Distributed Microscale Brain Implants with Wireless Power Transfer and Mbps Bi-directional Networked Communications

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Abstract— **To dramatically increase the scale and spatial resolution for future chronic electrocorticography (ECoG) applications, we propose a wireless brain-machine interface (BMI) system based on a high number (up to 1000) of freely distributed, sub-mm sized (0.25 mm^2) IC implants. The chip features an on-chip antenna for RF energy harvesting at 900 MHz and data backscattering at 10 Mbps. In order to synchronize and time-multiplex the uplink data transmission of the untethered chips, while allowing their oscillators to free-run to save power, a robust Mbps ASK-PWM downlink data protocol based on digital counters was implemented. To the best of our knowledge, this paper presents the first experimental validation of simultaneous wireless power transfer and bi-directional RF data communications on a network of (32) brain implant ICs over a single inductive coupling link.**

I. Introduction

Brain-Machine Interfaces (BMIs) based on wired, invasive neural sensors [1] had seen significant advancement, particularly its successfully transition into human clinical trials. To dramatically increase the density and the number of channels, a number of comparable BMI approaches comprising freely-distributed, mm-sized, RF-powered CMOS chiplets had been proposed recently [2-4]. For instance, the prototype system of [4] targets the surface of the brain, where the individual nodes are freely floating and organized into a 2-D grid as demonstrated in Figure 1(a). The brain implants are to be wirelessly powered by an external RF signal source, denoted as “Skinpatch” in the picture.

Although these emerging BMI schemes share the same vision, there exist important design differences for various optimization and application objectives. For instance, the node antenna of [2] is realized by a bondwire wound around the silicon die, while that of [3-4] is integrated on-chip with top metal interconnects. While the former offers higher quality factor, the latter excels in its repeatability and lower cost [5]. The choice of antenna implementation, together with the target footprint, dictate the optimum operating RF frequency and the achievable power transfer efficiency. Either way, successful wireless power transfer (WPT), as well as uplink data transmission (e.g. backscattering), have been experimentally demonstrated [2,4].

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In order to form a coordinated network out of individual chips, the external (epidermal) RF power/ signal source must also function as the communication hub. Specifically, as in a time-domain multiplex system, the Skinpatch transmitter must provide synchronization and scheduling signals to all wireless implants to trigger their (uplink) transmission in an orderly, no-collision manner. This paper demonstrates robust downlink circuits suitable for a very low-power, area-constrained implant environment. The protocol and circuits are designed to overcome asynchronous on-chip clocks (free-running oscillators) and the lack of a known, common voltage references (as implants are essentially untethered). We believe this is the first experimental demonstration of a wireless time-division multiplex network for brain implants.

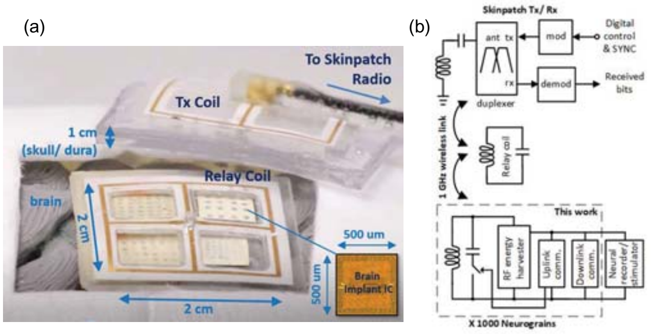

Fig. 1. (a) Proposed BMI system based on distributed wireless brain implants, known as “Neurograins”, and (b) system block diagram.

The remainder of this paper is organized as follows: *Section II* outlines the high-level BMI system specifications, *Section III* describes the test chip architecture, and the design of the ASK-PWM downlink circuits. *Section IV* describes the WPT and bi-directional communication measurements conducted in air and in brain liquid phantom. *Section V* provides a summary and discusses future directions in the context of BMI applications.

II. Overview of the Proposed BMI System

The downlink communication and wireless network study will be built upon the proposed distributed BMI system [4] shown in Figure 1. The 500 µm x 500 µm CMOS ASIC, known as a *Neurograin*, integrates the receive antenna on-chip. To overcome the resulting low electromagnetic coupling due to the

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small antenna size, a relay coil (a 2 cm x 2 cm antenna) is introduced to concentrate the flux from the Tx antenna at 1 cm distance [6]. WPT efficiency between -37 to -32 dB had been measured in brain liquid phantom, depending on where the ASIC is located within the 2D boundary of the relay coil.

Through the same inductive link, neural data recorded on the Neurograins will be BPSK modulated and RF backscattered to the external “Skinpatch” receiver. Similarly, the Skinpatch transmitter will downlink modulated commands/ data to all Neurograins. Figure 1(b) depicts the system block diagram. The dotted box shows the IC components described in this paper.

For the initial prototype, we have chosen to implement a 1000-channel system, with an overall system latency of < 100 ms (compatible with neural prosthetic applications). Design specifications such as uplink data rate (10 Mbps), downlink data rate (1 Mbps), packet duration (100 µs per channel), packet periodicty (100 ms data frame), and oscillator frequency (30 MHz) are derived from these considerations. Figure 2 shows the system timing diagram, highlighting the time-multiplex nature of the Skinpatch/ Neurograins bi-directional communication protocol.

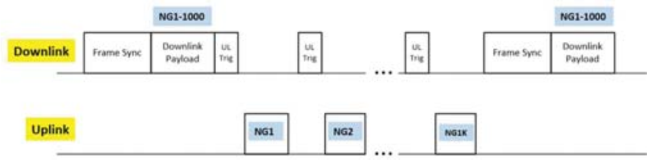

Fig. 2. Timing diagram of the Skinpatch/ Neurograins system.

III. NEUROGRAIN TEST CHIP

A. Test Chip Architecture

Figure 3 shows the block diagram of the Neurograin test chip for bi-directional data communication/ network demonstration. As in [4], an on-chip coil (part of the 3-coil relay system) couples RF power to the rectifier, which then produces the DC power supply voltage for all on-chip circuits. The oscillator is designed to generate an ~30 MHz clock signal upon free-running at start-up. For initial test purposes, we use a 32b linear feedback shift register and 16b PUF (the unique chip ID, to be explained) to produce a fixed uplink data pattern at 10 Mbps. When triggered, the uplink data will be BPSK-encoded by a digital modulator. A switchable capacitor in parallel to the on-chip inductor will be toggled to establish wireless uplink (backscattering) communication.

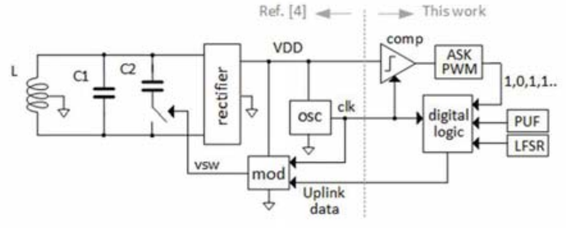

Fig. 3. Neurograin test chip block diagram.

Downlink data communication capability can be easily added to the Neurograin WPT and backscattering core. Figure 3 shows that one only needs to connect the input of a latched comparator (whose output drives the ASK-PWM decoder) to the rectifier output (VDD). As will be explained shortly, digital logic (a finite-state machine) will then decide whether uplink communication should happen, based on the received bits.

The above architecture implicitly assumes that Skinpatch communicates to the Neurograins by changing the RF tone power (or amplitude modulation). For robust downlink communication, one must address the issues of (1) free-running (and unsynchronized) Neurograin clocks, (2) unknown rectifier output and lack of usable reference for bit slicing, and (3) achieving a practical and area-efficient chip address (ID). They will be discussed in the next three sub-sections.

B. ASK-PWM Scheme

To keep the circuits simple and low-power, Neurograin oscillators free-run at ~30 MHz. These clocks will not be frequency/ phase aligned with each other nor the downlink data stream. Therefore, data/ frame synchronization cannot be achieved by simple ASK modulation. To address this challenge, we adopt a form of ASK-PWM (amplitude shift keying, pulse width modulation) [7] scheme for the downlink data. As shown in Figure 4, logic “1” is represented by a high pulse with long (2T) duration, followed by a low pulse with short (T) duration. And conversely, a logic “0” would be denoted by a high pulse with short (T) duration, followed by a low pulse with long (2T) duration. (For downlink rate of 1 Mbps, T equals 0.33 µs.) In other words, bits are encoded in the relative pulse width duration. Data synchronization is ensured by the low-to-high pulse transition, independent of the individual clock frequencies and phases of each Neurograin.

Unlike [7] which features a resettable integrator and second comparator, we implement the ASK-PWM demodulation scheme with two digital counters. “Counter H” will record the duration of a “high” pulse. (The counter begins and ends with a L/H and H/L transition, respectively.) Similarly, “Counter L” will record the low pulse duration. Logic “1” is detected if $N_H > N_L$ (with sufficient margin to avoid false detection), while logic equals “0” if $N_H < N_L$. As such, the absolute counter values, which is a function of the uncertain clock frequency, do not matter. Only their relative values do, rendering the demodulation insensitive to clock frequency variations.

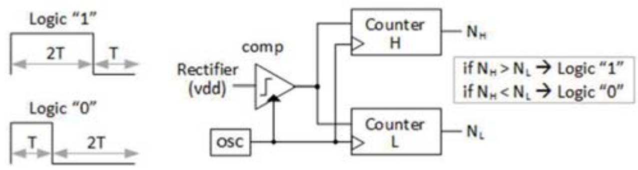

Fig. 4. Downlink ASK-PWM scheme and the logic decoder

C. Comparator Design

The downlink amplitude modulation depth is a delicate design choice for the distributed Neurograin network. One should recall, from the Introduction, that the inductive coupling strength varies significantly with respect to the location of the Neurograin on the 2D grid [6]. Assisted by HFSS EM modelling on realistic brain tissue, one can simulate the rectifier output voltages versus a wide range of transmit power at the strongest and the weakest (boundary) coupling locations. The results are presented in Figure 5.

At the strong coupling locations, the rectifier DC output will be heavily compressed. A higher modulation depth (bigger difference between high/ low Tx power) would be needed, or the swing (high/ low DC voltages) will be too small for the comparator to decipher. On the other hand, at the weak coupling locations, an excessively big modulation depth could potentially disrupt the wireless power transfer by dropping the VDD too low. In order to provide robust downlink to Neurograins at all locations, we decided to set amplitude modulation of the Tx Tone at 28.5 dBm ± 1.5dB (3dB variation).

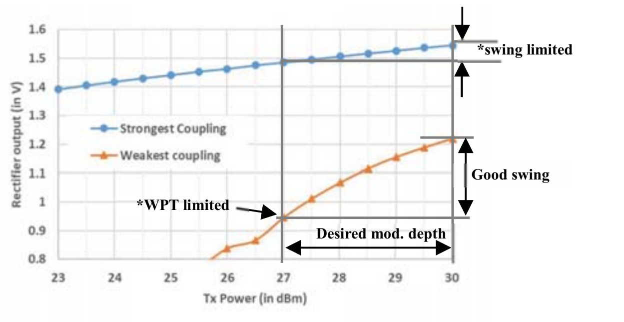

Fig. 5. Determination of amplitude modulation depth from the simulated rectifier outputs vs. Tx power with different coupling coefficients.

As the rectifier output voltage cannot be known *a priori*, an averaging (double RC filters of 400 KΩ/4 pF) circuit is used to set the reference. Figure 6 shows the self-reference strongARM comparator circuit for envelope signal slicing. To ensure the average voltage does not drift with data, Manchester-coding was employed. The circuit consumes 0.5 µA.

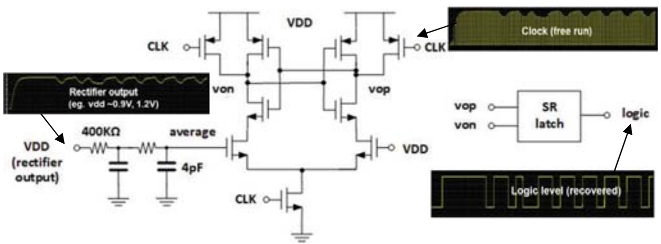

Fig. 6. Comparator circuit for slicing the downlink ASK-PWM envelope.

D. Chip Address and Test Features

To arrange individual neurograins into a network, each chip must have a unique ID. While this can be easily achieved by integrating metal interconnect structures to be laser-cut after fabrication, we chose instead to implement 16-bits of random PUFs (Physically Unclonable Functions) [8] and avoid any post-processing steps.

Logic was designed into the Neurograin such that when the chip is powered-recycled (i.e., when RF power is switched from 0 dBm to 28.5 dBm), the PUF identity will be automatically and repeatedly broadcasted (backscattered) for about 100 µs. We have heavily utilized this built-in testability feature to discover the chip identity, as well as to debug the WPT efficiency and the basic internal circuit functionalities.

The on-chip finite-state machine implements a "call-and-response" protocol. After a unique SYNC command (high pulse for 5T, low pulse for 1T) is detected, the chip would store the next 16 bits it receives. When that matches its own unique PUF address, the chip's backscattering circuit will be triggered. A combination of the fixed 32-b LFSR pattern, plus its own 16-b PUF ID will be backscattered repeatedly for about 100 µs.

E. CMOS 65nm Neurograin Test Chips

The Neurograin test chip has been designed and fabricated in TSMC 65 nm CMOS LP process. Figure 7(a) shows the chip photomicrograph. The outer coil dimension is 500 x 500 µm^2. 32 of these chips are spatially distributed within the relay coil, as shown in Figure 7(b). They will be wirelessly interfaced with a single Skinpatch antenna to form a network.

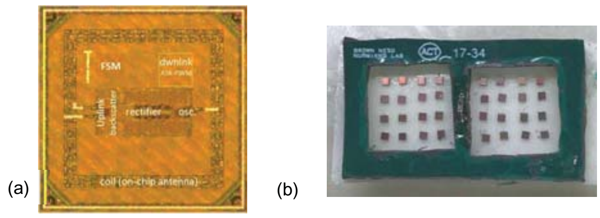

Fig. 7. (a) Neurograin test chip photomicrograph, and (b) 32-chip network

IV. Wireless Neurograin Measurement Results

Figure 8 shows the experimental set up. The Skinpatch RF communication hub is realized by a NI Chassis running the PXIe-5840 Vector Signal Transceiver module. Matlab programs run in background to seamlessly generate the required 1 Mbps ASK-PWM RF tone at 915 MHz. Through a power amplifier, the module drives the Skinpatch antenna, which is placed at about 0.8 cm away from the Neurograins. A microwave circulator isolates the backscattered signals (if any) at ~945 MHz. The received signal is further notch-filtered (to reject the leaked Tx tone) and down-converted to baseband. Finally, Matlab programs perform frequency/ timing recovery to recover the 10 Mbps BPSK modulated digital bit patterns sent from the Neurograins. The objective of the experiment is to simultaneously demonstrate WPT and bi-directional (down/ uplink) communication at the Mbps rate.

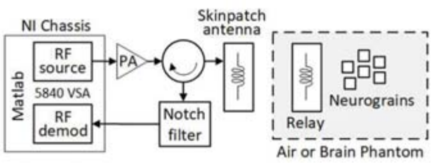

Fig. 8. Wireless test setup for neurograin network

A. Test in Air

Programming the specific PUF addresses into the ASK-PWM downlink stream, we were able to demonstrate the 32-chip wireless "call-and-response" network. Figure 9(a) shows the received baseband signals in the time-domain, where 32 downlink and uplink packets can be identified. Figure 9(b) displays 4 sampled recovered data after demodulation. For ease of evaluation, the backscattered packet of 1024-bits (~100 µs) is displayed in a color-coded 2D (32-bits x 30 cycles) array. It is evident that fixed 32b LFSR pattern (1st half of the map) and unique 16b PUF addresses (2nd half) are recovered as expected.

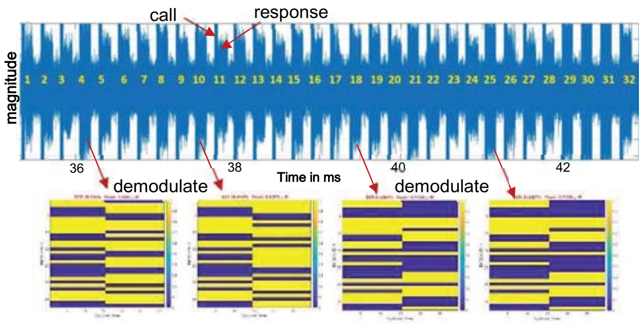

Fig. 9. Measured 32-Neurograin call-and-response network: (a) transient baseband data, and (b) samples of recovered bits dispalyed in 2D color map.

While performing demodulation on the received signal, we could handily monitor the Neurograin chip clock frequencies and the received power over all 32 locations. The results are displayed in Figure 10. As HFSS EM simulation indicates that the strongest (weakest) coupling exists at the innermost corner (empty center) of the relay coil, we also find the highest (lowest) clock frequencies and received power at the same locations. The left/ right symmetry is also evident.

Note that the fastest and slowest clocks in the network are measured to be 32.4 and 24.9 MHz, respectively. This corresponds to ±13% variation over a nominal clock frequency of 28.7 MHz. Nevertheless, synchronized downlink data transmission is still achieved, thanks to the ASK-PWM scheme.

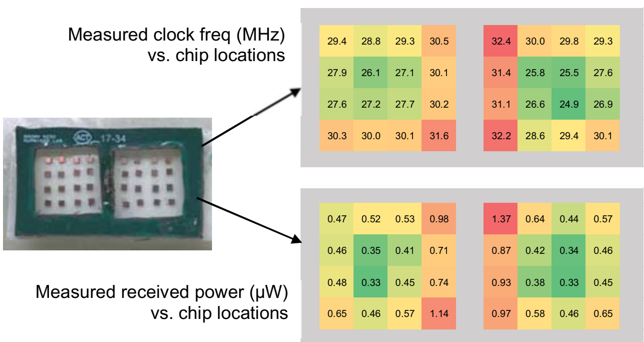

Fig. 10. Measured clock freq and received power versus chip locations

For this over-the-air test, the Tx power at the Skinpatch antenna was set to be +24.5dBm. With received power of 1.37 and 0.33 μW at the max/ min coupling, the overall round-trip path loss is -35 to -53 dB, respectively.

B. *Test in Liquid Brain Phantom*

To model the tissue loss, a wireless test is conducted in 8 mm depth of liquid brain phantom [6] with submerged relay coil and Neurograin. This is shown in Figure 10(a). A single un-encapsulated die has been tested on two locations (strongest and weakest coupling) over a range of Tx powers. The results are shown in Figure 11(b). A measured chip clock frequency denotes that backscattering has been successfully triggered by the downlink ASK-PWM command at the specific Tx power level. To satisfy both extreme cases, Tx power of +28 dBm should be selected, which is consistent with simulation results of Figure 5. The overall round-trip path loss is measured to be -39 and -64 dB for the strongest and the weakest coupling locations.

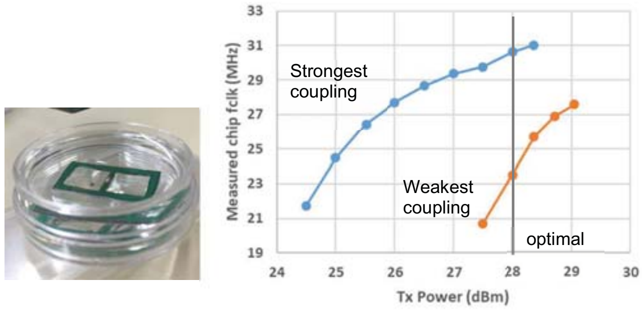

Fig. 11. Wireless "call-and-response test" on a Neurograin in liquid phantom.

V. Summary

This work discusses the design of ASK-PWM downlink circuits for distributed wireless brain implant ICs. To the best of our knowledge, it is the first experimental demonstration of simultaneous WPT and bi-directional RF data communications over a single inductive link for such applications. The communication core of this work will be integrated with neural-recorders and/ or stimulators to form a complete system.

VI. Acknowledgements

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