Enabling Ambient Backscatter Using a Low-Cost Software Defined Radio

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***Abstract*—Ambient backscatter communication enables ultra-low power wireless transmissions and is hence attractive for networking devices which operate on harvested energy. The data to be sent is modulated on an ambient signal, such as TV signals. Tag-to-tag backscatter communication requires rather strong ambient signals to achieve acceptable error rates and range. In this paper, we present a design and implementation of a backscatter receiver on a extremely low-cost software defined radio plattform (RTL-SDR), achieving higher sensitivity than state-of-the-art backscatter tags and thus enabling wide area ambient backscatter communication from low-power tags. Our measurements show that the TV signal is strong enough in most parts of a mid-sized Swedish city for our system to operate and communicate.**

I. Introduction

Backscatter communication enables wireless transmissions at an energy consumption several orders of magnitude lower than traditional radios. Backscatter achieves ultra-low power wireless transmissions by reflecting or absorbing ambient wireless signals, which consumes only µWs of power [4]. As a consequence backscatter communication is emerging as the mechanism of choice to network devices operating on harvested energy. Over the past few years there has been significant progress to make backscatter a viable mechanism to network Internet of Things (IoT) devices. Traditional backscatter systems, like RFID readers, required a dedicated device to generate the necessary carrier signal reflected by the tags. On the other hand, state-of-the art systems does away with the need for a dedicated device to generate carrier signals. Recent backscatter systems leverage the already deployed infrastructure such as WiFi [2], [11] or TV towers [4], [6] to generate the carrier signal.

Recent backscatter systems demonstrate the ability to leverage existing signals, such as TV, as the source of both carrier and energy. For example, Liu et al. present a proof-of-concept system that reflects ambient TV signals and enables tag-to-tag communication up to almost a meter. Parks et al. further improve the communication range to several meters by using analog coding [6]. While these systems can enable many applications, they are severely restricted to operate in the vicinity of television towers where ambient signal are sufficiently strong (approx $-30\,\mathrm{dBm}$). This is primarily due to the poor sensitivity of the receivers employed on these devices, which together with weak backscatter reflections severely limits the operating range from the tower. Furthermore, TV signals are known to vary greatly in strength [10] both over space, and in time, which further aggravates the problem of the limited range of ambient backscatter systems.

On the other hand, Software Defined Radios (SDRs) are powerful devices, and also have significant processing abilities. These devices offer high sensitivity levels, as compared to the receivers employed on typical ambient backscatter tags. Thus, SDRs might help to significantly improve the communication range, and also coverage area to receive ambient backscatter transmissions. Moreover the I/Q demodulator ICs, which represent the heart of an SDR system are very cheap as they are used a lot in digital communication. We are confident to be able to accelerate the research in the backscattering field, since we introduce a backscattering equipement, which is easily affordable by any student.

In this paper we explore the following questions: Can we leverage an SDR-based receiver to receive ambient backscatter transmissions?, and, Does the relatively high sensitivity of SDR receivers improve the range and coverage of ambient backscatter systems? A positive answer to the above questions would provide a flexible and low-cost experimentation platform to the wider research community to explore ambient backscatter systems.

Contributions. In this paper, we make the following novel contributions:

- We design the first system that leverages a low-cost SDR to receive ambient-backscatter transmissions.
- We demonstrate ambient backscatter using TV signals to be feasible in wide parts of a city. The range represents a significant improvement over the state-of-the-art, whose coverage area is restricted to close to the TV towers.

The paper proceeds as follows. First, we discuss relevant background information of backscatter communication, SDR and reception process. Next, we present the design of the transmitter and the receiver employed in this paper. We then present initial results which evaluates our system. Finally, we present concluding remarks.

II. Background

In this section we introduce some necessary background related to our work.

A. Quadrature Demodulation

Quadrature demodulation is the major feature of the *RTL2832U*, which makes it possible to decode a digitally amplitude- and phase-shifted signal. The received signal (behind the tuner at the input of the *RTL2832U*) can be interpreted as

$$s_{\mathrm{RF}}(t) = I(t) \cdot cos(\omega_0 t) + Q(t) \cdot sin(\omega_0 t) \tag{1}$$

This is multiplied with a cosine of the carrier frequency from a local oscillator.

$$\begin{aligned} s_{\mathrm{RF}}(t) \cdot s_{\mathrm{LO}}(t) = I(t) \cdot cos(\omega_0 t) \cdot cos(\omega_0 t) \\ + Q(t) \cdot sin(\omega_0 t) \cdot cos(\omega_0 t) \end{aligned} \tag{2}$$

With $2\,cos(a)cos(b) = cos(a-b) + cos(a+b)$ and $2\,sin(a)cos(b) = sin(a+b) + sin(a-b)$ follows

$$\begin{aligned} 2 \cdot s_{\mathrm{RF}}(t) \cdot s_{\mathrm{LO}}(t) = I(t) \cdot \big[1 + cos(2\omega_0 t)\big] \\ + Q(t) \cdot \big[sin(2\omega_0 t) + sin(0)\big]. \end{aligned} \tag{3}$$

One can see, that the interesting in-phase part (I) in this case is represented by a DC value after mixing. With a low-pass filter this DC value can be separated from the undesired rest. An analogous procedure is done with the quadrature part (Q) when mixing with a sine.

B. *Backscatter Transmissions*

Consider an unmodulated carrier wave impinging on a backscatter tag's antenna. In the presense of an umodulated carrier. The signal observed by the receiver is:

$$S_r(t) = S_{rc}(t) + \sigma B(t) S_{bc}(t) \tag{4}$$

where $S_{rc}(t)$ is the signal coming directly from the carrier generator and $S_{bc}(t)$ is the signal from the carrier generator that reaches the backscatter tag. σ is the tag's radar cross section and $B(t)$ is either zero or one and represents the instantaneous state of the backscatter tag: absorbing or reflecting, respectively.

Equation (4) reveals an important issue for backscatter communication systems: self-interference. The carrier signal $S_{rc}(t)$ interferes at the receiver with the data-carrying signal from the tag, $\sigma B(t) S_{bc}(t)$.

Recent work on generating backscatter transmissions has avoided self-interference through *frequency-shifted* backscatter [1], [3], [9], [10]. The tags modulate their antenna in such a way that their transmissions occur at a certain frequency offset from the carrier signal thus allowing the receiver to avoid interference from the carrier by tuning to the offset frequency where the tag is transmitting.

Consider the case when $B(t)$ periodically alternates between its two states at a frequency Δf while an unmodulated carrier of frequency f_c reaches the backscatter tag:

$$2\sin(f_c t)\sin(\Delta f t) = \cos[(f_c + \Delta f)t] - \cos[(f_c - \Delta f)t] \tag{5}$$

If we focus on only one of the two generated images, or employ single sideband backscatter [1], the data transmission can now be received at frequency $f_d = f_c + \Delta f$.

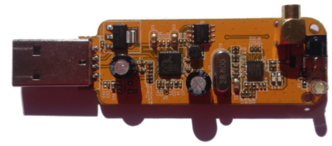

Fig. 1: *RTL-SDR* hardware with the DVB-T I/Q demodulator *Raeltek RTL2832U* (left IC) and the tuner with integrated LNA *Rafael Micro R820T/2* (right IC).

C. *RTL2832U*

The *Realtek RTL2832U* is a terrestrial digital video broadcast (DVB-T) demodulator IC, which is the main component in a wide range of USB-based DVB-T receiver dongles. One prominent feature of this chip is that it allows to retrieve the raw I/Q samples via USB. This is originally intended for the chip to work as a simple DAB/FM software receiver. Ham radio enthusiasts have combined their efforts to create a software driver (the *librtlsdr* [5]) that allows DVB-T dongles based on the *RTL2832* to be converted into low-cost wideband SDR receivers. The cost of traditional SDRs is in the range of a few hundred to thousands of USD. Albeit much less powerful than a typical SDR, a *RTL2832U*-based DVB-T receiver can be bought with antenna for less than 10 USD.

An RTL-SDR also contains a tuner that allows the user to select the received frequency. In our case the tuner is a *Rafael Micro R820T/2* which offers a tuning range from 42 to 1002 MHz [7]. Figure 1, shows a photograph of the RTL-SDR used in our work.

III. DESIGN

In this section, we describe the design of our system. We first describe the design of the transmitter, next we describe the design of the receiver.

A. *Transmitter*

We design our backscatter transmitter to be used with ambient television signals. We design the transmitter for ambient television signal present in the band with center frequency of 626 MHz. Crucial to the design of the transmitter is the implementation of an antenna, as the antennas are known to be frequency selective. To this end, we design an antenna on an unetched board made of FR4 substrate commonly used to design PCBs. The board acts like the ground plane, at the center of the board we have a wire acting as a monopole antenna element. The antenna has a quite good reflection coefficient S_{11} of -17 dB at 626 MHz, which is the frequency aimed for. This means, that arround this frequency the antenna absorbes more energy form the electromagnetic field compared to another band. A vector network analyzer (VNA) has been used to analyze antenna performance.

Backscatter operates by reflecting or absorbing impinging radio signals on the antenna. To purposefully toggle the antenna to achieve these states, we terminate the antenna to a RF switch. The RF switch enables us to alternate the impedance connected to the antenna between matched (50 Ω) and open state. We control the RF switch through an I/O pin on a low-powered MCU, Texas instruments MSP430. As discussed earlier, to reduce the effects of self-interference, we frequency-shift the backscatter transmission away from the TV signal.

Hence, we operate the RF switch using a 2 MHz intermediate frequency signal. Therefore the result is a frequency shift of the television signal by 2 MHz, when transmitting a bit 1, and no shift for a 0. Hence, we leverage amplitude modulation at receiver in our design.

B. Receiver

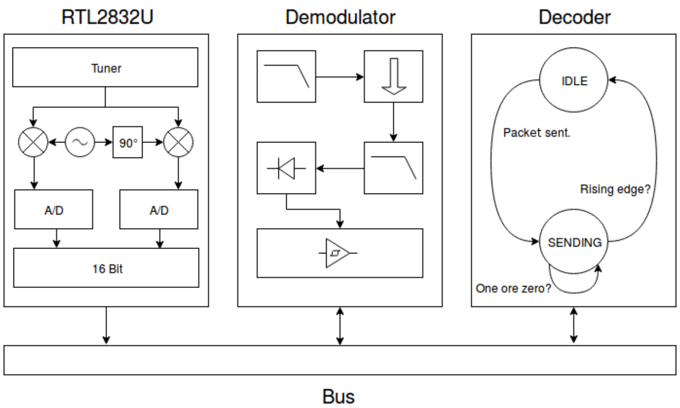

Fig. 2: *Design of the ambient backscatter receiver.* The flow of operation of the receiver is from the left to the right.

The receiver consists of three main modules interconnected by a bus. The RTL-SDR block is in charge of collecting samples from the SDR-device. The demodulator turns the sampled signal into a streams of ones and zeroes. Finally, the Decoder block is in charge of detecting frames. We provide our C++ receiver code publicly available under [8].

Figure 2 shows the architecture of our receiver, the signal flows from the left to the right. The raw I/Q data is available as two 8-bit values (real and imaginary) from the RTL-SDR. With these two values, the phase and magnitude of the data can be determined for every sample. The received signal can be represented as:

$$I + j\,Q = abs(I, Q) \cdot e^{j \cdot ang(I,Q)} \tag{6}$$

So the first block, entitled RTL2832U, provides the interface to the TV dongle. It controls the frequency f_{tuned}, where the receiver is listening as well as other interesting parameters e.g. the analog gain.

The demodulator block is responsible for converting the sampled signals into ones and zeroes. As part of the demodulation process the signal is down-sampled and low-pass-filtered two times. The last demodulation step is to rectify the signal (cf. equation 7) and decide with a software-defined Schmitt trigger whether a sample is a 1 or a 0.

$$abs(I, Q) = \sqrt{I^2 + Q^2} \tag{7}$$

The resulting values are sent through the bus to the decoder. After the decoder received the samples it decides if a frame is received or if the channel is idle. The decoder also includes a function to correlate the received bitstream with an expected pattern. Hence it is able to determine the bit error ratio (BER). Furthermore we have implemented a series of aditional tools that include different simulators for e.g. playing back recorded data and a tool (an oscilloscope) to plot the data, which is written into files by the demodulator. An example of a recorded data stream with 25 kS/s can be seen in Figure 3.

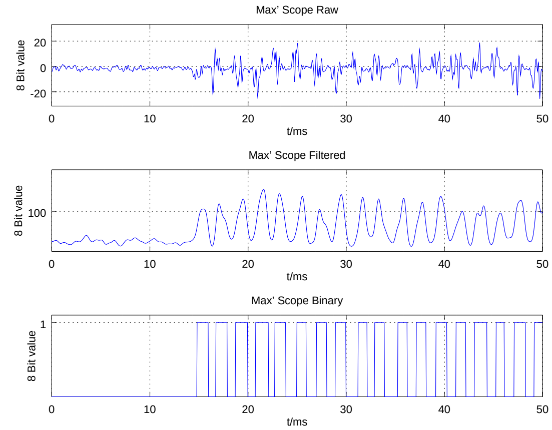

Fig. 3: *Plots from Octave oscilloscope showing the start of a transmission of 101010..* In the top plot one can see the raw analog signal, in the middle plot the filtered signal and finally at the bottom the signal after processing though the Schmitt trigger. The amplitude is quite low with an average of 12 % of the maximum, which is 127.5 due to a low signal strength. Sampling frequency is 25 kHz.

IV. Evaluation

In this section, we present the results of evaluation of our system. As experimental setup, we use RTL-SDR together with a signal processing algorithm implemented in Octave.

A. Spatial variation of ambient television signals

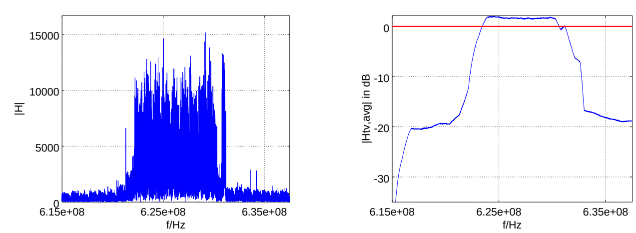

Fig. 4: *Observed spectrum of television signal*. The left hand image shows the raw spectrum of the TV signal, with centre frequency of 626 MHz. The right hand image shows the smoothed spectrum normalized to maximum average. The average is shown by the horizontal red line.

In this experiment, we investigate the variation of the television signal in space, i.e., how does the strength of the signal varies over the area of the city. We use the RTL-SDR reader to obsevre the signal strength. We perform the frequency sweep of the desired television band. Next, we obtain the sample in the time domain, and convert them to corresponding samples in frequency domain by performing fast-fourier transformation (FFT).

As we are not interested in realtime visualisation of the television signals, we acquire the signals offline and visualise the samples. RTL-SDR has a maximum sampling rate of 2.4 MS/s, which limits us to scanning a band of 1.2 MHz band in a single run. We keep some safety-margin, and sample the desired band at 900 kHz intervals. We sample the band 20 MHz

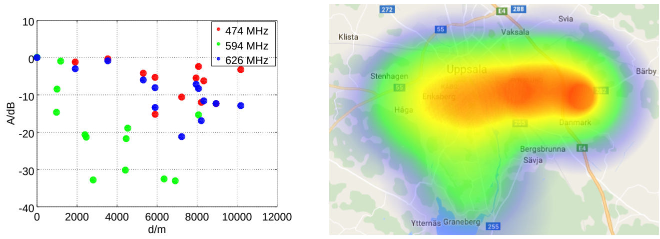

Fig. 5: *Spatial variation of TV signals in Uppsala city*. The left image demonstrates the signal strength of TV signal fading as opposed to observed signal strength near the TV tower. The right image visualises the signal strength as heatmap for the signal present in the 626 MHz band. Distances have been calculated with the Haversine formula.

wide, by stitching individual bands. In our experiments, it takes roughly 30 seconds for us to perform the scanning operation.

During the scanning process the gain is set to 40.2 dB. To get the signal strength we simply take the average over a 10 MHz band around the center frequency of the desired TV signal. This approach can be justified by the fact, that DVB-T 2 is specified up to 10 MHz bandwidth. And the local TV provider advertises to be transmitting DVB-T 2. The signal $|H|$ is calculated as follows.

$$|H| = \left| \sum_{n=0}^{N} FFT\Big(\Re\{s_{\text{band,n}}(t)\} \Big) \right| \tag{8}$$

where N is the total number of intervals accumulated over the entire frequency sweep. The FFT is only carried out over the real values, which are received from the *RTL-SDR*. $s_{\text{band,n}}(t)$ is the signal in the time domain of one interval (one subband). There are as many samples taken in one band as needed for an FFT of size 2048. To finally get $|H_{tv,avg}|$ one has to normalize everything and calculate the power. Before doing that, a simple smoothing algorithm (FIR) is applied on $|H|$.

$$|H_{\text{tv,avg}}| = 20 \cdot log(|H|) - 20 \cdot log(|H_0|) \tag{9}$$

where $|H_0|$ is a normalization value measured at a certain point in space.

Figure 5 demonstrates the result of combing the measured signal strength values, together with the haversine function enables us to calculate the distance from the point where the maximum signal has been captured. The fast fading of the signal has been proven to be highly fluctuating, but it is still hight enough to enable backscattering.

B. Communication Performance

In this experiment, we present some preliminary results to evaluate the communication performance of our system. In the experiment, we varied the bitrate of the transmitter from 1 bit/s up to 1 kbit/s. As we had seen earlier in the Figure 3, the strength of the backscattered signal is rather low leading to the appearance of significant quantisation noise. The experiments have been carried out with the maximum gain available from the tuner of 50 dB.

In an indoor environment, where the ambient signal strength is low, we are able to achieve a data rate of 1 b/s with distances of couple of meters. At higher bitrates, we observe a range of a few decimeters and the bit error rate is still approximately 40 %. We observed similar results outdoors. We acknowledge the high bit errors observed due to primarily limited gain available on the low cost dongles. In future, we will work to improve this. We note, existing ambient backscatter systems do not operate well indoors at large distances, and our results provide preliminary results of improvements possible by leveraging low-cost SDRs.

V. Discussion

Our system still has a lot of room for improvement. Different backscattering antennas could be tried to find the one with the best combination of gain, tuning frequency and bandwidth. Moreover the standard *RTL-SDR* antenna and its coaxial cable are of low quality. Hence a custom antenna would be beneficial. Furthermore some fine tuning can be made when it comes to the filter coefficients of the different filters in the demodulator chain. Finally errors can be further reduced by using one of many available forward error correcting codes.

We have shown, that spectrum scanning over a wide band with sweeping is possible using the *RTL-SDR*. This allowed us to perform a survey of the TV signal strength in the city. We found that the signal strength around most of the city is adequate for backscatter communication using our receiver. And finally we have shown for the first time, that backscatter communication is possible with the *RTL-SDR*.

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