John Edwards

# Signal Processing Advances Consumer Electronics

*New research impacts and improves the way users interact with mobile and wearable devices in daily life*

Signal processing has played a foundational role in the consumer electronics revolution of the past several decades. Mobile devices, smart-home technologies, digital cameras, and countless other cutting-edge products have benefited from signal processing-enabled innovations.

Signal processing's impact on consumer technologies shows no signs of slowing down. In fact, in areas ranging from wireless communication to personal health and fitness devices to virtual reality systems, signal processing continues to serve as an essential and irreplaceable tool.

## One chip/multiple frequencies

The wireless world is growing rapidly and so are the number of wireless technologies. To address the need for mobile devices that can seamlessly and efficiently accommodate communication on multiple bands, Cornell University engineers have developed a single-chip method for transmitting and receiving radio signals across a wide range of frequencies (Figure 1).

Building multiband support into ever-smaller communication devices, potentially down to the size of wearables, is not easy because each band requires a filter to block strong transmit signals from drowning out reception. A new software-defined distributed duplex technology, developed by Alyssa Apsel, a Cornell professor of electrical and computer engineering, and Alyosha Molnar, a Cornell associate professor of electrical and computer engineering, addresses this challenge. The technology they developed integrates all of the components necessary for multiband operation onto a single, field-programmable gate array (FPGA), an integrated circuit that can be programed in the field after manufacture.

"Originally, the concept was to enable high-performance, low-cost radios or even replace the multiple radios and duplexers in a phone with a single transceiver, making a very inexpensive and flexible phone possible," Apsel explains. "Now, we are exploring extensions to user-defined radio application, essentially envisioning the radio as an FPGA." Most radio-frequency (RF) transceivers (transmitter/receivers) are designed to support a narrow operating range. Transmitter circuits, receiver circuits, and duplexing elements are all developed and optimized for a restricted frequency set. "This is a decision made at design time that cannot be easily altered in situ," Apsel says. "This [new] architecture enables a simple software patch to reconfigure the electronics to operate across a range of frequencies and waveforms in situ."

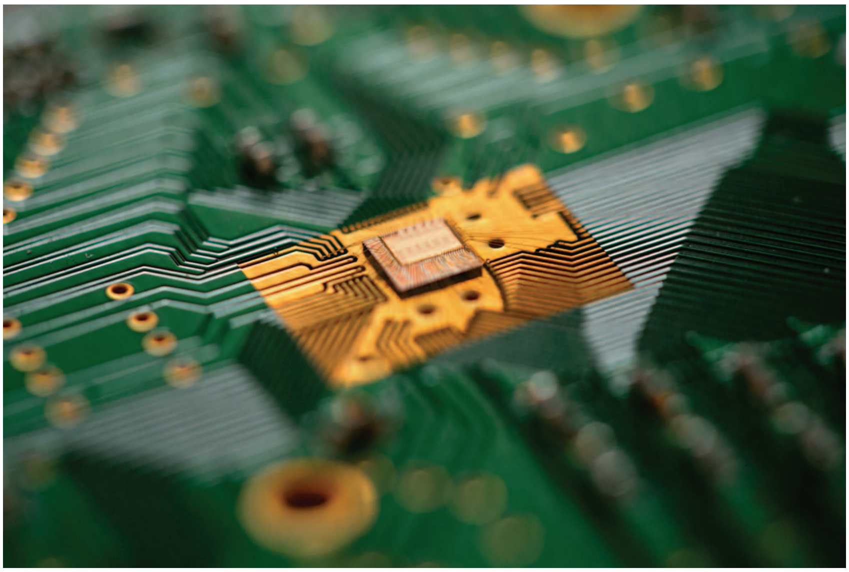

**FIGURE 1.** A single chip can be used to transmit and receive radio signals across a wide range of frequencies. (Photo courtesy of Cornell University.)

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The FPGA is actually an interconnected series of six subtransmitters. Each subtransmitter sends signals at regular intervals. The transmitters' individually weighted outputs are programmed to combine, producing an RF signal in the forward direction at the antenna port and canceling out at the receive port. The programmability of the individual outputs allows simultaneous summation and cancellation to be tuned across a wide range of frequencies and to adjust to signal strength at the antenna.

The architecture itself can be viewed as a signal processing element, Apsel observes. "It is a multiport network with a multitap input and nonreciprocal characteristic," she says. In one direction, the transmitter output is generated by the summation of in-phase signals. In the other direction, the receive port sees a filtering of the input signal through cancelations in the network. "This can be viewed as an FIR [finite impulse response] filter of the input signal with tunable weights," Apsel notes. "The calculation of the tunable weights is an optimization that can be done in several ways, including by calculation of a pseudo inverse to determine the optimal input vector."

Signal processing plays a significant role in the development of alternative network optimizations. "This is useful, for instance, in determining the most power-efficient weighting to achieve isolation between receiver and transmitter ports," Apsel says. Additionally, the network's entire design and optimization as well as weight selection is done in frequency space. "The ideal weights will change as a function of frequency and so must be redesigned for each operating frequency in Fourier space," she explains.

Finally, to provide receive band noise suppression, there's an additional level of filtering at each input. "We call this technique *degeneration*, since we degenerate the power amplifier stages to reduce noise at a single frequency," Apsel says. "We perform this degeneration with a poly-phase filter."

The research began as part of a DARPA project about four years ago and is still ongoing. "We have demonstrated the basic concept and explored a variety of noise-cancellation techniques and optimizations to improve performance," Apsel reports.

Looking forward, Apsel is excited by the prospect of transforming the FPGA into a commercial technology. "We have had funding for this project from Google and are currently working with other companies on variations of this technology for applications beyond radios," she says.

## Clearer hearing

Among mobile audio devices, the hearing aid holds the distinction of functioning as both a consumer product and a medical device, allowing users to experience sounds more clearly and accurately.

Like other mobile and wearable devices, hearing aids are currently benefitting from rapid technology and design advances. Hoping to bring hearing assistance technology to a new level of effectiveness, researchers at Denmark's Aalborg University are using both signal processing and machine learning to teach hearing aid software how to simultaneously remove unwanted noise and enhance speech.

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A serious challenge for anyone with hearing loss is understanding speech in noisy surroundings. The problem, often referred to as "the cocktail party effect," occurs in situations where many people are talking simultaneously, making it difficult to distinguish what is being said by any specific individual.

Although most modern hearing aids incorporate some form of speech enhancement technology, engineers are still struggling to develop a system that makes a significant improvement. Mathew Kavalekalam, a doctoral student in Aalborg University's Audio Analysis Lab, believes that artificial intelligence can be used to help minimize the cocktail party effect. He has turned to machine learning to develop an algorithm that enables a computer to distinguish between spoken words and background noise with a high degree of accuracy. The project is currently being conducted in collaboration with hearing aid researchers from intelligent audio technology development firm GN Advanced Science with financial support from Innovation Fund Denmark.

"We had to figure out how to approach the problem mathematically," Kavalekalam says. "The [current] state of the art is not mode based and does not work well in adverse conditions, like the cocktail party scenario, and, hence, it is difficult to figure out how to improve them." The team, therefore, decided to take a model-based approach, which would enable them to seek a solution in a principled way.

They began by developing a digital model that describes how speech is produced in a human body via the lungs, throat, larynx, mouth, nasal cavities, teeth, lips, and various other physical characteristics. The team then used the model to create a signal that could be used to identify a human voice. "[It's] a model of how speech is first produced and then influenced by background noise before being recorded by the microphones of a hearing aid, or a pair of hearing aids," Kavalekalam explains. "Other models are then trained on the parameter spaces of speech signals, different speakers, and various types of background noise based on signals recorded in a variety of acoustic environments."

Based on these models, the machine language algorithm finds the precise combination of speech and noise models that best explains the recorded signal, which is then enhanced using a Kalman filter. "This method was able to achieve considerable improvements in intelligibility and quality of the processed signals, which were validated by subjective listening tests," Kavalekalam notes. When it comes to speech enhancement, signal processing needs to be snappy, he stresses. If the sound is delayed in the hearing aid, it falls out of sync with mouth movements, potentially annoying or confusing the wearer.

A final prototype model was tested on 10 volunteers (Figure 2), who compared speech and background noise with and without the use of the algorithm. The test participants were asked to perform simple tasks involving numbers, letters, and colors, which were described to them in noisy environments. The test participants' speech perception improved by 15% in very noisy surroundings, Kavalekalam reports.

Existing state-of-the-art hearing enhancement methods, particularly methods based on so-called noise trackers, often degrade intelligibility, particularly in adverse conditions, such as the cocktail party scenario. Kavalekalam believes that his team's new approach considers, in a consistent manner, both the production of speech and the acoustic environment. "An important aspect of our work is the distributed processing across the left and right hearing aid, as most hearing aid users have two devices," he says.

The research is primarily based on a combination of well-known signal processing concepts, such as estimation and filtering, and machine-learning concepts, such as supervised learning and clustering, Kavalekalam notes. "We also found out that our method is closely related with nonnegative matrix factorization methods, which have enjoyed a lot of popularity in source separation, and we now think of it as a form of parametric nonnegative matrix factorization," he says.

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Additional work remains to be done before the software can find its way into a new generation of hearing aids. The algorithm must still be optimized to consume less processing power. Additionally, although hardware technologies are always shrinking and becoming more powerful, the researchers must still cope with the hardware limitations inherent in small form-factor hearing aids.

On the other hand, the new model-based speech-enhancement technology developed by Kavalekalam and his coresearchers promises multiple uses beyond hearing aids. "Some of the potential applications could be mobile phones, Internet telephony, headsets, digital assistants, speech recognition systems—basically, anywhere where enhancement of speech is important," he notes.

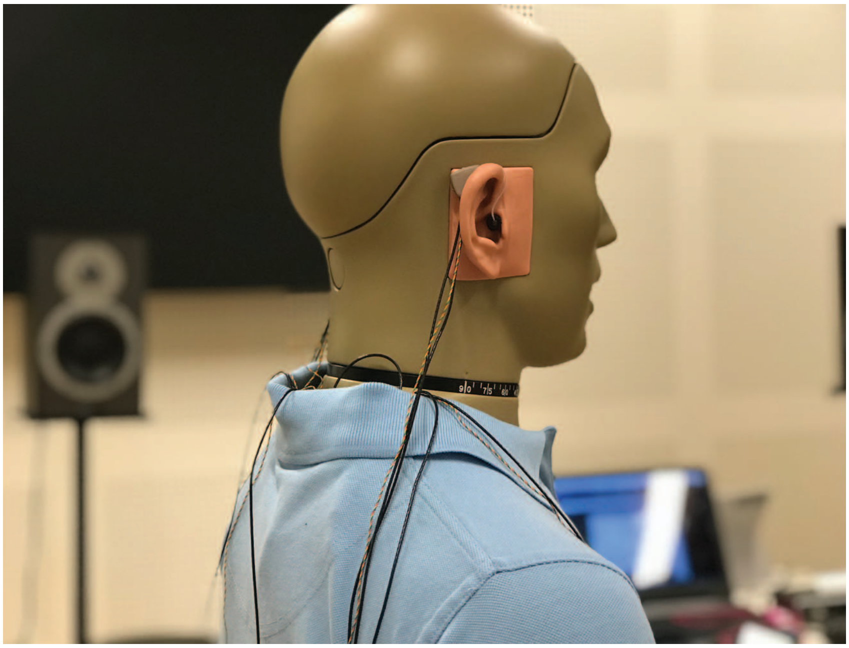

**FIGURE 2.** A prototype hearing aid that uses machine learning to address the cocktail party effect. (Photo courtesy of Aalborg University.)

## A soft, stretchable sensor

Emerging wearable consumer devices, ranging from health and fitness monitors to virtual-reality systems, rely on sensors for essential input signals. The problem is that many current-generation sensors are not designed for use with such applications.

A team of Purdue University researchers now believes that it has met the need for a durable, highly flexible sensor with a new type of soft and stretchable device designed specifically for use with wearable systems and other mobile devices (Figure 3). The technology, called *iSoft*, is capable of real-time multimodal sensing, the team reports.

As a promising input technology, capable of adding interactions to both rigid and elastic surfaces, stretchable soft sensors have been investigated and prototyped for many years, observes Karthik Ramani, a Purdue professor of mechanical engineering and director of the university's C Design Lab. However, the necessary multistep fabrication process and the need for expensive manufacturing equipment have prevented large-scale production. "In our work, iSoft allows users to fabricate soft sensors inexpensively, customize interfaces easily, and deploy them instantly," he says. "We are also able to develop and test new forms of wearables quickly and also personalize the wearable to a particular size—a glove, for example."

Unlike most currently available soft sensors, iSoft supports continuous contact and also can be quickly modified for custom purposes after manufacture. The device features a piezoresistive elastomer that, when touched, changes electrical resistance to generate sensing data.

Ramani notes that the iSoft platform has potential applications in areas ranging from artificial robotic skin to health monitoring to sports medicine as well as a tactile clothing interface. "There are lots of potential consumer electronic applications, such as smart textile products, game controllers, smart cases for electronic devices, smart surfaces for

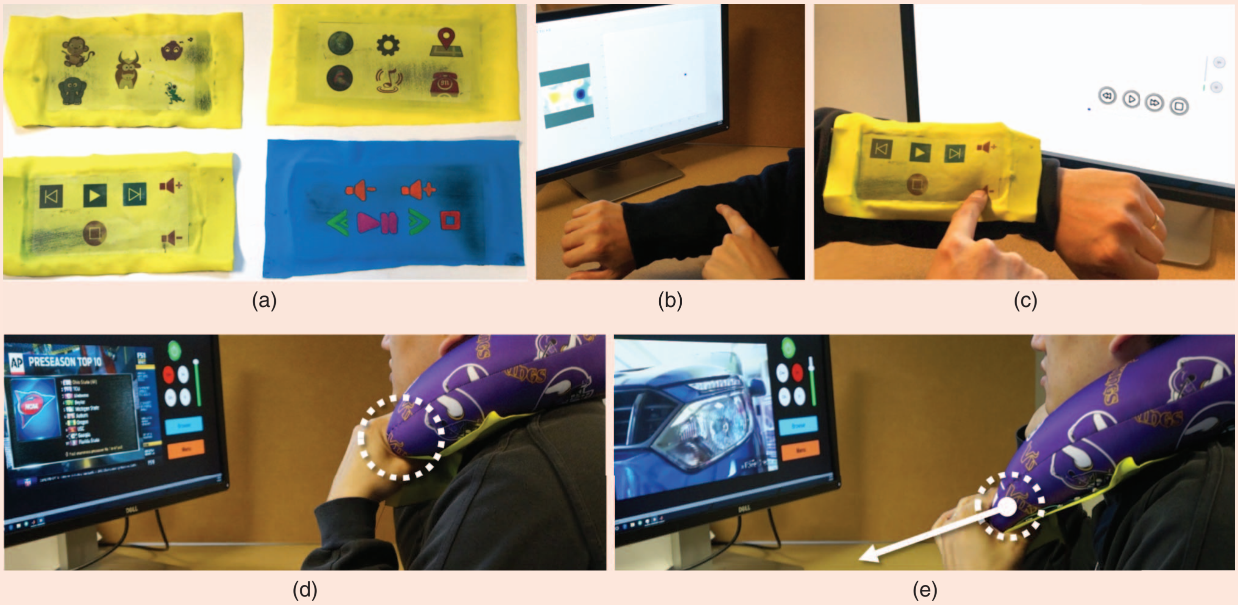


**FIGURE 3.** Examples of iSoft technology. (a) The technology allows for customizable interfaces. (b) The stretchable material can be worn over clothing. (c) The soft-sensor skin can be incorporated into wearables to create interactive devices for mobile environments. (d) and (e) The electrical impedance tomographic image reconstruction is accomplished by comparing measurements at two different instances. (Photos courtesy of Purdue University.)

electronic appliances, glove-like wearables, and, in general, turning everyday objects into interactive objects," he says.

The sensor is produced as a thin, rubbery sheet featuring a series of electrodes positioned around the periphery. The device is formed out of carbon-filled silicone rubber, a nontoxic piezoresistive material widely used in various types of research to create different types of low-cost sensors.

The project's signal processing approach is based on electrical impedance tomography (EIT), a well-known technique often used for reconstructing medical imaging from voltage measurement. Voltage measurements from around the sensor are used to construct a heatmap image, Ramani explains. "Imagine the material to be a network of resistances," he adds.

When a user interacts with the sensor, the deformation alters the device's current and voltage patterns. Voltage variations detected around the sensor's circumference determine where the property must have changed to cause it, Ramani explains. "We are solving an inverse problem in real time as the deformation occurs." Multiple channels are used to detect different kinds of deformation. "By [presenting] the change in property in the form of a heatmap, we can use a simple blob detection to localize the user's touch location," he notes.

EIT image reconstruction is accomplished by comparing the measurements at two different instances, says Sang Ho Yoon, a research team partner who was a Ph.D. student during the project. Another Ph.D. student, Luis Paredis, was also a project partner. "EIT-based image reconstruction allows us to provide touch sensing with fine resolution using minimal hardware," Ramani states. "Without this knowledge-driven approach, implemented by adapting finite element like models, it would be impossible to obtain this level of touch resolution by just utilizing thresholding on sensing signals."

"Signal processing is a core of our research," Yoon adds. "By interpreting the sensor signals with a proper approach, we achieve contact localization (touch sensing), stretch/bend sensing, and other modes of interacting with the sensor itself."

Ramani says that the researchers have verified the system's accuracy and evaluated user performance. "I think signal processing with soft sensors will become more popular as various types of soft sensors are proposed in various communities," he says.

Ramani foresees three possible directions for future development. He anticipates using machine learning to improve sensor performance in terms of accuracy and computation cost, integrating the soft-sensor skin into wearables to create interactive devices for mobile environments, and building sensor skin into robotic platforms. "This type of project can take on many dimensions, so we do not know when it will come to an end," he says.

## Author

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