A High-Sensitivity Fully-Passive Wireless Neurosensing System for Unobtrusive Brain Signal Monitoring

Cedric W. L. Lee[1], Asimina Kiourti[1], Junseok Chae[2], John L. Volakis[1]

[1]Department of Electrical and Computer Engineering, The Ohio State University

Columbus, Ohio, USA

[2]School of Electrical, Computer and Energy Engineering, Arizona State University

Tempe, Arizona, USA

Abstract — A high-sensitivity, fully-passive and wireless neurosensing system is presented for unobtrusive brain signal monitoring. The system is able to wirelessly detect neuropotentials down to 28 μV_{pp} in the frequency band of 100 Hz to 5 kHz. This is a 90-fold sensitivity improvement as compared to previous fully-passive implementations. Importantly, it implies detection of most neural signals generated by the human brain. The system consists of an implanted neurosensor and an exterior interrogator, and utilizes a highly-efficient microwave backscattering method for signal detection. High sensitivity is achieved via: (a) a sub-harmonic implanted mixer with high conversion efficiency, (b) a pair of highly-coupled implanted/interrogator antennas, and (c) a carefully matched interface between the implant antenna and mixer circuit. The proposed neurosensing system brings forward a new possibility of wireless neural signal detection using fully-passive technology.

Index Terms — Anti-parallel diode pair (APDP), biomedical telemetry, brain implants, neurosensing, passive circuits, sub-harmonic mixers.

I. Introduction

Brain implant technology has a strong potential to improve the individual's well-being. Among the possibilities are: epilepsy monitoring, early seizure detection, prosthetic control, trauma and addiction assessment, etc [1-3]. However, current/in-research brain implants have yet to overcome the following challenges: (a) wired connections to/from the implant pose infection risks and hinder natural lifestyle, (b) heat generated by the implant's battery and associated excessive electronics can disturb normal brain operation, and (c) existing fully-passive implementations exhibit low sensitivity, and cannot read low-level neuropotentials [4], [5].

In this paper, we propose a fully-passive and wireless neurosensing system for acquiring very-low-voltage neuropotentials from within the human brain [6-8]. It can detect neuropotentials as low as 28 μV_{pp} in the frequency-domain. The system can also recover demodulated neural signals down to 30 μV_{pp} in time-domain. This is a 90-fold sensitivity improvement as compared to previous fully-passive implementations [4]. This high sensitivity is obtained by minimizing circuit (harmonic mixer circuit improvements) and propagation losses. Importantly, the new sensor can read most neural signals generated by the human brain (see Table 1). Furthermore, its wireless operation allows for unobtrusive implant operation with minimal impact on the individual's activity. Concurrently, passiveness eliminates a need for bulky batteries that require replacement, and reduces circuit complexity and size. Though brain signal recording is considered in this paper, the achieved low signal detection is certainly applicable to other sensor applications.

TABLE I
VOLTAGE AND FREQUENCY RANGE OF SIGNALS GENERATED BY THE HUMAN BRAIN [6-8]

Neural signals	**Voltage Range** (V_{neuro})	**Frequency Range** (f_{neuro})
ElectroCorticographic (ECoG) signals	100 – 200 μV_{pp}	< 500 Hz
Neural "spikes"	100 – 2000 μV_{pp}	300Hz – 5 kHz
Local Field Potentials (LFPs)	20 – 2000 μV_{pp}	< 500 Hz

II. Neurosensing System

The block diagram of the proposed neurosensing transceiver is shown in Fig. 1. The system consists of two sub-systems: (1) the fully-passive brain implant (no battery and no power rectifier/regulator), and (2) the exterior interrogator. The interrogator sends a (2.4 GHz) local oscillator (LO) signal to the implant. The implanted sub-harmonic mixer then mixes the recorded brain signals (f_{neuro}) with the 2nd harmonic LO signal (4.8 GHz) to generate (4.8 GHz ± f_{neuro}). A key aspect of our implant is that the harmonic mixing is implemented via a Schottky anti-parallel diode pair (APDP). This anti-parallel diode arrangement captures both positive and negative legs of the 2.4 GHz LO signal, thus allowing for high-efficiency harmonic mixing at 4.8 GHz. Specifically, the rectification of the 2.4 GHz signal done by the anti-parallel diodes creates a natural harmonic at 4.8 GHz without the usual losses in a single diode.

The (4.8 GHz ± f_{neuro}) in the implant is mixed with the neurosignal prior to being transmitted to the exterior interrogator. The frequency difference between the transmitted (2.4 GHz) and received (4.8 GHz ± f_{neuro}) interrogator signals

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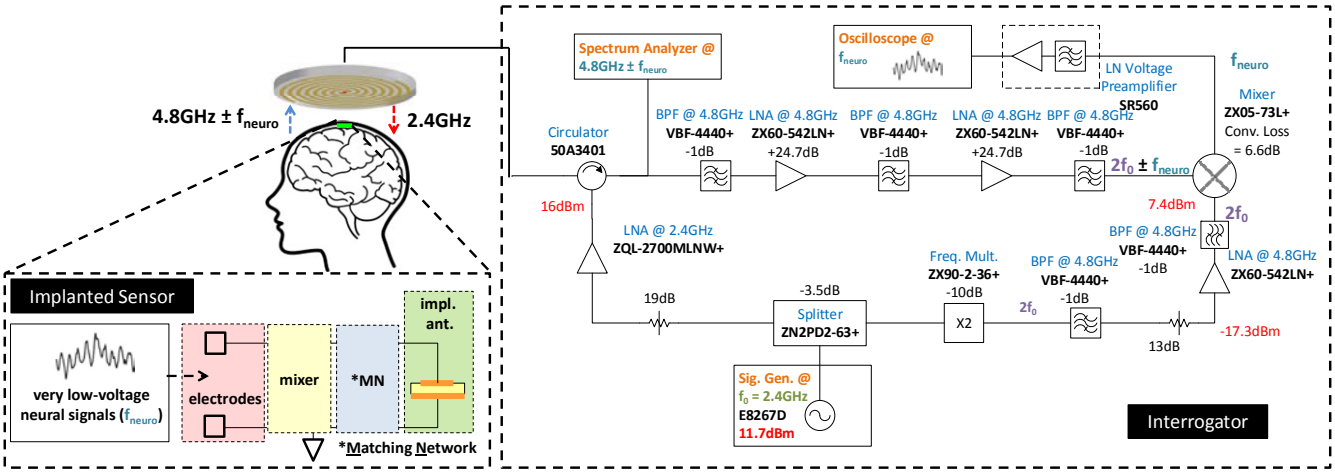

Fig. 1. Neurosensing tranceiver system block diagram.

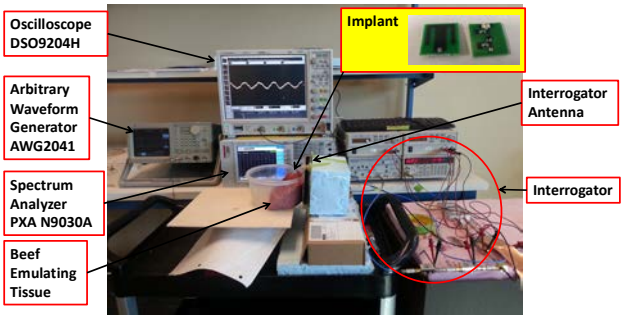

Fig. 2. Measurement set-up used to test the neurosensing system performance.

enables effective isolation. To reduce mismatch losses, a matching circuit was also employed between the implanted APDP mixer and implanted antenna. Also, for wireless communication, a dual-band (2.4/4.8 GHz) implanted patch antenna and a wideband (0.6-6 GHz) interrogator spiral antenna were used. The low-profile property of the spiral enhances its coupling with the implanted patch [9]. This is crucial in reducing system loss and for improving system sensitivity.

At the interrogator, the received signal can be viewed using a spectrum analyzer (frequency-domain) or demodulated and viewed on an oscilloscope (time-domain). Demodulation is performed by mixing the (4.8 GHz ± f_{neuro}) received signal with a (4.8 GHz) LO signal to recover the baseband (f_{neuro}) neuropotentials. Importantly, multiple stages of filtering and amplification were employed to improve the final signal-to-noise ratio (SNR) [10] at the system output (see Fig. 1).

III. System Performance

The neurosensing system shown in Fig. 1 can read brain signals as low as:

$$MDS_{Neuro}\,[dBm] = MDS_{RX}\,[dBm] + L_{sys}[dB] \quad (1)$$

where MDS_{RX} is the minimum detectable signal at the input of the interrogator receiver, and L_{sys} is the system loss. Therefore, for high detection sensitivity, L_{sys} must be minimized. The latter is given as:

$$L_{sys}\,[dB] = L_{conv}\,[dB] + L_{propag}[dB] + L_{match}\,[dB] \quad (2)$$

where L_{conv} is the implanted mixer conversion loss, L_{propag} is the propagation loss (i.e., transmission loss, $|S_{21}|$ between the implanted and interrogator antennas), and L_{match} is the matching loss between the implanted antenna and associated mixer circuit.

In our case, MDS_{RX} was calculated to be

$$MDS_{RX}\,[dBm] = kT(dBm/Hz) + log_{10}\,5kHz + NF + SNR$$
$$= -174 + 37 + 4 + 10 = -123dBm\,. \quad (3)$$

Therefore, to fulfill our goal of detecting neuropotentials as low as 30 μV_{pp} (-86 dBm), L_{sys} must be ≤ 37 dB. We note that for our system, loss = 36 dB.

To assess the minimum detectable neuropotentials of the proposed system, we carried out measurements as shown in Fig. 2. An arbitrary waveform generator was also used to generate brain neuropotentials at f_{neuro}. The implant (currently 16 mm × 15 mm × 1.5 mm in size) was immersed inside a ground beef phantom that emulated the electrical properties of average head tissue [11]. Below we discuss our measured data.

A. Measured Frequency-Domain Performance

The received signals (4.8 GHz ± f_{neuro}) first read on a spectrum analyzer at the interrogator side. System loss (L_{sys}) was calculated as the difference between the original neural signal power at f_{neuro} and the received signal power at 4.8 GHz ± f_{neuro}.

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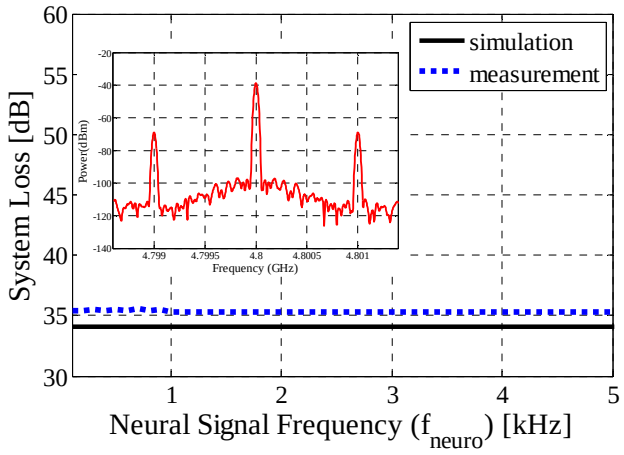
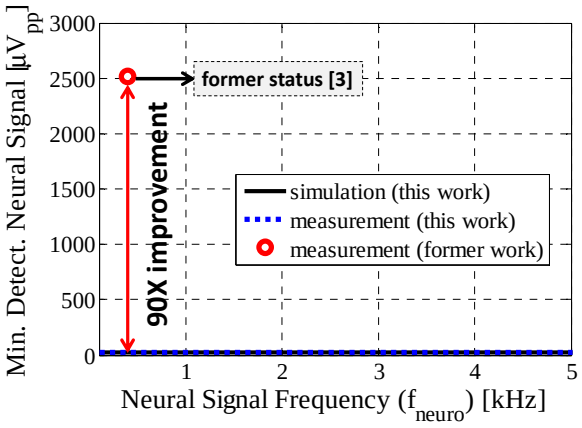
As shown in Fig. 3(a), system loss was measured to be 36 dB at 100 Hz < f_{neuro} < 5 kHz. From (3), this implies that neural signals as low as 28 μV_{pp} (-87 dBm) can be detected at the interrogator side (MDS_{Neuro} = -123 dBm + 36 dB = -87 dBm). This remarkable sensitivity implies that a very large portion of brain signals (see Table 1) can be detected using the proposed neurosensing system.

B. Measured Time-Domain Performance

To recover the original neuropotentials in time-domain, we down-converted the interrogator received signals (4.8 GHz ± f_{neuro}) to baseband (f_{neuro}), and then viewed them on an oscilloscope. The demodulator shown in Fig. 1 was employed. We found that at 100 Hz < f_{neuro} < 1 kHz, neuropotentials as low as 40 μV_{pp} (-84 dBm) can be recovered in time-domain. At 1 kHz < f_{neuro} < 5 kHz, neuropotentials down to 30 μV_{pp} (-86 dBm) can be detected. Importantly, as shown in Fig. 3(b), this is a 17-fold sensitivity improvement when compared to previous fully-passive implementations [4]. Fig. 4 shows



(a)



(b)

Fig. 3. (a) Measured system loss with inset showing spectrum analyzer measured data (P_{neuro} = -30dBm), and (b) minimum detectable neural signal (assuming MDS_{Rx} = -123 dBm) as a function of f_{neuro} achieved by the proposed neurosensing system.

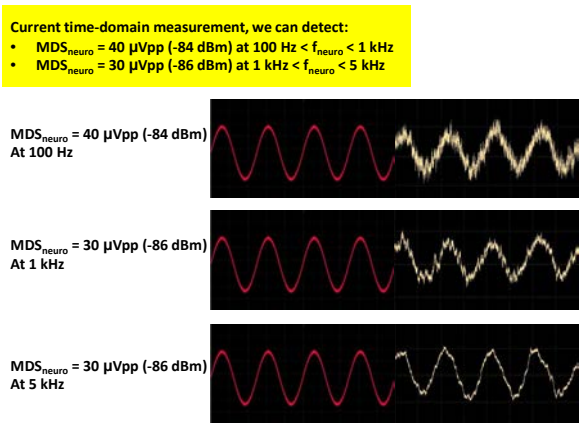


Fig. 4. Input signal vs. recovered waveforms at f_{neuro} = 100 Hz (MDS_{neuro} = 40 μV_{pp}), f_{neuro} = 1 kHz (MDS_{neuro} = 30 μV_{pp}), and f_{neuro} = 5 kHz (MDS_{neuro} = 30 μV_{pp}).

example input vs. recovered waveforms at f_{neuro} = 100 Hz (P_{neuro} = -84 dBm), f_{neuro} = 1 kHz (P_{neuro} = -86 dBm) and f_{neuro} = 5 kHz (P_{neuro} = -86 dBm). The relatively poorer detection performance at f_{neuro} < 1 kHz is due to the higher phase noise effect at those frequencies.

IV. Conclusion

A high-sensitivity, fully-passive and wireless neurosensing system was presented for unobtrusive monitoring of brain signals. This system can detect neuropotentials as low as 28 μV_{pp} in frequency-domain. In time-domain, detection down to 30 μV_{pp} was achieved. This is a 90-fold sensitivity improvement as compared to previous fully-passive realizations. This high sensitivity was mainly achieved by employing: (a) a sub-harmonic mixer consisting of an anti-parallel diode pair (APDP) with extremely low conversion loss in the 2nd harmonic, (b) a pair of highly-coupled interrogator and implanted antennas, and (c) a matching network to reduce matching losses between the implanted antenna and associated sub-harmonic mixer circuit.

Importantly, the achieved sensitivity implies reading of most neuropotentials generated by the human brain. Therefore, it introduces new possibilities in fully-passive and wireless detection of neuropotentials for a very wide range of applications. Future work will involve: (a) in-vivo acquisition of neuropotentials, and (b) further implant miniaturization.

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