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 ultra-low-power, analog, RF (wireless), micro-sensing (mechanical, optical, fluidic, chemical), ultra-low-noise, noise-robust, feedback, energy-harvesting, networked, and hybrid analog-digital computing and control systems.

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).

Bionic Ear

Work in the lab has led to a bio-inspired asynchronous interleaved sampling algorithm (AIS) and chip for low-power processing and neural stimulation. The AIS algorithm encodes phase information with good fidelity, an important requirement for music. A novel ear-inspired companding algorithm that arose out of work on the silicon cochlea has shown promise for improving recognition in noise in cochlear-implant subjects.

Circuits for Biomedical and Other Applications

Several circuits in our lab developed for biomedical applications have uses in other domains and advance frontiers in ultra-low-power, precision, or feedback-circuit design. For example, an energy-harvesting RF-ID tag that can rectify RF energy at levels as low as 6uW, can be used for battery-free heart monitoring of electrocardiogram signals or in general-purpose RF-ID tags to create a battery. Several circuits developed for use in the bionic ear processor, e.g., low-power microphone front ends, automatic gain control circuits, filtering circuits, energy-extraction circuits, and logarithmic analog-to-digital converters, are useful in other application domains. A predictive comparator with adaptive control, developed in our lab, has been used in Professor Wyatt's lab for improving the energy efficiency of an RF power system for the blind and has applications in power-electronic systems. An ultra-low-noise capacitance-measuring circuit, capable of detecting a 1 part per 8 million change in capacitance of a MEMS capacitance sensor, is being explored for use in various bio-molecular sensing applications. Our lab has developed an analog memory element with an ultra-low-leakage switch that achieves 5 electrons per second leakage in 0.5um technology and is capable of storing an 8-bit number without degradation for over 4 hours.

An RF Cochlea

The biological inner ear or cochlea is an amazing custom analog computer capable of the equivalent of 1GFLOPS of spectral-analysis and gain-control computations with 14uW of power on a 150mV battery and a minimum detectable signal of 0.05 angstroms. It achieves such efficiency because of the clever use of an active nonlinear transmission line implemented with fluids, membranes, active piezoelectret cells, micromechanics, and electrochemistry.The cochlea has an amazingly large input dynamic range of 120dB, analyzes frequencies over a 100-fold range in carrier frequency (100Hz-10kHz), and amplifies signals at 100kHz even though its cells have time constants of 1ms. We use inspiration from the cochlea to construct an RF cochlea a fast, ultra-broadband, low-power spectrum analyzer. Instead of working with sound waves from 100Hz to 10kHz as in the audio cochlea, we work with radio waves from 100MHz to 10GHz but the principles of wave processing are similar and inspired by the biological cochlea. The actions of fluid mass in the ear are mimicked with inductors, the actions of membranes in the ear with capacitors, and the actions of outer hair cells in the ear with active RF amplifiers. Electrically, the cochlea can be modeled as an active, nonlinear, adaptive transmission line with characteristic frequencies that scale exponentially with position. Nonlinear behavior is important in the biological cochlea, particularly for signal detection in noise and gain control. We are researching how the RF cochlea may be used as a front end for universal radios, software radios, and cognitive radios and improve the detection of radio signals in noise.

Publications

Journal Articles, Published

Salthouse, C. and R. Sarpeshkar, "Jump Resonance: A Feedback Viewpoint and Adaptive Circuit Solution for Low-Power Active Analog Filters," *IEEE Transactions on Circuits and Systems I*, Vol. 53, No. 8, pp. 1712-1755, August 2006.

Baker, M. and R. Sarpeshkar, "Low-Power Single Loop and Dual-Loop AGCs for Bionic Ears," *IEEE Journal of Solid-State Circuits*, Vol. 41, No. 9, pp 1983—1996, September 2006.

Yang, H. and R. Sarpeshkar, "A Bio-inspired Ultra-Energy-Efficient Analog-to-Digital Converter for Biomedical Applications", *IEEE Transactions on Circuits and Systems I, special issue on Life Sciences and System Applications,* Vol. 53, No. 11, pp. 2349 – 2356, November 2006.

Sit, J., A. M. Simonson, A. J. Oxenham, M. A. Faltys, and R. Sarpeshkar, "A low-power asynchronous interleaved sampling algorithm for cochlear implants that encodes envelope and phase information", *IEEE Transactions on Biomedical Engineering,* Vol. 54, No. 1, pp. 138-149, January 2007.

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Oxenham, A. J., A. M. Simonson, L. Turicchia, and R. Sarpeshkar, "Evaluation of Companding-Based Spectral Enhancement Using Simulated Cochlear-Implant Processing," *Journal of the Acoustical Society of America*, Vol. 121, No. 3, pp. 1709-1716, March 2007.

Mandal, S. and R. Sarpeshkar, "Low Power CMOS Rectifier Design for RFID Applications," *IEEE Transactions on Circuits and Systems I*, Vol. 54, No. 6, p. 1177-1188, June 2007.

Journal Articles, Accepted for Publication

Raj, B., L. Turicchia, B. Schmidt-Nielsen, and R. Sarpeshkar, "An FFT-based Companding Front End for Noise-Robust Automatic Speech Recognition", *EURASIP Journal on Audio, Speech, and Music Processing*, special issue on Perceptual Models for Speech, Audio, and Music Processing, in press, 2007.

Journal Articles, Submitted for Publication

Wattanapanitch, W., M. Fee, and R. Sarpeshkar, "An energy-efficient micropower neural recording amplifier," *IEEE Transaction on Biomedical Circuits and Systems*, submitted May 2007.

Sit, J.-J. and R. Sarpeshkar, "A low-power, capacitor-free, charge-balanced electrode-stimulator chip with less than 6nA DC error for 1mA full-scale stimulation," *Transactions on Biomedical Circuits and Systems*, under review, July 2007.

Sit, J.-J. and R. Sarpeshkar, "An Asynchronous Cochlear-Implant Processor that can Encode Music and Lower Neural Stimulation Power," *IEEE Pervasive Computing*, under review, August 2007.

Meeting Papers, Presented

“Going Beyond Moore’s Law with Analog and Bio-inspired Processing”, Invited Speaker, International Technology Roadmap for Semiconductors Workshop on Emerging Research Architectures, San Francisco, CA, July 2006.

“Ultra Low Power Electronics for Body Sensor Networks”, Invited speaker, NIH Workshop on Life Sciences and Systems Applications, Bethesda, MD, July 2006.

“Bioelectronics”, Invited Speaker, Seminar Series in Electrical Engineering, University of Illinois at Urbana Champaign, Champaign, IL, August 2006.

“Bioelectronics,” Packard Fellowship Speaker, Monterey, CA, September 2006.

“Analog and Bio-inspired Architectures for Sensing and Computing,” Defense Advanced Research Agency, Immersive Operations Panel, invited speaker, Washington, DC, December 2006.

“Ultra Low-Power Electronics for Bio-Medical Systems,” IEEE Biomedical Circuits and Systems Conference, invited tutorial presentation, London, UK, December 2006.

Meeting Papers, Published

Sarpeshkar, R., W. Wattanapanitch, B.I. Rapoport, S.K. Arfin, M.W. Baker, S. Mandal, M.S. Fee, S. Musallam, and R.A. Andersen, “Low-Power Circuits for Brain-Machine Interfaces,” *Proceedings of the IEEE International Symposium on Circuits and Systems (ISCAS 2007)*, pp. 2068-2071, May 27-30, 2007.

Theses

Christopher Salthouse, *Analog adaptive nonlinear filtering and spectral analysis for low-power audio applications*, PhD thesis, Department of Electrical Engineering and Computer Science, August 2006.

Jijon Sit, *An Asynchronous, Low-Power Architecture for Interleaved Neural Stimulation, Using Envelope and Phase Information*, PhD thesis, Department of Electrical Engineering and Computer Science, May 2007.

Michael Baker, *A Low-Power Cochlear-Implant System*, PhD thesis, Department of Electrical Engineering and Computer Science, May 2007.