A 158 pJ/bit 1.0 Mbps Bluetooth Low Energy (BLE) Compatible Backscatter Communication System for Wireless Sensing

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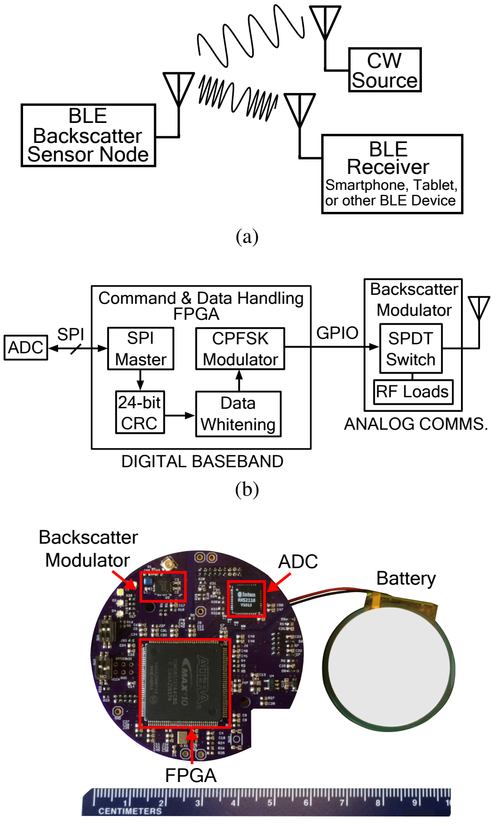
***Abstract*— Wireless links using backscatter communication offer the advantages of reduced complexity and orders of magnitude lower power consumption than active radios. However, the need for specialized receiver systems has limited the use of backscatter in wireless sensing applications. To address this need, we introduce the first backscatter-based wireless sensor tag that can stream sensor data to any of the billions of existing Bluetooth 4.0 Low Energy (BLE) devices, including smartphones, tablets, and PCs. The FPGA-based "BLE Backscatter Sensor Node" (BBSN) uses an external carrier source and requires no modifications to smartphone, tablet, or PC hardware or software whatsoever. The device transmits a 1.0 Mbps data stream with BLE-compatible frequency-shift keying modulation. The backscatter modulator consumes only 158 pJ/bit, making it over 60X more energy efficient than a conventional BLE active radio (>10 nJ/bit).**

***Index Terms*— Backscatter, Bluetooth, BLE, communications, internet of things, RFID**

I. INTRODUCTION

A critical challenge for energy-constrained embedded wireless sensors is efficiently uplinking sensor data to existing wireless communications infrastructure. Backscatter communication systems are a candidate for solving this challenge, because they provide high data rates with orders of magnitude lower energy consumption per bit than traditional radio standards [1]–[3]. The increased energy efficiency arises from repartitioning the energy-hungry functions of frequency synthesis and radio frequency (RF) amplification from the sensor node to a more energy-rich host device, reducing backscatter RF front-end energy consumption to the pJ/bit regime.

The need for specialized backscatter receivers has been a barrier to entry in wireless sensing applications. This has sparked research in backscatter communication systems that are compatible with common wireless standards, i.e. Bluetooth and WiFi [2], [4], [5]. In this work, we expand on [2] by demonstrating an FPGA-based Bluetooth 4.0 Low Energy (BLE) Backscatter Sensor Node (BBSN) that is compatible with any existing Bluetooth 4.0 Low Energy host device. This approach leverages an externally-supplied RF carrier wave (CW) to stream digitized sensor data to an unmodified BLE device at 1.0 Mbps via BLE advertising packets. The sensor's RF front-end consumes only 158 pJ/bit, compared to >10 nJ/bit for conventional active BLE transmitters [6]. An overview of the proposed system is shown in Fig. 1a.



(a)

(b)

(c)

Fig. 1: (a) BLE Backscatter system architecture (b) BLE Backscatter Sensor Node (BBSN) block diagram (c) Photo of the BBSN prototype

II. BLE-COMPATIBLE BACKSCATTER COMMUNICATION SYSTEM

BLE operates in the 2.400-2.483 GHz industrial, scientific, and medical (ISM) band. The band is sub-divided into 40 channels, each 1 MHz wide, with 2 MHz channel-to-channel spacing. BLE specifies 37 data channels and 3 "advertising channels" (CH37 at 2.402, CH38 at 2.426, and CH39 at 2.480 GHz). These advertising channels provide a connection-less beacon mode in which a device can unidirectionally broadcast advertising packets without requiring acknowledgments. The structure of the advertising packets is shown in Fig. 2. This communication scheme is ideal for backscatter-based sensor uplinks, because all

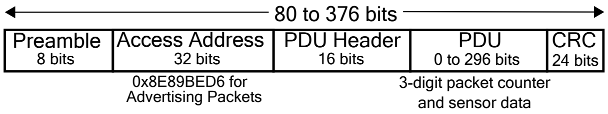


Fig. 2: Structure of a BLE advertising packet

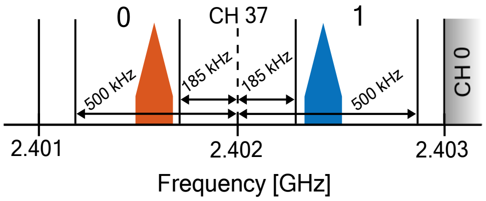


Fig. 3: Placement of FSK signal within a BLE advertising channel

BLE-compliant receivers are required to periodically tune to the advertising channels to receive beacon packets. By transmitting packets on advertising channels, a backscatter-based device is guaranteed to be able to uplink data to any BLE-compatible receiver.

A. Spectral Engineering for BLE Compatibility

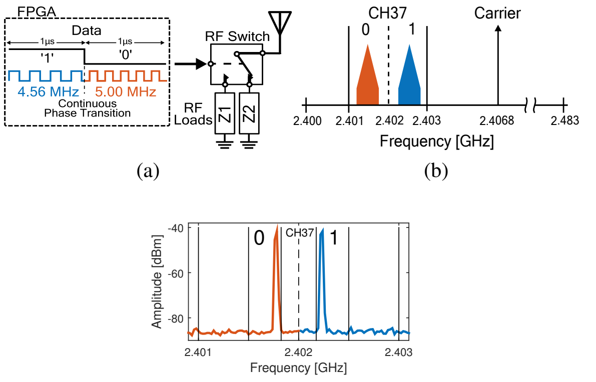
As shown in Fig. 3, the BLE physical layer is based on 1.0 Mbps binary frequency-shift keying (FSK), with one-sided frequency deviation δf_{sc} between 185 kHz and 500 kHz. A frequency deviation above the channel's center frequency represents a logic '1' (f_{sc_1}) and a frequency deviation below the channel's center frequency represents a logic '0' (f_{sc_0}).

The BBSN generates BLE signals through two simultaneous modulation processes portrayed in Fig. 4a. The FPGA generates a subcarrier frequency that feeds a backscatter modulator, comprised of an RF switch that connects the BBSN antenna to one of two impedances, Z_1 and Z_2. An external CW incident upon the BBSN antenna is thus phase modulated at the subcarrier frequency, which is in turn frequency modulated by baseband data at a rate of 1.0 Mbps, yielding the BLE-compatible spectrum shown in Fig. 3.

The CW frequency, F_{C}, is selected such that one of the generated sidebands falls in the desired advertising channel. Choosing the lower sideband, F_{C} can be calculated as $F_{\mathrm{C}} = F_{\mathrm{CH}} + f_{\mathrm{sc}_0} + \delta f_{\mathrm{sc}}$, where F_{CH} is the desired channel's center frequency, $\delta f_{\mathrm{sc}} = f_{\mathrm{sc}_0} - f_{\mathrm{sc}_1}$ and it is assumed that $f_{\mathrm{sc}0} > f_{\mathrm{sc}_1}$. For this work, f_{sc_0} was set to 5.00 MHz and f_{sc_1} to 4.56 MHz. We used BLE channel 37, so F_{C} was calculated to be 2.4068 GHz. The expected and measured spectrums of the BLE signals are shown in Fig. 4b and c.

B. BLE Backscatter Sensor Node (BBSN)

The BBSN is comprised of a multi-channel ADC to acquire sensor data, an Altera MAX10 FPGA, and a backscatter modulator to uplink data (Fig. 1b and c). An Intan RHS2116 analog front-end is used for the multi-channel ADC, and it provides a 16-channel, 16-bit resolution data acquisition system intended for biomedical sensing applications. Power is provided to the BBSN by a single-cell 500 mAh lithium polymer battery. As shown in Table I, while the BBSN draws 58 mA total, only 48 μA (0.08%) is used by the Backscatter Modulator.



(a)

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Fig. 4: (a) BBSN backscatter modulator block diagram (b) Expected spectrum of the BBSN given a 2.4068 GHz externally-supplied carrier (c) Measured spectrum produced by the BBSN with a 2.4068 GHz carrier

The Altera MAX10 FPGA performs command and data handling for the BBSN. It controls the multi-channel ADC via SPI to sample and digitize sensor data. BLE advertising packets are then formed by computing a 24-bit CRC and applying data whitening (Fig. 2). These packets are then serially output to the backscatter modulator of Fig. 4a.

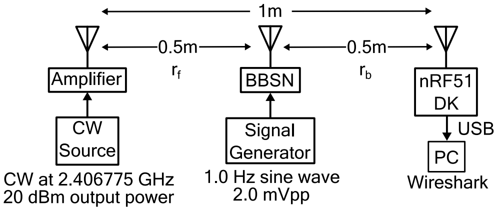
TABLE I: Measured BBSN power budget

	Current (mA)	Power (mW)	% of total
Intan RHS2116 IC	3.27	10.8	5.63 %
FPGA (static baseline)	53.11	175.3	91.37 %
FPGA (dynamic)	1.69	5.59	2.91 %
Backscatter Modulator	0.048	0.158	0.08 %
Total (static+dynamic)	58.12	191.85	

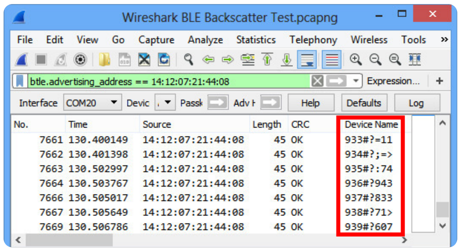
The backscatter modulator was implemented with an Analog Devices ADG904 SP4T RF switch (only two of the four throws were used for this work, so it can be viewed as a SPDT switch). The RF impedances were chosen to generate a large differential radar cross section and thus improve the power of the modulated backscatter signal [7]. The measured values of Z_1 and Z_2 on the BBSN were 25 + j 66 Ω and 82 - j 125 Ω, respectively, at 2.4068 GHz with an RF power level of 0 dBm.

III. EXPERIMENTAL VALIDATION SETUP

A commercial off-the-shelf (COTS) BLE device was used to receive advertising packets from the BBSN using the experimental setup shown in Fig. 5a. We used a Nordic Semiconductor nRF51DK development board



(a)



btle.advertising_address == 14:12:07:21:44:08

```
No.     Time        Source              Length CRC   Device Name
   7661 130.400149  14:12:07:21:44:08      45 OK    933#?=11
   7662 130.401398  14:12:07:21:44:08      45 OK    934#?;=>
   7663 130.502997  14:12:07:21:44:08      45 OK    935#?:74
   7664 130.503767  14:12:07:21:44:08      45 OK    936#?943
   7666 130.505017  14:12:07:21:44:08      45 OK    937#?833
   7667 130.505649  14:12:07:21:44:08      45 OK    938#?71>
   7669 130.506786  14:12:07:21:44:08      45 OK    939#?607
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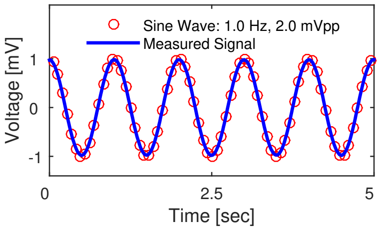
(b)



(c)

Fig. 5: (a) Experimental setup used to validate the BLE backscatter uplink (b) Screenshot from Wireshark showing the received ADC data in the BLE packets (c) Plot of the received data shows good agreement to the expected 1.0 Hz sine wave

based around the nRF51822 BLE-compatible system-on-chip. The nRF51DK software can be used without modification to stream packets via USB to Wireshark, a free packet analysis program. Received packets can then be exported for further processing or plotting in MATLAB. An Agilent N5181A RF Signal Generator and a MiniCircuits ZRL-3500+ RF amplifier were used to generate a carrier at 2.4068 GHz with an RF output power of +20 dBm. Both the CW source and the BBSN used L-COM HG2402RD-RSF antennas with a specified gain of 2.2 dBi.

IV. EXPERIMENTAL RESULTS

The BBSN was tested in an ordinary office/lab environment. An Agilent 33500B arbitrary waveform generator and a 20 dB attenuator were used to generate a 1 Hz sine wave with a 2.0 mVpp amplitude to mimic a low-amplitude biological signal such as an electrocardiogram. The BBSN was programmed to sample and stream the analog signal with 100 Hz sampling rate. Data was then collected using the nRF51DK and Wireshark on the PC, as shown in Fig. 5b. The received data is plotted in Fig. 5c, and shows that the original signal was successfully uplinked through the BBSN and captured by the COTS BLE device, the nRF51DK in this example.

V. CONCLUSIONS & FUTURE WORK

We present the first implementation of a BLE-compatible backscatter communication system that is capable of streaming sensor data at a rate of 1.0 Mbps with a backscatter modulator power consumption of only 158 pJ/bit. The all-digital implementation presented here reduces the hardware complexity of previous BLE-compatible backscatter systems [2], [8], and points the way to an ASIC implementation of the BLE-Backscatter concept. Future work will seek to quantify the performance of the system by investigating its maximum operating distance in mono-static, bi-static co-located, and dislocated arrangements. Finally, the high static power consumption of the Altera MAX10 device will be mitigated by considering other available FPGA families, and/or designing a custom ASIC to provide the BBSN functionality.

ACKNOWLEDGMENT

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