20.1 A 28μW IoT Tag That Can Communicate with Commodity WiFi Transceivers via a Single-Side-Band QPSK Backscatter Communication Technique

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Nearly all IoT devices require wireless connectivity, and to keep costs down and deployment opportunities up, communication should ideally occur with widely deployed commodity hardware such as WiFi. However, conventional WiFi transceivers (TRXs) require 10s to 100s of mW of active power. As a result, nearly all current WiFi-compatible IoT devices require either wall power, or large/frequently re-charged batteries (Fig. 20.1.1, left). While other standards such as BLE may require less power, very low power (<<1mW) is only achievable at very low throughputs via duty-cycling; and yet, despite low average power, very small coin cell batteries or energy harvesters cannot be used due to still relatively high peak-power requirements (e.g., a few mW for BLE), thereby limiting new products to certain minimum device sizes. More importantly, standards such as BLE do not have widely distributed infrastructure in most homes, offices, or other environments, making rapid low-cost deployment difficult. To enable a new class of miniaturized, battery-powered or energy-harvested IoT devices, backscatter communication, where an incident RF source is reflected via a low-power impedance modulating tag, has been proposed [1]. However, most current solutions rely on custom tone generators [1,2], and thus cannot be rapidly deployed at scale with low cost. To enable operation with existing infrastructure, recent work has shown that already-pervasive WiFi signals can be used as incident RF sources for backscattering, and through techniques such as codeword translation, commodity WiFi RXs can be used to receive backscattered data [3]. However, this prior art required a WiFi RF source (like a smartphone) within 6m of the tag, and two separate WiFi readers within 8m (Fig. 20.1.1, middle). More importantly, to date, there has not been any practical backscatter systems developed with low-power electronics to demonstrate the low-power potential of WiFi-based backscattering.

This paper presents a backscatter IC that demonstrates pragmatic, low-power communication with commodity WiFi hardware in more realistic network deployments as illustrated in Fig. 20.1.1 (right) by: 1) synchronizing to carefully-architected incident WiFi-compliant packets via an integrated 2.8μW energy-detecting wake-up receiver (WuRX); 2) modulating the phase of incident WiFi signals and frequency-translating them to another WiFi channel via a crystal-stabilized multi-phase LO, to enable clear and robust reception of protocol-compliant data; 3) utilizing an IQ mixer driving multi-phase-terminated backscatter switches to enable single-side-band (SSB) QPSK modulation to a single adjacent WiFi channel; and 4) receiving and decoding the tag data with a commercial WiFi TRX by XOR-ing the original incident WiFi data (via the cloud) and the received backscattered alteration.

The block diagram of the backscatter tag is shown in Fig. 20.1.2. In order to backscatter at the right time, the tag must wake-up to and synchronize with incident WiFi signals. Since building a full WiFi RX consumes too much power, synchronization is instead accomplished in this work by having the incident WiFi TX send two pre-specified-length packets at a pre-specified separation, that are energy-detected by the on-chip WuRX in a backchannel communication-like approach [4]. The WuRX consists of an impedance transformer and a passive pseudo-balun envelope detector (ED) [5], followed by an oversampled comparator and 11b digital correlator with soft-decision decoding to enable robust detection of the pre-specified WiFi signature.

After wake-up and synchronization, the tag counts for a pre-specified amount of time until the payload of the incident WiFi signal begins to be received at the tag's antenna. The most basic way to perform backscattering at this time would be to modulate a switch, connected on one side to the antenna and on the other to a 50Ω load, on and off, as depicted in Fig. 20.1.3 (top left) for OOK modulation. However, commodity WiFi RXs cannot decode this kind of data and, importantly, the reflected signal is at the same frequency as the incident signal, making signal separation difficult. Instead, the baseband data can be mixed with a 25MHz clock, which frequency translates the backscattered signal to ±25MHz away. If multiple phases of the clock were available, as depicted in Fig. 20.1.3 (top right), then the data can be QPSK instead of OOK modulated [1]. However, this double-side-band (DSB) approach will occupy all three main 2.4GHz WiFi channels if the incident signal is at channel 6, as backscattered replicas will undesirably occupy both channels 1 and 11. Since the tag does not have access to IQ LO signals directly, SSB modulation cannot be performed in the usual manner via a SSB mixer. Prior work suggested using a power splitter and a transmission line to provide a $\pi/2$ phase delay ($\pi/4$ in incident and reflected directions) to eliminate one of the sidebands [3]. In this work, SSB modulation is performed in a small, fully-integrated manner via two $\pi/2$-separated loads that cause $\pi/2$-rotated reflection coefficients, as illustrated in Fig. 20.1.3 (bottom), where $Z_{L,0}$ is an open circuit and $Z_{L,90}$ is a 1.2pF capacitor at 2.4GHz. By driving these switches alongside two switches terminated with 50Ω with the I/Q IF signals generated via the digital mixers, either upper sideband (USB) or lower sideband (LSB) modulation can be obtained, depending on the polarity of the adders, which can be reconfigured.

The backscatter tag IC was fabricated in 65nm CMOS, occupying a core area of 0.34mm^2. Wired benchtop tests with a 17dB-isolation circulator, used for characterization purposes only, show that an incident -40dBm 802.11b WiFi signal at channel 6 (-57dBm power shown on the spectrum analyzer due to finite circulator isolation), can be reflected to either channel 1 or 11 at -55dBm with 17dB of image rejection in the opposite channel (Fig. 20.1.4, top). During active mode, the backscatter circuits consume 28μW, largely dominated by the PLL which operates at 50MHz. Transient waveforms in Fig. 20.1.4 (bottom left) shows that the tag correctly wakes up upon reception of the specially-crafted yet standards-compliant WiFi packets, waits for the header to pass, and then backscatters during the payload. The WuRX achieves a sensitivity of -42.5dBm for a missed detection rate of 10^{-3} (Fig. 20.1.4, bottom right), which can support AP-to-tag wake-up distances of >30m as indicated by path loss measurements in Fig. 20.1.1 (bottom left). During wake-up/synchronization mode, the chip consumes 2.8μW: 1.5μW from the XO, and 1.3μW from the baseband and correlator.

The wireless over-the-air measurement setup is shown in Fig. 20.1.5, where a WiFi access point (AP1) transmits packets to the tag, which backscatters them to a different channel for reception by a TPLINK Archer C7 access point (AP2). As illustrated in Fig. 20.1.2 (bottom left) using BPSK for simplicity, AP1's PSK modulated data is effectively multiplied by the tag's baseband data and frequency-shifted during backscattering, and this altered signal is then received by AP2. The tag data is recovered by converting the +1/-1 modulated data to 0/1 binary values, and XOR-ing this with the binary representation of AP1's payload data, accessed via the cloud, in a similar manner to [3]. Wireless test show that the tag can successfully communicate at any distance between APs that are located 21m away from each other, or to a 91m away AP if the tag is within 1m of any other WiFi node. Compared to the prior-art listed in Fig. 20.1.6, this work is the first IC-based implementation of WiFi backscatter, and thus, also achieves the lowest power consumption and longest range. Compared to other prior-art backscatter solutions, this work enables SSB modulation and operation without a tone-generator. The developed 28μW WiFi-compatible tag can thus help enable a new generation of low-power devices that can communicate directly with existing WiFi infrastructure.

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References:
[1] A. Shirane et al., "A 5.8GHz RF-Powered Transceiver with a 113μW 32-QAM Transmitter Employing the IF-based Quadrature Backscattering Technique," *ISSCC*, pp. 248-249, Feb. 2015.
[2] B. Kellogg et al., "Passive Wi-Fi: Bringing Low Power to Wi-Fi Transmissions," *Usenix NSDI*, pp. 151-164, Mar. 2016.
[3] P. Zhang et al., "HitchHike: Practical Backscatter Using Commodity WiFi," *ACM SenSys*, pp. 259-271, Nov. 2016.
[4] N. E. Roberts et al., "A 236nW -56.5dBm-Sensitivity Bluetooth Low-Energy Wakeup Receiver with Energy Harvesting in 65nm CMOS," *ISSCC*, pp. 450-451, Feb. 2016.
[5] P.-H. P. Wang et al., "A 6.1 nW Wake-Up Receiver Achieving -80.5 dBm Sensitivity via a Passive Pseudo-Balun Envelope Detector," *IEEE Solid-State Circuits Letters*, vol. 1, no. 5, pp. 134-137, May 2018.

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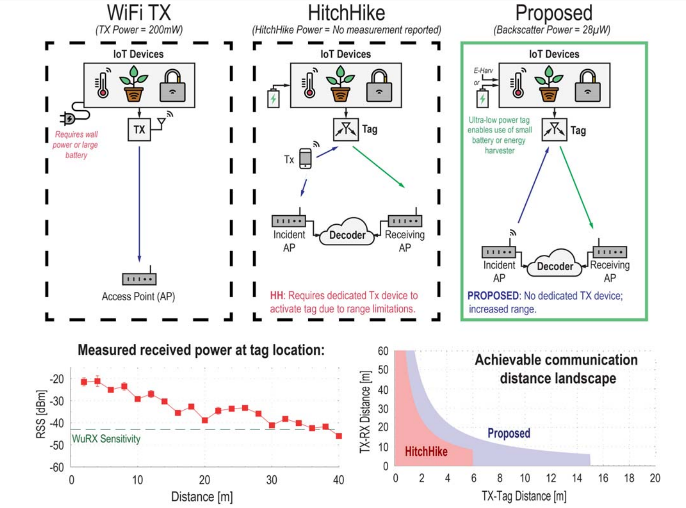


Figure 20.1.1: Proposed WiFi-compliant backscatter approach in contrast to existing art (top); measured RX power at tag location, indicating >30m wake-up range (bottom left); and achievable communication distance landscape.

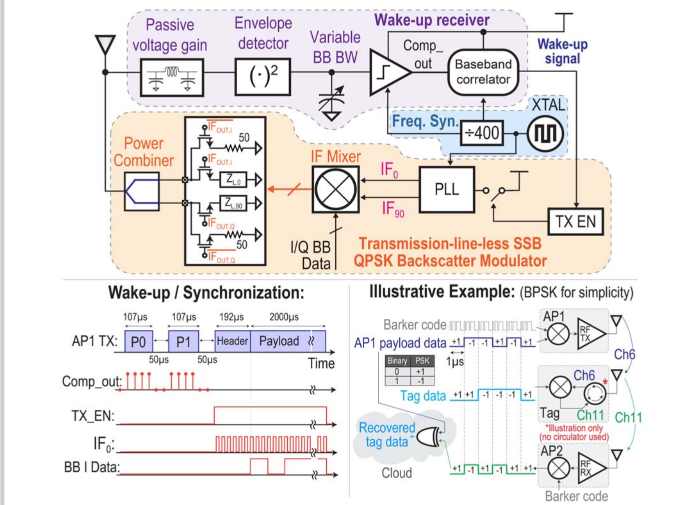


Figure 20.1.2: Block diagram of the proposed backscatter-based IoT tag (top); wake-up/synchronization and backscatter timing (bottom left); BPSK-based example of how tag data is decoded in the cloud (bottom right).

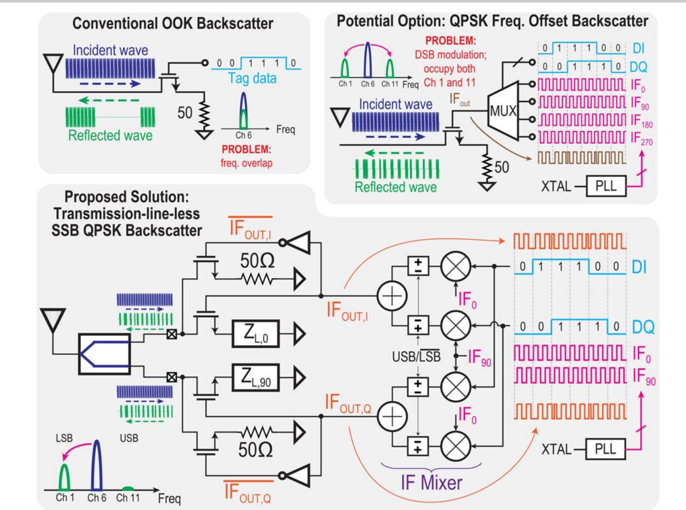


Figure 20.1.3: Methods to perform on-chip backscatter modulation: conventional frequency-overlapped OOK (top left); frequency-offset QPSK (top right); and the proposed transmission-line-less SSB QPSK approach (bottom).

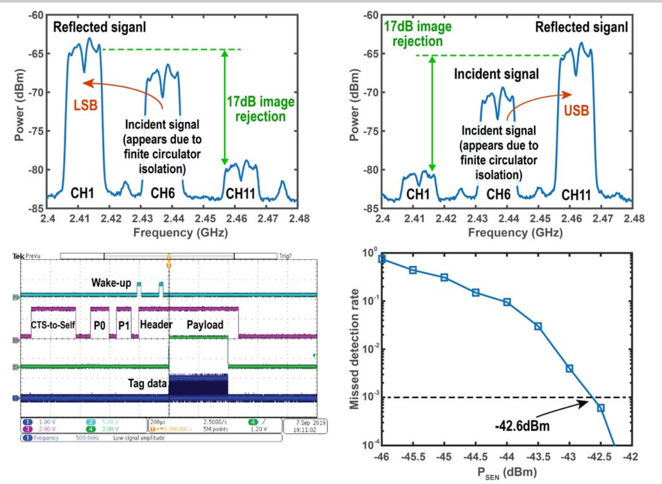
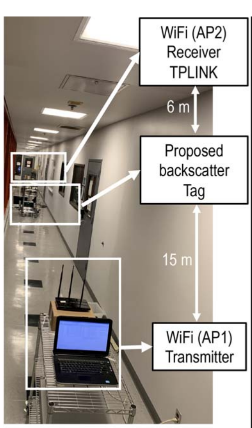
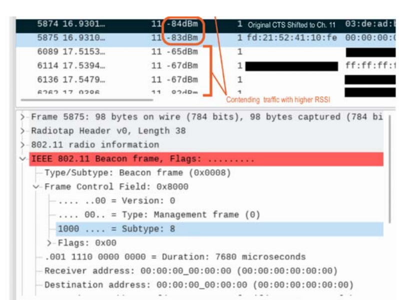


Figure 20.1.4: Measured spectrum showing SSB backscatter-based frequency translation to lower (top left) and upper (top right) sidebands with 17dB image rejection; measured wake-up and backscatter sequence (bottom left); measured missed detection rate for the WuRX (bottom right).



Experimental Setup in a long corridor



Screenshot showing decoded WiFi packets from Wireshark a network analysis at the Commodity WiFi receiver (TP-Link)

Tx to tag	Tag to RX	Received Power at decoder	BER
15 m	6 m	-84 dBm	1e-4

Table showing good received power and BER at the decoder

Figure 20.1.5: Wireless experimental setup (left); network analysis tool showing decoded backscatter packet with commodity WiFi RX (right).

		This Work	Kellogg NSDI'16	Zhang SenSys'16	Tabesh JSSC'15	Shirane ISSCC'15
Technology		65 nm	No chip	No chip	65 nm	65 nm
Chip area		0.34 mm²	No chip	No chip	4.44 mm²	0.26 mm²
Frequency	TX	2.4 GHz	2.4 GHz	2.4 GHz	60 GHz (TX)	5.8 GHz
	RX				24 GHz (RX)	
Range	Symmetric TX to tag = Tag to RX	10.5 m	4.6 m	6 m	0.5 m	0.1 m
	TX to tag =1m, Tag to RX distance	91 m	30.5 m	50 m	Does not work	Does not work
	TX to tag =15m, Tag to RX distance	6 m	Does not work (cannot wake up)	Does not work (cannot wake up)	Does not work	Does not work
Incident signal source		WiFi	Tone transmitter	WiFi	Tone transmitter	Tone transmitter
Reflected wave RX		WiFi	WiFi	WiFi	N/A	N/A
Max data rate		2 Mbps	11 Mbps	2 Mbps	12 Mbps	2.5 Mbps
Wake-up range		>30 m	2.1 m (BER=1e-2)	6 m	0.5 m	0.1 m
Wake-up sensitivity		-42.5 dBm	Not reported	-20 dBm	-10.5 dBm	-23 dBm
RX standby/wake-up power		2.8 μW	18 μW (COTS devices)	Not reported	1.5 μW	8.2 μW
Backscatter communication power		28 μW	Simulated 59.2 μW	Simulated 33 μW	N.R.	113 μW
SSB technology		On-chip impedance based	N/A	Delay line based	N/A	N/A

Figure 20.1.6: Table of comparisons to prior-art backscatter systems.

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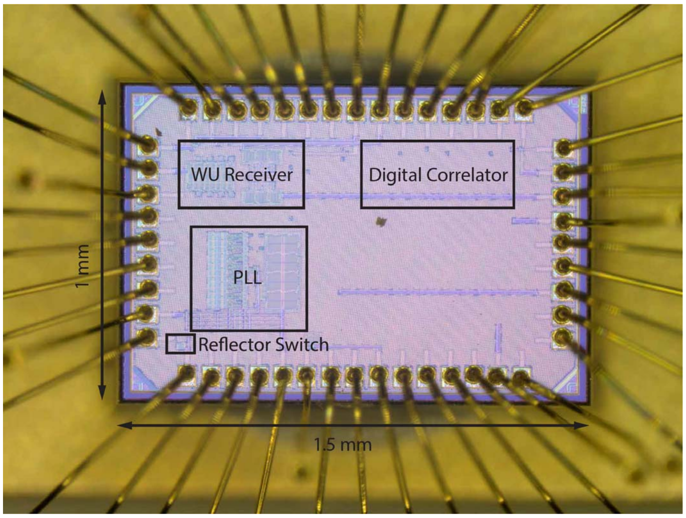

Figure 20.1.7: Micrograph of the backscatter chip.

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