Powering and Communication for OMNI: A Distributed and Modular Closed-Loop Neuromodulation Device

Ali Moin*†, George Alexandrov*†, Benjamin C. Johnson‡, Igor Izyumin‡, Fred Burghardt†, Kedar Shah§,
Sat Pannu§, Elad Alon†, Rikky Muller†‡, Jan M. Rabaey†

***Abstract*— A distributed, modular, intelligent, and efficient neuromodulation device, called OMNI, is presented. It supports closed-loop recording and stimulation on 256 channels from up to 4 physically distinct neuromodulation modules placed in any configuration around the brain, hence offering the capability of addressing neural disorders that are presented at the network level. The specific focus of this paper is the communication and power distribution network that enables the modular and distributed nature of the device.**

I. INTRODUCTION

Neurological disorders broadly affect a billion people worldwide and account for 6.3% of the global burden of disease [1]. Treatments for neurological disorders have traditionally been limited to pharmaceutical intervention, therapy, and counseling. For debilitating conditions, these therapies can be ineffective or even cause harmful side effects. Deep brain stimulation (DBS) is an effective solution for the symptomatic treatment of movement disorders such as Parkinson's Disease, Essential Tremor, and Dystonia. Unlike movement disorders, neuropsychiatric disorders manifest in the brain at the systems level, necessitating a distributed, network approach that acts in closed-loop and responds in real time. Recent research has demonstrated the potential of DBS and closed-loop neuromodulation in treating some neuropsychiatric disorders [2], yet a more sophisticated system than the current state-of-the-art is required in order to address disorders that manifest in complex neural pathways and affect physically distant regions of the brain.

Current research and commercial devices for the treatment of movement disorders and epilepsy such as Medtronic's Activa PC+S [3] and NeuroPace's RNS System [4] rely on specific anatomical targets and electrode placement for stimulation. More importantly, these devices are housed in a central hub with long leads connecting electrodes to recording and stimulation circuitry. This configuration limits the number of recording/stimulation channels to a small number per device, since each channel needs a corresponding wire from electrode to hub, reducing cable flexibility and increasing size and tissue displacement. There have been recent efforts to address these issues [5], but these consume too much power to be operated chronically.

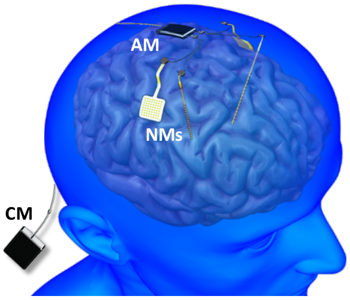


Fig. 1. OMNI device showing multiple NMs attached to the AM, sitting just above the skull, where data and commands are multiplexed. The CM is responsible for controlling and powering all sub-modules.**

In order to adequately address neurological disorders at the systems level, a device is required that has several unique features not found in current state-of-the-art neurostimulator systems:

Distributed: The device should be able to reach any region of the brain based on specific patient needs. Therefore, it should support multiple arrays, both cortical and sub-cortical, with a large number of recording and stimulation channels.

Modular: The architecture and physical placement of the device should be easily reconfigurable, allowing the clinician to decide the most effective configuration of implants for each individual patient based on his or her needs.

Intelligent: The device should operate in a closed-loop fashion, leveraging advanced signal processing to determine stimulation parameters and locations in real-time, and ensuring that stimulation is only delivered when and where it is needed.

Efficient: Since the device is implanted, it should be extremely energy-efficient to have minimal need for battery recharging or wireless power transmission without compromising the performance of the system in the above aspects.

We introduce the Octopus Mimetic Neural Implant (OMNI) device (Fig. 1). OMNI's modular and distributed approach to neuromodulation is a key enabler for a new class of closed-loop treatment of neurological disorders. Specifically, this paper focuses on the power and communication networks that alleviate the excessive cabling and interconnects required for high throughput recording and stimulation from hundreds of electrode sites.

The paper is organized as follows: Section II outlines the

---

*Authors contributed equally to this work.

†Ali Moin, George Alexandrov, Fred Burghardt, Elad Alon, Rikky Muller, and Jan Rabaey are with the department of EECS at the University of California at Berkeley, Berkeley, CA, 94720.

‡Benjamin C. Johnson, Igor Izyumin, and Rikky Muller are with Cortera Neurotechnologies Inc, Berkeley, CA, 94704.

§Kedar Shah and Sat Pannu are with Lawrence Livermore National Labs, Livermore, CA, 94550.

**Images courtesy of Lawrence Livermore National Labs.

various components of OMNI and how they contribute to creating a modular system. Section III describes the custom communication and power distribution networks. Section IV shows measurement results of the system, followed by a summary in Section V.

II. SYSTEM OVERVIEW

OMNI consists of three main types of modules. The Neuromodulator Modules (NMs) are "smart electrodes," each of which are comprised of a high-density thin-film electrode array integrated with a single custom low-power application specific integrated circuit (ASIC). The ASIC records and digitizes the neural signals at each electrode and sends the data in packets across a cable to a central router on the skull called the Aggregator Module (AM). The AM serializes and packetizes data from 1 to 4 NMs (scalable up to 8) and sends it through a single cable to the main processor of the device called the Control Module (CM). The CM performs advanced processing on the received data and determines stimulation locations and parameters. It then sends stimulation commands to the AM, which routes them to the desired NMs. This architecture enables advanced closed-loop neuromodulation in a highly scaled and distributed manner. Each module is discussed in detail below.

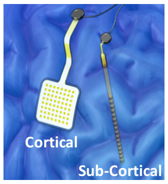


Fig. 2. NMIC package attached to cortical and sub-cortical electrode arrays.**

A. Neuromodulator Module (NM)

NMs are OMNI's interface to the brain. They are implanted in the brain and are responsible for recording neural signals and stimulating the desired brain targets. Based on the specific symptoms of an individual patient, the clinician can decide the number and placement of NMs. Each NM consists of two main parts:

1) Micro-Electrode Arrays: Thin-film high-density microfabricated arrays of either 32 or 64 electrodes are placed either on the surface of the brain cortex (cortical arrays) or penetrated into the brain tissue (sub-cortical arrays) as shown in Fig. 2. The ability to choose between these two types of electrode arrays enables OMNI to reach multiple brain regions in a patient-specific configuration.

2) Neuromodulator Module Integrated Circuit (NMIC): The NMIC is a 64-channel ASIC with simultaneous stimulation and recording capabilities to enable closed-loop neuromodulation. The chip features 4 reconfigurable stimulators that can be assigned to any of the 64 electrodes dynamically, coupled with the ability to simultaneously record on all 64 channels. Neural signals are acquired, digitized, and transmitted at the electrode interface by the NMIC, which requires a single 6-wire cable bundle for power and communication. To the authors' knowledge, OMNI is the first device with active digitization at the electrodes and a fully digital interface between its modules. Without this feature, 64 recording wires and 8 stimulation wires would be needed to match the capabilities of a single NM.

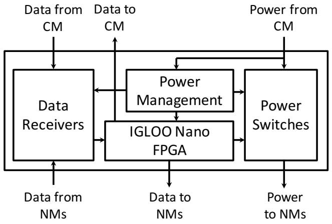
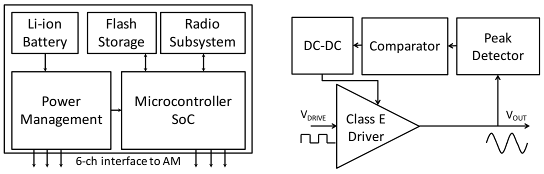


Fig. 3. Block diagram of Aggregator Module (AM).

B. Aggregator Module (AM)

The AM acts as a router for power and data, connecting up to 4 NMs (limited by connector design but scalable to 8) to the main processing unit of the system (CM). The AM is a key enabler for OMNI's modularity, allowing an arbitrary number and type of NMs to be connected to the rest of the system. It also enables two important features: (1) significant reduction in cable complexity, and (2) a safety mechanism in the event of a cable or NM failure by providing safe shutdown upon a detected error. Having a separate percutaneous cable to connect each NM directly to the CM increases implant complexity, infection risk, and failure risk. Therefore, the NMs are first routed through a short 10 cm cable to the AM, which is implanted just above the skull, and from there to the CM via a longer 50 cm cable.

Fig. 3 shows the block diagram of the AM. An IGLOO nano low-power FPGA is used for the digital protocol logic and I/O handling. The power management block generates the AM DC supply from the AC power distribution network. Also, since the data signals are single-ended and AC-coupled, there is a cross-coupled inverter pair as the receiver for each signal. These networks are discussed in detail in Section III.



(a) (b)

Fig. 4. Block diagrams of Control Module (CM) (a), and adaptive AC power driver (b).

C. Control Module (CM)

The Control Module (CM) is an integrated and programmable data processing, storage, and telemetry module that acts as the brain of the system. A block diagram of the CM is shown in Fig. 4(a). It houses a Cortex-M3 microprocessor which is capable of running algorithms required for closed-loop treatment, allowing the device to choose where, when, and how stimulation should take place. The on-board Nordic nRF51822 2.4 GHz radio provides a 2 Mbps bidirectional wireless link for remote logging and configuration. The CM is also responsible for efficiently and reliably powering the rest of the OMNI system. It achieves this by adaptively generating differential AC power signals from a single Li-ion battery. The block diagram of the power drivers is shown in Fig. 4(b) and the details of this distributed power delivery are discussed in Section III.

III. DATA AND POWER NETWORKS

The distributed nature of OMNI poses a challenge in powering and communicating with each sub-component. In order to keep the number of bundled wires in the cable and the number of physical connections from the NM to the AM small, we designed a 6-wire interface. Two differential power wires, three data signal wires and one common wire support a custom communication and power distribution protocol.

Similar to computer networks, a complete protocol stack from the physical layer (cables) up to the application layer (control interface) is defined. The cable design minimizes cross-talk and noise while keeping cable thickness minimized by using a symmetric cable structure with a central twisted-pair for the power wires. The following subsections describe the data link layer and power distribution network, respectively.

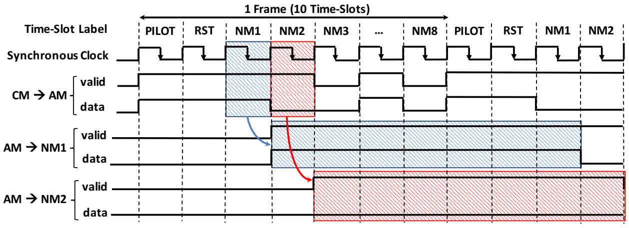


Fig. 5. Digital protocol showing command bits from CM to NMs. The PILOT and RST bits in the CM-AM frames signify the start of a valid command to the NMs and are followed by 8 slots for command bits to 8 NMs. This example shows valid command bits being sent from the CM to two NMs. Signals are shown after being recovered from the ac-coupled link at the AM and NM receivers.

A. Data Communication Network

A full-duplex data communication network transfers packets between the system modules. To support the modularity of the system, we have designed a custom time-multiplexed protocol that supports a variable number of up to 8 NMs. The 20 MHz bandwidth in the CM-AM link is divided into groups of 10 time slots called a *frame*, each slot with 2 MHz bandwidth and allocated to one of the 4 (up to 8) NMs. The first two time slots are used for synchronization between modules and some low-level controls such as reset. These are crucial control commands that should be at the lowest data layer and independent from the packet decoder.

There are two signals between modules in the downlink (CM-to-AM-to-NM) direction: *valid* and *data*. When there is data available for a time-slot, the *valid* signal is set to high during that time-slot and the *data* signal contains the actual bit value. Therefore, the receiver picks up the data whenever the corresponding *valid* is high, allowing the CM to address any subset of NMs. The packets in this direction are CM commands. Fig. 5 shows how these command bits are sent from CM to AM to particular NMs.

Unlike the downlink, the uplink (NM-to-AM-to-CM) direction does not need synchronization or control signals. Instead, data is transmitted on the NM-AM *data* line with a fixed header indicating the start of the packet, followed by 64 channels of neural data. This way, we omit the *valid* line in this direction to minimize the number of wires. The packets in this direction are either digitized neural signals or register read replies.

Although a differential signaling scheme would be more robust to interference, we have chosen a single-ended approach in order to minimize power and the number of wires in the cable. Moreover, based on medical implant regulations, the implanted cables must carry zero DC component to prevent long-term tissue damage and current flow into tissue in the case of cable failure. Therefore, the signals are AC-coupled at both ends of the cable and are recovered by the receiver circuits.

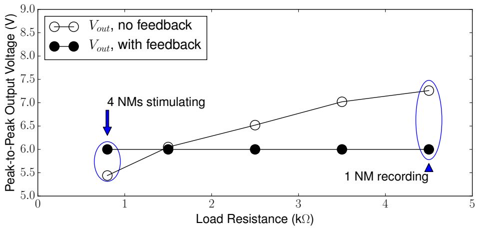


Fig. 6. Comparison of power driver output voltage with/without feedback.

B. Power Distribution Network

Unlike existing neuromodulation devices where battery, stimulators, and recording hardware are fixed and located in the same package, the OMNI system is comprised of a variable number of NMs with varying power requirements. This presents a challenge in powering the system since it must support a very broad range of load currents that are all dynamically changing. Each NM's power dissipation can vary from a few hundred μW to a few mW between recording and stimulation. Thus, the effective load that the power driver must drive can vary by a similar amount. Any powering scheme must be able to adjust its output power so the correct amount is delivered to each module while maintaining high power efficiency. Furthermore, to ensure efficient operation of the NMs, power should be delivered with a constant voltage across all load conditions. Finally, any implanted cables should carry zero DC component, so the power distribution must be AC.

In order to address these challenges, an adaptive powering scheme is implemented to ensure the correct amount of power is delivered safely and reliably to each individual NM and AM. This powering scheme consists of two differential AC voltage signals generated via a pair of Class E power amplifiers (refer to Fig. 4(b)). Each power signal's output voltage is independently set by a feedback network, allowing the power drivers to adapt to asymmetrical load variations. Fig. 6 illustrates how the feedback circuit produces a constant output voltage under various load conditions. Without feedback, the power drivers are supplied by a constant supply voltage and generate an output voltage that varies directly with load resistance. With feedback included, the supply voltage is adjusted automatically in order to set a constant output voltage.

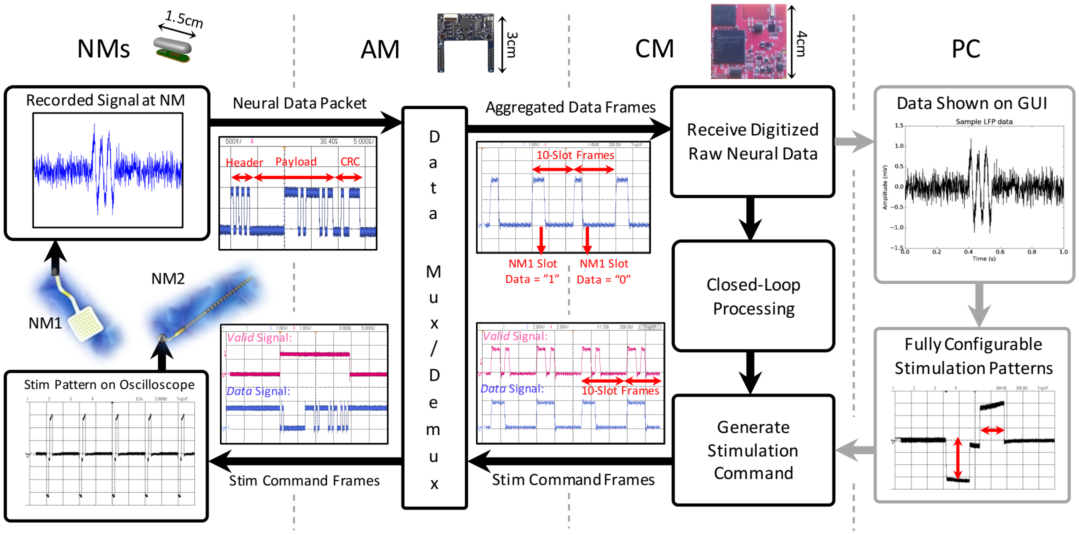


Fig. 7. Integrated system demonstration diagram showing benchtop testing of OMNI. Generated neural data is recorded by one NM and sent to the CM through a custom digital communication protocol. The CM communicates wirelessly with the GUI running on the PC, which processes neural data and sends stimulation commands back to the CM.

IV. INTEGRATED SYSTEM & RESULTS

Fig. 7 shows the integrated system benchtop demonstration setup which shows an OMNI configuration with two NMs. A sample neural signal is recorded on NM1 and sent as digital packets to the CM through the AM using our custom communication protocol. The intermodule signals are captured on an oscilloscope and displayed in the figure. For this demonstration, the CM streams data to a PC for offline computation and configuration of stimulation patterns, and sends stimulation commands to NM2. In practice, closed-loop algorithms can run on the CM to adaptively update the stimulation parameters and locations based on subsequent recorded signals, eliminating the need for a PC.

Recent efforts [5] have improved significantly on commercial systems [3], achieving a high-channel recording and stimulation system using mainly off-the-shelf components. However, this system cannot be operated chronically due to the high power dissipation of its off-the-shelf recording (Intan RHD2164) and stimulation (Cactus Semiconductor CSI021) hardware. While OMNI dissipates $2\,\mathrm{mW}$ for simultaneous recording on all 256 channels, a similar system using Intan ASICs would consume about $20\,\mathrm{mW}$ for the same number of channels. Compared to [5], OMNI supports a large number of channels at a significantly lower power consumption and with fewer implanted wires.

V. SUMMARY

OMNI advances state-of-the-art in implantable closed-loop neuromodulation systems by enhancing the ability to chronically record neural activity and perform closed-loop stimulation at the network level. The large number of channels, low power consumption, and reduced number of implant wires allow OMNI to cover more brain regions, simplify implantation, and operate continuously for longer periods of time. Through its modular and distributed approach to neuromodulation, OMNI is capable of addressing complex disorders that manifest in multiple brain regions at the systems level and require a dynamic approach to the therapy.

TABLE I
COMPARISON OF OMNI WITH CURRENT STATE-OF-THE-ART

Specification	**This Work**	**Wheeler [5, 6]**	**Stanslaski [3]**
Electrode Arrays	**4 (scalable to 8)**	5	2
Channels	**256 (scalable to 512)**	320	8
Stimulators Per Array	**4**	2	1
Wires Per Cable	**6**	10	4

ACKNOWLEDGMENT

This work was supported in part by DARPA Biological Technologies Office under contract W911NF-14-2-0043 and under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344, Lawrence Livermore National Security, LLC. The authors thank Simone Benatti and the sponsors of the Berkeley Wireless Research Center.

REFERENCES

[1] World Health Organization. *Neurological disorders: public health challenges*. World Health Organization, 2006. Chap. 2, p. 32.

[2] Helen S Mayberg et al. "Deep brain stimulation for treatment-resistant depression". In: *Neuron* 45.5 (2005), pp. 651–660.

[3] Scott Stanslaski et al. "Design and Validation of a Fully Implantable, Chronic, Closed-Loop Neuromodulation Device With Concurrent Sensing and Stimulation". In: *Neural Systems and Rehabilitation Engineering, IEEE Transactions on* 20.4 (2012), pp. 410–421.

[4] Felice T Sun and Martha J Morrell. "The RNS System: responsive cortical stimulation for the treatment of refractory partial epilepsy". In: *Expert review of medical devices* 11.6 (2014), pp. 563–572.

[5] J.J. Wheeler et al. "An implantable 64-channel neural interface with reconfigurable recording and stimulation". In: *Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE*. 2015, pp. 7837–7840.

[6] C.K. Bjune et al. "Package architecture and component design for an implanted neural stimulator with closed loop control". In: *Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE*. 2015, pp. 7825–7830.