# *In vitro* evaluation of a protocol and an architecture for bidirectional communications in networks of wireless implants powered by volume conduction

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***Abstract*— Wireless active implantable medical devices (AIMDs) can be an alternative for overcoming the drawbacks faced with superficial and percutaneous technologies. However, current AIMDs require bulky and rigid components for powering, hampering their miniaturization. AIMDs based on power transfer by volume conduction do not need these voluminous parts, allowing the development of thread-like devices that could be used for distributed stimulation and sensing of the neuromuscular system. In this paper, we present an *in vitro* evaluation of a protocol and an architecture for bidirectional communications in networks of injectable wireless implants powered and controlled by volume conduction. The wireless prototypes were successfully addressed from the external systems, and end-to-end bidirectional communication was performed at 256 kbps with a success rate of 87 %.**

## I. Introduction

Musculoeskeletal modelling and robotics are currently used to aid in the management of tremor suppression and spinal cord injury rehabilitation. However, both fields rely on superficial or percutaneous methods for electromyography (EMG) acquisition and electrical stimulation, which present several drawbacks including lack of selectivity in the former, and creation of infection pathways in the latter.

Wireless active implantable medical devices (AIMDs) are an alternative for overcoming these drawbacks. Yet their development has been hampered by the methods used to power them, as those usually require bulky and rigid components that result in devices that are too thick and stiff to be easily implanted through injection [1].

To overcome these limitations, we have proposed an implantable technology based on wireless power transfer by volume conduction: an external system delivers to the tissues high-frequency (HF) currents in the form of bursts, and these currents are picked up by thread-like injectable implants to power their electronics, and perform tasks such as electrical stimulation and EMG acquisition. This implantable technology will be used to develop minimally invasive "Bidirectional Hyper-connected Neural Systems" (BHNS) for distributed stimulation and sensing of neuromuscular activity, which could be used for tremor suppression management and spinal cord injury rehabilitation.

The BHNS will be composed of external systems and wireless implants (hereinafter "functional units" (FUs)). The external systems will consist of 1) one top-level control device (hereinafter "Brain") that will communicate with the FUs through 2) several low-level control units (CUs) that act as bidirectional gateways (i.e. protocol translators) between the Brain and the FUs. These CUs will apply bursts of HF currents through external electrodes. The FUs will pick up these currents and rectify them to obtain power and information, and to perform the task defined by the Brain.

In this paper we will present a first *in vitro* evaluation of a protocol and an architecture for bidirectional communications in networks of wireless FUs powered by volume conduction.

## II. Materials and Methods

### A. External systems

The Brain consists of a PC/104 board computer with a PCIe/104 stackable bus structure (CMA34CRQ2100HR, by RTD) and a 2.1 GHz Quad-Core processor. The CUs consist of: 1) a HF sinusoidal generator and modulator (4064 by BK Precision); 2) a digital control to manage the communication interfaces with the Brain, the FUs and controlling the whole CU; 3) a custom-made demodulator that decodes the modulation performed by the FUs for the uplink communication (i.e. from the FUs to the Brain); and 4) a custom-made high-power amplifier that applies the HF current bursts to the tissues through the external electrodes. The currents are delivered in the form of bursts to avoid tissue heating, and they are in HF to avoid unwanted electrostimulation [2].

The information between the external systems and the FUs is modulated in the HF current bursts. To avoid tissue heating,

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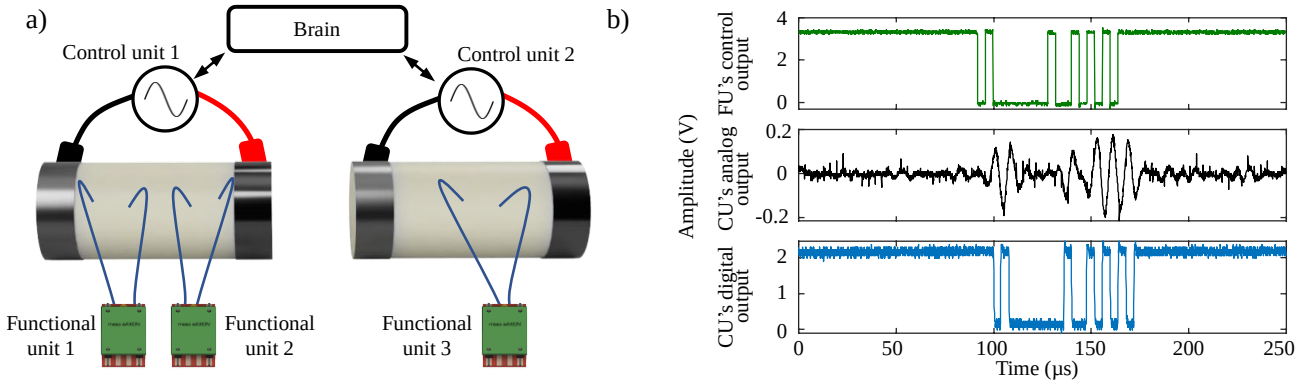


Fig. 1. *In vitro* evaluation of a protocol and an architecture for bidirectional communications in networks of wireless implants (FUs) powered by volume conduction. A) Setup used. B) Results obtained during an uplink sequence, including 1) control signal of the FU for its modulator; an acknowledge (ACK) message is sent to the CU according to the protocol stack, 2) filtered signal obtained by CU's demodulator, and 3) digital output of comparator circuit in CU's demodulator.

an *ad hoc* communication protocol stack was implemented. It consists of a four-layers architecture based on the Open System Interconnection (OSI) model. With the current protocol stack, thirteen different tasks can be performed.

### B. *Functional units – wireless devices*

The proof-of-concept FUs used in this evaluation are based on the architecture described in [3]. They are made only of off-the-shelf components soldered on a printed circuit board (PCB), which can be easily connected to wire electrodes, or to thin-film electrodes that can be injected using a needle [4]. For the uplink, the FUs digitally modulate the HF current bursts according to the protocol stack.

### C. *In vitro evaluation*

The *in vitro* setup, including Brain, CUs and FUs (Fig. 1a) is based on two 6.5 cm diameter agar cylinders made from a NaCl solution with a conductivity of 0.57 S/m, equivalent to that of muscle tissue at 3 MHz. Two aluminum external electrodes were strapped around the cylinders, at a distance of 10 cm, and each pair of electrodes were connected to one CU. The electrode pads of the FUs' PCBs were soldered to two silver plated copper wire electrodes with an exposed length of 3.65 mm and a diameter of 0.25 mm, and the ends of these wires were inserted into the cylinders, at a distance of 3 cm.

One Brain controlled the two CUs, each one delivering sinusoidal signals in the form of bursts, with an amplitude of 37 V, a duty cycle of 8% and a frequency of 3 MHz. The signals delivered by the FUs and those obtained by the CUs were recorded using an oscilloscope with isolated channels (TPS2014 by Tektronix).

Three sets of experiments were done: 1) downlink communication (i.e. request from the Brain to the FUs) to two FUs in a single agar cylinder (i.e. one CU); 2) downlink communication to two FUs, each one in one agar cylinder (i.e. two CUs); and 3) downlink and uplink communication (i.e. request from the Brain to the FUs and reply from the FUs to the Brain) using one FU in a single agar cylinder.

## III. Results

For experiments 1 and 2, as a visual demonstration, two LEDs were added to the FUs to show if the Brain was able to address each one of them independently. In both experiments, all the FUs were successfully addressed with no error. A video of experiment 2 is available in this link. In experiment 3, the whole system was able to perform end-to-end bidirectional communication between the Brain and one FU at 256 kbps with a success rate of 87 %.

Fig. 1b shows how the CU demodulates the uplink information coming from the FU. The modulation made by the FU is seen by the CU as variations on the current applied to the tissues. These fluctuations are filtered, amplified and passed through a Schmitt trigger, to obtain a digital signal that can be processed by the CU. The delay between the FU and the CU is only tens of microseconds.

## IV. Discussion

Here we *in vitro* evaluated a protocol and an architecture for bidirectional communications in networks of wireless implants powered by volume conduction. The communication speed is high enough for controlled electrical stimulation and EMG acquisition. The circuit architecture of the FUs used is the basis of a fully injectable device based on an application specific integrated circuit (ASIC). The resulting wireless device will have an unprecedented level of minimal invasiveness, which will be paramount for the viability of the BHNS for distributed stimulation and sensing of neuromuscular activity.

## References

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