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RF ENERGY HARVESTING PEEL-AND-STICK SENSORS

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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[1]. The system is embodied by a set of RF hubs that provide power to the automatically located sensor nodes, and relays data wirelessly to the building management system (BMS). The sensor nodes are flexible electronic labels powered by rectified RF energy transmitted by a 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. The sensor localization is performed automatically by the inclusion of a programmable multidirectional antenna array in the RF hub. Comparison of signal strengths when the RF beam is swept allows for sensor localization, further 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 a duty cycle less than a 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 dimensions was less than 5cmx9cm, demonstrating the possibility of small form factor for the sensor nodes.

INTRODUCTION
The widespread deployment of advanced sensors in the buildings sector has the potential to unleash significant energy savings through careful 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. However, wireless sensors currently rely on batteries with limited lifetime, or indoor-light harvesting, with high device cost and reduced power availability. Directed RF energy harvesting 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 addressing these issues: peel-and-stick credit card sized sensors nodes are remotely powered up to 10m away using RF energy distributed by a central hub with a multidirectional phased array. Additionally the RF hub can automatically locate the different nodes with 0.5m accuracy by correlating their 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 is centered around the main RF hub in charge of performing RF power distribution, sensor localization, communications with all the nodes, and transmitting all the information to the building management system (BMS), as illustrated in figure 1.

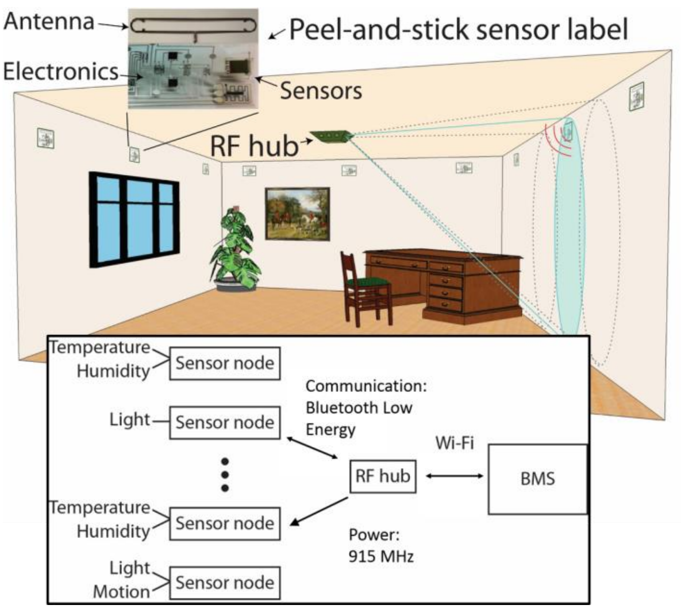

Figure 1: Sensor network overview

RF Energy harvesting & localization:

The RF hub distributes power and localizes the sensors using its multidirectional phased array metamaterials-inspired antenna. The antenna is capable of steering and focusing an RF energy beam, thereby enabling it to point the beam in any individual sensor's direction in order to deliver focused RF power to the sensor itself. Once enough energy has been delivered, the sensors node performs the measurements it is designed for (i.e. Temperature, humidity, CO2 or gas levels, occupancy, etc…) and communicates that information back to the hub. The sensor is also capable of communicating to the hub how much RF power it is receiving at any moment as well as its charge state. By scanning RF the beam around the room and correlating the received power at the sensors with the beam angle, the hub is 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 at a sensor 10m away, or -7.7dBm (170uW) for a sensor 5m away (assuming 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 per hub.

Communications:

Beyond 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 happen in parallel with the RF charging functionality of the hub. The hub keeps track of the different charge levels of the sensor nodes and delivers RF energy appropriately to ensure continual sensor powering and optimal data collection.

Communications between the RF hub and the BMS is done with a Wi-Fi connection, enabling compatibility with most BMS systems.

SENSOR TAG ARCHITECTURE AND PRELIMINARY PERFORMANCE METRICS

The sensor nodes comprise a 915 MHz antenna with a high efficiency rectifying and voltage booster 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 the block diagram presented in figure 2).

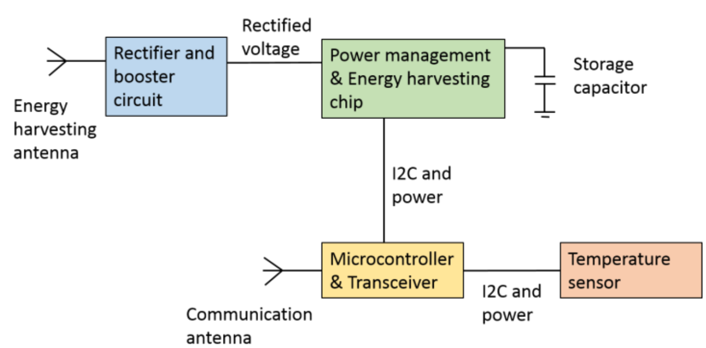

Figure 2: Block diagram of sensor tag

The size of the sensor node is dominated by the 915MHz energy harvesting antenna. PARC has already demonstrated all the required functionality using a prototype with a 5cmx9cm antenna, demonstrating the possibility of small form factor for the sensor nodes. The electrically small antenna was 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 rectifying and voltage booster circuit transforms the RF power to a DC voltage which is fed into the Energy harvesting chip. The energy harvesting chip contains a boost converter which brings the voltage to usable levels and stores the energy into a capacitor bank (300uF of capacitance), as well as provides the power management functionality. The chip is capable of cold-starting its boost converter with only 3uW 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 stored, the power supply to the MCU and transceiver is turned on. The MCU then samples the sensor and starts communication with the RF hub. 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 < 1uW of quiescent power. The distance at which the sensor can be placed from the RF hub is not limited by the communication link but by the charging link, meaning that the sensor can operate its transceiver at extremely low powers (-10 dBm), and enabling extremely low communication energy: a single transmission using BLE can consume as little as 100 uJ. This extremely low power operation enables the RF hub to handle several sensors with sampling rates ~ 1 min, which is compatible with building control systems, although slower rates are also acceptable. Faster sampling is generally not needed because of the long time constants associated with heating, cooling, and ventilating rooms.

A prototype of the sensor tag was built using development boards. RF charging of the tag and data collection demonstrated up to 20m away was demonstrated. Figure 3 shows the charging of the tag's capacitor 7m away from the RF source, followed by the initialization of the MCU and transmission of temperature and humidity data. The transmission power used at the sensor tag is larger than optimal at 14dBm, responsible for the use of 450uJ of energy. As discussed previously, BLE communications at 0dBm can consume as little as 100uJ of energy per transmission.

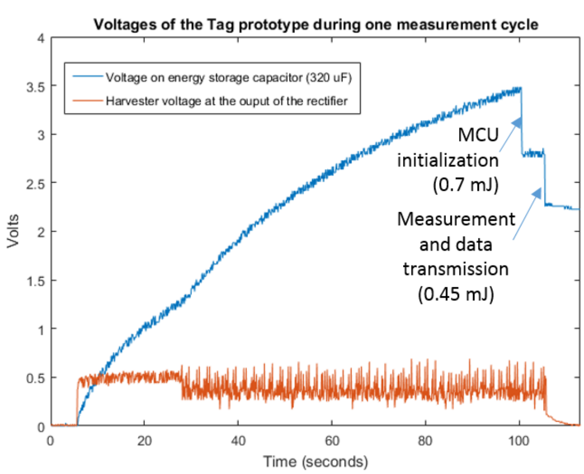

Figure 3: Voltage on the storage capacitor and at the output of the rectifier circuit as the tag is charged. RF power is turned on at 5s. At 30s the energy harvesting chip goes out of cold-start mode and the boost converter's efficiency increases, at 100s power is delivered to the MCU, and at 105s the temperature and humidity data is transmitted to the hub

PROJECTED COSTS

The sensor node will eventually be implemented using flexible hybrid electronics (FHE). 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 4 shows antennas fabricated using a roll to roll process. Through extensive analysis based on data from Xerox as well as leading RFID manufacturers, PARC has developed a cost model for FHE at scale. 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, fabrication and assembly on a 54-cm2 substrate is projected to cost $4.60. With a preliminary bill of materials and volume pricing, the total sensor tag cost is ~$10. No alternative wireless sensor technology has a greater potential for low cost.

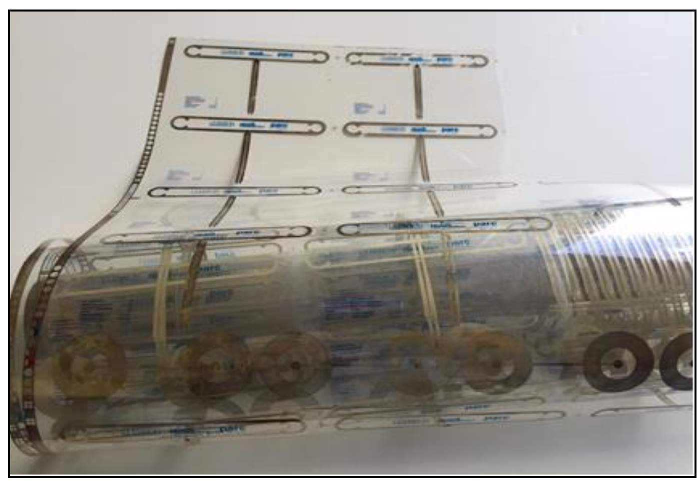

Figure 4: Roll to roll printed 915 MHz antennas

Based on volume PCB manufacturing and assembly costs, using the same transceiver as the sensor node, and with an additional 802.11-capable microprocessor for communication with the BMS, the RF hub hardware is calculated to cost $20-$30. With each hub servicing multiple sensors, the per-sensor cost can be extremely low. 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.

CONCLUSION

Sensor networks costs are often dominated by commissioning costs. Sensors requiring no battery and able to be automatically located offer a solution to drastically reduce these costs and enable enhanced energy savings in buildings. PARC is developing such a class of sensors using RF energy harvesting as the primary source of energy and has demonstrated very promising performance in early prototypes.

ACKNOWLEDGMENTS

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REFERENCES

[1] Erickson, et al., Proceedings of the 1st ACM Workshop on Embedded Sensing Systems For Energy-Efficiency In Buildings (BuildSys) 2009