Improving the Range of WiFi Backscatter Via a Passive Retro-Reflective Single-Side-Band-Modulating MIMO Array and Non-Absorbing Termination

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Miniature and ubiquitous IoT devices

- Enable new class of applications
- Require miniature size, long lifetime, wireless standard-compliant
Conventional wireless transmission

- ❌ Conventional WiFi TRXs require 10s~100s mW active power
- ❌ Size of IoT devices is limited by power consumption
- ✔ Higher order modulation is achievable but trades-off with power
WiFi compatible backscatter communication

- ✔ Elimination of active RF circuit enables low power consumption
- ✔ Recent work showed compatibility with existing standards
- ✔ Higher order modulation is achievable by implementing IF switches
- ✗ Range is limited due to passive nature
Backscatter - range calculation

**Downlink:** \( P_{\text{sens, \text{wu}}} \leq P_{\text{TX,AP}} - PL_1 \)

**Uplink:** \( P_{\text{sens,AP}} \leq P_{\text{TX,TAP}} - PL_1 - PL_2 - IL_{\text{TAG}} \)

- PL1 and PL2 are determined by D1 and D2
- D1 \( \times \) D2 is limited by system parameters
Link budget - Meshed network

Worst Case

- **AP1 (TX)**
  - EIRP = 30 dBm
  - D1 = 3 m

- **TAG1**
  - D1 = 6 m
  - PL1 = 56 dB
  - IL = 15 dB
  - P_{incident} = -26 dBm
  - P_{reflected} = -41 dBm

- **TAG2**
  - D1 = ~10 m

- **TAG3**
  - D2 = ~10 m

- **AP2 (RX)**
  - D2 = 16 m
  - PL2 = 64 dB
  - P_{rx} = -105 dBm

**Worst Case**

- D1 × D2 = 96 mm²

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Wang et al., ISSCC20
Tags can work if placed anywhere in the shaded area.

Wang et al., ISSCC20
Link budget – single AP or co-located APs

- Always in the worst-case scenario
- Range improvement is needed for pragmatic adoption in homes and offices with single AP or co-located APs

- WiFi AP/
  Co-located APs
- EIRP = 30 dBm
- $P_{rx} = -105$ dBm

- IoT tag
- $D_1 = 10$ m
- $D_2 = 10$ m
- $PL_1 = 60$ dB
- $PL_2 = 60$ dB
- $P_{incident} = -30$ dBm
- $P_{reflected} = -45$ dBm
- $IL = 15$ dB

$D_1 = 10$ m
$D_2 = 10$ m
Range improvement

- **TX power**: can not be increased, standard in commodity WiFi APs and FDA limits to maximum of 30dBm

- **RX Sensitivity**: ~-100dBm is the standard for commodity WiFi APs

- **D1xD2**: cannot be improved due to the passive nature of backscatter communication

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**Improve the **insertion loss** or apply **MIMO gain** to improve the covered range**
Outline

• Motivation
• Prior-art and proposed SSB QPSK backscatter with retro-reflective MIMO array and non-absorbing termination
• Proposed fully-WiFi-compliant backscatter
• Circuit implementation
• Measurement results
• Conclusion
Conventional OOK backscatter

- Tag data modulates the input impedance via a single switch directly
- 🗑️ OOK modulation only
- 🗑️ Reflected wave spectrum overlaps with incident wave
QPSK frequency translation backscatter

- 4 phase of IF clock is selected by IQ tag data and mixed with incident signal via a single switch
- QPSK modulation
- Double-side-band modulation occupies 2 adjacent channels
SSB QPSK backscatter

- ✔ QPSK modulation
- ✔ Single-side-band modulation occupies only one adjacent channel
- ❌ Range is limited to 10m with co-located APs
Proposed fully-reflective SSB QPSK backscatter
Proposed fully-reflective SSB QPSK backscatter

• IQ tag data is first upconverted to IF via a SSB digital mixer
Proposed fully-reflective SSB QPSK backscatter

- Two 90° separated loads provide 90° rotated reflection coefficients
  - \( Z_{L,0} = \text{open}; \Gamma_{L,0} = 1 = e^{j\times0°} \)
  - \( Z_{L,-90} = -j = e^{j\times-90°} \)
  - \( Z_{L,180} = \text{short}; \Gamma_{L,180} = 1 = e^{j\times180°} \)
  - \( Z_{L,90} = j\times50 = 3.3\text{nH}\@2.4\text{GHz}; \Gamma_{L,90} = -j = e^{j\times90°} \)
- Quadrature IF signal modulates quadrature RF loading => SSB backscattering
  - Power splitter => Insertion loss
  - Single antenna => No gain

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Passive MIMO – Van Atta antenna array

- Passively steers an incident beam back to its source with MIMO gain
  - ✔️ Reflected signal power is increased
  - ❌ No data can be modulated onto reflected signal
Passive MIMO: one possible implementation

- ☑️ Modulated data is reflected with increased signal power
- ❎ Absorbing termination decreases signal power
- ❎ Double-side-band modulation occupies 2 adjacent channels
Proposed retro-reflective SSB MIMO QPSK backscatter

Incident

Reflected

LSB

USB

Ch 1  Ch 6  Ch 11  Freq

IF_{OUT,Q}

IF_{OUT,Q}

IF_{OUT,I}

IF_{OUT,I}

IF_{OUT,I}

IF_{OUT,I}

IF_{OUT,Q}

IF_{OUT,Q}

IF_{OUT,Q}

IF_{OUT,Q}

MIMO

IF Mixer

DI

DQ

USB/LSB

IF_{90}

IF_{0}

IF_{0}

PLL

XTAL

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12.2: Improving the Range of WiFi Backscatter Via a Passive Retro-Reflective Single-Side-Band-Modulating MIMO Array and Non-Absorbing Termination
Proposed retro-reflective SSB MIMO QPSK backscatter

Theoretically improve reflected power by 18dB!
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Block diagram of proposed IoT tag
Block diagram of downlink

- Direct envelope detection architecture for low standby power
- 8dB passive voltage gain from input matching network
- WiFi packets counter supports robust WiFi compatible wake-up and multi-tag wake-up regardless of the length of inter-packet gaps
A PLL based backscatter modulator enabled by wake-up signal
PLL provides 25/50MHz frequency translation for backscatter
IF mixer controls impedance loading for tag data modulation
Wake up and backscatter timing

- Robust WiFi-compatible wake-up regardless of the length of gaps between T0 and T1
- A PLL based backscatter modulator enabled by wake-up signal
- PLL provides 25/50MHz frequency translation for backscatter
- IF mixer controls impedance loading for tag data modulation
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Passive pseudo-balun envelop detector

- Single-ended input RF to differential output BB signal
- 2× conversion gain w/o output BW penalty
- 1.5dB sensitivity improvement
- Tunable $V_{th}$ via DNW device bulk control for PVT

Wang et al., SSCL’18
PLL and digital SSB IF mixer

- Ring oscillator based integer-$N$ PLL: 4-phase of output
- Digital SSB IF mixer

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Die micrograph

- 65nm CMOS
- 0.44mm$^2$ active area
Downlink sensitivity

- $-43.4 \text{ dBm}$ downlink sensitivity for $1 \times 10^{-3}$ wake-up event missed detection rate

- $> 30 \text{ m}$ wake-up range
SSB frequency translation

- Incident signal at CH6 reflected to either CH1 or CH11 based on logic setting with up to 18dB image rejection
- 11dB improvement of passive MIMO compared to reflective method and 15dB improvement over absorbing method
Wake-up and backscatter transient measurement

Packet envelope

Wake-up signal

Backscatter En

Tag data
Wireless experiment - range

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Place for Speaker's video (5cm x 3.5cm)
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Wireless experiment - angle

place for speaker's video (5cm x 3.5cm)

MIMO Tag

Co-Located Transmitter and Receiver

23m

Indoors

Outdoors

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## Comparison to prior art

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<thead>
<tr>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Fully-Reflective</td>
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<tr>
<td>Technology (nm)</td>
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<td>Scheme</td>
<td>Backscatter</td>
<td>Backscatter</td>
<td>SSB WiFi Backscatter</td>
<td>SSB Partially Absorbing WiFi Backscatter</td>
<td>SSB Fully Reflective WiFi Backscatter</td>
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<tr>
<td>Frequency (GHz)</td>
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<td>2.4</td>
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<td>Incident signal source</td>
<td>Tone Transmitter</td>
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<td>WiFi</td>
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<td>Wake-up power (μW)</td>
<td>8.2</td>
<td>18 (COTS)</td>
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<td>4.5</td>
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<td>Backscatter communication power (μW)</td>
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<td>59.2**</td>
<td>33**</td>
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<td>Range: equidistance TX and RX (m)</td>
<td>0.1</td>
<td>4.6</td>
<td>6</td>
<td>10.5</td>
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*Simulated

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Conclusion

• The first IC demonstrating WiFi-compatible passive MIMO backscatter communication to cover >1600 m² area towards pragmatic adoption in home and office environment

• A fully-reflective backscatter communication with ~13 m communication range for device-area-restricted applications

• Low power: A 4.5µW standby power, 32µW for fully reflective and 38µW for passive MIMO

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