

# Center for the Design of Analog-Digital Integrated Circuits (CDADIC)

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## Incremental Analog-to-Digital Data Converters

Wearable devices are crucial to the Internet of Things (IoT), with more than 35 million connected wearable devices in use at the end of 2014. In wearable devices and other IoT applications, integrated sensor interface circuits are required to prepare the analog sensor output for digital signal processing. In some cases, such as image sensors and electroencephalograms (EEG), a single interface needs to be shared among many sensors. Often the sensors operate in battery-powered devices, and hence power dissipation in the interface circuitry is of great concern. The interfaces usually require high-accuracy ultra-low-power analog-to-digital converters (ADCs) with low signal bandwidth.

Incremental analog-to-digital converters (IADCs) represent an excellent choice for use in such sensor interfaces. They apply a combination of signal processing and noise shaping to achieve high accuracy. Their sample-by-sample operation allows sharing a single ADC among multiple sensors.



*A potential application of the incremental ADC in a wearable device, and its integrated hardware implementation.*

CDADIC researchers have developed novel IADC architectures that achieved both high accuracy and excellent power efficiency. A particularly useful new IADC configuration was recently found, which reuses a single active component multiple times. This breakthrough hardware recycling technique extends the accuracy of the converter with very low power consumption. Compared to the conventional single-step IADC of the same accuracy, the new ADC reduces the power requirement by a factor of close to 1000.

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Fabricated on an integrated chip, the novel device demonstrated superior performance. It offers a power-efficient realization for various integrated sensor interfaces used in industrial, medical and environmental applications.

**Economic Impact:** The next big wave of data-driven technological innovation will connect physical devices embedded with tiny computing devices to the Internet. This will help advance wearable electronic systems and smart appliances in homes and offices. These has the potential to greatly improve the efficiency and safety of daily activities. As a result, it is predicted that there will be a rapidly growing market for sensor and micro-actuator interface devices, which require micro-power high-accuracy ADCs as their key components. The data converters developed under the proposed research will play important roles in such interfaces. There is considerable interest by high-technology companies in this work, as shown by grants and gifts received from several CDADIC companies (and many outside ones) to support more research in this field. Incremental analog-to-digital converters have been receiving attention in the many applications. They allow the translation of analog signals into digital form in a sample-by-sample manner, and are able to achieve high accuracy just like noise-shaping converters.

Since these converters can be multiplexed among many sensor channels, and require minimal amount of power using our hardware recycling technique, they represent excellent choices for wearable devices. The total number of connected devices in which our circuits may be used - including smart home appliances, "wearables," smart metering systems, robots and autonomous vehicles. These are projected to grow to tens of billion by 2019. The integrated circuit industry will benefit from innovations in this field. The country will benefit by maintaining our global competitive advantage in the digital economy.

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## RF-energy Harvested mm-Wave SoC for mm-Wave RFID

The Internet-of-Everything (IoE) envisions a connected world with multibillions of sensors that communicate through the Internet, providing real-time information that guides decisions. IoE is projected to be a key driver of the global economy with overall market size projected to reach \$1.7T by 2020. A key limitation to realizing this vision of a fully-sensed and networked world is the development of the sensors itself. An ideal sensor must be physically tiny, have almost infinite battery life, be able to wirelessly communicate with the networks. All of this must achieve this at costs that are compatible with widespread consumer applications (for example, adding a sensor to every object in a store). However, when sensor dimensions are limited to a few millimeters, useful lifetime is limited by the capacity of miniature batteries. Often, it is not practical or cost effective to replace batteries or even physically access the sensor for recharging. Wireless power transfer is a convenient and robust way of powering/recharging sensors remotely but the acceptable distance between wireless power source and sensor needs to be increased for practical applications.

In this CDADIC project, researchers sought to achieve longer wireless powering range for ultra-miniaturized mm-scale sensors. Such tiny sensors can be potentially low-cost. Their small size, however, limits application of traditional wireless powering optimization techniques. Researchers achieved improved performance by developing a systematic circuit design algorithm that optimizes wireless powering for a given sensor area and/or frequency of operation. They also recently demonstrated how this breakthrough's novel circuitry improves energy harvester performance when starting from zero stored energy. In all cases, the

focus has been on integrated technologies that have proven track records of low-cost manufacturing. Such developments have enabled the digital revolution of the past decades.

Other researchers have also been looking at this challenge - prior work on ultra-miniaturized mm-scale sensor transmitters and receivers have shown “pad-less” operation, i.e., the transmitter, receiver, and energy harvesting circuits are all fabricated in a single, inexpensive, integrated circuit that does not require any subsequent packaging or other components.

This breakthrough approach extends the range of such “pad-less” integrated sensor wireless transmitters and receivers by increasing the range of wireless powering. The work also includes a new way of fabricating a miniature antenna along with the transmitter and receiver on the integrated circuit (IC). The new wireless approach ensures more power from the transmitter is radiated by the antenna compared to current state-of-the-art, which means that less energy is required from the battery to wirelessly send a given amount of information.

The wirelessly-powered sensors targeted in this research can significantly impact tracking objects of interest - they can be used for asset-tracking for miniature objects (for example, individual units in a store) or people tracking (for example, elder-monitoring in assisted-living facilities).

**Economic Impact:** The IoE represents the next stage in the evolution of society towards real-time data analysis and optimized control. The ways in which everyday technologies and tasks can be impacted by the IoE is only limited by individuals’ imagination. This will translate to new technologies that improve productivity and health in society. Miniaturizing such sensors and making them inexpensive enables both replacement of sensors in current applications as well as open new applications. Therefore, such sensors will form a significant enabler for the >\$1T IoE economy. CDADIC researchers are working with Texas Instruments and Intel towards the next generation of such sensors to enable commercialization. Finally, on-going research is preparing graduate students for careers in industry and research, creating engineers who will drive future innovations.

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