A Low-Cost 1 Mbps Frequency Shift Keying Backscatter Receiver and Carrier Wave Generator System for Wireless Neural Recording

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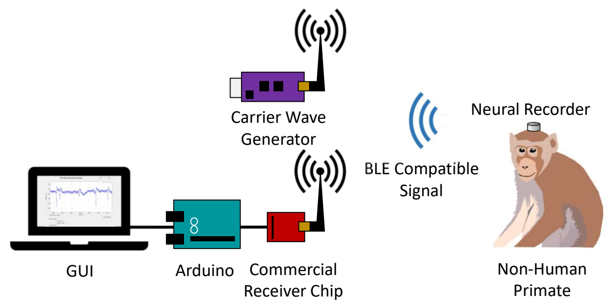
***Abstract*— We present a low-cost, highly configurable receiver and external CW generator for frequency shift keying (FSK) based backscatter communication systems. The receiver uses a Nordic Semiconductor nRF24L01+ chip and an Arduino UNO to enable backscatter communication on any of 125 channels within the 2.4 GHz industrial, scientific, and medical (ISM) band. The receiver supports FSK modulation at up to 2.0 Mbps. Paired with an Arduino-based carrier generator, this system allows users to choose a backscatter uplink channel that minimizes interference from other 2.4 GHz devices (e.g. Wi-Fi and Bluetooth). As an example of a power-critical sensing application where backscatter can be used favorably, we present a wireless, digital neural recording system that leverages a 1.0 Mbps FSK backscatter uplink. The neural recording system has a 3 dB frequency response of 0.8 Hz to 220 Hz and uplinks up to 120 kbps of biopotential data at a sample rate of 500 Hz, with 16 bits of precision per sample. The packet uplink rate is 500 packets per second.**

***Keywords*— Backscatter, Bluetooth, BLE, neural recording**

I. Introduction

Brain-computer interfaces (BCIs) enable powerful interventions to treat neurological disorders. Most experimental BCIs rely on flexible cables to facilitate power and data transfer. Wires connecting the BCI device to external computers must penetrate the skin and skull, increasing the potential for infection and limiting mobility of the subject person or animal [1]. To achieve widespread adoption, BCIs must become fully wireless, while minimizing power consumption to extend their operational lifetime and reduce the risk of causing thermal damage to neural tissue. We present a highly configurable system for wireless communication with backscatter uplink (see Fig. 1) that uses a custom carrier wave (CW) generator and commercial off-the-shelf (COTS) receiver to communicate with a custom neural recording system.

Wireless telemetry for implanted BCIs often rely on Bluetooth Low Energy (BLE) to communicate with an external computer [2]. BLE is a ubiquitous protocol in the 2.4 GHz ISM band which permits the use of a wide range of commercially available hardware (including portable devices such as iOS and Android smartphones and tablets), decreasing receiver cost. However, commercially available BLE chipsets consume approximately 10 mW when transmitting, which can easily dominate the power budget of a low-power sensor. In comparison, backscatter devices, as shown in Fig. 1,



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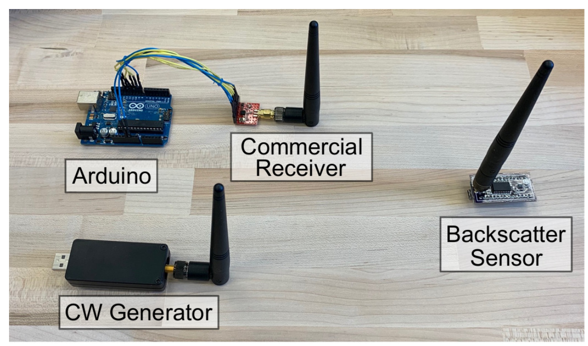

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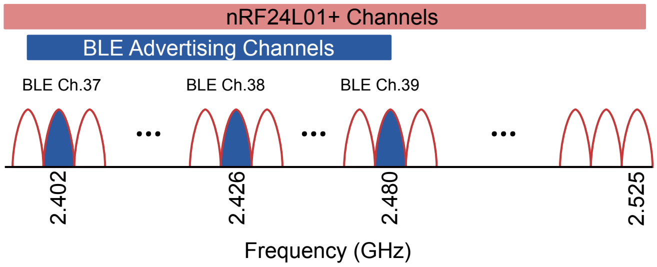
Fig. 1. (a) Cartoon depiction of the presented BCI application with non-human primate subject (b) Photo of receiver, CW generator, and a generic backscatter sensor

operate at orders-of-magnitude lower power - on the scale of μW - by repartitioning the radio frequency (RF) oscillator and amplifiers to an external carrier wave generator [3]. Backscatter devices uplink data by selectively switching the impedance presented to an antenna among two or more impedance states, thus modulating the externally provided carrier to signal with a change in amplitude and/or phase [4], [5].

Although backscatter communication can reduce the power consumption of an energy constrained device, it results in a more severely constrained RF link budget. This is because the backscatter signal must make a two-way trip from the CW generator, to the backscatter device, then to the receiver. As a result, co-channel interference can easily result in data drop-outs for backscatter devices. This is especially true in the



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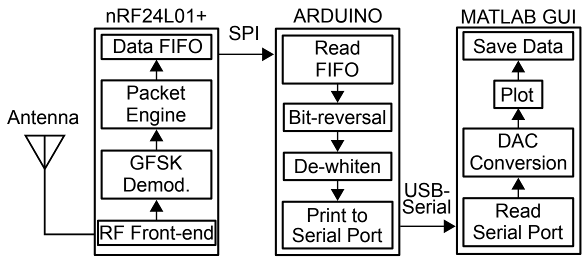

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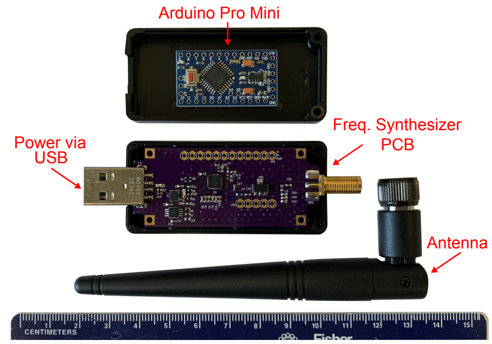
Fig. 2. (a) Frequency range for the nRF24L01+ chip and BLE ISM band (b) Block diagram showing data path of received signal



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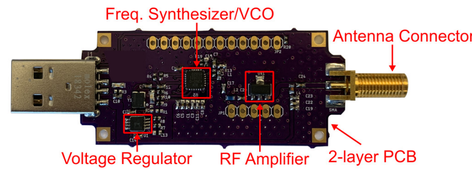

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Fig. 3. (a) Photo of the complete carrier wave generator with a 2.4 GHz antenna (b) Zoomed-in photo of the frequency synthesizer printed circuit board (PCB)

2.4 GHz ISM band due to the vast number of BLE, Wi-Fi, and other wireless devices that crowd this commonly used band.

Co-channel interference can be mitigated by changing frequencies to a less active channel. The Nordic Semiconductor nRF24L01+ chip supports the existing BLE protocol but allows for a wide range of channel selections beyond those specified in the BLE standard, as shown in Fig. 2a. This allows streaming data uplinks on less crowded data channels, reducing the risk of interference and dropped packets during mission critical situations. This has an added benefit for applications in electrophysiology using freely behaving non-human primates (NHP) within a cage environment [6]. As the NHP moves through the cage, it creates time-varying multipath interference as a result of the resonant effect within the cage. Having a flexible CW generator and receiver system enables the selection of the best available communication channel and paves the way for development for frequency hopping spread spectrum backscatter approaches.

This work presents low-cost, flexible tools that facilitate access to backscatter-based wireless sensors for research across disciplines. Section II presents the receiver design and specifications. Section III provides an overview of the CW generator and characterization of its performance. Section IV presents measured results using the receiver and CW generator with a wireless BCI using FSK backscatter communication. Conclusions and future work are then discussed in Section V.

II. Commercial Off-the-shelf Receiver

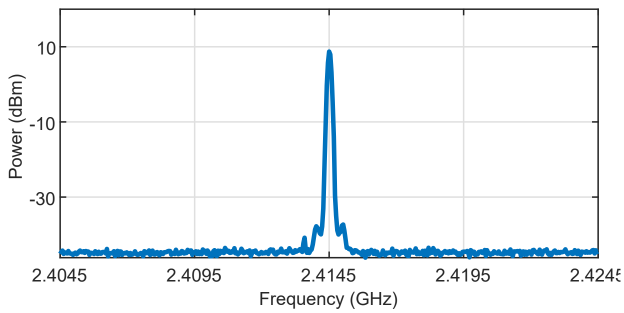
Use of a COTS wireless receiver eliminates many challenges of designing a custom receiver [5], [7]. Several COTS solutions are available for protocols such as Wi-Fi (IEEE 802.11), ZigBee (IEEE 802.15.4), and BLE, and other solutions offer compatibility with existing protocols along with customizable features.

The Nordic Semiconductor nRF24L01+ transceiver is an example of a COTS chip that can be used with BLE or custom protocols in the 2.4 GHz ISM band. The chip supports a broad frequency range, giving the flexibility to use standardized BLE channels or alternative channel plans outside the BLE standard to escape interference from other radios. The nRF24L01+ chip can be used for FSK modulation with 250 kbps, 1 Mbps, and 2 Mbps data rates across 125 channels on the 2.400-2.525 GHz spectrum, at a sensitivity between -82 and -94 dBm. The chip uses a serial peripheral interface (SPI) and has existing open-source libraries for use with the Arduino and other development boards, allowing it to be easily configured for custom packet structures or traditional BLE advertising.

For backscatter communication, the receive channel of the nRF24L01+ can be coordinated with the configurable CW generator presented in Section III, enabling access to channels across the entire frequency band without requiring modification to the transmitting hardware. Since FSK backscatter creates both an upper and lower sideband offset from the CW tone, one must carefully select the CW frequency so that one of the resulting sidebands falls within the desired channel [4]. The following equation can used to determine the external carrier wave frequency, F_{CW}:

$$F_{CW} = F_C \pm f_{sc} \pm \delta f, \tag{1}$$

where F_C is the channel center frequency (e.g. 2.52 GHz), f_{sc} is the subcarrier frequency (e.g. 4.5 MHz), and δf is the frequency deviation (e.g. 500 kHz). To use the upper sideband of the backscatter signal, we add the subcarrier frequency and frequency deviation, and to use the lower sideband we subtract the subcarrier and deviation frequencies.



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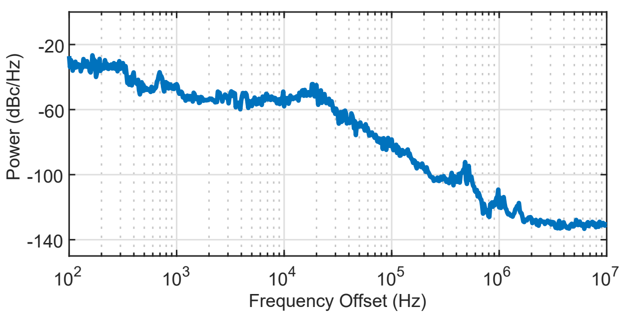

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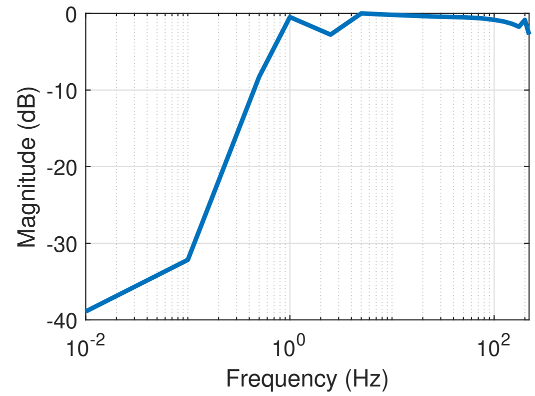
Fig. 4. Laboratory measurements of the CW generator showing its (a) wideband frequency spectrum and (b) phase noise



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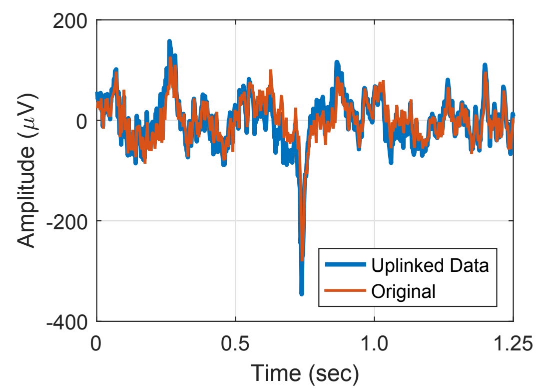

(b)

Fig. 5. Plots of (a) the measured frequency response of the wireless BCI and (b) Pre-recorded neural data uplinked to the receiver versus the original data

Fig. 2b shows the processing of data received by the system. Data is received by the nRF24L01+ chip where it is demodulated and stored in a first in, first out (FIFO) queue to be sent to the Arduino over a SPI connection. The Arduino receives data from the nRF42L01+ chip, where it is then de-whitened according to BLE protocols. This de-whitening process uses a linear feedback shift register (LFSR) to ensure that the data received corresponds to the selected channel, thus mitigating adjacent channel interference. A custom MATLAB graphic user interface (GUI) receives data through a continuous USB serial read where it is converted to a digital representation of the original analog signal. Data undergoes a two's complement conversion for AC-coupled signals digitized by the Intan Technologies RHS2116 biopotential data acquisition integrated circuit. Biopotential signals are displayed in the GUI in real time and can be exported for further analysis.

III. Low-Cost Carrier Wave Generator

The expense and complexity of backscatter communication carrier wave generators and receivers based on laboratory equipment (e.g. Agilent or Keysight equipment) can create a barrier-to-entry entry for end-users and researchers hoping to use ultra-low power wireless communication. To facilitate the design and deployment of backscatter communication systems, we developed the low-cost, small-form factor CW generator shown in Fig. 3.

The CW generator can be assembled for operation in the 900 MHz or 2.4 GHz ISM bands, including both North American and European frequencies. The device consists of an Analog Devices ADF4360 digitally-configurable integrated frequency synthesizer and voltage controlled oscillator (VCO) that is controlled by an Arduino Pro Mini (5 V, 16 MHz) over a SPI. A Mini-Circuits LHA-23LN+ RF amplifier provides approximately 20 dB of gain in either ISM band, yielding up to 14 dBm RF power. The device is housed in 2.3" x 1" (5.8 cm x 2.5 cm) housing with a USB plug for power. The entire bill of materials costs less than $50 USD, including the Arduino Pro Mini, printed circuit board (PCB), and enclosure.

The frequency of the CW generator can be configured for single tone operation in the 900 MHz or 2.4 GHz ISM band by using the ADF4360-0 or ADF4360-1, respectively. Output power can be configured to between 7-14 dBm. Measurements of the RF spectral output and phase noise are provided in Fig. 4, and an over-the-air demonstration is performed with a BLE backscatter tag.

IV. Measurements & Results

The neural recording system was validated through a series of cabled measurements with the NeuroDisc BCI using 1 Mbps FSK backscatter communication. This system is a fully digital, FPGA based backscatter system with a backscatter modulator power consumption of 0.198 mW [3]. This system differs from previous work in that it does not use analog oscillators (further reducing power consumption), has different frequency offsets, and is FPGA based rather than microcontroller based [4]. Cabled experiments were performed to measure the frequency

Table 1. Calculated packet success ratio versus received signal strength

Received Signal Strength (dBm)	Packet Success Ratio
≥-55 dBm	0.9999
-65 dBm	0.9983
-75 dBm	0.9959
-85 dBm	0.9981
≤-95 dBm	≈ 0

Table 2. Calculated packet and bit error ratio versus distance

Distance (in)	Packet Error Ratio	Bit Error Ratio
≤25 cm	3.20%	0.41%
38 cm	1.80%	0.23%
50 cm	1.60%	0.20%
63 cm	2.41%	0.30%
76 cm	1.33%	0.17%
88 cm	1.60%	0.20%
101 cm	1.60%	0.20%
114 cm	3.60%	0.46%
127 cm	1.50%	0.19%
139 cm	2.00%	0.25%
152 cm	1.70%	0.21%

response of the BCI and to validate that biologically relevant data could be successfully received by the nRF24L01+ receiver. The CW generator, BCI, and nRF24L01+ were connected by a Mini-Circuits ZABDC10-25HP-S coupler. The BCI's analog front-end was connected to an Agilent 33500B arbitrary waveform generator (AWG) with an output signal level of 200 μV, and the BCI was configured to sample the signal at 500 Hz for all experiments. The frequency response of the BCI was analyzed by sweeping the AWG frequency from 0.01 Hz to 220 Hz while recording 20,000 packets at 16 different frequencies. The plot of Fig. 5a shows a 3 dB frequency response bandwidth of 1-200 Hz with nearly flat response between 10 Hz and 200 Hz. This allows for analysis of a range of biological signals, including but not limited to electrocardiogram (ECG), electromyography (EMG), and local field potentials (LFPs) from implanted microelectrode arrays.

To validate system applications, pre-recorded neural data was output from the AWG to be measured by the BCI and received by the external system. The pre-recorded neural data came from electrophysiological measurements with an implanted electrode array in the primary motor cortex of a NHP. Fig. 5b compares the data receiver over the backscatter uplink to the original data. To account for the frequency response of the BCI, the original data was filtered using a Butterworth bandpass filter in MATLAB with low- and high-cutoff frequencies of 1.25 Hz and 200 Hz, respectively. The uplinked data showed good agreement with the original filtered data, having a normalized root-mean-square deviation of 5.06% based on 5,000 samples (10 seconds of data).

The packet success rate of a backscatter system is largely a function of the strength of the backscattered signal at the receiver. The backscattered signal strength is in turn a function of design and environmental parameters, such as the gain of antennas in the system, the differential radar cross section of the backscatter device, multipath interference, and others [8]. To validate the sensitivity of the nRF24L01+ to backscattered signals, a cabled experiment was performed as before, but with the addition of a variable attenuator before the receiver. The attenuation was incrementally increased, with $>$7,500 packets being transmitted at each step. For each step in attenuation, a packet counter transmitted by the BCI was processed in MATLAB to determine the number of dropped packets, yielding the packet success ratio, as shown in Table 1. The nRF24L01+ was able to successfully receive nearly every packet down to a backscattered signal strength of -85 dBm.

To determine operating distance, over-the-air tests were performed using plastic carts in a long hallway to reduce multipath interference. An Agilent CW generator and nRF24L01+ receiver were held on separate carts at a fixed location while the cart holding the BCI was moved by set intervals, shown in Table 2. The bit error rate (BER) was calculated using the following equation, where PER is the packet error ratio, and n is the number of bits per packet.:

$$BER = 1 - (1 - PER)^{1/n}, \qquad (2)$$

For each recording, the packet error calculation was done over 1000 packets received, all with a packet error rate less than 3.60%.

V. Conclusions & Future Work

This work demonstrates the feasibility of leveraging low cost, existing wireless communication chipsets to form a 2.4 GHz backscatter data link. This work has a 3 dB frequency response in the 1 to 200 Hz region and an ability to receive signals with a strength as low as -85 dBm. We demonstrated successful receiving of pre-recorded neurological data from a non-human primate. In comparison to other receivers, this device can be used in accordance with existing BLE protocols, or a custom backscatter uplink.

The flexibility of the Nordic Semiconductor nRF24L01+ chip enables researchers to operate across 125 data channels without having to modify the transmitting device. This enables future work comprising of a fully-implanted neural recorder as it eliminates the need to reprogram the backscatter uplink device to accommodate interference sources in the environment. This feature also opens the door to adaptive frequency hopping for overcoming multipath interference within resonant cavities like NHP cages.

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