A Wireless Neurosensing System for Remote Monitoring of Brain Signals

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***Abstract*—We propose a wireless, fully-passive neurosensing system for remote monitoring of brain signals. The system comprises a neurosensor, an implanted antenna matched to the sensor, an external RF interrogator antenna, and integrated RF circuits. To enable continuous and reliable sensor monitoring using a nearby mobile device (cell phone, tablet, etc), the neurosensing system is further interfaced with a wearable body area network (BAN). Design and link budget issues are discussed, highlighting the challenges of detecting actual electrocorticographic (ECoG) signals of tens of μV_{pp}.**

***Index Terms*—body area network, neural telemetry, neurosensing, signal to noise ratio.**

I. Introduction

Brain implant technology has the potential to improve the individual's well-being. Among the possibilities are these of physical control restoration, early seizure detection, prosthetics control, and so on [1], [2]. However, development of this promising technology has yet to be adopted, because of two major concerns. They are: (1) wired techniques are typically used to connect the intra-cranial implants to the external interrogator units implying severe restrictions to the patient, and (2) heat generated by the employed dense electronics, that can potentially disturb normal brain operation.

In this paper, we propose a wireless, fully-passive neurosensing system for continuous and unobtrusive monitoring of electrocorticographic (ECoG) signals, with minimum impact to the individual's activity. The monitoring system consists of implanted neurosensors and exterior interrogators, all integrated with a self-powered wearable body area network (BAN) for remote and unobtrusive monitoring. This wireless and fully-passive (no battery used for the subcutaneous sensors) approach for ECoG signal acquisition provides for very minor invasiveness and heating. As such, it minimizes injury and trauma to the brain while preserving natural lifestyle and comfort.

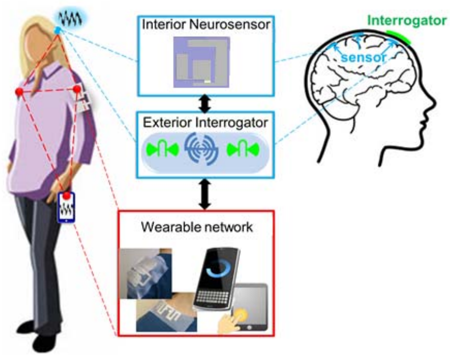

Fig. 1. Overview of the proposed wireless neurosensing system.

The design and link budget issues of the proposed neurosystem are discussed next, highlighting the challenges of detecting actual ECoG signals of tens of μV_{pp} from within the human brain.

II. Overview of the Neurosensing System

As illustrated in Fig. 1, the proposed neurosensing system consists of two major components: (1) wireless and fully-passive neurosensors with exterior wireless interrogators, and (2) self-powered BAN for continuous and unobtrusive monitoring. The implanted neurosensors utilize a highly-efficient microwave backscattering method to acquire ECoG signals. This enables fully-passive operation, meaning that the neurosensors are 100% driven by power generated from outside the head. In other words, signal gathering is performed in much the same way as in passive RFIDs.

The resolution of the detectable ECoG signals is required to be in the tens of μV_{pp}, frequency of the order of kHz. Importantly, the miniature size of the neurosensor (footprint close to 10mm×10mm×0.5mm) implies for use of multiple sensors across the brain's surface. To enable continuous and reliable sensor monitoring, the external brain interrogator is interfaced with a self-powered wearable BAN. The BAN captures the signals from the interrogators, and transfers them to a nearby mobile device (cell phone, tablet, etc). The collected signals are subsequently transferred to remote medical professionals for analysis and diagnosis. Further, if need be, the BAN can be powered by efficient power harvesters which recycle ambient RF energy. The harvester can be built with textiles for enhanced comfort and flexibility.

III. Neurorecording Microsystem and Link Budget

A block diagram of the neurorecording microsystem is shown in Fig. 2 [3]. The exterior interrogator sends a carrier signal at f_0 = 2.45 GHz to activate the neurosensor.

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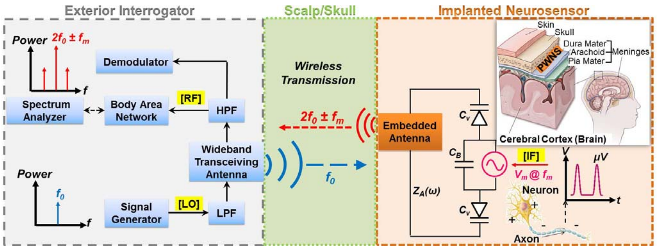

Fig. 2. Block diagram of the employed neurorecording microsystem [3].

Subsequently, the implanted neurosensor detects the ECoG signals which "radiate" at a frequency f_m, of the order of kHz. These detected signals are then used to modulate the resonant circuit attached to the sensor. The resulting frequency to the neurosensor antenna is $2f_0 \pm f_m$. We remark that the bypass capacitor (C_B) isolates the low frequency signal from the high frequency ones. Once the $2f_0 \pm f_m$ signal is received by the exterior interrogator, it is demodulated, and then down-converted to retrieve the original signals (f_m). It can then be re-transmitted by the BAN to the nearby mobile device.

A proof-of-concept sensor prototype has been fabricated and characterized in [3]. The sensor was implanted in a frog to detect compound action potentials (CAPs) from the sciatic nerve, and was found to detect a minimum signal of 500 μV_{pp} at 2-140 Hz. However, to use this sensor for the acquisition of ECoG, the sensitivity must be in the range of tens of μV_{pp}, viz. about 30 times better. Thus, the signal to noise ratio (SNR) is a critical parameter to lower the minimum detectable voltage.

Table 1 lists the major causes of loss in SNR that contribute to the SNR deterioration. They include: implanted mixer, wireless path loss and exterior interrogator. As mentioned above, earlier work has demonstrated detection of signals as small as 500 μV_{pp} [3]. Of course, the RF wireless path loss is determined by the given tissue environment, and cannot be reduced. Therefore, our focus is on reducing losses in the implanted mixer, and interrogator. Another challenge is the design and performance of the implanted and exterior antennas. As can be realized, the implanted antenna must be as small as possible to minimize tissue trauma. Concurrently, the antenna must provide good matching and gain with sufficient bandwidth to mitigate tissue variations among different individuals. The exterior antenna is less restricted in size. However, it should be well matched even when its location and nearby tissues vary.

TABLE I. MAJOR CAUSES OF LOSS IN SNR FOR THE WIRELESS NEURORECORDING MICROSYSTEM

Relative Loss Factor	**Earlier work [3]**	**Future Goals**
Implanted Mixer	30 dB	25 dB
Wireless Path	23 - 29 dB	23 - 29 dB
Exterior Interrogator		
Oscillator Phase Noise	21 dB	0.1 dB
Front-End LNA	2.7 dB	0.4 dB
Exterior Noise Coupling	0 - 20 dB	0 - 5 dB
Minimum Detectable V_m	**500 μV_{pp}**	**15 μV_{pp}**

IV. SELF-POWERED BODY AREA NETWORK (BAN)

The self-powered BAN is employed to transmit the collected ECoG signals from the implant(s) to a nearby mobile device (cell phone, tablet, etc). Specifically, the BAN will be powered by harvesting and storing the ambient RF energy from mobile base stations and TV/radio stations. The goal is to avoid use of batteries at both the BAN and the exterior interrogator. This could allow for continuous uninterrupted communication with the neurosensors, while mitigating heat challenges, and eliminating surgical operations to replace batteries. Charging occurs periodically during the day, and "on demand." By adapting highly efficient matching and rectifying circuits, the RF harvester exhibits low voltage turn-on capabilities [4]. Thus, the RF energy can be harvested, even when the available power levels are extremely small.

The harvester and BAN circuits employ textile-based wearable antennas for communication at multiple frequencies (Bluetooth and WiFi among others) [5] [6]. The wearable antennas are fabricated by embroidering the antennas and associated circuits in the garments in a manner that enables communication diversity. The efficacy of the proposed textile antennas has already been validated for some wearable RF antennas and sensors [5] [6]. The antennas have been found to exhibit comparable performance to their copper counterparts. This is due to the fiber's high conductivity (D.C. resistivity < 0.8 Ohm/m) and mechanical reliability enabled by their composite microstructure.

V. CONCLUSION

This paper presents a wireless, fully-passive neurosensing system for remote monitoring of brain activity. The uniqueness of the system lies in its passive operation and continuous acquisition of ECoG signals. As such, it improves safety and enables better wireless connectivity for the neurosensors, allowing for unprecedented long-term monitoring of the brain. Design and link budget issues are discussed, highlighting the challenges of detecting low-voltage (tens of μV_{pp}) ECoG signals from within the human brain. Other body sensors can also be integrated into the BAN to record a multitude of physiological conditions.

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