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PEEL-AND-STICK SENSORS POWERED BY DIRECTED RF ENERGY

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ABSTRACT
PARC, a Xerox Company, is developing a low-cost system of peel-and-stick wireless sensors that will enable widespread building environment sensor deployment with the potential to deliver up to 30% energy savings. The system is embodied by a set of RF hubs that provide power to automatically located sensor nodes, and relay data wirelessly to the building management system (BMS). The sensor nodes are flexible electronic labels powered by rectified RF energy transmitted by an RF hub and can contain multiple printed and conventional sensors. The system design overcomes limitations in wireless sensors related to power delivery, lifetime, and cost by eliminating batteries and photovoltaic devices. Sensor localization is performed automatically by the inclusion of a programmable multidirectional antenna array in the RF hub. Comparison of signal strengths while the RF beam is swept allows for sensor localization, reducing installation effort and enabling automatic recommissioning of sensors that have been relocated, overcoming a significant challenge in building operations. PARC has already demonstrated wireless power and temperature data transmission up to a distance of 20m with less than one minute between measurements, using power levels well within the FCC regulation limits in the 902-928 MHz ISM band. The sensor's RF energy harvesting antenna achieves high performance with dimensions below 5cm x 9cm.

INTRODUCTION
The widespread deployment of advanced sensors in the buildings sector has the potential to enable significant energy savings through optimized control of Heating Ventilation and Air Conditioning (HVAC) settings, yet this is currently limited by the high cost of hardware and installation. Wireless communication can greatly reduce installation cost, but currently wireless sensors rely on batteries with limited lifetime, or indoor-light harvesting, with high device cost and reduced power availability. Directed RF energy delivery can provide robust power using simple, inexpensive components. Plug-and-play sensors that self-locate can reduce installation and commissioning labor costs, while providing dense environmental and room configuration information.

PARC is developing a wirelessly powered sensor network comprising peel-and-stick credit-card-sized sensor nodes that are remotely powered at distances of 10m or greater by RF energy transmitted by a central hub. The RF hub uses a multidirectional phased array to automatically locate the sensor nodes with 0.5m accuracy by correlating received power with the directionality of the beam. This addresses two of the main issues relating to sensor commissioning: power and localization.

NOMENCLATURE
BMS: Building Management System
HVAC: Heating, Ventilation and Air Conditioning
FHE: Flexible Hybrid electronics
RF: Radio Frequency
MCU: Micro Controller Unit
ISM: Industrial, Scientific and Medical
BLE: Bluetooth Low Energy

SENSOR NETWORK SYSTEM OVERVIEW

The sensor network consists of one or more RF hubs each serving multiple peel-and-stick sensor nodes. Each hub transmits RF power to the sensor nodes, automatically locates the nodes, receives sensor data, and relays that data to the building management system (BMS), as illustrated in figure 1.

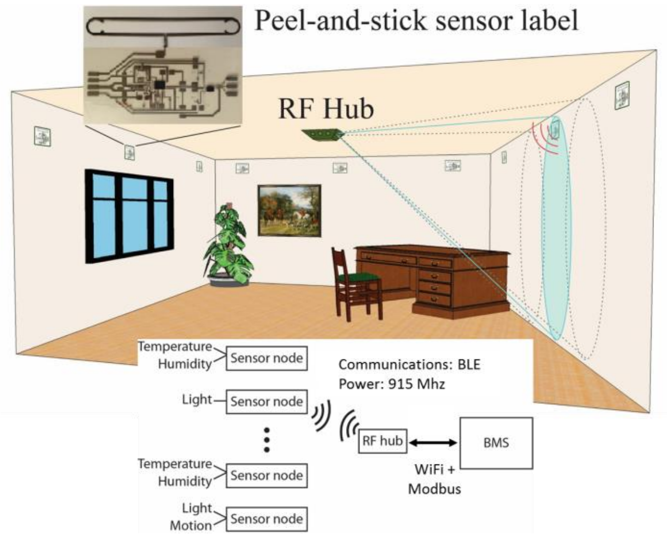

Figure 1: Sensor network overview

RF Energy harvesting & localization:

The RF hub transmits power and locates the sensors using a multidirectional phased array of metamaterials-inspired antennas. The system is capable of steering and focusing an RF energy beam towards any individual sensor to deliver RF power to the sensor node. When sufficient energy has been accumulated at the sensor node, the node reads its multiple sensors, which can include temperature, humidity, concentrations of CO_2 and other gases, occupancy, and other parameters relevant for building operations or comfort. The data is then communicated back to the hub for transfer to the BMS. Each sensor is also capable of measuring and communicating how much RF power it is receiving at any moment as well of the state of charge of its energy storage components. By scanning the beam around a room or floor and correlating the received power at the sensors with the beam angle of transmitted RF power, the hub is expected to be capable of localizing the sensors within its range with 0.5m accuracy. The frequency used for the RF energy transmission is in the Industrial, Medical and Scientific (ISM) band between 902 and 928 MHz, with an allowed RF transmitted power up to 30dBm (1 Watt) and an antenna gain of 6dBi (4X gain). This allows up to -13.7 dBm (42 uW) of power delivered to a sensor at a distance of 10m, or -7.7dBm (170uW) at 5m (with 2dB of antenna gain at the sensor node). Given the extremely low power consumption of the sensors, this is sufficient to continuously operate several sensors.

Communications:

In addition to powering and localizing the sensor nodes, the RF hub is responsible for sensor management, data collection, and communication of this data to the BMS. Communications between the sensors and the RF hub are performed using a Bluetooth Low Energy (BLE) protocol, which is operated in the 2.4GHz ISM band. The use of a separate band from the RF power delivery system enables communications between the RF hub and the sensor nodes to occur simultaneously with power transmission. The hub keeps track of the state of charge of each sensor node and delivers RF energy appropriately to ensure continual sensor operation and optimal data collection.

Communications between the RF hub and the BMS can be configured based on the building hardware and software. In the demonstration system being developed, a combination of Wi-Fi and Modbus are used, for broad compatibility.

SENSOR TAG ARCHITECTURE AND PRELIMINARY PERFORMANCE METRICS

The sensor nodes comprise a 915 MHz antenna with a high efficiency rectifying voltage boost circuit, an energy harvesting and power management chip, a capacitor bank for energy storage, a microcontroller unit (MCU) and transceiver radio, a Bluetooth antenna and one or several sensors (see Figure 2).

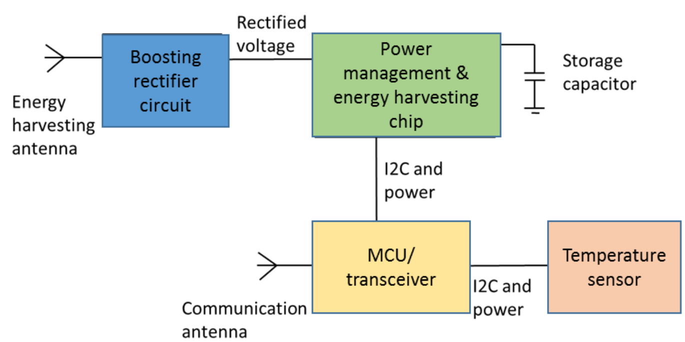

Figure 2: Block diagram of sensor tag

The size of the sensor node is dominated by the 915MHz energy harvesting antenna, which is required to have high efficiency to maximize power transfer. PARC's prototype uses an electrically-small 5cm x 9cm antenna matched to a 50-Ω impedance, with a gain of 2.2 to 2.9 dB within the ISM band, and a voltage standing wave ratio (VSWR) <1.4, indicating excellent performance.

A boosting rectifier circuit transforms the RF power to a DC voltage which is fed into an energy harvesting chip. The energy harvesting chip stores the rectified energy in a capacitor bank (300µF of capacitance), and provides power management functionality. The chip is capable of cold-starting with only 3µW of input power, even when the storage capacitor on the sensor node is entirely depleted. This ensures that the sensor node can be left uncharged for as long as desired and can be rebooted using only RF power delivery. When enough energy is accumulated, the energy harvesting chip enables the power supply to the MCU and transceiver. The MCU then reads the sensors and initiates communication with the RF hub over the BLE channel. Depending on the hub's response, the sensor node may continue its sensing operation or enter different sleep modes to save energy, with its lowest energy sleep state consuming < 1µW of quiescent power. The distance from the RF hub to the sensor node is not limited by the communication link but by the charging link. Thus the sensor can operate its transceiver at extremely low powers (-10 dBm), enabling extremely low communication energy. A single transmission using BLE can consume as little as 100 µJ. With this extremely low-power operation, the RF hub can power and communicate with multiple sensors at sampling periods ~1 min, sufficient for building control applications. Faster sampling is generally not needed because of the long time constants associated with heating, cooling, and ventilating rooms.

An initial prototype of the sensor tag was built using development boards. With this system, RF charging of the tag and data collection were demonstrated up to 20m. Figure 4 shows the voltage on the capacitance on a sensor node at a distance of 7m from the RF source. Charging is followed by the initialization of the MCU and transmission of temperature and humidity data. In this example, the transmission power is 14dBm, greater than the minimum required, and drains 450µJ from the capacitor array. When optimized, BLE communications at 0dBm consume as little as 100µJ of energy.

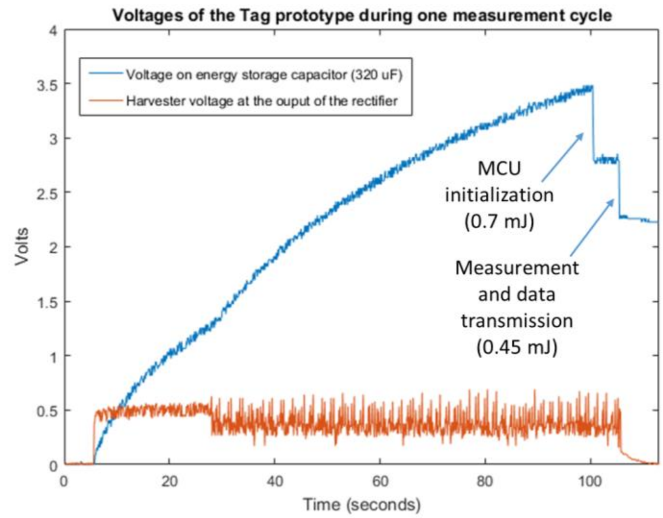

Figure 4: Voltage on the storage capacitor and at the output of the rectifier circuit as the tag is charged. RF power is turned on at 5s. At 30s the energy harvesting chip exits cold-start mode and its internal boost converter's efficiency increases. At 100s power is delivered to the MCU. At 105s temperature and humidity data are transmitted to the hub.

<u>Peel-and-Stick Form Factor</u>:

After design and optimization, the sensor node will be implemented in a flexible hybrid electronics (FHE) platform. This will enable extremely low-effort installation that does not require dedicated expertise. Sensors will be installed simply by peeling them from a roll and sticking them on a wall or other structure. The sensor localization feature of the system enables straightforward relocation or replacement of sensors.

FHE fabrication, typified by ubiquitous RFID tags, leverages roll-to-roll manufacturing to achieve economically viable costs at volume. RFID manufacturing yield is over 99% and printed-antenna yields are expected to be similarly high. Figure 5 shows antennas fabricated using a roll-to-roll process. At high production volumes, roll-to-roll manufacturing process cost is driven by utilization of capital equipment with a fixed throughput and is largely a function of device area. The cost of component placement and assembly with direct die attachment is calculated per-device based on current equipment. In PARC's model, the total sensor cost, including components, fabrication, is project to be <$10.

The number of sensors per hub depends on the deployment scenario. Tracking sunlight throughout the day could be enabled by installing sensors along room walls at 1-m spacing, *i.e.*, ~25 in a typical office. Personal comfort and occupancy monitoring would benefit from sensors placed near desks, tables, etc., at 1-5 per room. HVAC and lighting monitoring could be achieved with sensors at diffusers or light fixtures, at 4-10 per room.

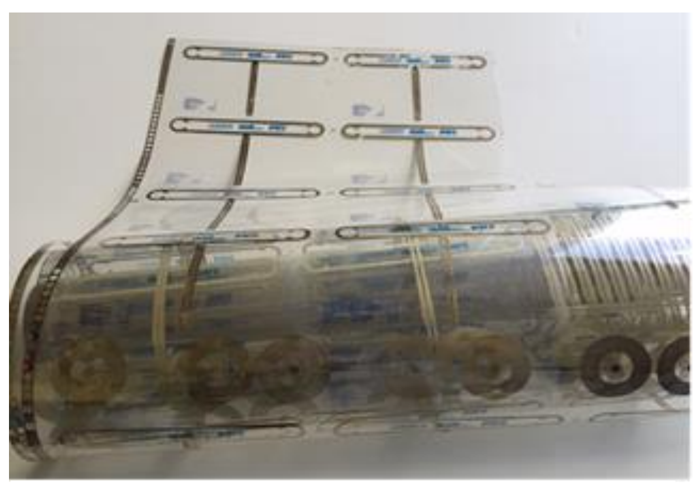

Figure 5: Roll-to-roll printed antennas.

CONCLUSION

The cost of distributed sensor networks is often dominated by commissioning and maintenance. Sensors that requiring no battery and are able to be automatically located can significantly reduce these costs and enable enhanced energy savings in buildings. PARC is developing such a class of sensors using directed RF energy and has demonstrated very promising performance in early prototypes.

ACKNOWLEDGMENTS

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