Run-Length Limited Codes for Backscatter Communication

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Abstract—In backscatter communications, ultra-low power devices signal by modulating the reflection of radio frequency signals emitted from an external source. Unlike conventional one-way communication, the backscatter channel experiences unique self-interference and spread Doppler clutter. Run-length limited (RLL) codes provide a method for spectrum shaping that requires no hardware changes to the communicating devices. The proposed coding framework is suitable for any arbitrarily-shaped pulse train or continuous wave reader waveform. It exploits the unique channel Doppler spread statistics to offer a tradeoff between interference rejection and data rate. Analysis shows that code rates of 1 and 4/5 are achievable when dealing with low spread Doppler channels, which is an improvement over the current rate 1/2 with current mainstream backscatter communication techniques. Simulation results with realistic channel assumptions are analyzed and discussed to confirm the theoretical analysis.

Index Terms-Backscatter, channel coding, clutter, wireless

I. INTRODUCTION

Backscatter communication is an emerging wireless communication method that has attracted a growing interest in recent years both in the academic community as well as in industry circles. Its key advantages of ultra-low power usage and simple design [1] of the nodes enable applications to bio-signal recording, logistics monitoring, and environmental sensing [2]–[4]. Unlike traditional communication where the information source modulates an energetic carrier waveform, a backscatter transponder (i.e., RF tag) modulates an already existing waveform coming from a stand-off transmitter [1]. This allows for a simple, low power design of the tag.

A backscatter system operates in the dyadic backscatter channel, a pinhole channel composed of a forward and backscatter link [5]. Strong spread-Doppler self-interference (clutter) at the reader masks the signal of interest coming from the backscatter tag [6].

Previous work has explored the use of coding in the backscatter channel. Error correcting codes were employed to increase the range of operation [7] and space-time coding that requires additional antennas at the reader and the RF tag has been proposed [8]. A more channel specific work considered coding for the case of simultaneous tag energy harvesting and data communication [9]. Clutter mitigation for the backscatter channel was addressed in works proposing hardware additions to the RF tag that avoid lower frequencies dominated by





Fig. 1: Backscatter communication between RF tag and a reader with common channel interferences

clutter. Such were the addition of a local oscillator [10], or the use of multiple antennas on the reader and the tag [8].

The EPC Gen-2 protocol, which standardizes radiofrequency identification (RFID) backscatter systems, offers two coding methods: Miller code and FM0. Both codes operate at a maximum rate of 1/2 designed to mitigate static clutter, but are limited to reader signals based on a continuous wave (CW) [11]. More recent work studied pulse based linear frequency modulated (LFM) transmitted waveforms from the reader and using differential coding at rate 1, that targeted static clutter mitigation [6].

We propose the use of coding to avoid Doppler-spread interference in the backscatter channel. A coding framework based on run-length limited (RLL) codes is developed to allow for Doppler spectrum shaping of the RF tag message signal. The resulting Doppler spectrum shaping effectively pushes the RF tag signal away from the clutter interference, thus providing resilience against the clutter impairment (see Fig. 2). Moreover, the framework enables a tradeoff between interference mitigation and data rate. Simulations compare the performance of different RLL codes and their effectiveness in mitigation of spread-Doppler clutter and interference.

II. BACKSCATTER COMMUNICATION SIGNAL MODEL AND CARRIER REMOVAL

Backscatter communication consists of a reader and an RF tag that signals data as shown in Fig. 1. The carrier signal

consists of an interrogating waveform generated by the reader. The illuminating waveform can be either a continuous wave (CW), which consists of a pure sinusoid [12], or as recently proposed [6], a pulse train, which consists of an arbitrarily shaped waveform. The framework developed in this paper is general and applies to either waveform.

The signal transmitted by the reader is

$$s(t) = \sum_{n = -\infty}^{\infty} p(t - nT_p) \tag{1}$$

where p(t) is a time-limited single pulse such that p(t) = 0, $t < 0 \cup T_p \le t$, T_p is the pulse duration and carrier freq. is omitted for clarity. This signal model is also a generalization of CW, as long as the pulse p(t) consists of an integer number of sinusoid wavelengths, such that the continuous phase is maintained from pulse to pulse.

The RF tag modulation is generated by a phase modulator connected to the antenna as shown in Fig. 1. It is assumed that the RF tag is provided with the energy required for the operation of the modulator. A portion of the incident interrogation signal is reflected, phase modulated and reradiated back to the reader. This operation allows information to be sent from the tag to the reader. Information sent in the other direction is outside the scope of this work. We also assume that the RF tag and the reader are either stationary or moving slowly so that the respective Doppler frequency shift is negligible within a single symbol period.

The message signal driving the RF tag's modulator is

$$m(t) = \sum_{k=-\infty}^{\infty} a_k \cdot q(t - kT_s)$$
⁽²⁾

where a_k is a constellation symbol from a finite symbol alphabet such as binary phase shift keying (BPSK) constellation, and q(t) is a rectangular pulse of duration T_s representing a single symbol period.

The reflected backscatter signal from the RF tag received at the bi-static reader with noise is

$$w(t) = \alpha(r) \sum_{n=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} p(t - nT_p - \tau) \cdot a_k \cdot q(t - kT_s - \delta) + N(t)$$
(3)

where $\alpha(r)$ is the attenuation due to the two-way backscatter path of length r, τ is the time delay associated with the twoway backscatter path of length r, δ is the phase delay between the reader clock and the tag's clock and N(t) is additive white Gaussian noise (AWGN).

The reader processes the received signal with the goal of extracting the message signal of the tag. The reader match filters the received signal against a copy of the interrogation signal. This allows removal of the reader carrier signal. When a pulse train is used as an interrogating waveform, an intermediate step also requires the reader to estimate the two-way propagation time delay τ such that the outcome is eventually identical to that of the continuous wave [6].

After processing, the signal resembles a conventional phase modulated signal

$$v(t) = w(t) * s^*(t) = \alpha(r) \sum_{k=-\infty}^{\infty} a_k \cdot q(t - kT_s - \delta) + \widetilde{N}(t)$$
(4)

where $\widetilde{N}(t)$ is N(t) passed through the matched filter.

III. SELF-INTERFERENCE AND SPREAD-DOPPLER CLUTTER MODEL

In backscatter communication the majority of interference is from reflections of the illuminating reader signal in the environment, manifesting as self-interference and spread-Doppler clutter. These interferences have a very distinctive signal structure that is highly correlated with the reader signal rather than the signaling RF tag modulation [13]. Additionally, the signalto-interference ratio is orders of magnitude weaker than what is usually found in a conventional one-way communication channel due to the relative weak return from the RF tag.

Self-interference is a result of the reader's illuminating signal propagating, reflecting and scattering (sometimes multiple times) from static elements in the environment. At the reader input, every reflection will exhibit a phase shift corresponding to the path length traveled

After the initial processing of match filtering with the interrogation signal at the reader, each of the reflections will contribute some DC magnitude offset corresponding to its phase, which is constant over time.

When considering any practical system, an assumption of a completely static environment can not hold. Backscatter channel measurements exhibit some degree of Doppler spread, as evident in the measurements in [6] and therefore a different model of clutter is needed.

Spread-Doppler clutter is the result of the illuminating signal reflecting in a dynamic environment, which include sources of movement such as turbulence and other small-scale flows [14]. With greater power and ranges of operation, the resulting channel is more exposed to spread Doppler effects.

After the receiver processing, the reflections will translate into a collection of sinusoids with their frequencies and phase corresponding with the amount of Doppler shift [6]. Since the sources of movement change their velocity over time, it is usually best to model the signal as a band-limited random process with spectral content centered around DC. Different models have been proposed in the literature [15]. However, in order to focus on the coding rather on specific clutter modeling, simulations in this work use a simplistic clutter distribution that is inversely proportional to the Doppler frequency $S(f) \propto 1/f_D$.



Fig. 2: Delay-Doppler simulation of a signaling RF tag coded with RLL(1,3) with spread-Doppler clutter (<200 Hz) at arbitrary power. Scale is in dB.

At the reader input, spread-Doppler reflections result in

$$b(t) = \sum_{n=-\infty}^{\infty} \sum_{u=1}^{U} \alpha(r_u) p(t - nT_p - \tau_u) \cdot X_u(t)$$
 (5)

where U is the number of spread Doppler clutter returns, $\alpha(r_u)$ is the attenuation due to the two-way backscatter path of length r_u , $X_u(t)$ is a random process modeling the Doppler spread reflections and τ_u is the time delay associated with the two-way backscatter path of length r_u .

After receiver processing,

$$d(t) = b(t) * s^{*}(t) = \sum_{u=1}^{U} \alpha(r_{u}) X_{u}(t).$$
 (6)

IV. DOPPLER RUN LENGTH LIMITED CODING

A. RLL codes overview

RLL coding manipulates the binary message data to limit the placement of ones in the sequence, which map to flux flips (zeros for non-flux flips). Limiting long stretches between ones controls the lower frequency content, while enforcing a minimum distance between ones controls the higher frequency content. This provides a way to shape the spectrum of the message, which provides resilience to specific channel impairments at the expense of lower data rate. Codes consist of blocks and are defined by four parameters: D,K,M,N. D is the minimum and K is the maximum number of zeroes between consecutive ones, and M/N is the rate of the code. The interested reader is referred to the extensive literature on RLL codes design and analysis, especially [16]–[18].

B. Doppler RLL encoding setup

An arbitrary bit stream is broken into blocks, whose length L corresponds to the ratio between the interrogating pulse duration T_p and the tag symbol/bit duration T_s , such that $L = T_p/T_s$ is an integer number of bits per pulse. Choosing L determines effectively the Doppler sampling rate. A higher

sampling rate will allow better mitigation of Doppler interference in the lower band near DC.

The blocks are then assembled side by side to create a rectangular matrix whose columns are time (L) and rows are pulse index (M). For synchronization purposes at the decoder, we mark these $L \cdot M$ bits as a single frame length. The matrix organization is adapted from radar pulse-Doppler signal processing [19], where the columns are dubbed *fast time* and the rows are *slow time*.

An RLL code with rate M/N is now employed over the *slow-time* rows. Note that the coding does not change the number of bits per pulse, hence no change to the hardware symbol rate is needed. The *slow-time* encoding allows the Doppler spectrum manipulation across pulses.

The next step of encoding is using non-return to zero inverted (NRZI) mapping of each row from binary to two level physical symbols, suitable for BPSK constellation modulation. The first column relates to the last column from the previous frame to maintain continuity of the differential mapping across pulses.

The matrix is then re-organized into a stream of symbols, which are then fed into the phase modulator.

The above encoding considers a pulse train interrogating signal. However, when a CW is used the presented framework is still valid by setting L = 1, such that notion of a pulse becomes unnecessary.

C. Doppler RLL decoding setup

We assume that the carrier has been removed as described in section II and the tag and receiver clocks have been synchronized.

The next step is organizing the received processed signal into the same *fast time-slow-time* matrix structure. Each column consists of the processed return from a single pulse and consecutive pulses are aligned side by side.

Next, a reverse mapping of NRZI is performed over the rows. This is done by subtracting each column from the adjacent column, which contains the next pulse return (effectively removing the differential NRZI mapping). When considering the first column in a frame, we can use the last column from the previous frame as a reference for subtraction. In addition to the re-mapping, this step effectively also performs Doppler filtering, which is discussed later in section V.

The next step is performing a matched filter for the rectangular symbol pulses q(t) and sampling the output. Then a maximum-likelihood estimation (MLE) decoding criteria is used to choose among all codewords, and infer the respective information bits. The last step is converting the matrix structure back into serial.

V. CLUTTER REJECTION

The clutter rejection is accomplished in two layers of the decoding process. The first layer is a result of the reverse mapping of the NRZI. The subtraction of two neighboring pulses inverts the differential mapping but also acts as a



Fig. 3: Run-length limited Doppler encoding and decoding process

Doppler spectrum filter. Eventually each point of the received signal is subtracted from a point exactly one pulse duration T_p apart. The second layer comes from the run-length limited coding that shapes the Doppler spectrum of the message signal and pushes it outside of the interference domain.

VI. SIMULATION RESULTS AND DISCUSSION

Since the focus of this paper is on the coding rather than on specific clutter models, a simplistic statistical model is chosen as described in section III. The clutter model allocates equal energy to spread-Doppler and static clutter. The spread Doppler clutter was synthesized by combining 5 random frequency fluctuations for every row of the encoding matrix.

The codes chosen for simulations are: RLL(0,1) with rate 1/2 (effectively this is the FM0 code proposed in the EPC Gen-2 protocol), RLL(1,3) with rate 1/2 (effectively this is the Miller code proposed in the EPC Gen-2 protocol, also known as MFM (modified frequency modulation)), RLL(0,2) with rate 4/5 and uncoded NRZI mapping for benchmark purposes with rate 1.

Fig. 4 shows how different RLL codes compare with changing power level of spread-Doppler interference in the backscatter channel. Note that choosing an RLL code provides a trade-off between interference rejection and data rate. The use of RLL(0,2) with rate 4/5, for example, provides a good balance between a decreased data rate with better interference rejection. A similar trend can be seen in Fig. 5, this time comparing different RLL codes with the spread-Doppler bandwidth of interference.

VII. CONCLUSIONS

The use of RLL codes in the unique spread-Doppler selfinterference backscatter channel provides an increase in rate by up to a factor of two. RLL codes also provides a tradeoff between interference rejection and data rate, which leads naturally to future work considering RLL coding that can adapt



Fig. 4: Robustness to spread-Doppler self-interference power of various RLL codes. Averaged over 2000 iterations, 1:1 energy ratio of static and spread-Doppler, clutter bandwidth is < 5 Hz, no noise added.



Fig. 5: Robustness to spread-Doppler self-interference bandwidth of various RLL codes. Averaged over 5000 iterations, 1:1 energy ratio of static and spread-Doppler, $E_s/P_{clutter} = -20$ dB, no noise added.

the coding rate in response to the level of Doppler spread sensed in the backscatter channel.

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