Development in Ambient Backscatter Communications

Citation for published version:
Chang, S & Ding, Y 2023, 'Development in Ambient Backscatter Communications', IET Microwaves, Antennas and Propagation. https://doi.org/10.1049/mia2.12419

Digital Object Identifier (DOI):
10.1049/mia2.12419

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Peer reviewed version

Published In:
IET Microwaves, Antennas and Propagation

General rights
Copyright for the publications made accessible via Heriot-Watt Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
Heriot-Watt University has made every reasonable effort to ensure that the content in Heriot-Watt Research Portal complies with UK legislation. If you believe that the public display of this file breaches copyright please contact open.access@hw.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 03. Oct. 2023
Title: Development in Ambient Backscatter Communications

Authors: Shujuan Chang, Yuan Ding

Departmental & institutional affiliation for Shujuan Chang:
The School of Electronic Engineering, Xi’an University of Posts & Telecommunications, Xi’an, 710121, China

Departmental & institutional affiliation for Yuan Ding:
The Institute of Sensors, Signals and Systems (ISSS), Heriot-Watt University, Edinburgh, EH14 4AS, UK

Corresponding author: Yuan Ding, The Institute of Sensors, Signals and Systems (ISSS), Heriot-Watt University, Edinburgh, EH14 4AS, UK, yuan.ding@hw.ac.uk

Conflict of interest statement: None.

Funding information: Yuan Ding’s work was supported in part by the EPSRC (UK) under Grant EP/V002635/1, and in part by the Royal Society International Exchange Award, UK, under grant number IEC\NSFC\211118.

Data availability statement: Data openly available in a public repository that issues datasets with DOIs
Development in Ambient Backscatter Communications

Shujuan Chang¹ and Yuan Ding²*

¹ The School of Electronic Engineering, Xi’an University of Posts & Telecommunications, Xi’an, 710121, China
² The Institute of Sensors, Signals and Systems (ISSS), Heriot-Watt University, Edinburgh, EH14 4AS, UK

*Corresponding Author: yuan.ding@hw.ac.uk

Abstract: Backscatter communication (BackCom), the underlying technology for modern-day Radio Frequency Identification (RFID), has been studied as a promising solution for future ultra-low power Internet-of-Things (IoT) applications. Its development has pushed the performance boundaries significantly, in terms of communication distance, data transmission rate, and power consumption. In this paper, we conduct an up-to-date review of one branch of BackCom systems, namely Ambient BackCom, which utilises the already available ambient signals, instead of a dedicated radio frequency (RF) carrier in most of the BackCom works, to establish BackCom links. This further reduces the cost and complexity of the system and opens an opportunity for mass deployment.

1. Introduction

The vision of future Internet-of-Things (IoT) is to build a pervasive communication fabric that allows information flow among people, objects/things, and environment. This gigantic network, if based upon current prevalent wireless communication technologies that append/modulate data onto locally generated radio frequency (RF) carriers, become prohibitively affordable, with regard to the cost of RF chains, and energy consumption. Under this context, a passive wireless communication scheme, i.e., backscatter communication (BackCom), has become attractive. Instead of actively generating RF carriers locally at BackCom devices, they apply modulations directly at incoming electromagnetic waves during the antenna scattering. This is commonly achieved by changing the loading impedance of the antennas in BackCom devices/tags, resulting in different signal reflection coefficients at the interface between antennas and their loads. This removes the need for costly and power-hungry RF chains; thus, it drastically reduces the power consumption of the wireless link down to tens of µW, at least 3 orders of magnitude lower compared with its active counterparts.

This BackCom technology is not new, but it underpins the modern-day RF Identification (RFID) systems. In order to extend its applications in wider IoT applications, its performance boundaries on communication range, data rates, and power consumption have been pushed significantly in recent years. For example, huge improvements on BackCom uplink range have been achieved [1–3], wherein BackCom links reaches hundreds of metres [1], even a few kilometres [2, 3], thanks for frequency-shifted and chirp spread spectrum (CSS) modulation schemes. This is a massive leap compared with a few metres in conventional ultra-high-frequency (UHF) RFID systems. In addition, the range can be further extended when exploiting the gains provided by tunnel diodes [4], retrodirective arrays [5, 6], 1-D and 2D lenses [7, 8], and high gain leaky wave antennas [9]. While as for enhancing data rates, two approaches have been adopted. The first is to employ higher order modulation schemes, like quadrature amplitude modulation (QAM) [10] and multicarrier [11]. The other attempt is to explore more available frequency resources in higher frequency bands, such as in millimetre wave (mmWave) and sub-THz range [9, 12–14], where the transmission rates of a few Gbps were achieved. Some efforts have been made to reduce the power consumption, so that a truly power autonomy solution, e.g., via RF energy harvesting, can be viable. In [15] the core BackCom tag switch was estimated to consume merely 185 nW, though when combining the energy required for controlling tens of µW was needed. Estimated using ASIC simulation, less than 10 µW power consumption was reported in [2].

Though massive improvements have been made, from the BackCom system’s perspective, one limitation of requiring a dedicated RF carrier station nearby unfortunately increases the system cost, hindering its deployment in large scale. This type of BackCom system is labelled as dedicated BackCom, in contrast to ambient BackCom which utilises available signals in ambient environments. However, more complexity associated with the tag and reader design has been brought in. One early milestone work in 2014 [16] turbocharged the development of the ambient BackCom. It works on ambient TV signals at 539 MHz, though at a very high-power level (from ~30 dBm to 0 dBm) at backscatter tags. It equips the backscatter receiver with multiple antennas, so that the unknown and dynamic wireless channels can be largely cancelled out when the ratio of received signals by different antennas is used for backscatter data extraction. This scheme, named by authors as µmno, successfully increases the ambient BackCom data rate from kbps to Mbps. In addition, a CDMA-like coding scheme, named as µcode, extends the communication range up to 24 metres and it also enables concurrent transmission for multiple tags. A summary of the

<table>
<thead>
<tr>
<th>Table 1. Pros and Cons for Currently Reported Dedicated and Ambient BackCom Systems.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link Range</td>
</tr>
<tr>
<td>Data Rate</td>
</tr>
<tr>
<td>EM Energy Density for Harvesting</td>
</tr>
<tr>
<td>System Cost</td>
</tr>
<tr>
<td>Deployability</td>
</tr>
</tbody>
</table>
pros and cons of the dedicated and ambient BackCom systems has been provided in Table 1.

There have been a few review papers on BackCom technologies, such as [17–25]. The recent review papers [17] and [18] have been focused on the BackCom RF electronics designs and system prototypes, while the BackCom fundamentals were comprehensively covered in [19–21]. The above review works have been biased more on dedicated BackCom, with the ambient BackCom discussed more in [22–25]. The review [22] discussed the coexistence and spectrum sharing between ambient BackCom systems and other legacy active wireless networks including traditional active Radar. Another comprehensive overview on bistatic and ambient BackCom was presented in [23], which focused more on hardware architecture, prototypes, backscatter tag authentication and transmission security, as well as the interplay and integration with other IoT networks. The work in [24] is devoted to the signal processing aspect of ambient BackCom, while another paper in [25] summarised the development of circuits and MAC-layer designs for commercial compatible ambient BackCom systems up to year 2021. Thus, it lacks a few important developments on recent ambient BackCom systems. Different to those existing review and tutorial-type papers, we intend to review ambient BackCom literatures from modulations or waveforms’ perspective in Physical Layer. A summary of the focus of these reported review papers and our presented work here is provided in Table 2. In Section 2 ambient BackCom systems for various commercial ambient signals are discussed. Different BackCom modulation strategies are presented. This review paper focuses on BackCom systems exploring some prevalent ambient signals, like Wi-Fi and Bluetooth for indoor applications and FM and LoRa for outdoor applications. This is followed by the recent progress aiming to address another major challenge on signal detection in ambient BackCom links. The authors’ vision on future research challenges in Section 3 in order to make ambient BackCom more practical to facilitate industrial uptake. In particular, the potential research directions to recover the performance drop compared with the dedicated BackCom, seen in Table 1, are discussed. Conclusions are drawn in Section 4.

Table 2. Summary of Some Reported BackCom Review Works.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Year</th>
<th>Review Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>[17]</td>
<td>2022</td>
<td>Antenna and backscatter circuit designs</td>
</tr>
<tr>
<td>[18]</td>
<td>2021</td>
<td>Backscatter circuits and system prototypes</td>
</tr>
<tr>
<td>[19]</td>
<td>2019</td>
<td>Comprehensive reviews on BackCom fundamentals</td>
</tr>
<tr>
<td>[21]</td>
<td>2018</td>
<td>Spectrum sharing with other networks</td>
</tr>
<tr>
<td>[22]</td>
<td>2023</td>
<td>Hardware, prototype, security, and interplay</td>
</tr>
<tr>
<td>[23]</td>
<td>2018</td>
<td>Signal processing in BackCom</td>
</tr>
<tr>
<td>[24]</td>
<td>2022</td>
<td>Circuit and MAC designs up to year 2021</td>
</tr>
<tr>
<td>Our Work</td>
<td>2023</td>
<td>Dedicated to ambient BackCom that is compatible with commercial transceivers</td>
</tr>
</tbody>
</table>

2. Ambient BackCom for Various Ambient Signals

BackCom is a technology that the incoming electromagnetic (EM) waves at the tags are modulated while they are scattered. Thus, mathematically it can be considered as a transfer function transforming incoming waveforms to BackCom waveforms. Keeping BackCom tags simple and low-power, the achievable transfer functions are generally lossy (because of consisting of only passive components) and harmonics-rich [26] (because of discrete load impedance selections). The common modulation schemes can be applied in backscatter processes, like in amplitude-, phase-, and frequency-domains, as well as their combinations, by manipulating the sequence of the reflection coefficients seen by the tag antennas. Further complexity arises when the incoming ambient signals are dynamic and unknown to the BackCom receivers, making the resulting ambient BackCom more challenging.

This section is not organised to provide a comprehensive review on ambient BackCom systems, but it focuses on a few milestone-type works that have guided their recent developments. They are presented for different prevalent ambient signals, namely WiFi, Bluetooth, FM, and LoRa, which are followed by discussions on signal detection at the receiver end.

2.1. Wi-Fi backscatter

There are many generations of Wi-Fi standards, such as direct-sequence spread spectrum (DSSS)-based IEEE 802.11b and OFDM-based IEEE 802.11a/g/n/ac.

The first Wi-Fi BackCom was reported in 2014 [27]. It applied the On-Off-Keying (OOK) backscatter modulation on ambient Wi-Fi signals which can be either DSSS or OFDM waveforms. These BackCom modulated bits can be recovered by monitoring the Received Signal Strength (RSS) at a very few commercial Wi-Fi receivers that grant access to RSS. Since the RSS is only updated and reported for every Wi-Fi frame, this proposed Wi-Fi backscatter has very low data rate. In addition, this amplitude-based modulation scheme unfortunately is susceptible to channel noise and ambient interference. All these factors limit the uplink performance to around 100 bps at 65 cm or 1 kbps at 30 cm distance, even with a high beamforming gain provided by an array of 6 antennas.

Building upon the breakthrough presented in [27], a few attempts have been made to improve the system performance, though in many cases compromises have to be made. Authors in [28] proposed to synthesise IEEE 802.11b compatible backscatter waveforms so that the modulation rate for BackCom can be significantly improved compared with that in [27]. The phase-domain DBPSK and DQPSK backscatter modulations were achieved by utilising the fact that the time-domain delay of the backscatter square waveforms is equivalent to the phase shifts when only fundamental frequency component is of concern. This method, however, can only be used for DSSS-based IEEE 802.11b. More critically, this 'Passive Wi-Fi' requires the ambient signal to be a dedicated Continuous Wave (CW) source. Thus, technically speaking this is not an ambient BackCom system. The first limitation was recently overcome in [11] where OFDM-based IEEE 802.11g backscatter waveforms were generated using time-domain synthesis method. This multicarrier backscatter becomes possible since the dual-transistor enabled backscatter circuits, seen in Fig. 1a, are able to synthesise continuous impedance on Smith chart (see time domain reflection coefficients corresponding to IEEE 802.11g preambles on Smith chart in Fig. 1b), instead of discrete impedance loads available in switch-based backscatter tag circuitry. This circuit in Fig. 1a was first
introduced in [29] and named as IQ backscatter modulator. It consists of a Wilkinson power splitter (for splitting captured incoming signals) or combiner (for combining two branches of backscattered signals for re-radiation), and two impedance varying loads, two transistors in this case. A $45^\circ$ phase difference is introduced between two branches, which gives $90^\circ$ phase difference of backscattered signals from two branches since signals travel back and forth. Thus, it enables the tag controlling backscatter signals independently along I and Q axes. The second limitation was addressed in [30], where the dedicated CW source was replaced by another commercial Wi-Fi transceiver, see the system model in Fig. 2. The authors proposed to use a Wi-Fi transmitter to synthesise a standard IEEE 802.11g preamble that is appended with OOK modulated control signal and CW section. The preamble is captured by receiver for synchronisation purpose, and the OOK modulated downlink signal is to coordinate multiple tags, e.g., allocating them with different OFDM subcarriers and different orders of QAM schemes. The CW section used by tags for backscattering was achieved by reverse engineering, i.e., by figuring out the input bit sequence given the target output bit sequence, which are mapped onto a single point on IQ plane, and the processing functions of bit scrambler, convolutional encoding and interleaving. This proposed OFDMA BackCom link for a single tag achieved 110 kbps at 100 metres or 440 kbps at 35 metres in line-of-sight (LoS) uplink environment.

Another approach to performing high BackCom data rate on uncontrollable ambient Wi-Fi signals was proposed in [31], named by the authors as BackFi. It is arranged as monostatic architecture, where the Wi-Fi access point (AP) was a bespoke design to accommodate wideband self-interference cancellation. The implementation concept was borrowed from the recent development on full-duplex radios. This added module removes most ambient Wi-Fi signals at the receiver chain. Since in monostatic architecture, the transmitter and receiver are collocated, the BackCom data, being PSK modulated on ambient Wi-Fi signals, can be recovered by comparing (in mathematical or circuitry term by performing XOR) transmitted and received/backscattered Wi-Fi waveforms. This BackFi scheme boosted the BackCom data rate up to Mbps, though with a very limited communication range of up to 5 metres. Following the same principle, HitchHike Wi-Fi BackCom was developed in 2016 [32]. This HitchHike removes the need of self-interference cancellation module by exploring frequency-shifted BackCom [26]. Thus, ambient Wi-Fi IEEE 802.11b signals and the backscattered Wi-Fi compatible signals can be made appear in different frequency channels. In order to avoid interference caused by imaging spectrum, the single sideband (SSB) modulation was adopted. The separation of ambient and backscattered Wi-Fi signals in frequency domain also allows them to be received by two Wi-Fi receivers. Again, after comparing the received data (commonly in the cloud) the backscatter bits can be recovered. This bistatic HitchHike, however, was limited in the downlink range because the tag wake-up circuit was not sufficiently sensitive. This aspect was further looked into by authors in [33]. It was the first ASIC implemented BackCom tag that integrated bespoke Wi-Fi envelope detector (ED) and BPSK or QPSK BackCom modulators. Its 4-stage passive pseudo-balun ED has pushed wake-up detection sensitivity down to as low as $-42.6 \text{ dBm}$, which translates to detection range of about 30 metres, sufficient for most applications in indoor environments. The function blocks in ASIC have been illustrated in Fig. 3. Implemented using 65nm CMOS, its energy consumption was reduced to 2.8 $\mu$W in wake-up stage, and 28 $\mu$W in BackCom uplink with the communication range of tens of metres. Extending ambient Wi-Fi BackCom to accommodate multiple antennas (at ambient transmitter, tags, and receivers), a versatile MIMO Wi-Fi backscatter, labelled as VMscatter, was developed in [34]. It is able to achieve full diversity gain as traditional MIMO by implementing space-time coding at the tags. Practically it does not require tags to have full channel information, the un-orthogonality introduced at the tags is compensated by a novel pre-scatter channels elimination and a post-scatter channels equalization. This proposed VMscatter dramatically decreases bit error rate (BER) and increase throughput with negligible overhead.

![Passive Voltage Gain](Image)  
![Envelope Detector](Image)  
![Wake-up Receiver](Image)  
![XTAL](Image)  
![PL](Image)  
![TX Enable](Image)  

Fig. 1. (a) Dual-transistor based IQ backscatter modulator. Source: Belo et al. [53] @ 2019, IEEE. (b) The scaled 320 preamble samples in IQ plane in the IEEE 802.11g (some samples are overlapped), fitting into the spanned achievable impedance by the modulator in (a). Source: Yuan et al. [11] @ 2020, IEEE.

![Backscatter Tags](Image)  
![Backscatter Modulated CW](Image)  
![OFDM Wi-Fi Tx](Image)  
![Preamble & PHY Header](Image)  
![OM To-tag Frame](Image)  

Fig. 2. Reverse engineered OFDM Wi-Fi transmitter-assisted Wi-Fi backscatter [30].

![Architecture](Image)  

Fig. 3. Architecture of backscatter-based IoT tag IC. [33].
2.2. Bluetooth Low Energy (BLE) backscatter

Bluetooth, especially its low energy version — Bluetooth Low Energy (BLE), is also prevalent in indoor environments, since nearly all smart phones, wearables, electronic gadgets have it integrated. Even though it claims to be low energy, it still consumes in the order of mW and requires coin batteries for powering up. This motivates researchers around the world to develop ultra-low power backscatter tags that can ‘talk’ to BLE devices. The first attempt was made back in 2015 [35] where an ambient CW signal was modulated/backscattered to synthesise 2FSK waveforms in advertising channels defined in BLE physical layer. With commercial BLE module in smart phones, the BackCom uplink raw data rate could reach 1 Mbps for about 9.4 metres. Later by the same research group, two different types of circuits, i.e., analogue version in [36] and full-digital version in [37], were developed to add pulse-shaping function to backscatter, so that the Gaussian-shaped 2FSK (GFSK) modulation that is identical to that in active BLE modules was made possible. This improvement further extended the uplink BackCom range to 13 metres [36], and single sideband (SSB) modulation was enabled to reduce interference to other BLE channels [37].

These earlier works though generate backscatter waveforms that can be read by BLE receivers, they can only operate with incoming CW signals. Thus, technically speaking and similar to the Passive-WiFi in [28], they are not ambient BackCom systems. The breakthrough to removing the need for a dedicated CW source was reported in 2017 [38] when the concept of ‘FreeRider’ was proposed. It works on a principle called ‘codeword translation’. It backscatters signal waveforms generated from a standard BLE transmitter. After the backscattering and following the concept of frequency shifting [26], the backscattered signals can be moved to a different BLE channel. The backscatter data bits can be coded during this translation. For example, bit 1 is coded as changing the original GFSK frequency derivation from positive (or negative) to negative (or positive), while bit 0 is coded as keeping original GFSK with no change. Thus, to recover the coded BackCom bits, two BLE receivers, unfortunately, are needed. Tag information is extracted by comparing the backscattered data from one receiver and the original data from another receiver. This FreeRider architecture and the codeword translation concept are illustrated in Fig. 4. There are a few issues associated with the FreeRider BLE backscatter. First, in BLE channel where backscattered waveforms locate, the cyclic redundancy check (CRC) section is the same as the original ambient BLE signals, thus after the codeword translation the checksum of FreeRider packets is always invalid. Some BLE chipsets in this case do not perform decoding. Second, SSB modulation is not applicable when performing frequency shifting, which may cause in-band and out-band interference to other wireless links. Last but not least, it requires precise time-domain synchronisation to identify the beginning of the original BLE data packets and modulate backscatter data bits at the same rate as the original BLE data rate.

Inspired by the Inter-Technology Backscatter described in [39], where the authors successfully reverse engineered the BLE physical layer protocol so as to generate a single CW tone using commercial BLE transmitters, RBLE was proposed in [40, 41]. Since it backscatters on CW signals which are synthesised in data payload section in BLE advertising channel packet, a new backscatter BLE packet, including CRC section, can be generated in a different BLE channel, leading to low packet error rate (PER). In [40], the uplink goodput of 16.6 kbps was achieved for a range up to 25 metres indoor and 56 metres outdoor. The simulated ASIC power consumption, including envelope detection and BLE backscatter, is as low as 37 μW. In the same year, this RBLE scheme was further improved by incorporating channel hopping [42] and GFSK modulation [43, 44] that are defined in commercial active BLE transceivers. Here the GFSK was performed by the insight that a frequency modulated signal can be generated by properly varying its instantaneous phase instead of directly varying its frequency. This is more suitable for low power IoT devices. Finally, it has been found that the length of optimal guard interval when backscattering for different ambient BLE devices is different [45]. In the same work, the authors proposed a device identification approach, with an accuracy of 98%, so that the guard interval can be dynamically adjusted, making link goodputs more consistent when linking with BLE chipsets from different vendors. In [46] different BLE backscatter synchronisation methods were introduced for uncontrolled BLE excitors. It shows minimum BER of 0.5%, which is 60 times better than that of the reported FreeRider [38].

2.3. FM backscatter

The above elaborated Wi-Fi and BLE BackCom systems are suitable for indoor applications, while FM BackCom has been studied primarily for outdoor use, since FM signals cover wide areas with a decent power level. For example, at a location of 34.5 km away from an FM tower the signals can still reach as high as around ~50 dBm, reported in [47]. Unlike the Wi-Fi and BLE cases, here there is no chance that the ambient FM signals can be altered or be known a-priori. Hence the early FM backscatter modulation was only applied on amplitude domain, e.g., OOK in [47] and 4-Pulse-amplitude modulation (4PAM) in [48]. The time period of the backscattered symbols has to be long enough so that after filtering (or averaging) the dynamic FM signals can be largely removed. The different load impedance was achieved using either RF switches or RF transistors with different gate voltages applied. Again, this amplitude-domain BackCom modulation is susceptible to channel noise and dynamic ambient signals, the data rates and communication distances reported are limited.

One important breakthrough was made in 2017 [49] where a single tone CW, either dedicatedly generated or 19 kHz shifted pilot tone embedded in FM ambient signals, was FM backscattered so that it can be demodulated by a standard FM receiver. This addresses the issue of using bespoke FM receivers in earlier works. However, it works only when the ambient FM signals are in Mono mode, which, unfortunately, are increasingly rare. It backscatters (in the meantime frequency shifts) that 19 kHz pilot tone to Stereo Audio channel to mimic an FM audio in Stereo mode. Another all-

---

Fig. 4. Codeword translation concept proposed in FreeRider [38].
digital FM backscatter work was presented in [50]. This digital solution, on the other hand, removes the need of analogue devices connected to the backscatter antennas. Instead, it re-uses IO pins, in different configurations such as Input, Output High, or Output Low, to generate different reflection coefficients seen by the backscatter antennas. It was experimentally found that the IO pin impedance between Output High and Output Low configurations was not distinctively different, but they were far apart on Smith chart when it was configured to be Input and Output (either High or Low) for frequency lower than 1 GHz. Thus, the IO pins can be used as different loads and be connected directly to backscatter antennas. This all-digital solution, though having relatively low operation frequency, is more suited for legacy devices where no extra components can be retrospectively added. Apart from the above works, it has been demonstrated that 2FSK and CSS modulations can also be applied on ambient FM signals, achieving the longest FM BackCom link distance reported so far, up to 107 metres for 2FSK FM BackCom in [51] and 130 metres for CSS FM BackCom in [15]. This type of FM BackCom system block is presented in Fig. 5. It can be seen that at the backscatter node the conventional RF switch-based circuit is used. The novelty lies in the receiver algorithm. Borrowed and adapted from quadrature demodulation, it becomes possible to largely separate backscatter signals from ambient signals in frequency domain. This pre-processing stage at backscatter receiver spreads the energy of ambient signals in wider bandwidth, becoming part of the noise floor, and it makes the backscatter tones clearly visible, see the experimental validation in Fig. 6, as well as the field test video in [52]. It is worth pointing out that this promising approach has the potential to be applied to a diverse of ambient signals other than FM.

![Fig. 5. 2FSK or CSS modulated FM backscatter [15, 51].](image)

![Fig. 6. Measured 2FSK spectrum on ambient FM signals after proposed pre-processing at backscatter receiver [51]. Two frequencies of 60 kHz and 70 kHz were chosen for 2FSK modulation.](image)

2.4. LoRa backscatter

Another type of ambient BackCom system for outdoor applications is LoRa-type backscatter, aiming for long communication distances. This is because the CSS modulation employed by LoRa has superior receiving sensitivity, though at the expense of low data rates. In commercial LoRa, the sensitivity can reach as low as −149 dBm, well below noise floor in most receivers. The research in LoRa backscatter, understandably, started from backscattering CW tones to LoRa-compatible chirp waveforms in 2017 [2]. Here the voltage-controlled oscillator (VCO) was used to generate chirp symbols, and an SPST, instead of commonly used SPDT, RF switch was selected to eliminate mirror harmonics. This CSS modulation was extremely effective in extending BackCom link range, and in this work, it reached as far as 2.8 km. Using VCO and high-order RF switches is not ideal due to power required and insertion loss introduced. In [53] the authors proposed to repurpose IQ impedance modulators for LoRa CSS waveform backscatter. In the tag node, it requires only two RF transistors with impedance controlled by varying their gate voltages. Since the transistors always operate in off-state, they consume very little energy. This work exploited the fact that frequency is the derivation of the instant phase over time. Hence, frequency chirp signals can be synthesised by controlling phases of backscatter signals. The experimentally generated spectrogram of backscatter CSS signals was shown in Fig. 7a with the corresponding FFT bins after decoding in Fig. 7b [53]. It clearly demonstrated the effectiveness of this IQ modulator enabled LoRa BackCom link. It was once believed that in order to span achievable load impedance in 2-D space in Smith chart, at least two impedance-varying components are required, like the two transistors used in IQ modulator circuit in [53]. However, it has been derived and experimentally tested in [14] that with only one transistor (an enhancement-mode high-electron mobility transistor) higher order complex constellation, like 16QAM, BackCom modulations were possible. This was achieved by introducing an Intermediate Frequency (IF) stage which was controlled by real-valued transistor bias. In the same work, as well as in [54], the pulse-shaping filter was introduced to limit frequency bandwidth of backscatter signals for better interference suppression. The most power consuming part to achieve Chirp modulation is the generation of control signals for frequency sweeping. In [55] a clever approach was proposed that shifts the complexity and power requirement to a nearby power beacon. When the ambient power can be controlled, the output voltage of the rectifier at backscatter node can be adjusted, which, in turn, can be applied to VCOs to synthesise Chirp signals. This method, however, asks for a well calibrated system, since rectifier and VCO are nonlinear devices, and it is also highly dependent on the wireless channel for energy harvesting. Contrary to this analogue tag circuitry, a digital version was elaborated in [56] wherein the Direct Memory Access (DMA) was used to reduce MCU power consumption. Comparing with the Wi-Fi and BLE backscatter, this LoRa backscatter involves further complexity as LoRa physical layer itself is proprietary and hence not publicly available. Thanks to some experimentally validated LoRa reverse engineering [57], it became possible to synthesise LoRa-compatible waveforms that can be decoded by commercial LoRa receivers.
All LoRa BackCom systems discussed above, unfortunately, only work for CW ambient signals, while the first backscatter on ambient LoRa signals was presented in 2018, named by authors as ‘PLoRa’ [58]. It employs a similar concept of code translation presented in FreeRider [38]. It was implemented by frequency shifting a standard LoRa signal to a different LoRa channel, while applying backscatter modulation (an additional frequency shift 0 or half of the channel bandwidth) upon them. At the receiver end, by detecting the peaks after FFT processing, the backscattered bits can be recovered. In this PLoRa scheme, we can only modulate one bit per single LoRa symbol, but the communication link distance was more than 1 km. A more recent work in 2022 [59] applies OOK on ambient LoRa signals. However, at the receiver end the authors proposed some processing approach to convert the OOK modulation in magnitude domain to frequency domain so that it became more resilient to noise and interference. It achieved a data rate up to around 200 kbps and the uplink range reached around 300 metres. Furthermore, in order to improve the total network throughput by allowing concurrent access within the same frequency band, the non-linear CSS chirps enabled OOK BackCom was proposed in [60]. It utilised quasi-orthogonal nonlinear chirps, such as sine, quartic, and quadratic, which can be separated at receiver end by multiplying corresponding inverse chirps. It, consuming 695μW, supports 700 tags to transmit concurrently with bit error rates (BERs) less than 1%.

2.5. Signal detection in ambient BackCom

Backscattered signals are commonly several orders lower, in power, than the ambient signals due to the passive lossy circuits and components in tags, as well as the extra path loss. This makes signal detection or demodulation a big challenge. Researchers have been developing theories and (quasi-) closed-form formulations to evaluate the signal detection performance for ambient BackCom systems [61–70]. The performance analysis of ambient BackCom link is fundamentally different from that of traditional wireless communication systems as there are more wireless channels involved, i.e., channels between any pairs among the ambient signal source, the tag, and the receiver. The performance for coherent signal detection was experimentally and theoretically investigated in [61], [62], where the optimal detection threshold for minimum BER was presented. In order to eliminate the necessity of channel estimation, the problem of signal detection for an ambient BackCom that adopts the OOK differential encoding was studied in [63], [64]. Two closed-form BER upper and lower bounds for minimum-BER and balanced-BER were derived, and their corresponding detection thresholds were presented and validated through simulation. It was later found that this maximum a posteriori (MAP)-based detector, exploiting the energy difference between two states of OOK modulated backscatter signals, causes much information loss during the energy subtraction. To overcome this reduced signal detection performance, the maximum likelihood (ML) detector that directly utilises the two energies was studied in [65]. In the same work, its low-complexity sub-optimal version without requiring knowledge of ambient signals and channel state information (CSI), called joint-energy detector, was proposed. Through extensive simulations, it showed a significant enhancement in signal detection performance compared to the work in [63]. The above energy-based signal detection is based on the assumption that the ambient BackCom modulation rate is much lower than the modulation rate of the ambient source signals, thus average energy among a number of consecutive samples can be used to extract BackCom data from ambient signals. This, on the other hand, limits the BackCom data rate to one bit per symbol period. To increase the data rate, a higher-order M-PSK BackCom modulation was employed in [66], where the optimal multilevel energy detector and the closed-form symbol error rate were derived. Furthermore, [67] extended the studies to BackCom links with IQ imbalance caused by the backscatter tags. This study is useful as the IQ imbalance in low-cost tags can be prominent. From simulation it is realised that the energy-difference based detector is more sensitive to the phase imbalance over amplitude imbalance.

The energy-based signal detection is susceptible to interference, thus a maximum-eigenvalue-based ambient BackCom detector, showing superior performance, was developed in [68]. However, it can only work on BackCom links with multiple antennas. In [69] the authors suggested to use nonlinear rectifier model for energy harvesting function. They proposed to use an adaptive ratio of power splitting between energy harvesting and BackCom. The impact of co-channel interference on the outage probability for both BackCom link and legacy link was investigated. It has been found that the co-channel interference leads to the outage saturation phenomenon in the backscatter and legacy links, and the conventionally used linear energy harvesting model will result in an overestimated outage performance for the BackCom link while the impact on the legacy link is very small. However, it has to be pointed out that a reconfigurable power splitter of low power consumption and low insertion loss is still a big challenge, especially if the required ratio is highly unbalanced [60].

The above signal detection works all assume amplitude or phase domain BackComs, so the ambient signals and backscattered signals interfere with each other. The frequency domain ambient BackCom modulation is able to shift the backscattered signals away from the ambient signals in spectrum [26], making most of the above analyses inapplicable. This demands more systematic studies in this aspect.
3. Research Challenges on Ambient BackCom

BackCom technology, especially the ambient BackCom version, is one of the key enablers to support future pervasive IoT networks in our everyday life. Its distinctive and disruptive advantage compared to other IoT solutions lies in its passive nature, i.e., removing the need of active RF carrier generation at the BackCom tags. Research outputs on ambient BackCom systems have been booming in recent years, ranging from tag hardware designs [3, 13–15], physical-layer and MAC-layer protocols [71, 72], to network capacity optimisation [73, 74]. The focus of our work is on the review of ambient BackCom systems that are compatible with commercial wireless systems, such as Wi-Fi, BLE, FM, and LoRa. The reported relevant BackCom tag prototypes of these systems are plenty, however, of which only a handful are compatible with both ambient dynamic sources and commercial receivers. These high-impact prototypes are collated and summarised in Table 3.

Among the above 4 types of ambient BackCom systems, BLE backscatter is more mature. This is because the BLE physical layer and modulation scheme is simpler, so that it is possible to un-whiten the bits to create CW tones using commercial BLE transmitters. This enables the ambient BLE backscatter system enjoying the benefits of dedicated backscatter systems. The state-of-the-art Wi-Fi backscatter systems are more complicated, and the latest high data rate versions can only operate on legacy non-OFDM Wi-Fi waveforms, and the un-whitening in multicarrier schemes is complicated. In addition, it requires two Wi-Fi receivers, to be tuned to different Wi-Fi channels, in order to extract BackCom raw data bits [32]. Current FM backscatter systems suffer low data rate and relatively limited uplink distance, and LoRa backscatter tags are still complicated making them difficult to be powered with ambient RF energy alone. With the understanding of the pros and cons of these ambient BackCom systems, the authors envision some future research trends, which are listed as below;

1) From the hardware of BackCom tag’s perspective:
   - It can be useful to design a simple yet reconfigurable backscatter tag circuitry which can be adapted for different ambient signals at a set of selected frequency bands. This has potential to massively increase of volume of tag production which will lead to lower tag and system costs;
   - The possibility of 2-D or even 3-D printed BackCom tags, especially in low cost and flexible materials, could further reduce the fabrication cost in mass production;
   - In order to enable truly power autonomous BackCom tags, the ambient energy harvesting strategy needs to be carefully integrated. Since the ambient RF energy harvesting commonly suffers from low efficiency due to extremely weak ambient energy density, a strategy of harvesting energy from multi-modal sources is preferable. The approach to efficiently coordinate and manage multi-source energy harvesting is critically needed.

2) From signal processing or waveform synthesis’ perspective:
   - It is useful to develop a universal BackCom receiving strategy. The data or sample accessibility in commercial receivers should be better understood in order to develop a more sensitive and flexible receiving processing algorithms;
   - More generic than InterScatter proposed in [39], different forms of physical layer waveform translation among various wireless protocols should be enabled using backscatter mechanisms, avoiding more power-hungry active solutions in current practice.

3) From physical-layer and MAC-layer protocols’ perspective:
   - Physical-layer and MAC-layer of BackCom networks are required to accommodate massive individual and/or distributed collaborative BackCom links such that the important applications like decision fusion and/or distributed inference [76] can be made a reality;
   - Security strategies, both for BackCom network access authentication and link information integrity [77], need to be incorporated;
   - Combining BackCom technology with Intelligent Reflecting Surface (IRS) [78] is an attractive research direction since IRS has been identified as a disruptive technology for future high-throughput wireless networks [79];

Table 3. Summary of Reported Ambient BackCom Prototypes that are Compatible with Commercial Transceivers (TRxs).

<table>
<thead>
<tr>
<th>Refs</th>
<th>Year</th>
<th>Commercial TRxs</th>
<th>Key Components in Tags</th>
<th>Key Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>[27]</td>
<td>2014</td>
<td>Wi-Fi (802.11b)</td>
<td>MCU + RF switch</td>
<td>100 bps @ 65 cm; 1 kbps @ 30 cm</td>
</tr>
<tr>
<td>[30]</td>
<td>2019</td>
<td>Wi-Fi (802.11g)</td>
<td>FPGA + IQ backscatter modulator</td>
<td>5.2 - 16 Mbps aggregate throughput for 48 concurrent tags; 110 kbps @ 100 m (LoS); 440 kbps @ 35 m (LoS); 60 µW (ASIC simulation)</td>
</tr>
<tr>
<td>[32]</td>
<td>2016</td>
<td>Need two Wi-Fi receivers (802.11b)</td>
<td>FPGA + IQ backscatter modulator</td>
<td>Up to 0.3 Mbps; 200 kbps @ 54 m; 33 µW (Theoretical simulation)</td>
</tr>
<tr>
<td>[33]</td>
<td>2020</td>
<td>Need two BLE receivers (802.11b)</td>
<td>65nm CMOS ASIC</td>
<td>Maximum 2 Mbps; 21 m in monostatic arrangement; 28 µW</td>
</tr>
<tr>
<td>[38]</td>
<td>2017</td>
<td>Need two BLE receivers</td>
<td>FPGA + RF switch</td>
<td>Up to 60 kbps; up to 13 m; 30 µW (ASIC simulation)</td>
</tr>
<tr>
<td>[45]*</td>
<td>2022</td>
<td>BLE</td>
<td>FPGA + RF switch</td>
<td>Goodput over 250kbps @ 12 m; Up to 3.2 kbps; ranges of 1.5 to 18 m; 11 µW</td>
</tr>
<tr>
<td>[49]</td>
<td>2017</td>
<td>FM</td>
<td>65 nm CMOS ASIC</td>
<td>284 bytes every 17 mins; downlink up to 1.1 km; 20µW (Theoretical simulation)</td>
</tr>
<tr>
<td>[58]</td>
<td>2018</td>
<td>LoRa</td>
<td>FPGA + RF switch + 2 antennas</td>
<td>11.27 kbps for 101 tags; downlink up to 2.2 km; 320 µW</td>
</tr>
<tr>
<td>[75]</td>
<td>2021</td>
<td>LoRa</td>
<td>MCU + DAC + VCO + RF switch</td>
<td></td>
</tr>
</tbody>
</table>

* The works in [40–45] are from the same research group and they follow a similar principle, thus only the latest work [45] was listed here.
• Anti-collision direct tag-to-tag communications and interference-resilient decoding and protocols are useful to enable future networks of the co-existence of massive BackCom tags and ambient legacy wireless devices.

4. Conclusion

This paper provided a review on recent ambient BackCom systems from signal waveform synthesis perspective. In particular, for indoor applications Wi-Fi and BLE compatible ambient BackComs were presented, while for outdoor applications FM and LoRa compatible systems were elaborated. For each category, they were discussed largely in chronological order, so that the trend for future development can be sensed. The authors believe that the tradeoff among power, data rate, and link distance will always present, though weighted differently in a vast number of potential applications to enable future everything-connected smart infrastructure.

Acknowledgments

Y. Ding’s work was supported in part by the EPSRC (UK) under Grant EP/V002635/1, and in part by the Royal Society International Exchange Award, UK, under grant number IECN5FC21111.

References


