

Analog VLSI and Biological Systems

RLE Group

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Introduction

Our group's research focuses on BIOELECTRONICS: We work in 3 interdisciplinary areas, **biomedical** electronics, **bio-inspired** electronics, and **circuit modeling** of **biology**. Our work advances frontiers and has applications in 10 different kinds of systems:

1. Ultra-low-power systems
2. Analog systems
3. RF (wireless) systems
4. Micro-sensing (mechanical, optical, fluidic, chemical) systems
5. Ultra-low-noise systems
6. Noise-robust systems
7. Feedback systems
8. Energy-harvesting systems
9. Networked systems
10. Hybrid analog-digital computing and control systems.

Biomedical Electronics

Low-Power Brain-Machine Interfaces

Recent pioneering work on monkeys and humans by several neurobiologists around the world has resulted in brain-machine interfaces that promise a cure for patients who are paralyzed: Such interfaces use electrodes to record from neurons in motor regions of the brain, decode the intention of the subject to move, and use this decoded signal to move a robotic limb or a computer cursor. Such interfaces require neural recording and amplification from 10 to 100 electrodes, digitization and decoding of these signals to extract the intention to move, wireless telemetry of information from implanted circuitry within the brain to circuitry outside the brain, wireless telemetry of programming parameters from outside the brain to implanted circuitry within the brain, and wireless recharging of implanted circuitry for power.

Work in our lab focuses on building ultra-low-power and miniature circuitry for brain-machine interfaces which could enable them to work on an implanted 100mAh battery for 10 years or more

and minimize heat dissipation in the brain. Current interfaces are bulky, 100-10,000 times more power hungry, and often lack wireless capabilities. As part of these ongoing efforts, we have just built the world's most energy-efficient and low-power neural amplifier, developed very efficient wireless recharging links, and successfully stimulated the brain of a zebra finch bird wirelessly. We are researching the development of ultra-low-power analog decoding algorithms for compression, decoding, and learning, ultra-low-power circuits for spike sorting, recognition, and decoding, adaptive strategies for neural amplification to further lower power, and ultra-low-power wireless telemetry circuits. We are also researching strategies for decoding and recording that will enable longevity of implanted electrodes in the brain. Our work promises to enable large-scale, chronic experimental neuroscience systems (100 to 10,000 electrodes or more). It is useful in prosthetics for paralysis, for the blind, for Parkinson's disease, and for epilepsy. Brain-machine interfaces are important for several future applications as well in other sensing, motor, or cognitive modalities. Our work is being done in collaboration with neurobiologists and engineers including Professor Richard Andersen's group at CalTech (work on paralysis), Professor Michale Fee's group at MIT (work on experimental neuroscience), and with Professor John Wyatt's group at MIT (work on the blind).

Wireless Noninvasive or Wearable Medical and Cardiac Monitoring

New electronics for non-invasive medical monitoring promise low-cost, maintenance-free, and lightweight devices. These devices are critical in long-term medical measurements and in home-based tele-monitoring services, which are extremely important for the reduction of health care costs.

Our work on non-invasive cardiac monitoring has led to a battery-free tag for medical monitoring that functions with harvested RF energy and to an ultra-low-power pulse oximeter for measuring oxygen saturation.

Bio-Inspired Electronics

Cytomorphic Electronics: Electronics Inspired by Gene-Protein and Protein-Protein Circuits in Cells

Circuits in cell biology and circuits in electronics may be viewed as being highly similar with biology using molecules, ions, proteins, and DNA rather than electrons and transistors. This project exploits the astoundingly detailed similarity between the equations of chemistry and the equations of subthreshold analog electronics to attempt to create large-scale nonlinear dynamical systems that mimic the sensing, actuation, and control systems of biological cells at ultra-fast time scales including their stochastic properties. Such work can shed insight into robustness-efficiency, analog-digital, and other feedback-circuits-and-systems tradeoffs in cells just as in ultra-low-power analog circuit design. Ultra-low-power analog electronic circuits face very similar tradeoffs like cells in biology because of their need to operate quickly, accurately and robustly in spite of mismatched and noisy components and signals, a necessary consequence of having very low levels of available power and space. Thus, analog circuit engineering can shed insight into cell biology just as it has in the past in extensive prior research in our lab on analog circuit models of neurobiological systems. Cell biology, in turn, which performs 10 million biochemical operations at 1pW of power, can inspire new circuit and system designs as several neurobiological architectures in the ear, eye, and brain have previously done in our lab. Hence this project has applications in both systems biology, which aims at an engineering understanding of molecular networks within the cell, important for treating diseases such as cancer and diabetes, and in synthetic biology, which aims to reengineer biology using circuits concepts to perform useful functions.

Publications

Books

Sarpeshkar, R. Ultra Low Power Bioelectronics: Fundamentals, Biomedical Applications, and Bio-Inspired Systems. Cambridge University Press, Cambridge, U.K., February 2010.

Journal Articles

Arfin, S., M. Long, M. Fee, and R. Sarpeshkar, "Wireless Neural Stimulation in Freely Behaving Small Animals," *Journal of Neurophysiology*, Vol. 102, No. 1, pp. 598-605, July 2009.

L. Fay, V. Misra, and R. Sarpeshkar, "A Micropower Electrocardiogram Amplifier," *IEEE Transactions on Biomedical Circuits and Systems*, Vol. 3, No. 5, pp. 312-320, October 2009.

Mandal, S., L. Turicchia, and R. Sarpeshkar, "A Low-Power Battery-Free Tag for Body Sensor Networks," *IEEE Pervasive Computing*, Vol. 9, No. 1, pp. 71-77, January-March 2010.

M. Tavakoli, L. Turicchia, and R. Sarpeshkar, "An Ultra-low-power Pulse Oximeter implemented with an Energy-Efficient Transimpedance Amplifier," *IEEE Transactions on Biomedical Circuits and Systems*, Vol. 4, No. 1, pp. 27-38, February 2010.

Proceedings of Refereed Conferences

Rapoport, B. I., W. Wattanapanitch, H. L. Penagos, S. Musallam, R. A. Andersen, and R. Sarpeshkar, "A Biomimetic Adaptive Algorithm and Low-Power Architecture for Implantable Neural Decoders," *Proceedings of the 31st Annual International IEEE Engineering in Medicine and Biology Society (EMBS 2009)*, Minneapolis MN, pp. 4214-4217, September 2009.

Turicchia, L., S. Mandal, M. Tavakoli, L. Fay, V. Misra, J. Bohorquez, W. Sanchez, and R. Sarpeshkar, "Ultra-low-power Electronics for Noninvasive Medical Monitoring," Invited Paper, 6-5, *Proceedings of the 2009 Custom Integrated Circuits Conference (CICC 2009)*, San Jose, CA, pp. 85-92, September 13-16, 2009.

Mandal, S. and R. Sarpeshkar, "Circuit Models of Stochastic Genetic Networks," *2009 IEEE Symposium on Biological Circuits and Systems (BioCAS)*, Beijing, China, pp. 109-112, November 2009.

Mandal, S. and R. Sarpeshkar, "A Cochlear Heterodyning Architecture for an RF Fovea," accepted for publication, *Proceedings of the 2010 IEEE Symposium on Circuits and Systems (ISCAS 2010)*, Paris, France, pp. 3825-3828, May 30-June 2nd, 2010.

Do Valle, B., C. T. Wentz, and R. Sarpeshkar, "An Ultra-Compact and Efficient Li-ion Battery Charger Circuit for Biomedical Applications," *Proceedings of the 2010 IEEE Symposium on Circuits and Systems (ISCAS 2010)*, Paris, France, pp. 1224-1227, May 30-June 2nd, 2010.

Invited Lectures

September 2009, "Ultra Low Power Electronics for Medicine," Invited Speaker, Special Forum on Biomedical Applications, Custom Integrated Circuits Conference 2009 (CICC 2009).

October 2009, "A Bio-inspired Active Radio-Frequency Cochlea," MA-COM, Guest Speaker, Nashua, N.H.

October 2009, "Bioelectronics," Keynote Speaker, "Neuro Electronics Research Flanders (NERF)" institute launch event, Leuven, Belgium.

Chapter 27. Analog VLSI and Biological Systems

November 2009, "Bioelectronics," Industrial Liaison Program, MIT.

January 2010, "Bioelectronics," Lincoln Labs Technology Seminar, Lincoln, Massachusetts

January 2010, "Bioelectronics," Wright-Patterson Air Force Base, Dayton, Ohio.

January 2010, "Bioelectronics," Distinguished Lecture Series (DLS) Speaker, University of British Columbia, Vancouver, Canada.

January 2010, "Bioelectronics," Sharp Labs, Portland.

January 2010, "Bioelectronics," California Institute of Technology, RF and Microwave Seminar, Pasadena, CA.

February 2010, "Bioelectronics," Electrical Engineering Seminar, University of California at Davis, Davis, CA.

March 2010, "Bioelectronics," Electrical Engineering Seminar, Columbia University, New York, New York.

June 2010, "Bioelectronics", NEWCAS keynote speaker, Montreal, Canada.