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

Po-Han Peter Wang\textsuperscript{1,2}, Chi Zhang\textsuperscript{1}, Hongsen Yang\textsuperscript{1}, Dinesh Bharadia\textsuperscript{1}, Patrick P. Mercier\textsuperscript{1}

\textsuperscript{1}University of California, San Diego, La Jolla, CA
\textsuperscript{2}Broadcom Inc., San Diego, CA

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 important, 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 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-translation 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-sideband (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 backscatter tag IC was fabricated in 65nm CMOS, occupying a core area of 0.34mm\textsuperscript{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 wavesforms 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\textsuperscript{-5} (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 multiplexed 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.

Acknowledgments:
This work was supported in part by the National Science Foundation under Grant No. 1923902. The authors would like to acknowledge Manideep Dunna for helping with wireless experiments.

References:
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).

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

Figure 20.1.6: Table of comparisons to prior-art backscatter systems.
Figure 20.1.7: Micrograph of the backscatter chip.