A Dual-Band Shared-Hardware 900 MHz 6.25 Mbps DQPSK and 2.4 GHz 1.0 Mbps Bluetooth Low Energy (BLE) Backscatter Uplink for Wireless Brain-Computer Interfaces

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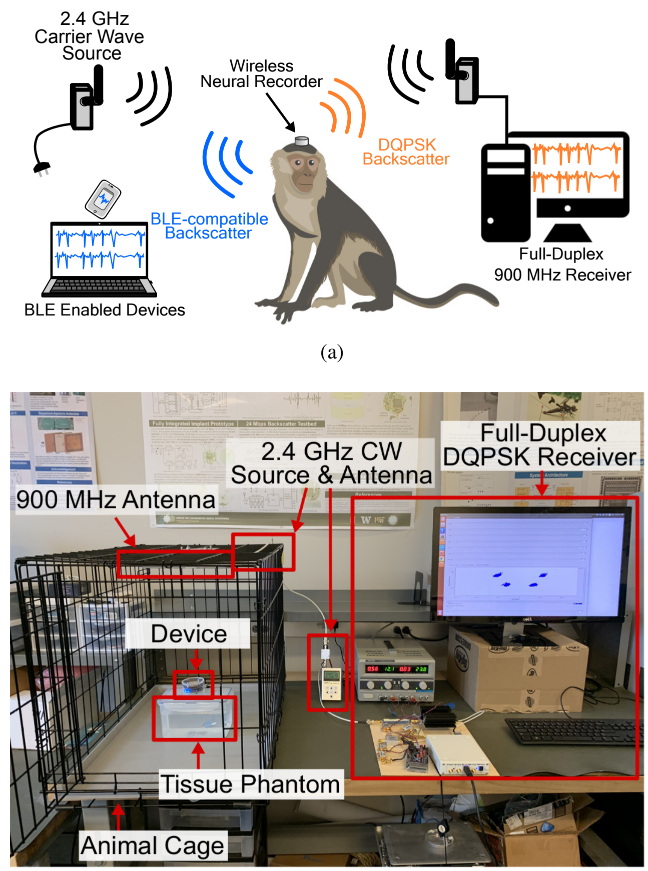
***Abstract*— We present a dual-band, dual-mode shared hardware approach for backscatter based data uplinks. This all-digital approach yields a custom 900 MHz 6.25 Mbps differential quadrature phase-shift-keying (DQPSK) backscatter uplink and a 2.4 GHz 1.0 Mbps single sideband (SSB) BLE-compatible backscatter uplink from a single hardware device. The DQPSK mode achieves a per-bit modulator energy efficiency of 12.4 pJ/bit, while the SSB BLE backscatter mode achieves 198 pJ/bit, which is >50X lower than typical off-the-shelf BLE transmitters. The two modes are time-division multiplexed and share all the same hardware. Results from over-the-air testing are presented and confirm the successful reception of data streams from both modes using a custom full-duplex DQPSK receiver and unmodified Apple and Nordic Semiconductor BLE devices.**

***Keywords*— backscatter communication, RFID, brain-computer interfaces, biomedical implants.**

I. Introduction

Wireless brain-computer interfaces (BCIs) are an emerging technology with applications in fundamental neuroscience research, clinical medicine, and consumer electronics [1]. To advance the state-of-the-art in neuroscience research, they can be used to measure individual neurons and neuronal populations in freely moving animals, enabling new insights into the relationships between single cells and high-level behaviors. Ideally these electrophysiological experiments could be performed in freely moving animals for multiple days or weeks, but experimental durations are generally limited to <2 days due to the high power consumption of conventional wireless transmitters [2], [3].

Backscatter communication offers an energy-efficient alternative to conventional wireless transmitters and could be used to reduce the power consumption of wireless BCIs. Backscatter communication derives its energy savings by removing the need for RF carrier generation and RF amplification from the energy-constrained, battery-powered device, e.g. the wireless BCI. Instead, an external continuous wave (CW) carrier generator with access to an energy-rich supply, e.g. mains power, can be used to broadcast a carrier in the environment. To transmit data, the wireless BCI can then change the impedance presented to its antenna to selectively reflect the CW carrier. This technique has been shown to achieve high data rates with an energy consumption per-bit that is orders of magnitude lower than typical wireless chipsets for e.g. WiFi and Bluetooth Low Energy [4], [5], [6].



(a)

(b)

Fig. 1. Example deployment of a wireless neural recorder leveraging a dual-band backscatter data uplink.

A trade-off when using backscatter communication is choosing whether to use a custom or standards-based communication approach. Custom modes offer greater flexibility and can be used to achieve high data rates with high per-bit energy efficiencies, but they require custom receivers that could be burdensome to end-users because of higher cost and complexity than fully-integrated

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single-chip receivers available for standards-based approaches. In contrast, standards-based approaches simplify the system by enabling compatibility with existing commercial-off-the-shelf (COTS) receivers [5], [6], [7]. For example, BLE-compatible backscatter can be received by any of the billions of existing BLE-enabled devices, such as smartphones, tablets, and laptops [5], [7]. However, implementing a standards-based approach may reduce the data rate and/or energy efficiency of the backscatter uplink.

In this work, we present a dual-mode backscatter uplink that combines the benefits of a radio supporting both custom and standards-based uplinks. The system provides a custom 900 MHz differential quadrature phase-shift-keying (DQPSK) backscatter uplink with 6.25 Mbps throughput and a 2.4 GHz single sideband (SSB) BLE-compatible backscatter uplink with 1.0 Mbps data rate (Fig. 1a). A dual-band antenna enables operation in both frequency bands. Previous backscatter systems have been designed to operate in separate frequency bands for data and wireless power transfer, such as in [8], however, only one communication mode was used. Other works have demonstrated a backscatter system capable of transmitting two different standards-based protocols in the 2.4 GHz band [6] and a backscatter modulator that can operate in both the 900 MHz and 2.4 GHz bands [9]. However, to the author's knowledge, this work is the first to demonstrate a dual-band, dual-mode backscatter uplink that leverages a high-rate custom protocol and a standards-based protocol.

The dual-mode backscatter uplink is a unique contribution to the literature on wireless BCIs by presenting an ultra-low power wireless system that meets the needs of multiple stakeholders involved in NHP research. For example, with the same piece of hardware researchers can use the high-rate DQPSK mode to retrieve data from electrophysiological experiments, while technicians can use the BLE mode to monitor the health and status of the NHPs' implanted electrodes by simply checking an app on their smart phones. A comparable system designed using commercially-available active radios would incur significant additional complexity in hardware and software. Each radio would each require their own power, data, and mechanical interfaces, and a significantly larger power budget would be needed to support two individual RF frequency synthesizers.

II. NeuroDisc Overview

The dual-mode wireless backscatter uplink presented in this paper was designed for the NeuroDisc brain-computer interface, an FPGA-based neural recorder that can measure microvolt-scale electrophysiological signals and wirelessly uplink data via a switched-impedance backscatter modulator.

Table 1. Backscatter modulator impedances

Z	Impedance L/C Value	Γ 900 MHz	Γ 2.4 GHz
Z_0	1.5 pF	-0.60 - j0.52	-0.05 + j0.45
Z_1	20 nH	0.01 - j0.75	0.36 - j0.40
Z_2	8.4 pF	-0.68 + j0.25	-0.26 - j0.55
Z_3	3.3 nH	0.55 + j0.26	-0.50 - j0.24

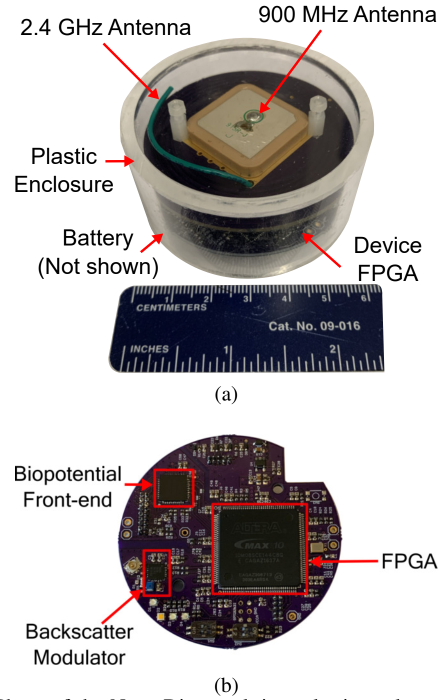


Fig. 2. (a) Photo of the NeuroDisc stack in a plastic enclosure (b) Photo of the NeuroDisc FPGA printed circuit board

A photo of the complete NeuroDisc is shown in Fig. 2a with a zoomed-in photo of the FPGA circuit board shown in Fig. 2b. The FPGA provides the high-speed digital logic required to sample and process multiple neural channels with high temporal resolution. The NeuroDisc's command and data handling functionality is implemented on an Altera MAX10 FPGA using approximately 5600 logic elements, internal non-volatile SRAM, and a 100 MHz clock, as shown in Fig. 3. The specific FPGA and oscillator were chosen to facilitate prototyping, and therefore are not the optimal choices for small size and low power consumption. Future revisions of the NeuroDisc could use a smaller FPGA and lower-power oscillator, such as a Lattice Semiconductor iCE40 FPGA. Eventually, the HDL code could be synthesized in an application-specific integrated circuit for further reduction of size and power consumption.

The NeuroDisc's biopotential front-end uses an Intan RHS2116 integrated circuit that enables recording from up to 16 electrophysiological channels with 16-bit resolution at up to 20 kSamples/s per channel. The backscatter modulator is comprised of an Analog Devices ADG904 single-pole-four-throw (SP4T) RF switch and four discrete reactive elements (two capacitors and two inductors) whose values are provided in Table 1. The RF switch connects to the NeuroDisc's antenna via a UMCC coaxial connector. Using an SP4T RF switch for the backscatter modulator enables the realization of two backscatter modulation schemes, quadrature phase-shift keying (QPSK) and single sideband (SSB) frequency-shift keying (FSK), without modification to the NeuroDisc hardware.

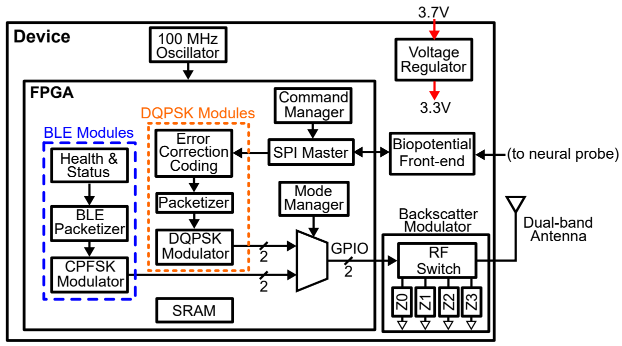


Fig. 3. Block diagram of the FPGA-based digital logic

III. Dual-Protocol Backscatter Uplink

A dual-protocol, time-division-multiplexed backscatter uplink was implemented on the NeuroDisc, as shown in Fig. 4. The uplink is comprised of a custom 900 MHz 6.25 Mbps differential-QPSK (DQPSK) protocol and a 2.4 GHz 1.0 Mbps SSB Bluetooth Low Energy (BLE)-compatible protocol, both implemented using the Verilog hardware description language. A unique feature of this system is that both protocols share the same backscatter modulator and discrete impedances. By sharing the backscatter modulator, the size, weight, power consumption, and overall complexity of the circuit are reduced. If commercially-available active radios were used instead, the system would likely incur significant increases in cost, complexity, and power consumption. The power consumption of the RF switch was measured using a Keithley source-measure unit (SMU). During transmission of DQPSK packets, the power consumption is 77.5 μW, yielding a per-bit energy efficiency of 12.4 pJ/bit. During transmission of the BLE packets, the power consumption is 198 μW, yielding a per-bit energy efficiency of 198 pJ/bit.

A. DQPSK Mode Overview

The DQPSK mode is designed for operation in the 900 MHz North American industrial, scientific, and medical (ISM) band. DQPSK modulation was chosen because it enables two bits to be transmitted for every one symbol, increasing the data rate while reducing switching frequencies and power consumption. To implement DQPSK modulation in a backscatter communication system, four load impedances can be selected to generate four unique, complex-valued reflection coefficients. Oscilloscope measurements of the DQPSK signals used to actuate the RF switch are shown in Fig. 4b, while additional details about implementing DQPSK backscatter modulation can be found in [10].

The DQPSK mode transmits data using a custom packet structure. One 1024-bit packet is transmitted every 800 μs at a symbol rate of 3.125 MSymbols/s (Fig. 4b). Each packet includes 528 bits of biological data from the biopotential front-end, and these bits are encoded with a Hamming(11,16) error correction code to form 48-bit frames (generally, one frame corresponds to one channel of measured biological data). A 16-bit frame marker precedes each 48-bit frame to facilitate processing at the receiver, yielding a total packet length of 1024 bits.

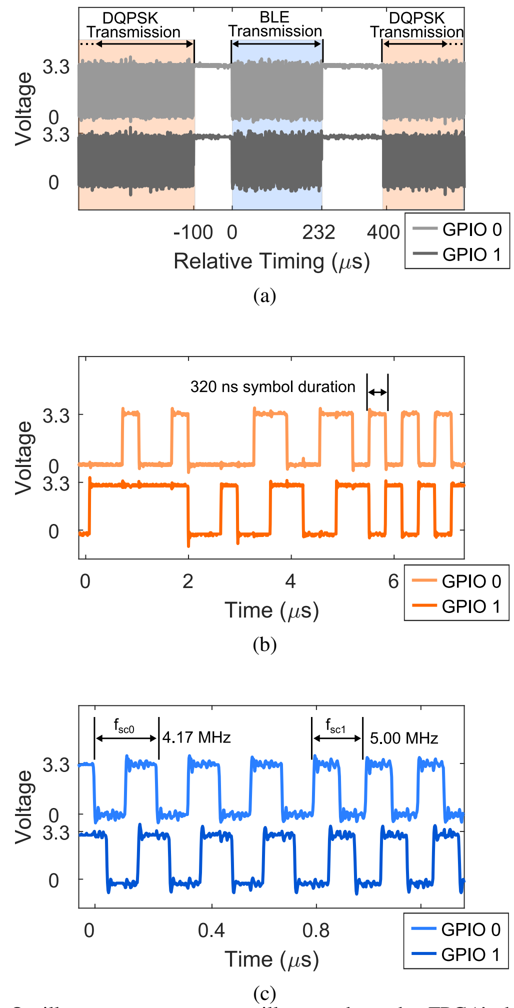


Fig. 4. Oscilloscope measurements illustrate how the FPGA's backscatter modulator control signals, GPIO 0 and 1, are used to transmit DQPSK and BLE packets: (a) Plot showing how BLE packets are transmitted in-between DQPSK packets, (b) Zoomed-in plot of the DQPSK control signals showing a minimum symbol duration of 320 ns, yielding a symbol rate of 3.125 MSymbols/s, and (c) Zoomed-in plot of the BLE control signals showing the two subcarrier frequencies, f_{sc0} and f_{sc1}.

B. BLE Mode Overview

The BLE backscatter uplink transmits BLE-compatible advertising packets in the 2.4 GHz ISM band. This mode generates a 1.0 Mbps frequency-shift keying (FSK) modulation process with a frequency deviation of 830 kHz in compliance with the BLE physical layer specification which requires a frequency deviation between 370 kHz and 1 MHz. FSK modulation is implemented on the NeuroDisc by switching between two or more load impedances at a frequency that is modulated by the data bits. Specifically two subcarrier frequencies, f_{sc0} = 4.17 MHz and f_{sc1} = 5.00 MHz, are used to transmit logic levels 0 and 1, respectively. On the NeuroDisc, these subcarrier frequencies are output on two GPIO pins and used to actuate the RF switch, as shown in

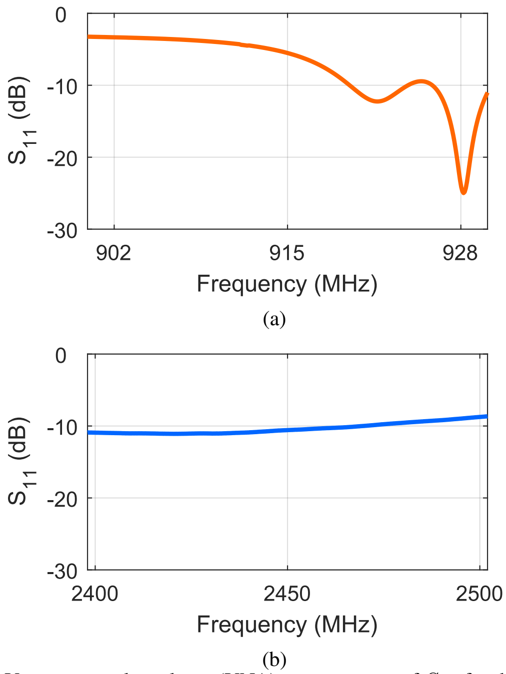


Fig. 5. Vector network analyzer (VNA) measurement of S_{11} for the dual-band antenna in the (a) 900 MHz ISM band and (b) the 2.4 GHz ISM band.

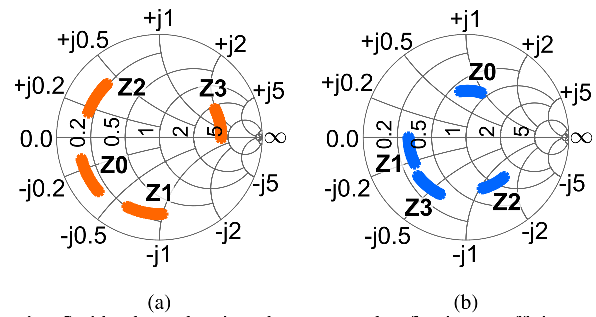


Fig. 6. Smith chart showing the measured reflection coefficients of the backscatter modulator for (a) the 900 MHz ISM band and (b) the 2.4 GHz ISM band.

Fig. 3. Oscilloscope measurements of the subcarrier signals are shown in Fig. 4c. To improve the in-channel signal strength and reduce out-of-channel emissions, the BLE backscatter uplink uses single sideband (SSB) modulation [6], [7]. The SSB modulation is implemented in the continuous-phase FSK (CPFSK) modulator block shown in Fig. 3. Additional details about implementing SSB BLE backscatter modulation can be found in [7].

The BLE mode transmits data using advertising packets. Advertising packets are used by BLE devices to broadcast data to nearby BLE receivers without requiring connection, making them well-suited for a unidirectional backscatter uplink. The NeuroDisc advertising packets carry 64 bits of payload data, yielding a total packet length of 232 bits when the required packet preamble, headers and cyclic redundancy check are included. The commercial BLE receivers we tested began dropping packets at packet rates over 500 packets/s since that exceeds the BLE specified advertising packet rate. Given this constraint, the NeuroDisc was configured to transmit single BLE advertising packets between DQPSK packet transmissions at a rate of 500 packets per second, yielding an effective throughput of 148 kbps via BLE.

C. Time-Division Multiplexing

Time-division multiplexing was used to achieve high overall data rates, high reliability, and low power consumption. The BLE protocol is designed around a time-division multiple access approach using a randomized ALOHA approach for advertising packets. Given the relatively long intervals between BLE packets (>2 ms) and the relatively short duration of BLE packets (232 μs) configuring the BCI for time-division multiplexing was a logical choice for sharing a backscatter channel among two protocols. Oscilloscope plots of the backscatter modulator control signals in Fig. 4 illustrate how BLE packets are sent during gaps between DQPSK transmissions. Other channel access methods, such as frequency-division multiplexing, are discussed in Section V.

D. Dual-Band Antenna

The NeuroDisc's dual-protocol uplink requires an antenna that is resonant in both the 900 MHz and 2.4 GHz frequency bands. To meet this requirement, two different antennas were integrated into a single assembly. A 900 MHz commercial off-the-shelf ceramic patch antenna (Abracon APAE915R2540ABDB1-T) was mounted to a circular 5 cm-diameter printed circuit board (PCB). On the bottom layer of the PCB, the antenna feed pin connects to a UMCC coaxial connector via a balanced-unbalanced transformer. To achieve dual-band functionality, a 2.4 GHz monopole antenna was added to the antenna PCB by soldering a 6 cm-long piece of 24 AWG wire to the RF signal trace of the PCB. The return loss of the dual-band antenna was measured using an Agilent N5222A vector network analyzer, with the measurements plotted in Fig. 5. The antenna achieves a 10 dB return loss bandwidth of 6 MHz in the 900 MHz band with a center frequency of 928.2 MHz, and 70 MHz bandwidth in the 2.4 GHz band, with a center frequency of 2.435 GHz.

E. Impedance Constellation Design

To implement QPSK and SSB FSK backscatter communication, a system must be able to present at least four unique impedances to its antenna [7], [10]. Since the NeuroDisc uses an SP4T RF switch as its backscatter modulator, four discrete impedances outlined in Table 1 were chosen to generate four reflection coefficients in separate quadrants of the Smith chart with approximately the same magnitude. The components were initially selected for use in the 900 MHz ISM band, although as the vector network analyzer measurements in Fig. 6 show, the resulting reflection coefficients are suitable for use in the 2.4 GHz ISM band as well.

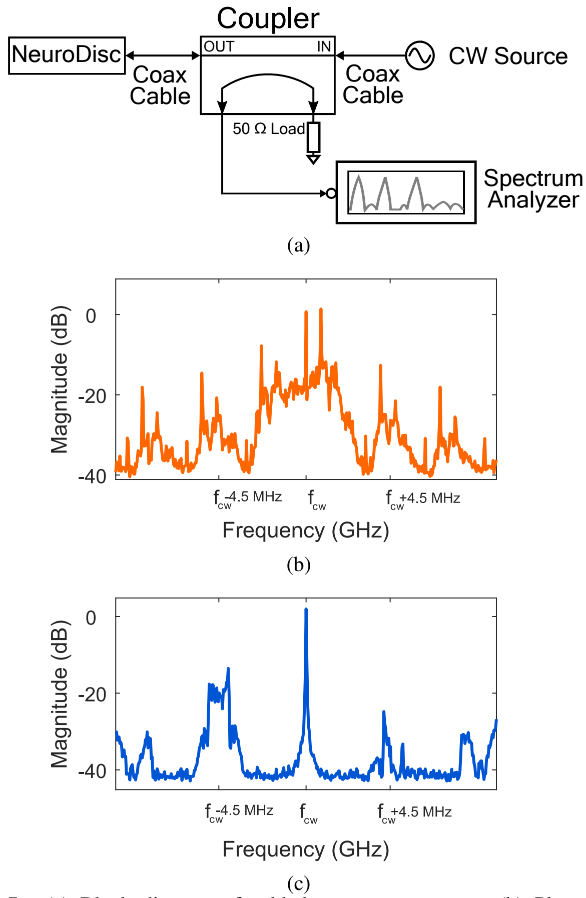


Fig. 7. (a) Block diagram of cabled measurement setup (b) Plot of the measured spectrum for DQPSK packets (c) Plot of the measured spectrum for SSB BLE packets.

IV. Measurements & Results

A. Cabled Measurements

The power spectrum of the DQPSK and SSB BLE backscatter uplinks were measured using the cabled setup shown in Fig. 7a. An RF signal generator was used as the CW source and an Agilent N9320B spectrum analyzer was used to make the measurement. Fig. 7b shows the spectrum of the custom DQPSK uplink. The asymmetry of the spectrum is a result of the transmitted data having structure, which could be removed with the application of a data whitening filter. Fig. 7c shows the spectrum of the SSB BLE backscatter uplink. The plot shows the lower sideband (LSB) approximately centered about f_{cw}-4.5 MHz and the upper sideband (USB) approximately centered about f_{cw}+4.5 MHz. The LSB was selected as the desired sideband, providing a measured gain of 2.8 dB in the LSB and an attenuation of 7.2 dB in the unwanted USB, yielding a total sideband rejection ratio of 10 dB.

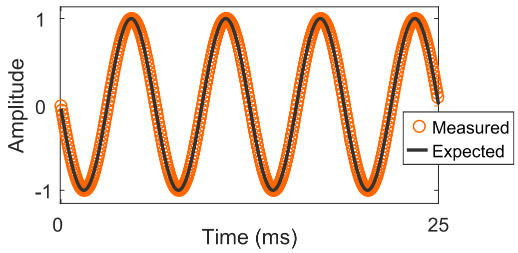
B. Over-the-air Validation Measurements

Wireless, over-the-air validation measurements were performed using the test setup shown in Fig. 1b. Previous work in [11] and [12] found that 900 MHz DQPSK and 2.4 GHz BLE backscatter uplinks could successfully communicate to a receiver mounted on the top inner panel of the cage from nearly all locations inside a typical non-human primate cage. These works measured the channel transfer function for each frequency band at different locations and orientations and conducted packet error tests to verify the integrity of the wireless link. To maintain consistency with the measurements in [11], [12], an animal cage was used to house the NeuroDisc to approximate a non-human primate's home cage where wireless electrophysiology experiments would likely be performed. The NeuroDisc was similarly placed on a tissue phantom comprised of a plastic container filled with approximately 1 liter of saline solution to account for the effects of a monkey on the antenna radiation pattern and the channel propagation characteristics. Mounted to the top, inner wall of the cage were a 900 MHz right-hand circularly polarized patch antenna (Laird Technologies) and a 2.4 GHz linearly polarized patch antenna (L-Com). The 900 MHz antenna was connected to a custom, software defined radio-based, full-duplex DQPSK receiver based on the design in [10]. The 2.4 GHz antenna was connected to an RF signal generator and RF amplifier to broadcast a CW carrier at 15 dBm.

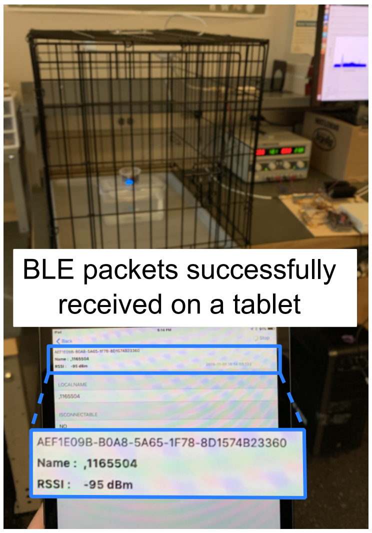
To mimic the uplink of biological data, the DQPSK protocol was used to transmit a 20 kSamples/s sampled 180 Hz sine wave stored in the FPGA. The 180 Hz sine wave was chosen because it is in-band with respect to the desired neural data. A plot of the received data is shown in Fig. 8a. The SSB BLE protocol was then used transmit health and status data from the FPGA, in this case including an 8-digit packet counter, as shown in Fig. 8b. An unmodified iPhone, iPad, and Nordic Semiconductor nRF51822 BLE development board were then used to validate successful reception of the SSB BLE backscatter packets. Data from both protocols could be successfully received and decoded effectively simultaneously from the perspective of the user due to the tight interleaving of both communication modes. Because of the interleaved packet structure, the different symbol rates, and the different backscattered spectra, the two modes do not create apparent interference between each other.

V. Conclusions & Future Work

This work presents a dual-band, dual-mode backscatter uplink leveraging shared hardware that combines a custom DQPSK mode at 900 MHz and a SSB BLE-compatible mode at 2.4 GHz. The DQPSK mode provides a data rate of 6.25 Mbps with a measured power consumption of 75 μW at the backscatter modulator, yielding a modulator efficiency of 12.4 pJ/bit. The SSB BLE-compatible mode provides a 1.0 Mbps data rate while consuming 198 μW at the backscatter modulator, yielding a modulator efficiency of 198 pJ/bit, which is >50X lower than most off-the-shelf BLE transmitters. The sideband rejection ratio was measured to be 10 dB, improving the in-channel signal strength and reducing out-of-channel emissions.



(a)



(b)

Fig. 8. Over-the-air validation experiment: (a) Plot of sine-wave test data received via the DQPSK uplink at 6.25 Mbps, and (b) Photo of BLE packets received on an Apple iPad at approximately 2 m from the animal cage.

This system provides real-time neural data uplink across both the 900 MHz and 2.4 GHz ISM bands, which to the best of our knowledge is unique in the literature on wireless BCIs. The dual-band compatibility of the backscatter front-end provides end-users and researchers the ability to leverage frequency diversity depending on the communication channel, offering experimental flexibility that could be advantageous in commercial applications outside of neural engineering as well.

This work uses time-division multiplexing to switch between DQPSK and BLE transmissions. We believe that truly simultaneous transmission could be achieved with frequency-division multiple access by engineering the spectra of the DQPSK and CPFSK (BLE) modulations. Two methods could be considered: (1) The DQPSK symbol rate could be modified to 1 MSymbol/s such that nulls in the spectrum occur at 1 MHz intervals. The CPFSK subcarrier frequencies could then be chosen so that they are still 1 MHz apart per the BLE specification while falling within the nulls of the DQPSK spectrum. The carrier wave generator for the CPFSK signal could be adjusted so that the backscatter signal aligns with one or more BLE advertising channel(s); and (2) the CPFSK subcarrier frequencies could be chosen such that they are far outside the DQPSK spectrum. This would require higher CPFSK subcarrier frequencies and a modest increase in power consumption at the backscatter modulator.

Future work involves maturing the system for *in vivo* electrophysiology experiments with non-human primates (NHPs). This work includes implementing the FPGA and RF switch designs onto a custom application specific integrated circuit (ASIC) to further reduce the size, weight, and power consumption. Additionally, updating the 900 MHz full-duplex receiver for the 2.4 GHz band could reduce system complexity by switching the DQPSK mode from 900 MHz to 2.4 GHz, eliminating the need for a dual-band antenna and an additional CW carrier generator at 2.4 GHz.

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