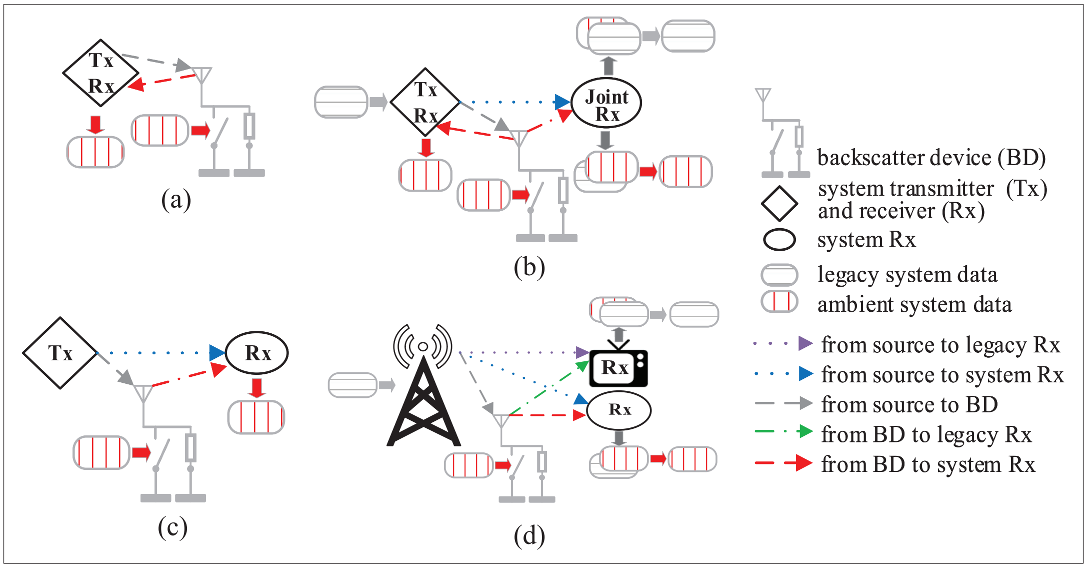

Figure 1. Backscattering and AmBC configurations: a) mono-static backscattering; b) AmBC with a joint receiver; c) bi-static backscattering; d) AmBC with ambient and legacy receivers.

An AmBC system can operate in different configurations including mono-static, bi-static co-located, and bi-static dislocated configuration, while using joint receivers for both legacy and AmBC transmissions. One important feature of AmBC is that the ambient sources can be non-cooperative and completely unaware of the AmBC or can be co-operative to aid joint decoding at the receiver.

al wireless communication solutions. However, their operation is not optimized for self-sustainable operation, which would be desirable in many IoT deployments. Although the aforementioned systems along with available and emerging energy harvesting technologies provide a solution for certain applications, their feasibility is limited to use case scenarios that can accommodate temporary energy storage and complicated radios.

Figure 1 depicts samples of backscattering communication (BC) and AmBC configurations. The mono-static BC configuration consists of a backscattering device (BD), and a co-located transmitter (Tx) and receiver (Rx) device. This configuration requires a carrier emitter, for example, for RFID or radar applications. In bi-static configuration, the Tx and the Rx are two separate devices. In AmBC, a BD modulates the ambient signal of the legacy system by scattering the RF energy impinging on its antenna in a controlled manner. An AmBC system, as shown in Fig. 1, can operate in different configurations including mono-static, bi-static co-located, and bi-static dislocated configuration, while using joint receivers for both legacy and AmBC transmissions. One important feature of AmBC is that the ambient sources can be non-cooperative and completely unaware of the AmBC or cooperative to aid joint decoding at the receiver.

Available AmBC Systems

MTC in an AmBC system relies on the existence of legacy systems such as LoRa, WiFi, FM radio, and TV broadcast. The first approach available in the literature is to build an AmBC-capable system by modulating the legacy signals using controlled scattering. Although the resultant energy variation due to operation of the BD can be used for decoding the signal when the BD data rate is low, for high-data-rate operation the systems are designed using frequency shifting, which also enables easier mathematical analysis. This option requires a dedicated receiver to decode the data emitted by the BD. An alternative option is to alter the ambient signal from one communication technology waveform into the waveform of another technology, for instance, from continuous wave to BLE, from BLE to WiFi, and from BLE to IEEE 802.15.4, to use commodity receivers to decode the backscattered signal. This option is only suitable when the deployment can satisfy the operation requirements of the commodity receivers, and does not scale well. For the sake of generality, in the remainder of this article, we just consider the first option.

Applications and Opportunities

To promote sustainable backscatter-based IoT applications, researchers from the University of Washington have developed, for instance, a living IoT platform, a battery-free high-definition video streaming system, and a battery-free cell phone. The success of IoT depends on the sustainability of deployments and their resilience to the emerging application demands. In this regard, AmBC systems benefit the overall IoT architecture in two ways: first, these systems provide local access to ultra-low-power or passive "thing," and second, they improve the capacity and the reliability of other wireless IoT solutions with zero or negligible cost in terms of energy and complexity. In the following, we summarize various conceptually proven application verticals of the AmBC technology such as medical science, environmental monitoring, and network communications.

Medical Applications: AmBC has rich application opportunities in healthcare because of its battery-free operation and small form-factor. An AmBC-enabled on-body and battery-less temperature sensor can be designed as a comfortable wearable gadget. A more challenging application of communicating with smart contact lens using a commodity WiFi or with Bluetooth radios has already been demonstrated. More importantly, in-vivo smart medical devices with extremely low-power and small form-factor energy harvesting components can be realized for accessing deep-tissue micro implants. The experiments have shown that implantable neural recording devices can communicate with mobile devices within a short communication distance.

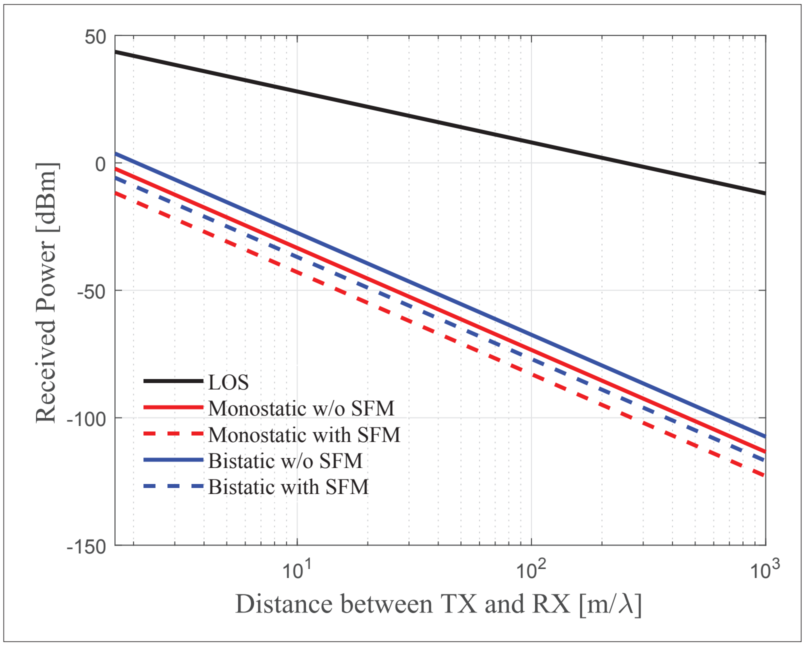

Figure 2. Received power as a function of the separation between the Tx and the Rx for several AmBC configurations. The transmit power of the ambient source is 10 kW. The SFM is 9.5 dB.

Environmental Applications: The AmBC technology has various environmental applications, for instance, wireless humidity sensing, agricultural monitoring, and indoor space sensing applications. The BDs in these applications are distributed over a large area, and thus have long distance between the ambient source and the BD. These applications utilize the ambient FM broadcasting signals and augment the receiver by adding relay stations to improve the signal strength.

Generic Machine Type Communication Applications: The AmBC technology enables MTC, card-to-card, or even multihop communications [2]. The work in [3] has developed a passive LoRa-enabled AmBC system relying on opportunistic uplink and downlink piggybacking schemes to utilize intermittent LoRa signals. Moreover, the AmBC technology can promote vast applications for wearable devices.

Network Enhancements: The AmBC technology not only improves the energy efficiency of IoT devices, but also improves network performance as a whole. The authors of [4] have concluded that AmBC improves the spectral efficiency of the channel as an AmBC link can coexist with a legacy wireless system under certain conditions. Another networking enhancement provided by AmBC is improved security, as presented in [5].

Characteristics of AmBC

Since the advantages of AmBC systems stem from the scattering mechanism used by the BD, we present the impact of the scattering mechanism on the fading and propagation channels, discuss the spectral properties of the AmBC, and address the energy-related considerations.

Propagation and Fading

The BC channel is a concatenation of the channel from the Tx to the BD and the channel from the BD to the Rx, which is a two-way keyhole channel [4]. This type of channel has two main characteristics: deeper small-scale fades than that of a conventional one-way channel even in the line of sight (LoS); and the keyhole characteristic remains in both LoS and non-LoS conditions. Any keyhole channel can be modeled as the cascade of two channels; keyhole diversity is available in a rich scattering environment caused by modulating a backscatter signal with multiple antennas. Since a backscattering channel is a spatial keyhole channel, where each RF backscattering antenna acts as a keyhole, backscatter readability is a serious problem due to deep signal fading.

The authors of [6] validated the link budget models for mono-static and bi-static AmBC configurations. The work concludes that a close match can be achieved between the simulated and measured values by considering different factors of backscatter signal propagation along with realistic system parameters. Different margins, slow fading margin (SFM), and fast fading margin play a vital role in modeling the backscattering link. Figure 2 shows the link budget with and without the SFM for the mono-static and bi-static dislocated configurations, considering the BD is located in the middle of the ambient source and the receiver. The LoS curve denotes the link budget of the direct path between the ambient transmitter and the receiver. It confirms that there is a significant difference between the power of the direct path and the backscatter link. Therefore, it is a challenging task to design an AmBC receiver capable of recovering the desired signal in the presence of strong direct path interference.

Spectrum Efficiency Enhancement

AmBC can be viewed as a spectrum sharing method, where the AmBC device coexists with a legacy system that generates the ambient signal. Figure 3 illustrates the two achievable rate regions. Region A-B-D-E depicts the scenario in which two active transmitters share the spectrum. Region A-B-D-C illustrates the case of the AmBC system sharing the spectrum with a legacy system. The rate region of the AmBC case is fundamentally different in comparison with the active transmitter scenario as the AmBC device in certain conditions increases the rate of the legacy system (point C) compared to what it can achieve alone (point E) [4]. The transmission rate of the AmBC system incurs different interference to the legacy receiver. If an AmBC symbol duration is much longer than the legacy system frame duration, the legacy system is able to track the channel variations caused by the AmBC and treat AmBC signal as just an additive multipath component. Hence, AmBC can be used to improve the communication quality of the legacy system by transmitting, for example, known pilots. On the other hand, if an AmBC symbol duration is short, the legacy receiver is not able to track the channel variations caused by the AmBC device, and the AmBC-modulated signal paths appear as interference to the legacy receiver (point B).

Energy Harvesting and Rate-Energy Trade-off

Battery-free or semi-passive tags require energy for transferring and/or decoding information operations, which can be harvested from the ambient RF signals. The amount of energy harvested from the ambient RF signals depends on the RF source, the distance between the source and the backscatter device, and the time duration for harvesting. For instance, up to 61 μW can be obtained from 680 MHz TV signal of a tower located 4.1 km away from a BD [7].

One of the critical problems is to achieve better trade-off between the harvested energy and the decoded information rate, as practical BD circuits are unable to decouple the RF energy required for encoding the information from the RF energy for harvesting. The schemes of allocating the RF energy, such as time splitting, static power splitting, and on-off splitting, have been studied through analyzing the rate-energy curves for different scenarios [8]. It is consistent with the result in [2], which suggests different operation modes among RF energy harvesting and information transformation according to the signal-to-noise ratio (SNR) obtained by the devices. For the BD close to the ambient Tx or to the Rx (i.e., in the high SNR region), static power splitting is preferable; while in intermediate SNR cases, on-off splitting is the optimal scheme.

Challenges and Solutions

Since AmBC systems piggyback their information onto an ambient signal in the air, the AmBC receiver operates with the signals from two sources: first, the signal transmitted by the legacy system, and second, the signal modulated by the BD. This problem poses itself as the primary challenge for decoding AmBC signal, which we refer to as *direct path interference*. The direct path interference defines the signal-to-interference-plus-noise ratio (SINR) operating point for the AmBC receivers, which raises stringent constraints on the receiver design. In this section, we first present the direct path interference problem and its available solutions. Then we summarize three different ambient signal decoding schemes of AmBC receivers.

Direct Path Interference

The AmBC system deployments can be in a mono-static or bi-static configuration as shown in Fig. 1. In a mono-static configuration, the receiver can be designed to mitigate the leakage of the transmitted signal. In the bi-static case, however, the backscatter-modulated signal is superimposed with the direct path signal at the receiver. In practical deployments, the direct path signal strength is several orders of magnitude higher than that of the scattered signal component. Hence, in bi-static AmBC systems, a receiver needs to operate at a large dynamic range to be able to reach acceptable performance in terms of bit error rate (BER).

The analog front-end of a commodity-communication-system receiver is usually configured to capture the desired signal in as good condition as possible. This operation utilizes the dynamic range of the analog-to-digital converter (ADC) by pushing the undesired components and noise sources to a few least significant bits. Since the AmBC signal is restrained to a few least significant bits of the ADC output, such operation is not suitable for decoding the weak AmBC signal along with the strong direct signal, which results in high packet error rate. This issue can be mitigated by first eliminating the strong direct path ambient signal and then decoding the AmBC information.

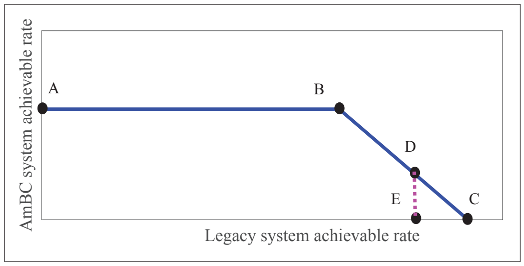

Figure 3. An illustration of achievable rate regions: A-B-D-E for two active spectrum-sharing the spectrum, and A-B-D-C for AmBC system sharing the bandwidth with a legacy link.

One approach to mitigate the direct path interference is to use hybrid analog-digital domain null-steering beamforming techniques [9]. The direct path signal is attenuated in the analog domain by steering the null of the multiple receiver antennas toward the direct path direction so that the automatic gain control unit of the receiver operates at the level of the weak AmBC signal. This allows the usage of a common ADC to sample the received signal. Thereafter, the digital samples of the weak AmBC-modulated signal buried in the residual direct path signal and the noise can be decoded using a non-coherent receiver. To further improve the performance of the receiver, the BD adopts orthogonal channelization codes (e.g., Hadamard codes) to avoid requiring the knowledge of the instantaneous channel state information (CSI).

Figure 4 shows the BER of an AmBC system as a function of the received SNR per antenna of the direct link [9]. The considered carrier frequency of the ambient RF signal is 500 MHz. The linear receive antenna array has eight elements with a half-wavelength spacing of the carrier, and the angle of arrival (AoA) estimation is carried out using the Bartlett method [9]. The ambient RF source is located at 60°, and the backscatter is located at 90°. The notation H_M denotes a length-M Hadamard codeword, and d_1 is the distance between the AmBC device and the receiver. The results confirm that the proposed novel design allows the AmBC receiver to non-coherently detect the non return to zero binary phase shift keying (BPSK) signals of the BD without decoding the ambient RF signals for a large distance between BD and Rx. The achieved BER is on the order of 0.001 without applying error correction techniques.

Receiver Design

Receivers extract the backscatter data using the available information at the receiver. For AmBC systems, attenuating the direct path signal increases the SINR of the signal in the digital domain. However, the improvement in SINR is limited by two factors. In addition to the keyhole effect of the backscattering link, the legacy system causes the AmBC link to experience very fast fading because the unknown legacy signals might have much higher data rate transmission compared to the rate of BD. The first factor also limits the performance of the signal processing methods adopted by the receiver (e.g., for AoA estimation and beamforming). The second factor limits the use of coherent modulation schemes such as BPSK. The rest of this section summarizes

Any keyhole channel can be modeled as the cascade of two channels; keyhole diversity is available in a rich scattering environment caused by modulating a backscatter signal with multiple antennas. Since a backscattering channel is a spatial keyhole channel, where each RF backscattering antenna acts as a keyhole, backscatter readability is a serious problem due to deep signal fading.

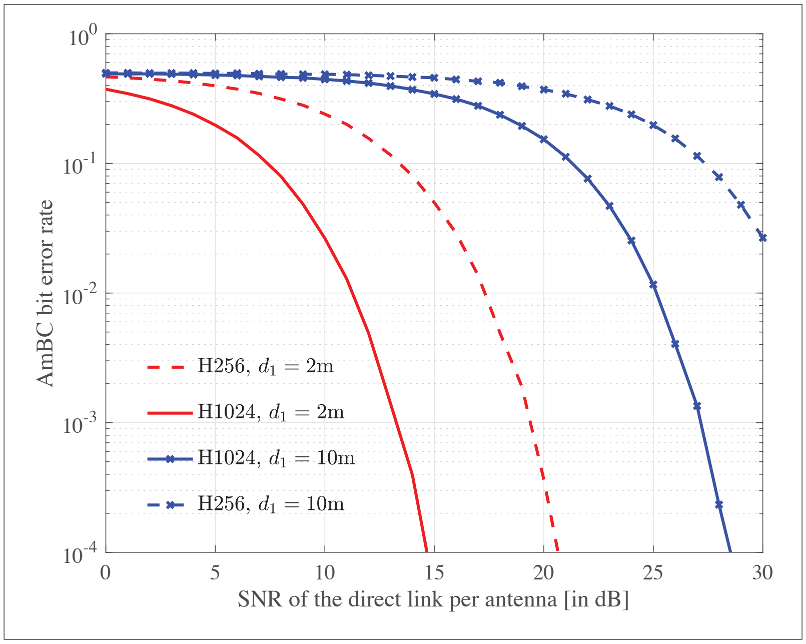

Figure 4. BER as a function of the received SNR of the direct link.

available receiver designs for AmBC systems. We first summarize coherent (including semi-coherent) receivers, and then non-coherent receivers. Thereafter, recent emerging machine-learning-based algorithms are presented.

Coherent Receiver: A cooperative maximum likelihood (ML) detector can be utilized at the AmBC receiver with the availability of all the CSI. In particular, the work in [10] has proposed a coherent and a partly coherent detector for AmBC, where the CSI needs to be estimated by sending the pilot sequences from the Tx and from the BD. Such requirements limit the use case scenarios that may allow the coherent reception in practice. Ambient signals that have been generated using orthogonal frequency-division multiplex (OFDM) modulation have a repeating structure that can be exploited in the AmBC waveform and receiver design, as suggested in [11].

Non-Coherent Receiver: Non-coherent detection avoids the necessity of tracking sensitive phase knowledge of the received signal, which degrades the performance of the AmBC system in general. Considering the on-off keying (OOK) or differential BPSK modulation schemes at the BD, several works realized non-coherent demodulation by energy detector and ML detector. Due to the error floor issue of an energy detector, coding methods have been applied to improve the BER of an energy detector, such as Manchester coding or spread coding. In [12], we proposed a time domain covariance matrix based method that allows demodulation of BPSK data without explicit knowledge of the ambient signal phase. For constant envelope ambient RF signals, an ML detector for AmBC modulated symbols has been proposed in [13].

Machine-Learning-Based Receivers: In certain deployment scenarios of AmBC systems, the receiver cannot access or estimate the CSI and the constellation of the legacy system. In such cases, machine learning methods of detecting and/or estimating some latent variables is an attractive option, since it relaxes the system design constraints. The authors of [14] have designed a receiver-based Gaussian mixture model when the modulation information of the ambient signal is available at the receiver. The authors of [15] have proposed a detection method of the desired AmBC signals using classification algorithms. The design enables the AmBC system to retrieve the BPSK-modulated information with practically acceptable performance without having knowledge of the CSI and the constellations of the legacy system. Although machine-learning-based receiver designs can be used in several components of the receivers, their applications to AmBC are still in its early stage.

Future Research Trends

Recent AmBC developments have shown that the technology has great potential for enabling sustainable IoT deployments. However, as new application areas are emerging, new research trends come forth to address certain practical aspects of the technology. This section presents potential future research trends.

Strong Direct Path Interference and Weak AmBC Signal Recovery

Various AmBC signal recovery techniques proposed and studied in the literature are subject to some limitations. In addition, the current designs require a large number of samples or some knowledge of the backscatter channels or the noise variance. The sample covariance matrix distance-based method in [12] also has some limitations. If the BD modulates the ambient OFDM signal at a very high rate, the backscattered path frequency response will shift to another band in the frequency domain. If the receiver has a sharp and narrow band-pass filter, the AmBC signal can be filtered out. In the case of a wideband receiver, an AmBC transmission will cause severe adjacent band interference.

Feedback/Downlink Channel Design

The physical layer protocol design for AmBC integration calls for both the downlink signaling channel and uplink data channel. The downlink signaling is constrained by the capabilities of the AmBC nodes to act as a receiver. For an energy detector, the symbol length used by OOK must be much larger than the symbol length used by the legacy communication system in order to average out the underlying modulated signal. A non-coherent receiver is likely to be simpler than a coherent one, and thus is a more attractive option for power-constrained AmBC nodes. Hence, solutions are needed to build a downlink control channel that can be superimposed on the legacy data symbol in the downlink.

Intermittent Transmission and Synchronization

For an AmBC system using legacy systems with intermittent transmissions, the ambient signal must be tracked by the BD to successfully piggyback its information. For this purpose, the BD should be time synchronized to the Tx and know in advance when to start its transmission. Such a requirement results in a challenging design problem for battery-free devices, which requires efficient algorithms instead of traditional power-hungry detectors. For instance, the ambient LoRa signals are intermittent in nature, so the BDs need to ask for novel packet detection methods to synchronize with the ambient LoRa symbols [3].

Smart Antennas for AmBC

Multi-antenna technologies have been applied in various wireless communication systems including AmBC systems to boost the performance. The field of smart antennas for AmBC is still relatively unexplored. Unlike the current state-of-the-art solutions, the new smart antennas for AmBC systems should allow the antenna to tune to the characteristics of the ambient signal. Multiple antennas per device should be exploited in an efficient but low-complexity manner. Hence, novel antenna and device designs, communication schemes (algorithms, protocols, and their implementation), and novel scalable data aggregation schemes for multi-antenna BDs are topics for future research.

Security and Privacy

Security and privacy issues are critical in all IoT applications. The special challenge in AmBC is the limited computational and communication resources, which dictates that the used authentication and encryption methods need to be lightweight. Additional security for AmBC links can be obtained by using physical-layer security (PLS) methods. Despite several works investigating the PLS, higher-layer security, and privacy preserving protocols for RFID systems, only a little has been done for AmBC due to the power and design limitations of the low-cost AmBC devices.

Conclusions

The AmBC technology has the potential to revolutionize current IoT connectivity by enabling sustainable applications. In this article, we have presented the trends of AmBC from the aspects of practical implementation, communication features, and detection techniques. An overview of important challenges and the corresponding potential research for future AmBC system design have been presented. Through numerical simulation, we have demonstrated the superiority of applying hybrid beamforming and coding techniques for the AmBC system. This can be a potential solution for the large dynamic range problems suffered by a simple AmBC receiver to recover desired information.

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