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We briefly summarize our key accomplishments during the grant period: These include the creation of bio-inspired systems that are important for improving speech intelligibility in noisy environments or for reducing noise exposure. They also include the creation of ultra-low-power electronics useful in portable hearing applications such as cochlear implants, hearing aids, hybrid hearing implants, intelligent personal protective equipment, and noise dosimeters. Together these accomplishments will be important in making miniature, intelligent hearing systems practical for many applications. The details are described in eight publications and three patents that are cited in the productivity section of this report.

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**AN ELECTRONIC SYSTEM FOR ULTRA-LOW-POWER  
HEARING IMPLANTS**

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## **Motivations and Approach**

Improving speech intelligibility in noisy environments while reducing noise exposure is important for military personnel. Prior bio-inspired algorithms from our lab and the use of intelligent low-power filters and circuits have been successful in reducing noise exposure while improving speech intelligibility. Ultra-low-power electronics can implement such techniques in compact chips useful in portable equipment.

Power and size are huge cost and technology drivers for implantable and miniature systems that need to be small and have low enough power dissipation to function on a small battery. A small, portable, low-power system can make possible solutions in tightly constrained spaces of the body with low tissue heating in medical applications that could not have been dreamed of before. Thus, our work has the potential to completely revolutionize systems for acoustic trauma and hearing loss in cochlear implants, in hybrid cochlear implants and hearing aids, in intelligent personal protective equipment, and in noise dosimeters.

## **Summary of Accomplishments**

We report key achievements toward our objectives:

- 1) We have developed bio-inspired intelligent filters for operating effectively in noisy environments such as in environments with jet-engine noise, shipboard engine noise, machine-gun noise. Figure 1 shows how the algorithm is able to extract soft sounds buried in machine gun noise. Our intelligent filters have been shown to be effective in improving the performance of the hearing impaired in noise and can be beneficial in intelligent personal protection equipment of the future. They are founded on our prior bio-inspired work on hearing reported in [1], [2] in the Productivity section of this report. In addition, we have put speech and hearing in a feedback loop to improve hearing in noise via an analysis-by-synthesis technique that is based on a model of the vocal tract [6].
- 2) We have developed a new stimulation strategy that allows efficient transfer of energy both to and from the electrode, just as in an electric car that recycles energy into the car's battery during braking. Our novel design is based on an adaptive voltage stimulator with inductive energy storage and recycling for adiabatically driving an electrode with a continuum of possible voltages, instead of just the discrete steps offered by a capacitor bank, thus minimizing energy consumption. It also utilizes a shunt current-sensor to monitor and regulate the current through the electrode via feedback, thus enabling flexible and safe stimulation. A publication [4] and filed patent [9] describe this work in more detail. This work could greatly impact several implantable medical devices including cochlear implants for the deaf, hybrid hearing implants, brain-machine interfaces, and other neural stimulation devices. In addition, an ultra-low-power neural amplifier array [7] enables closed-loop monitoring of such devices and an implantable glucose battery [3] could enable powering of such ultra-low-power devices from the glucose in the body. A publication [8] describes how wireless neural stimulation with audio input enabled control of a bird's song.

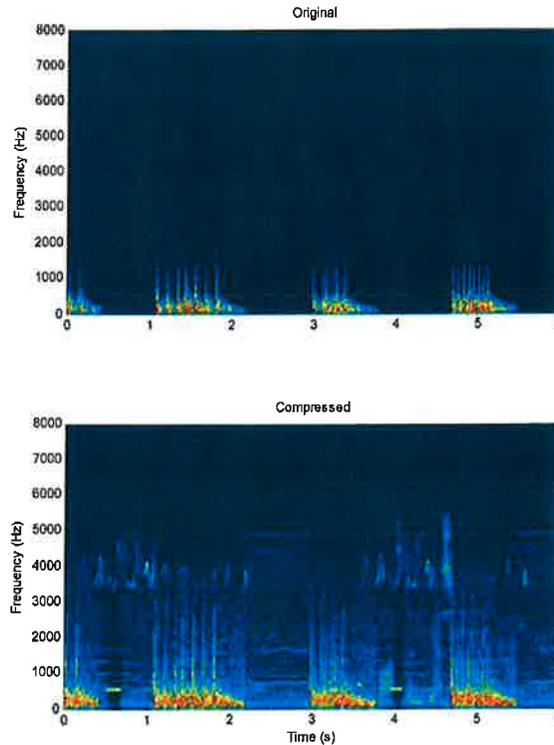


Figure 1: Intelligent filtering of speech and animal sounds immersed in machine gun noise. (Top) Not filtered. (Bottom) Filtered with our algorithm.

3) We have developed a new design for a bandpass filter that achieves better energy efficiency at high Q's or quality factors. The filter topology improves the noise and power efficiency over current designs. Using the product of power consumption and the input-referred noise as a figure-of-merit, simulations show that the new filter should outperform the current design by a factor of 3 at a Q of 1, and up to a factor of 24 at a Q of 8. Efficiency at high Q values is very important: As more and more channels are added to a speech processing system, greater frequency selectivity is needed to minimize overlap between adjacent channels. A 3x improvement in noise\*power figure-of-merit at a Q of 1 would allow a system with the new filters to double the number of filter channels, double the Q of the filters, and still outperform the old filters by a factor of 1.5. This work could greatly improve the efficiency of state-of-the-art ultra-low-power analog spectrum analyzers [1], [2], useful in several hearing systems.

4) We have designed and built a lithium-ion battery-recharging circuit that exploits a novel analog control strategy with a tanh-like transconductance amplifier to automatically cause the charging in of a lithium-ion battery to transition from constant-current to constant-voltage charging, essential in maintaining battery robustness, efficiency, and efficiency. It is approximately one order of magnitude smaller than previous designs while achieving

comparable power efficiency. A publication [5] and patent [10] describe this work in more detail. It is important in portable hearing equipment and in ultra-low-power miniature electronic equipment.

## **Productivity and References**

### **Books**

[1] R. Sarpeshkar. *Ultra Low Power Bioelectronics: Fundamentals, Biomedical Applications, and Bio-inspired Systems*, Cambridge University Press, Cambridge, U.K., Kindle Edition, February 2011.

[2] R. Sarpeshkar. *Ultra Low Power Bioelectronics: Fundamentals, Biomedical Applications, and Bio-inspired Systems*, Cambridge University Press, Cambridge, U.K., February 2010.

### **Refereed Journal Articles**

[3] B. Rapoport, J. Kudziński, and R. Sarpeshkar, "A Glucose Fuel Cell for Implantable Brain-Machine Interfaces", accepted for publication, *PLoS ONE*, in press, 2012.

[4] S.K. Arfin and R. Sarpeshkar, "An Energy-Efficient, Adiabatic Electrode Stimulator with Inductive Energy Recycling and Feedback Current Regulation", *IEEE Transactions on Biomedical Circuits and Systems*, Vol. 6, No. 1, pp. 1-4, 2012.

[5] B. Do Valle, C. Wentz, and R. Sarpeshkar, "An Area and Power-Efficient Analog Li-Ion Battery Charger Circuit," *IEEE Transactions on Biomedical Circuits and Systems*, Vol. 5, No. 2, pp. 131-137, 2011.

[6] K. H. Wee, L. Turicchia, and R. Sarpeshkar "An Articulatory Silicon Vocal Tract for Speech and Hearing Prostheses," *IEEE Transactions on Biomedical Circuits and Systems*, Vol. 5, No. 4, pp. 339-346, 2011.

[7] W. Wattanapanitch and R. Sarpeshkar, "A Low Power 32-channel digitally-programmable Neural Recording System", *IEEE Transactions on Biomedical Circuits and Systems*, Vol. 5, No. 6, pp. 592-602, 2011.

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

### **Filed Patents**

[9] Arfin, S., and R. Sarpeshkar, "Electrode Stimulator with Energy Recycling and Current Regulation", U.S. and PCT Patent Application, PCT/US11/34351, filed 28th April 2011.

[10] B. Do Valle, R. Sarpeshkar, and C. T. Wentz , Efficient Battery Charging Control Scheme, U.S. Patent Application, 61/334403, filed May 13<sup>th</sup> 2010.

[11] D. Adams and R. Sarpeshkar, "Inductive Element Feedback Loop Compensator", U.S. and PCT Patent Application PCT/US11/051678, filed September 15<sup>th</sup> 2011.