Guest Editorial
Special Section on Wireless Neural Interfaces

I. Introduction

ALTHOUGH the human brain is largely responsible for our evolution into the dominant species on our planet, its unparalleled complexity has impeded its ability to fully understand itself. Even today, despite the prime importance of the brain in determining individual behaviors, complex social interactions, as well as our personal and national success, brain researchers continue to have great difficulty completely understanding even small regions of the brain. Clearly, a thorough understanding of the brain and effective means for addressing its diseases represent truly grand challenges for the scientific, engineering, and medical communities.

The advancement of brain research and therapies is dependent on the technologies used for quantifying the properties of and the activity within the nervous system. Throughout human history, there are many examples that establish a clear connection between advances in technology and advances in brain research and therapies. Although the traditional distant separation of these two fields of human endeavor has resulted in this connection not being easy or fast, indeed it is often serendipitous, its positive impact is undeniable.

A prominent method for monitoring neural activity is the use of electrical probes and amplification circuitry. Indeed, the field of neural electrophysiology has greatly advanced our understanding of many regions of the brain and the neural circuits between them. The technology used to perform neural electrophysiology has included the physical interface (i.e., electrodes and probes) and the electronics needed to amplify and process the neural signals. Through history, the form and function of the physical interface and the supporting electronics have evolved to provide ever-greater amounts of information with less and less perturbation of the organism being studied or treated.

Advances in the technologies used at the physical neural–electronic interface, which have been driven by government funding and the relatively small but growing microelectromechanical-systems (MEMS) industry, have resulted in higher numbers of electrodes to be positioned in the brain at greater densities. Although these micromachined interfaces have contributed to the advancement of basic scientific understanding, they have not been effective in a clinical setting due to their poor long-term stability and reliability. Successfully addressing these critical practical issues is its own grand challenge that must be solved in order to realize the true potential of all the applications of neural–electronics interfaces (e.g., prosthetics).

Advances in the underlying electronics technologies, which are used to amplify and process neural signals, have proceeded swiftly while being driven by the enormous integrated-circuit (IC) industry for far larger and nonbiological applications (e.g., computation, communications, etc.). Despite the fact that the electronics used for neural interfaces started out as large rack-mounted equipment, the advent of ICs and the technology-development trend, illustrated by Moore's "Law," in which the performance of ICs of the same size doubles every 18–24 months, has resulted in higher-performance neural-interface electronics to be available in smaller forms, at lower costs, and with greater functionality.

Although the priorities for the development of electronics for brain research and therapies differ depending on your perspective (i.e., neuroscientist, clinician, prosthesis engineer, government regulator, insurance company, or patient) and intended application, the basic building blocks of functionality (i.e., amplification, processing, and telemetry) and ideal performance goals (i.e., tiny size, many channels, low power, low temperature, biocompatible, efficient and accurate processors, and reliable long-range wireless telemetry) are well understood.

Unlike the fundamental challenges impeding the development of the physical neural–electronic interface, progress on the advancement of the electronics has been steady. Indeed, for the scale and target performance of neural-interface systems being considered today, it appears that the underlying IC technology that is continuously advancing will, in principle, be able to meet the target goals. Of course, what remains is the research and development needed to realize the target electronic systems. The six papers in this special issue represent a sample of some of the significant advances being made in the area of wireless neural telemetry.

II. Paper 1

In the first paper titled "A 128-Channel 6 mW Wireless Neural Recording IC With Spike Feature Extraction and UWB Transmitter," Chae, Yang, Yuce, Hoang, and Liu from the University of California, Santa Cruz, demonstrate a 128-channel neural recording IC with on-the-fly spike feature extraction and wireless telemetry. Their chip has an 8-way front-end recording block with 16 channels per block, spike detection and feature extraction DSP, and an ultra-wideband (UWB) transmitter. A programmable front-end can support various types of biological signals. A time-shared analog-to-digital converter (ADC) allows the analysis of a varying number of channels to go with

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an on-chip DSP block. The UWB link can transfer raw data from 128 recording channels at a data rate of 90 Mb/s. The chip is implemented in a 0.35-μm CMOS process with an area of 8.8×7.2 mm^2 and consumes 6 mW of power. The chip operation has been verified in *ex vivo* extracellular recordings.

III. Paper 2

In the second paper titled "Wireless Neural Recording With Single Low-Power Integrated Circuit," Harrison and colleagues present a setup for conducting *in vivo* implantable recording and wireless telemetry experiments on cats and nonhuman primates. They have designed a chip that contains 100 amplifiers, a 10-bit ADC, 100 threshold-based spike detectors, and a 902- to 908-MHz frequency-shift-keying (FSK) transmitter, and fabricated the chip in a 0.6-μm BiCMOS process. Neural recordings from a selected amplifier are sampled by the ADC at 15.7 KSps and transmitted over the inductively coupled FSK wireless link. With 8 mW of power, the chip is suitable for implantation in future systems. The chip will be integrated with a Utah Electrode Array to create a fully implantable integrated neural interface for use in both neuroscientific and medical applications.

IV. Paper 3

In the third paper titled "HermesC: Low-Power Wireless Neural Recording System for Freely Moving Primates," Chestek and colleagues from Stanford University and the University of Utah, present the latest evolution of their work to develop a radio-frequency [(RF) 900 MHz] wireless neural telemetry system for long-term recording from freely moving animals in a caged environment (range is $<$4 m). Due to a more efficient design (63.2 mW versus 284 mW at 4 V), this latest one-channel (15.7 kS/s) version can operate continuously in a much smaller enclosure ($51 \times 38 \times 38$ mm^3) for 2.9 days with a 1120-mA-hr battery. The system design presented in this paper is ready for subsequent INI chip designs that will enable data from more channels to be transmitted simultaneously.

V. Paper 4

In the fourth paper titled "Active Microelectronic Neurosensor Arrays for Implantable Brain Communication Interfaces," Song and colleagues from Brown University present their work on a wireless implantable microelectronic device for transmitting cortical signals transcutaneously. A fundamental uniqueness of their work is the use of a vertical-cavity surface-emitting laser (VCSEL) diode for the optical telemetry of a digital stream of infrared light pulses through the skin. Their 16-channel implant has a flexible dual-panel liquid-crystal-polymer substrate, onto which they have assembled chips for amplification, analog multiplexing, analog-to-digital conversion, digital control, and infrared telemetry. The implant can be powered by RF induction or infrared light directed to the implant.

VI. Paper 5

In the fifth paper titled "An Ultra Low-Power CMOS Automatic Potential Detector," Gosselin and Sawan from École Polytechnique de Montréal, Canada, discuss a CMOS analog biopotential detector for many-channel neural recording. They use an energy-based preprocessor and a linear-delay element in their circuit to achieve automatic discrimination of action potential (APs) from the background activity, which improves the detection accuracy of neural signals. The circuit is integrated in a 0.18-μm CMOS and dissipates just 780 nW in 0.07 mm^2. The power consumption is lowered thanks to the use of subthreshold operational transconductance amplifiers (OTAs). Such low-power consumption allows the use of the proposed technology in many-channel neural recording systems.

VII. Paper 6

In the sixth paper titled "Using Pulse Width Modulation for Wireless Transmission of Neural Signals in Multichannel Neural Recording Systems," Yin and Ghovanloo from Georgia Institute of Technology examine the use of pulse-width modulation of time-division-multiplexed signals to reduce the complexity, size, and power consumption of the implantable transmitter. A penalty of this approach is adding to the complexity of the receiver—a trade-off that is acceptable in neural electrophysiology laboratories but perhaps less so in mobile prosthetic applications. The have designed, simulated (MATLAB-Simulink), fabricated (0.5-μm standard CMOS process), and tested a 15-channel wireless implantable neural recording (WINeR) system prototype, which consumes 4.5 mW from $\pm$1.5-V supplies and can acquire and wirelessly transmit up to 320 kS/s to a 75-MHz receiver with 8.4 bits of resolution ($\sim$2.56 Mb/s). The complete analysis and comparison of simulated and measured results presented in this paper should be informative for the design of PWM-TDM-based systems for wireless biomedical applications.

We hope that you enjoy the papers presented in this special issue, and we look forward to the chance to discuss the latest work in this area at future meetings.

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From 1996 to 1997, he worked for Silicon Light Machines, Inc., Sunnyvale, CA, an optical-MEMS startup company. Since 1997, he has been on the faculty of the Electrical Engineering Department and the Biomedical Engineering IDP at the University of California, Los Angeles, where he is a Professor. He is also a member of the UCLA Brain Research Institute (BRI) and the California Nanosystems Institute (CNSI). At UCLA, he also cofounded and has directed the world's first formal academic program in neuroengineering with support from the NSF IGERT Program. His research interests center on the novel design, fabrication, and application of micro and nano technologies. His neuroengineering research interests include micromachined neural–electronic interfaces, wireless neural telemetry, brain–machine interfaces, MEMS-enabled hydrocephalus shunts, and miniature coils for high-resolution MRI. Since 2009, he has also been with the Defense Advanced Research Projects Administration (DARPA) in their Microsystems Technology Office (MTO).

Dejan Marković (S'96–M'06) received the Dipl.Ing. degree from the University of Belgrade, Serbia, in 1998, and the M.S. and Ph.D. degrees from the University of California, Berkeley, in 2000 and 2006, respectively, all in electrical engineering. In 2006, he joined the faculty of the Electrical Engineering Department at the University of California, Los Angeles, as an Assistant Professor. He is also a member of the Biomedical Engineering IDP program at UCLA. His current research is focused on digital integrated circuits and architectures for parallel data processing in future radio and healthcare systems, design with post-CMOS devices, optimization methods, and CAD flows. His neuroengineering research is focused on hardware technology for digital signal processing for use in both neuroscientific and clinical applications.

Dr. Marković was awarded 2007 David J. Sakrison Memorial Prize at UC Berkeley in recognition of the impact of his Ph.D. work. He received an NSF CAREER Award in 2009.