Passive DSSS: Empowering the Downlink Communication for Backscatter Systems

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Backscatter: an ultra-low-power communication solution for IoT devices

Ubiquitous connectivity
Towards 100’s of meters

Seamless communication
streaming data

Full-Duplex LoRa Backscatter [NSDI 21]
PLoRa [Sigcomm 18]
LoRa backscatter [IMWUT 17]

WiTag [Sigcomm 20]
Video Streaming [NSDI 18]
Polymorphic Radios [Sigcomm 18]
When we make backscatter practical for IoT applications…

We meet a problem…
Downlink and Uplink are highly asymmetric

- Sophisticated receiver (e.g., IQ)
- Interference cancellation

Long range backscatter (above 100m)
Downlink and Uplink are highly asymmetric

Short range downlink (typ. < 10m)

energy-constrained

- Envelope detector
- Prone to interference and noise
Downlink and Uplink are highly asymmetric

Downlink is a major limit to the effective range
Practical backscatter systems need **downlink transmissions**

channel mediation  data rate adaptation  gateway ACK  sensor control

**Downlink control is important** to backscatter systems
How to improve downlink communication?

\[ \text{SINR} = \frac{\text{Signal power}}{\text{interference} + \text{noise}} \]

1. Increase signal power
2. Suppress interference and noise
How to improve downlink communication?

1. Increase signal power
2. Suppress interference and noise

Limited Max. Tx power

Distributed MIMO:
- Multiple gateways
- need synchronization
- complexity of deployment

[NSDI’19]
How to improve downlink communication?

1. Increase signal power
2. Suppress interference and noise

We show the other way that uses spread-spectrum techniques (e.g., DSSS) to suppress interference

None of existing techniques can directly work for the downlink due to high power consumption
We propose Passive DSSS (Direct-Sequence Spread Spectrum)

- The first DSSS scheme for the downlink of backscatter devices
- Design Passive DSSS modulation at gateway
- Build a hardware prototype for Passive DSSS receiver

16.5 dB SINR improvement
3x longer downlink range
Key challenge to achieve DSSS on the downlink

- **Baseband** (contain carrier)
- Spreading code
- **DSSS signal**
- **Wireless channel**
- **Recovered signal**
- **Correlation & synchronization**
- **Local spreading code**

**DSSS demodulation**
- Spreading interference
- Recovering baseband
Key challenge to achieve DSSS on the downlink

- **Recovering baseband needs synchronization**
  - Rx DSSS signal
  - Local spreading code
  - \[ S(t) \oplus \hat{c}(t) = b(t) \oplus c(t) \oplus \hat{c}(t) = 1 \]
  - Rx baseband
  - Rx spreading code

- **Power-starving synchronization**
  - Tracking phase \( c(t) \)
  - Generating \( \hat{c}(t) \)
  - Need DSP
  - (mWs of power)

DSSS synchronization is infeasible on backscatter devices

- DSSS demodulation
  - Spreading interference
  - Recovering baseband

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Basic idea of Passive DSSS

shifting generation and synchronization of the spreading code to gateway

- channel 1: transmit the baseband after the DSSS modulation
- channel 2: transmit the spreading code reference
- both channels are synchronized at the gateway
- the receiver combines the two channels to demodulate DSSS

\[
\begin{align*}
\text{channel 1} & \quad \text{channel 2} \\
\text{Carrier 1} & \quad (\text{contain baseband}) \\
\text{Carrier 2} & \\
\text{spreading code} & \\
\text{envelope detector} & \\
\text{envelope detector} & \\
\end{align*}
\]

\[b(t) \oplus c(t) \oplus c(t) = b(t)\]
Challenge 1: cannot demodulate existing DSSS signals

Conventional DSSS uses phase modulation

Backscatter devices can only obtain amplitude information
Challenge 1: cannot demodulate existing DSSS signals

Our solution:
1. signal envelope to convey DSSS signals
2. difference between the two spreading codes to convey baseband

envelope detectors and XOR gates are available on backscatter devices
Challenge 2: how to suppress interference from both channels each channel may suffer from different interference signals

Interference from each channel

DSSS signal envelopes

Interference composition (cannot be suppressed)
Challenge 2: how to suppress interference from both channels

Our observation: low correlation of interference across two individual channels

![Interference Envelope](image)

- ~0.002
- \[ \int_0^T I_1(t) \cdot I_2(t) \, dt \approx 0 \]

one-week measurement in real environments

- record interference signals
- compute the cross-correlation

Our solution: Interference cancellation by calculating the correlation
Challenge 3: correlation calculation requires signal processing

Conventional method:
- need high precision ADC (8~12 bits)
- digital correlation computing
  - mWs of power

Our solution:
- 1-bit ADC
- analog correlation computing circuit
  - 166.5 $\mu W$ totally

received signal envelope is fully analog
Passive DSSS receiver design
Passive DSSS receiver design

- Two operations to compute correlation:
  - Multiplication (done by demodulation)
    \[ a \oplus b = a + b - 2ab \]
  - Integration (integrator circuit)

Interference cancellation

\[ \int_{0}^{T} I_1(t) \cdot I_2(t) \, dt \approx 0 \]
Experimental setup

- Antenna
- Received downlink data
- MCU for recording bit stream
- Passive DSSS prototype
- USRP
Evaluation – Performance and baseline

SNR (dB)

BER

Conventional (1 channel)

share the same hardware with Passive DSSS

conventional receiver (1 channel)
Evaluation – Performance and baseline

BER vs. SNR (dB)

- Conventional (1 channel)
- Conventional (2 channels)

 constant wave (CW) on the other channel

conventional receiver (2 channels)
Evaluation – Performance and baseline

![Graph showing BER vs. SNR for different systems.]

- **Conventional (1 channel)**
- **Conventional (2 channels)**
- **Passive DSSS (0dB gain)**

- Data rate of spreading code = baseband
- Slight propagation delay
- Mismatch between two channels
Evaluation – Performance and baseline

For next evaluations

baseline

BER

SNR (dB)

Conventional (1 channel)
Conventional (2 channels)
Passive DSSS (0dB gain)
Passive DSSS (10dB gain)
Passive DSSS (20dB gain)
Evaluation – Interference Resistance

The measured downlink throughput when RFID or LoRa interference exists.

Passive DSSS (500 KHz each channel) has higher resistance against RFID interference (100KHz) than LoRa (500KHz)
Evaluation – Downlink Range

Passive DSSS receiver

Gateway side

52 m

Gateway

Receiver side

3x improvement at “excellent” quality

Gateway side

52 m

Gateway

Receiver side

3x improvement at “excellent” quality