Towards Wide-area Backscatter Networks

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ABSTRACT

Backscatter communication —reflecting or absorbing ambient wireless signals — enables transmissions at several orders of magnitude lower energy cost when compared to conventional low-power radios. The past few years have seen signficiant progress with systems demonstrating the ability to synthesise transmissions that are compatible with WiFi, ZigBee or BLE at µWs of power consumption. However, these systems achieve a maximum communication range of tens of meters which severely limits the possible applications. On the other hand, our recent system LoRea demonstrates that backscatter communication can achieve a significantly longer range reaching upto a few kms when the tag is co-located with the carrier source. In our vision, such a large range could be a key enabler to develop wide-area networks of battery-free sensors. In this paper, we build on our system LoRea and identify issues of improving the reliability of weak backscatter links, increasing the range and supporting the operation of multiple tags as the key challenge to our vision, and present our preliminary efforts to address them.

KEYWORDS

Battery-free sensors, Backscatter, long range communication, LoRa

1 INTRODUCTION

The past few years have seen significant interest in deploying wireless low-power systems that achieve large communication ranges. Wireless standards like LoRa, SigFox and NB-IOT are being widely deployed, and enable applications such as smart cities, and industrial monitoring. One of the key challenges these applications face is the relatively high energy consumption to enable long-range wireless networks. High energy consumption forces the sensors to operate on batteries. The use of batteries is, however, challenging due to the logistics involved in replacing them. Energy harvesting is difficult because of the size of energy harvesters such as solar cells required to operate traditional radios.

Backscatter communication, that is transmissions by reflecting ambient wireless signals, enables wireless communication at a power consumption several orders of magnitude lower than traditional radios. This transmission method is emerging as the mechanism of choice to provide wireless connectivity to sensors operating on harvested energy. However, till recently, the challenge in using backscatter communication was its relatively short communication range. For example, RFID provides a range of a few meters, whereas recent works that employ standard wireless protocols like BLE [4], ZigBee [8] and WiFi [3] achieve a range of tens of meters.

On the other hand, LoRea [16] demonstrates for the first time that backscatter can achieve communication ranges as long as few kms while consuming µWs of power at the tag. LoRea, overturns notion of backscatter transmissions being a short range communication mechanism. LoRea, uses narrow bandwidth FSK backscatter, and shows the ability to communicate to distances as high as 3.4 km while consuming 70 µWs at the tag with co-located carrier source. Similarly, in a concurrent released work to LoRea, Talla et al. [14] demonstrate that LoRa backscatter —based on Chirp Spread Spectrum (CSS)— when in proximity to a carrier source can achieve a communication range of 2.8 km. Such high ranges combined with ultra-low power transmissions dispels the assumption that wireless communication in the range of hundreds of meters requires transmitting radios on sensor devices to consume mWs of power.

We envision that the long range possible with backscatter communication can enable wide-area networks of battery-free tags. Such a network could consist of a vast number of tags dispersed over a large geographical area, with multiple carrier generators providing the necessary carrier signal. The ultra-low power nature of the transmission mechanism could enable operations from minuscule amounts of energy harvested from the environment, e.g., using tiny solar cells. However, while the long communication range and ultra-low power consumption is a key enabler, there are several unsolved challenges that hinder deployment. We build on our system LoRea and present our efforts to identify, and to solve, some of the challenges to enable wide-area backscatter network.

One of the key challenges to enable our vision is to improve the reliability of the backscatter links. This is difficult due to the extremely weak signal strengths that are inherently prevalent when communicating over long distances. For example, our system receives backscatter transmissions as weak as −124 dBm, which is 40 dB weaker than the lowest detectable signals for modern WiFi transceiver TI CC3200. The challenge is that operations at such low

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signal strengths may result in high bit error rates (BER). To ameliorate the particular issue, we improve the reliability of FSK backscatter systems by implementing forward error correction (FEC) and Direct Sequence Spread Spectrum (DSSS) mechanisms at the backscatter tag. Our initial results demonstrate that these mechanisms help to improve reliability especially when operating at low signal conditions. Furthermore, we also improve the maximum communication range achieved due to gains achieved by using such a coding.

The second challenge to our vision is to mitigate the harmful effects of in-band and out-of-band interference, particularly also from the carrier signal. Existing backscatter systems [3, 16] use heterodyning to keep the carrier and the backscattered signal apart in frequency to reduce self-interference. However, this causes out-of-band interference from the carrier signal. To reduce such interference from the carrier signal, we investigate the effect of transceiver filter bandwidth to reject out-of-band interference. We show that a small bandwidth ensures significant out-of-band rejection even at small frequency offsets which supports more efficient use of the spectrum. Furthermore, the tags themselves operate in spectrum that is shared with other devices, which can cause in-band interference. We show that DSSS mechanisms devised over FSK backscatter improve resilience against such in-band interference.

Finally, support for concurrent transmissions from tags is crucial to any wide-spread deployment. There exists a significant body of work that devises mechanisms to support concurrent transmissions [7, 11]. However, tags in these systems backscatter at the same frequency, and require significant processing at the reader device to recover information from collided backscatter transmissions. In this paper, we instead leverage hetrodyning to allocate each tag a distinct transmit frequency helping to support concurrent transmissions. We devise a mechanism to share the medium using a scheme similar to frequency division multiple access (FDMA). Our results show that it is possible to have tags transmit concurrently without incurring collisions that are prevalent in traditional designs [7, 11].

2 BACKGROUND AND RELATED WORK

In this section we present some necessary background aspects along with a brief overview of the most relevant related work.

Ambient backscatter. Ambient backscatter leverages radio signals such as TV signals [9, 12] to dispense with the need for an external reader or a device to generate the external carrier. Ambient backscatter, however, is limited to operate only in the vicinity of TV towers where the signal is strong (approx. −30 dBm) with a limited range of 30 m [12]. Thus, with the current state of the art it is difficult to achieve wide-area networks using ambient backscatter.

Backscatter as mixing process. Recent backscatter systems leverage the spectral mixing property of backscatter transmissions to displace the frequency of backscatter transmissions away from the carrier to reduce self-interference [3, 4, 17, 18]. This displacement reduces interference from the carrier signal on the weak backscattered reflection [3, 18]. We build upon this technique to efficiently avoid the effects of self-interference. Further, we also investigate the affect of receiver bandwidth on rejecting such interference.

Long range backscatter. There have been two approaches to achieve several km long backscatter links. The first approach backscatters LoRa transmissions to achieve a range as high as 2.8 km with a co-located carrier source [14]. LoRa uses Chirp Spread Spectrum (CSS) to improve receiver sensitivity. The second approach is used by our system LoRea, and use narrow bandwidth FSK transmissions to improve sensitivity and range. LoRea demonstrates a maximum communication range of 3.4 km with a co-located carrier source [16]. The key advantage of these approaches is that they leverage commodity radio transceivers for reception which *enables pervasive* deployment due to the very low cost (few USD) of receivers when compared to software defined radios (SDRs).

FSK vs LoRa backscatter. LoRa-based systems by using CSS modulation scheme and when operating at very low bitrates (18 bps) achieve the highest sensitivity levels among different different long-range technologies [14]. However, it is debatable if transmitting at such low birates (tens of bps) is helpful for battery-free sensors which are usually intermittently powered, and can have hundreds of power failures within a second [10]. Extremely low bitrate, tens of milliseconds of active time and intermittent operation make it challenging to transmit even a single byte of sensor readings in such scenarios. Further, LoRa as a technology, is patented by a single company [13] and requires commercial licensing agreements.

As a comparison, FSK transceivers using narrow-band transmissions achieve similar receive sensitivity to LoRa at more practical bitrates. For example, at a bitrate of 3.9 kbit/s, the sensitivity level the of LoRa transceiver employed (BW 62.5 kHz, SF 6, CR 2) by Talla et al. [14] is very close to the CC1310 (RX BW 39 kHz), the FSK transceiver we employ. Further, narrow-band FSK transmissions offer other advantages. *First*, they enable better usage of the spectrum especially to support operations of multiple tags. *Second*, narrow receive bandwidth significantly reduces out-of-band interference even at a small frequency offset. For example, we can place the carrier at a small offset of 100 kHz from the receiver frequency, whereas Talla et al. [14] require an offset of 1-3 MHz. This helps to operate on regulated spectrum that is shared with other devices. *Finally*, FSK is an open technology, and allows development of the custom reliability and other mechanisms, as we demonstrate.

However, unlike established standards like LoRa, FSK lacks mechanisms required to support wide-area networks, and we precisely tackle this issue. We introduce building blocks for FSK backscatter systems to enable our vision of wide-area backscatter networks. Our present work is complementary to LoRa backscatter: at the moment it is unclear which of the long distance technology will be widely adopted, especially for battery-free sensors.

3 CHALLENGES AND DESIGN

In this section, we identify and discuss our efforts to develop building blocks to enable wide-area backscatter networks.

3.1 Improving reliability and range

One of the crucial design elements to enable long-range backscatter systems is to use low-cost commodity transceivers with very high receive sensitivity. For example, LoRea receives using a transceiver with a minimum sensitivity level of −124 dBm.

The extremely low signal levels prevalent when communicating over large distances introduces challenges to maintaining the reliability of the backscatter links. The issue is exacerbated by interference from the carrier signal, and even harmonics generated from

Table 1: Spreading codes used to improve ability to mitigate in-band interference, and also improve range.

Spreading mode	Symbol 0	Symbol 1
1X	0	1
2X	00	11
4X	1100	0011
8X	00111100	11000011

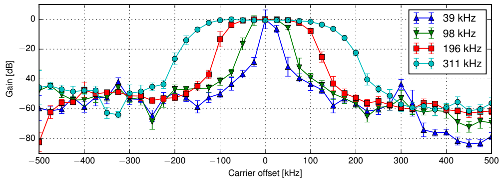


Figure 1: *Out-of-band interference rejection ability*. A large receiver bandwidth results a in lower out-of-band rejection. 39 kHz bandwidth is sufficient to attenuate a carrier 150 kHz away by 60 dB.

backscatter transmissions [14]. Hence, it is important to develop mechanisms to improve the reliability of backscatter links.

To improve the reliability of FSK backscatter links, we implement widely used forward error correction (FEC) mechanisms [15]. We implement a 1/2 rate non-systematic non-recursive convolutional encoder with a constraint length of $K = 7$ and the following polynomials: ($g^{(0)} = [1, 0, 0, 1, 1, 1, 1], g^{(1)} = [1, 1, 0, 1, 1, 0, 1]$). The code outputs two symbols for each data bit. We implement this particular encoder because of two reasons: *First*, convolutional codes have been widely used for almost half a century to enable reliable long distance wireless links [5]. Convolution codes can be easily generated using digital logic elements which helps to keep the power consumption at the tag to be µWs. *Second*, many commodity transceivers, including the one we employ CC1310, supports convolution codes which reduces complexity of the reception logic.

3.2 Mitigating in-band and out-of-band interference

Mitigating interference is crucial to the operation of any wide-area network. There are two primary sources of interference that backscatter networks encounter:

1. The carrier signal required to enable backscatter transmissions contributes to out-of-band interference. Recent backscatter systems [3, 4, 8, 14, 16] keep the carrier and the backscatter signals apart to significantly reduce this interference.
2. Receptions at very weak signal strengths aggravates the issue of in-band interference from unregulated traffic operating in the same frequency band.

To mitigate the harmful effects of in-band interference, we devise a spreading mechanism similar to DSSS. To mitigate out-of-band interference —for example from the carrier signal— we leverage the adjacent channel rejection abilities of radio transceivers similar to existing systems [3, 8, 14]. This, however, is challenging as the attenuation of the carrier, and thus the resulting interference, depends on the frequency offset of the carrier and the receiver bandwidth. While the effect of the frequency offset is well studied [3, 16], the impact of receiver bandwidth is largely unexplored. We advocate to keep the receiver bandwidth small to ensure significant out-of-band interference rejection.

Table 2: Communication range achieved when tag and carrier generator are separated by a distance of 1 m with carrier signal of strength 24 dBm.

Transmission mode	Maximum achieved distance
FEC and Spreading 8X	1.35 km
FSK	1.05 km

Direct-sequence spread spectrum. Bit spreading is commonly employed in protocols like WiFi and ZigBee to improve resilience to interference, and to improve the sensitivity level of the receiver due to the coding gain. State-of-the-art backscatter systems have also leveraged spreading to improve range and resilience, e.g., Parks et al. improve their tag-to-tag range to approximately 30 m [12] using a coding mechanism. To achieve the aforementioned benefits, and improve the reliability of FSK backscatter links, we also devise a direct-sequence spread spectrum (DSSS) scheme with the spreading sequences shown in Table 1. We assign a known chip sequence to each transmitted symbol. For example, with a spreading mode of 8X, we spread the symbol 0 to the sequence 11000011, and the symbol 1 to the sequence 00111100.

However, spreading each of the symbols to a chip sequence further decreases the effective data rate. With a spreading factor of 8 and a chip rate of 3000 bit/s we can achieve data rate of 187.5 bit/s (=3000/8/2). However, tags are usually powered from ambient sources, and operate on small energy storage such as capacitors that keep the device active for a very short duration [10]. Low data rates due to DSSS, could make it difficult to transmit even few bytes of information. In such scenarios, the tag could select the best spreading mode based on the prevailing link conditions and the available energy in the capacitor. We leave a more detailed analysis of this trade-off to future work.

Receiver bandwidth. Receiver bandwidth is a crucial parameter since it dictates the bandwidth of the signal that can be received. More importantly, the parameter controls the ability of the transceiver to reject out-of-band interference. We next perform an experiment to understand the impact of the receiver bandwidth on the out-of-band interference rejection ability of the receiver.

We set up an SDR to perform a frequency sweep over a 1 MHz range centered on the receiver's tuned frequency f_c. Meanwhile, the receiver records the received signal strength at the different carrier offsets. We perform the experiment for four different filter bandwidths, i.e., 39 kHz, 98 kHz, 196 kHz and 311 kHz. Figure 1 depicts the result normalized to the minimum rejection which naturally occurs at zero offset. The figure shows that for the same frequency offset, the ability to attenuate the carrier signal decreases with higher filter bandwidth. Thus, there is an implicit tradeoff between the out-of-band rejection ability, and employed bitrate. Hence, we conclude that to ensure maximum out-of-band rejection the smallest receiver bandwidth should be used.

A filter bandwidth of 39 kHz results in an out-of-band rejection as large as 60 dB at an offset of 150 kHz. As a comparison, transceivers for commodity protocols demonstrate a similar rejection capability at a frequency offset a few MHz away [3, 4, 18]. Furthermore, this filter bandwidth also helps to improve the sensitivity of the receiver. Hence, in our experiments we leverage the particular filter bandwidth of 39 kHz. To keep the backscatter signal within the bandwidth, we operate at low bitrates of around 3 kbit/s. We use

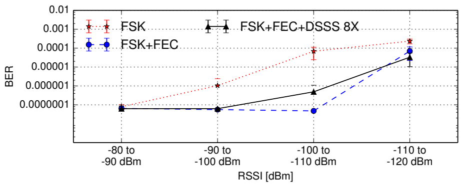


Figure 2: *Reliability under spreading*. Spreading with FEC improves reliability over FSK transmissions when operating near low SNR.

FSK as a modulation scheme and employ a frequency deviation of 13 kHz between the two frequencies corresponding to bit 0 and 1.

3.3 Supporting concurrent backscatter transmissions

Multiple access is commonly addressed by either multiplexing the medium into channels (e.g., TDMA, FDMA, CDMA), or by coordinating channel contention using channel sensing and collision detection. Backscatter tags in most existing systems transmit at the same frequency, and encounter collisions that requires complex reception logic [7, 11]. To support multiple access, we exploit hetrodyning and the out-of-band rejection ability to support simultaneous transmissions from tags without collisions.

Concurrent transmissions using dedicated channels. FDMA schemes divide the spectrum into a number of channels, where each channel is allocated to a single link. The key challenge is to plan the frequency of the channels in such a way that they are separated enough to limit out-of-band interference from each other but close enough to use the spectrum efficiently.

We leverage out-of-band channel rejection ability of transceivers to space channels at 50 kHz offset, a value slightly larger than the receiver bandwidth. At this spacing, we observe an out-of-band rejection ability of approx −40 dB. Each of these channels can be allocated to one or more devices. In a large scale deployment, it could be challenging to allocate each device a separate sub-channel. In such deployments, we might have to devise more complex medium access mechanisms which we leave to future work.

4 PRELIMINARY RESULTS

In this section, we discuss preliminary results achieved with our design. We focus on improvements in reliability and range, and the support of multiple uncoordinated tags.

Implementation. We implement our system based on the ultra-low power design we have presented earlier [16]. The tag generates FSK transmissions, at a power consumption of 70 µW when operating at 2 V. As a carrier generator and receiver, we leverage the Texas Instruments CC1310 radio transceiver. We select it because of its high sensitivity, and its support for DSSS and FEC operations. To generate the carrier signal, we use the test mode present on the module together with an external amplifier.

Experimental setup. We perform the experiments in two different environments. To investigate the maximum communication range, we perform the experiment outdoors in an open field with trees and other vegetation. We perform all other experiments in the university building, which spans several floors. In our experiments, we generate a 24 dBm carrier signal. The carrier generator features an omnidirectional antenna with 3 dBi gain, while the backscatter tag has an antenna with a gain of 8 dBi. We note, the carrier strength is significantly lower compared to recent systems [3, 14]. As the range scales with the carrier strength, we expect significantly longer ranges with stronger carrier signals. We send over 500 packets with a randomly generated payload of length 36 B in each independent instance of the experiment. We perform at least three instances of each experiment. We keep the backscatter tag and the carrier generator 1 m apart as others have done previously [3, 4].

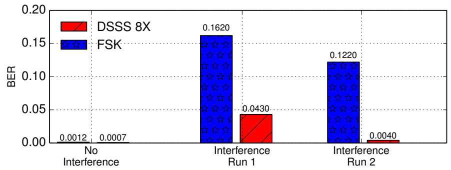
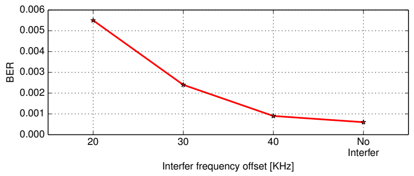


Figure 3: *Reliability under in-band interference.* Reliability mechanisms (FEC+DSSS 8X) improve reliability under in-band interference when compared to FSK transmissions.

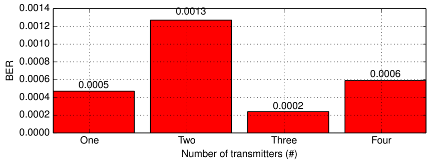
Link reliability. First, we investigate whether spreading and FEC mechanisms improve the reliability of backscatter links. In the experiment, we configure the tag to transmit with three different modes, i.e., FSK, FEC, and finally DSSS 8X. To vary the link conditions, we move the tag and the carrier generator inside the building. To achieve the lowest signal levels, we place the tag in the ground floor of our university building. The receiver is located in our offices on the third floor, and is not moved. We calculate the bit-error rate for each mode. Figure 2 demonstrates the result of the experiment. When the link conditions are good, i.e., the RSSI is between −80 dBm and −90 dBm, all the modes achieve a low BER. On the other hand in low SNR conditions, the use of FEC and spreading demonstrates a significantly lower BER when compared to FSK. We observe slightly anomalous behaviour when RSSI was between −100 dBm to −110 dBm. However, BER for both FEC and DSSS 8X is still significantly lower than observed for FSK.

Reliability against in-band interference. Next, we investigate the resilience to in-band interference. We perform the experiment in the setup described earlier. We set up another CC1310 about 15 m from the receiver, and program the device to transmit packets at the same frequency as the receiver, thus acting as a source of in-band interference. We perform three runs of the experiment. In the first run we turn off the interferer. In the next two runs we vary the transmit power of the interferer (14 dBm, 8 dBm). Figure 3 demonstrates that in the absence of interference, both DSSS and FSK demonstrate a low BER. In the presence of interference, we achieve a lower BER with DSSS than with FSK.

Communication range. Next, we investigate whether spreading and FEC can support higher communication ranges. We perform the experiment outdoors in an open field, and keep tag and carrier generator separated by 1 m. We program the tag to alternatively transmit in the DSSS 8X and FSK mode. We find the maximum range as the distance up to which we can receive at least half of the transmitted packets (PER of 0.5 or lower). Table 2 illustrates the result of our experiment. We find the mode DSSS 8X (with FEC) achieves a communication range of 1.35 km, while with FSK we achieve a range of about 1.15 km. The results demonstrate that spreading and FEC not only improve reliability, but also improve the communication range due to the coding gain. We note, the range



(a) Reliability and frequency offset of interfering tag. A separation of 40 kHz is sufficient to enable concurrent transmissions.



(b) *Concurrent transmissions using FDMA.* Out-of-band interference rejection ability helps support simultaneous tags even at a channel spacing of 50 kHz.

Figure 4: *Supporting simultaneous transmissions.*

scales with strength of carrier signal, as we use much lower carrier strength when compared to LoRea [16] and LoRa backscatter [14], we achieve lower communication range. We leave a detailed characterization of range with the carrier strength as our future work.

Support concurrent transmissions. Finally, we investigate the ability of tags to operate on dedicated channels. We position the tags and carrier generator about 40 m away from the receiver. In a first experiment we measure the inter-channel interference for different channel separations in terms of BER. We program the reference tag to transmit on channel 868.147 MHz using FSK. Figure 4 shows that a spacing of 20 kHz is enough to achieve a BER below 1% and 40 kHz achieves under 0.1%. Next, we increase the number of transmitting tags incrementally from one to four, with an inter-channel spacing of 50 kHz. Figure 4 shows the BER in all instances of the experiment. Our experiment confirms the feasibility to support simultaneous transmissions on dedicated channels.

5 CONCLUSION AND FUTURE WORK

We have presented our efforts to devise wide-area backscatter networks. Next, we discuss further challenges to our vision and potential directions to solve them. We focus on issues related to medium-access control, and further improving communication range.

Coordinating carrier generators and tags. To enable our vision, we need to deploy several powerful carrier generators. However, carrier generators operate on spectrum shared with other devices which further contributes to wireless contention. We anticipate two key challenges: *First*, placement of carrier generators to cover a large number of deployed tags. *Second*, signalling mechanisms to ensure carrier generators synchronise with the tags and among themselves. To solve the first challenge, we can build on a large body of work dealing with the placement of cellular base stations. On the other hand, the second challenge has been only partially solved, and the efforts have concentrated on synchronising tags and carrier generators [3, 14, 18].

Improving communication range. We have presented our initial efforts to improve the range and reliability of backscatter links using DSSS and FEC mechanisms. We have used tags that, like existing systems [3, 14, 18], backscatter without any amplification. Amato et al. use reflection amplifiers to achieve a significant gain for backscatter transmissions (34 dB) while consuming only µWs [1]. We will incorporate their design to further improve the range.

Ultra-low-power receiver design. The ability to receive messages enables the design of robust medium access control mechanisms. However, receivers employed in existing backscatter systems are envelope detectors which have poor frequency selectivity [8]. Further, envelope detectors are incompatible with FSK used for transmissions and require carrier generators to transmit specialized amplitude modulated messages [3, 14]. An emerging research direction leverages the external carrier signal to act as an external local oscillator and down-convert RF signals which enables the design of ultra-low power receivers. Ensworth et al. demonstrate the ability to receive FSK-based BLE transmissions using such a design [2]. We will explore this research direction to support receptions from other types of tags, and also develop medium access control mechanisms.

Hybrid radio. Another interesting direction is to combine active radio with backscatter tags [6] in order to overcome limitations in reception. Existing medium access control protocols have been designed under the assumption of similar energy consumption for transmitting and receiving. However, when combining active and passive radios, transmitting is orders of magnitude less costly than receiving. Hybrid radios also demonstrate asymmetric abilities in terms of achievable range [6]. Designing medium access protocols under these conditions is an interesting research challenges.

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