

Peel-and-Stick Sensors Powered by Directed RF Energy

David Eric Schwartz*, Clinton J. Smith, Joseph Lee, Shakthi Priya Gowri, George Daniel, Christopher Lalau-Keraly, Quentin Baudenon, J. R. M. Saavedra

Palo Alto Research Center Inc. (PARC), Palo Alto, California – 94304, USA
*Email: *David.Schwartz@parc.com*

Abstract

PARC, a Xerox Company, is developing a low-cost system of peel-and-stick wireless sensors that will enable widespread building environmental 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 the 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 as the RF beam is swept allows for sensor localization, reducing installation effort and enabling automatic recommissioning of sensors that have been relocated. PARC has already demonstrated wireless power and temperature data transmission up to a distance of 20m with 71s 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 of 5cm x 9.5cm.

Keywords: Energy harvesting; RF power; Peel-and-stick; Flexible-hybrid electronics; Building efficiency; Sensor

1. 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 and lack of interoperability, among other challenges [1]. Increased availability of sensor data has been shown to enable significant primary energy savings through improved building operation. Up to 30% potential savings in HVAC, and up to 13% in lighting are predicted to be available through finer control enabled by higher sensor density [2,3,4]. Wireless communication can greatly reduce installation cost, but wireless sensors currently rely on batteries with limited lifetime (*e.g.*, <1 year with 2900 mAh battery and 1% operation duty cycle), or indoor-light harvesting with high device cost, large area rigid structures, and limited power availability [5]. Additionally, such devices lack an automated commissioning system, requiring a user with sufficient authority and system knowledge to physically deploy them and incorporate them into the building control system.

Directed radio-frequency (RF) energy delivery can provide robust power using simple, inexpensive components. While RF is an attractive means of powering distributed sensor nodes, ambient RF energy has limited and variable availability [6]. Use of a dedicated RF source can provide consistent power within range of the transmitter [7]. The addition of beam steering allows for higher transmission power by enabling the use of high-gain antennas, and also admits additional functionality, including sensor localization. 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 10 m or

greater by RF energy transmitted by a central hub. The RF hub uses a multidirectional antenna to automatically locate the sensor nodes with 0.5-m accuracy by correlating received power with the directionality of the beam. This addresses two primary issues in sensor commissioning: power and localization.

2. Experimental Setup

The sensor system 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.

The sensor tags are first being prototyped using conventional PCB technology. Once performance is established, a flexible-hybrid electronics (FHE) version will be implemented. In FHE, electronic components are assembled and bonded on a flexible substrate, often polyester or polyimide, with printed interconnect, most commonly based on nanoparticle silver inks [8]. The process is compatible with high-volume fabrication and enables low cost, flexible sticker-like form factors for easy installation.

3. RF power and localization

The RF hub transmits power and locates the sensors using a set of metamaterials-inspired antennas. By selectively energizing combinations of antennas, the system is capable of steering and focusing an RF energy beam towards any individual sensor node to deliver RF power to that node. When sufficient energy has been accumulated at the sensor node, it reads its multiple sensors, which can include temperature, humidity, concentrations of CO₂ 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 node is also capable of measuring and communicating how much RF power it is receiving at any moment as well 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 capable of localizing the sensors within its range with an expected accuracy of 0.5 m.

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 30 dBm (1 Watt) and an antenna gain of 6 dBi (4X gain). Thus, with 2-dBi receiving antenna gain, up to -13.7 dBm (42 μ W) of power can be delivered to a sensor at a distance of 10 m, or -7.7 dBm (170 μ W) at 5 m. As each sensor label consumes <400 μ J per transaction (reading the sensor and transmitting the data), this is sufficient for powering ~1 transaction per minute, including full accounting of power conversion losses.

4. Communications

In addition to powering and localizing the sensor nodes, the RF hub is responsible for sensor management, data collection, and transfer of data to the BMS.

Communications between the sensors and the RF hub use a Bluetooth Low Energy (BLE) protocol, which is operated in the 2.4-GHz 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 a sufficient sensor operational duty cycle 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, the Modbus protocol over WiFi is being used for wide interoperability.

5. Sensor Tag Architecture and Preliminary Performance Metrics

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

PARC's prototype uses a 6-cm-by-9.5-cm antenna matched to a 50- Ω impedance. Achieving high performance with a small antenna is critical for this application, as the antenna is the largest component on the sensor label and sensor charge time is inversely proportional to antenna efficiency. Figure 3 shows the sensor label 915-MHz power antenna and 2.4-GHz communications antenna as fabricated on a FR-4 substrate. The power antenna has a measured gain in the range of 2.2 to 2.9 dBi within the power ISM band, and a voltage standing-wave ratio (VSWR) <1.4, indicating excellent performance. In the final FHE implementation, these antennas will be printed.

A boosting rectifier circuit transforms the RF power to a DC voltage which is fed into an energy-harvesting integrated circuit (IC) that manages energy storage and power delivery. The rectified energy is stored in a low-leakage capacitor bank (840 μ F of capacitance). The energy-harvesting IC is capable of cold-starting with only 3 μ W of input power, even when the storage capacitor on the sensor node is entirely depleted. This ensures that the sensor node can be left completely uncharged for as long as desired and can be rebooted using only RF power delivery. When enough energy is accumulated, the

power supply to the MCU/transceiver is enabled, causing the MCU to boot up (~ 1.6 mJ). The MCU then reads the sensors (~ 300 μ J) and initiates communication with the RF hub over the BLE channel (~ 120 μ J). Depending on the hub's response, the sensor node may continue its sensing operation or enter different sleep modes to save energy, with the lowest energy sleep state of the MCU consuming < 1 μ W 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. Table 1 shows the energy consumption of various processes on the sensor label. For an active tag, the total energy required to read a sensor and transmit its data is ~ 349 μ J. With 840 μ F of energy storage capacitance, the tag is able to sample and transmit 9 messages before the supply voltage cannot support the MCU and it is shut down. 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.

With the PCB-based sensor label prototypes, RF charging of the tag and data collection were demonstrated at a distance of 20 m. Figure 4 shows the voltage on the capacitance on a sensor node at a distance of 7 m from the RF source using 320 μ F storage capacitance. Charging is followed by the initialization of the MCU and transmission of temperature and humidity data. In this sequence, the transmission consumes 14 dBm of power and drains 349 μ J from the capacitor array. The BLE communications consume 120 μ J of energy.

6. Peel-and-Stick Form Factor

After design and optimization, the sensor node will be implemented in an FHE platform. This will enable extremely low-effort installation that does not require dedicated expertise. Sensors nodes can be installed by peeling them from a roll and sticking them on a wall or other structure. In combination with the sensor localization feature, this enables straightforward relocation or replacement of sensors, for example upon sensor failure or room or cubicle reconfiguration.

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. 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 manufactured sensor node cost is projected to be <\$10.

Figure 5 shows antennas fabricated using a roll-to-roll process and an FHE circuit fabricated at PARC [9]. PARC has developed a manufacturing-compatible process for placing components on flexible polyethylene naphthalate (PEN) substrates with screen-printed interconnect, physically bonding, and electrically connecting them. In addition to packaged ICs and passive components, in an FHE process, it is possible to bond bare silicon dies as well as dies thinned so as to be flexible. PARC's preferred process uses printed anisotropic conductive paste (ACP) for component connection. A similar material, often used for flip-chip bonding, is anisotropic conductive film (ACF) [10].

Both contain conductive particles that form electrical connections with the application of heat and pressure. In ACF the active material is supported by a substrate film.

7. Conclusions

The cost of distributed sensor networks is often dominated by commissioning and maintenance. Sensors that do not require a 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

PARC would like to acknowledge the Building Technologies Office (BTO) in the Department of Energy (DOE) for funding this project under grant number DE-EE0007679.

References

- [1] Agarwal, Y., Balaji, B., Gupta, R., Lyles, J., Wei, M. and Weng, T., 2010, November. Occupancy-driven energy management for smart building automation. In *Proceedings of the 2nd ACM workshop on embedded sensing systems for energy-efficiency in building* (pp. 1-6). ACM.
- [2] Lu, J., Sookoor, T., Srinivasan, V., Gao, G., Holben, B., Stankovic, J., Field, E. and Whitehouse, K., 2010, November. The smart thermostat: using occupancy sensors to save energy in homes. In *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems* (pp. 211-224). ACM.
- [3] Feldmeier, M. and Paradiso, J.A., 2010, November. Personalized HVAC control system. In *Internet of Things (IOT), 2010* (pp. 1-8). IEEE.
- [4] Siemens, 2012, "Building Automation – impact on energy efficiency."
- [5] Stamatescu, G., Chițu, C., Vasile, C., Stamatescu, I., Popescu, D. and Sgârțiu, V., 2014, June. Analytical and experimental sensor node energy modeling in ambient monitoring. In *Industrial Electronics and Applications (ICIEA), 2014 IEEE 9th Conference on* (pp. 1615-1620). IEEE.

- [6] Paradiso, J.A. and Starner, T., "Energy Scavenging for Mobile and Wireless Electronics," *IEEE Pervasive Computing*, January-March 2005, pp 18-27
- [7] Farinholt, K.M., Park, G., Farrar, C.R., "EF Energy Transmission for a Low-Power Wireless Impedance Sensor Node," *IEEE Sensors Journal* 9(7), July 2009, pp 793-800
- [8] Schwartz, D.E., Rivnay, J., Whiting, G.L., Mei, P., Zhang, Y., Krusor, B., Kor, S., Daniel, G., Ready, S.E., Veres, J., Street, R.A., "Flexible Hybrid Electronic Circuits and Systems," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems* 7(1), March 2017, pp 22-37
- [9] Schwartz, D.E., Mei, P., Krusor, B., Zhang, Y., Street, R., Rivnay, J, Mercier, P., Wang, J. "Flexible Hybrid Mouth-Guard-Based Electrochemical Biosensing," *Meeting Abstracts*. No. 42. The Electrochemical Society, 2017
- [10] Kim, S.-C., Kim Y.-H., "Review paper: Flip chip bonding with anisotropic conductive film (ACF) and nonconductive adhesive (NCA)," *Current Applied Physics*, 12 suppl. 2, July 2013, pp S14-S25

List of Figure Captions

- Fig. 1 Sensor system overview
- Fig. 2 Block diagram of sensor tag
- Fig. 3 Sensor tag antennas
- Fig. 4 Voltage on the storage capacitor and at the output of the rectifier circuit as the sensor label is charged. RF power is turned on at 5 s. At 30 s the energy harvesting IC exits cold-start mode and activates its high-efficiency internal boost converter. At 100 s, power is connected to the MCU. At 105 s temperature and humidity data are transmitted to the hub.
- Fig. 5 (a) Roll-to-roll printed antennas and (b) flexible-hybrid electronics (FHE) circuit printed at PARC

List of Table Captions

Table 1 Sensor tag energy consumption

Accepted Manuscript Not Copyedited

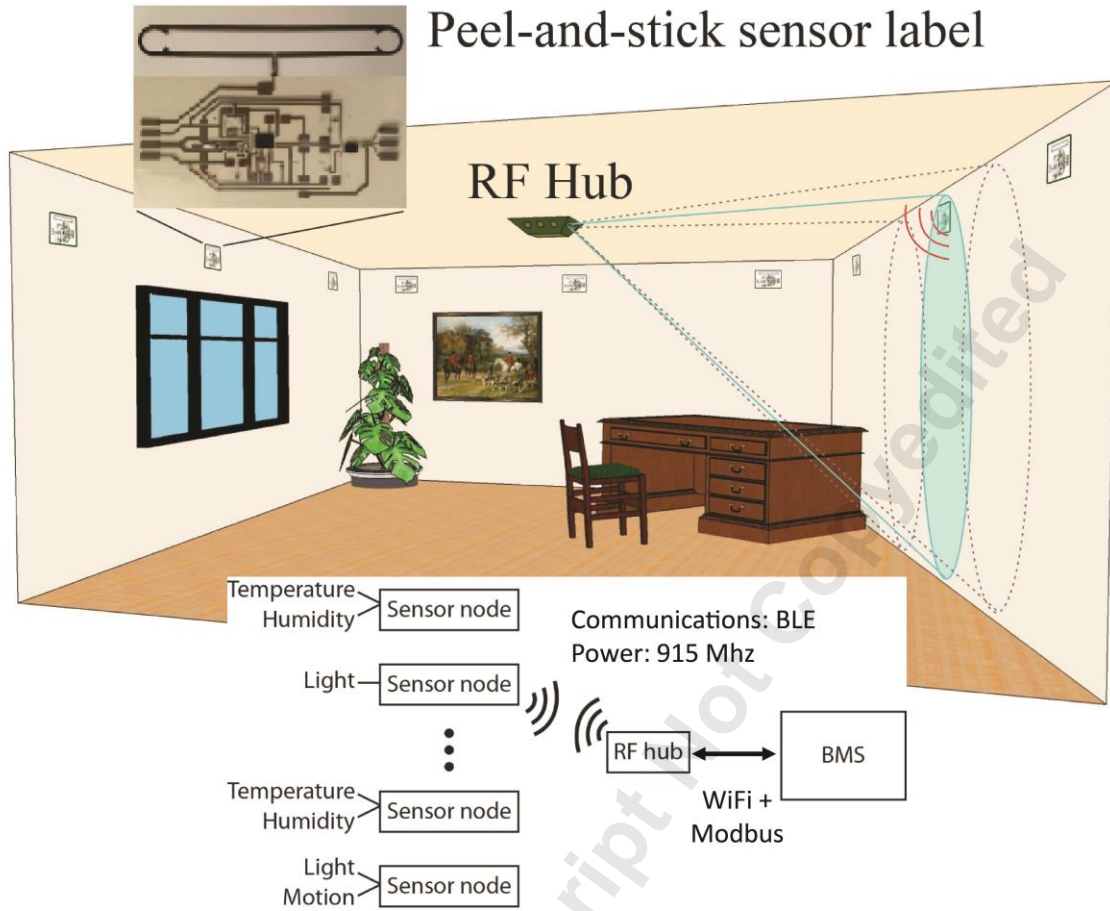


Figure 1 Sensor system overview

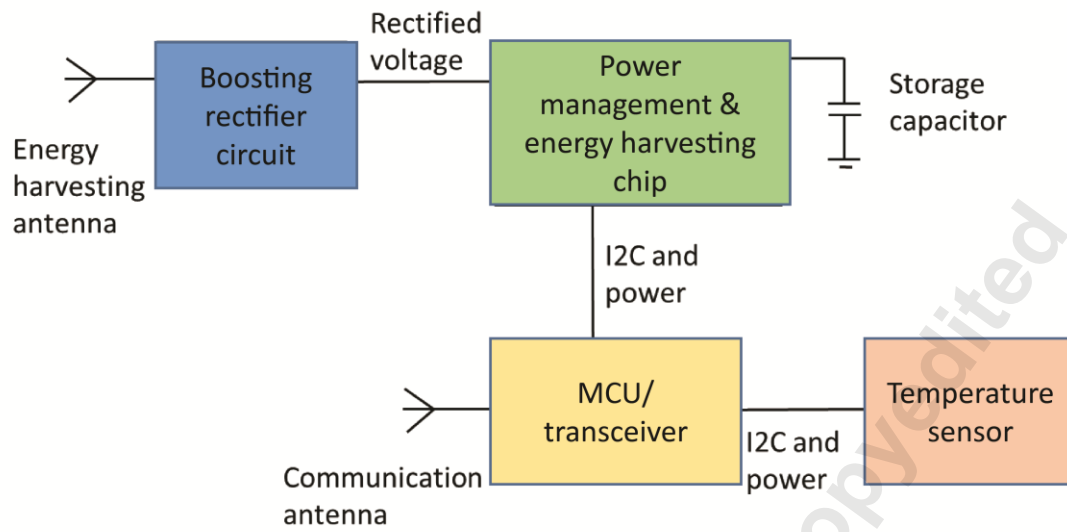


Figure 2 Block diagram of sensor tag

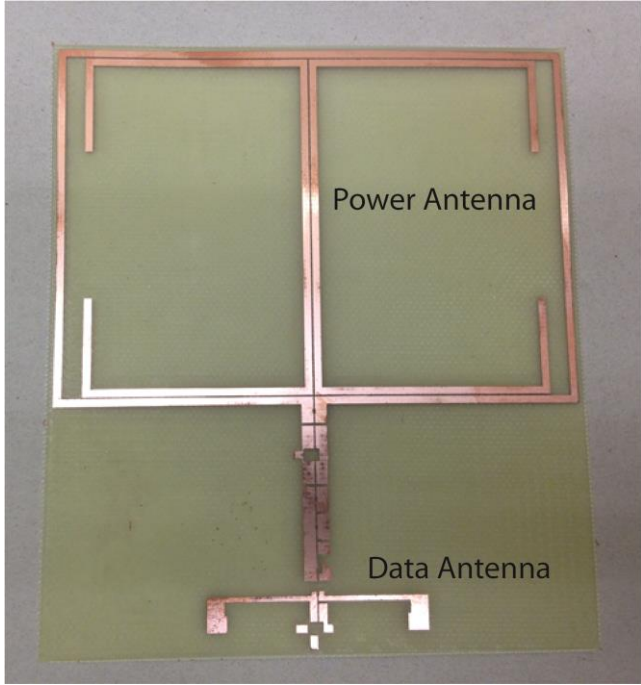


Figure 3 Sensor tag antennas

Accepted Manuscript Not Copyedited

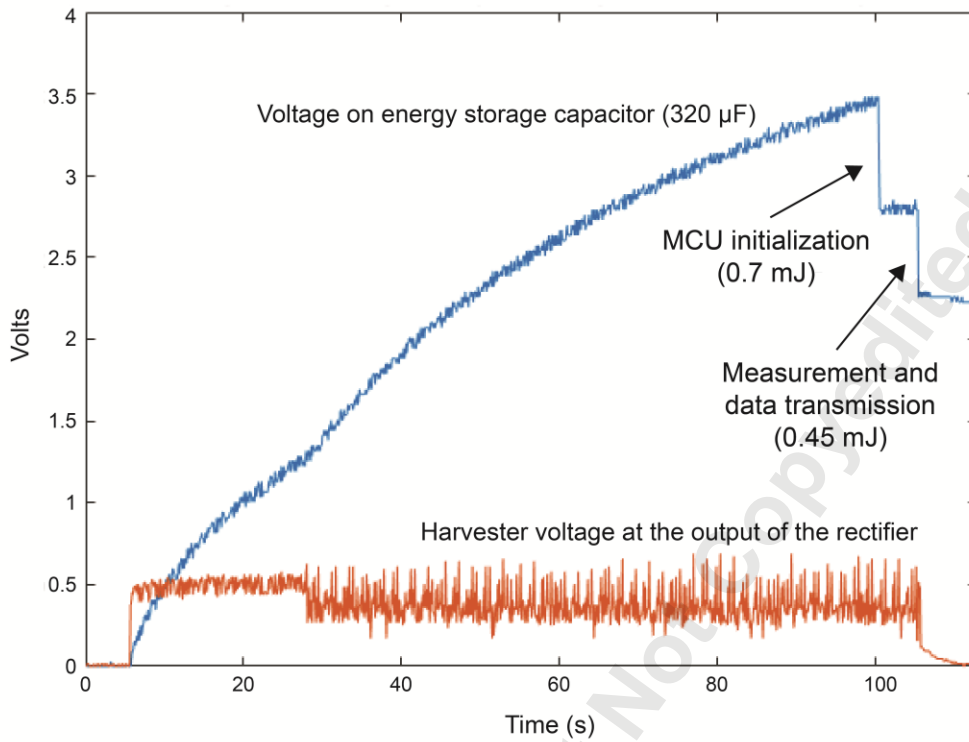


Figure 4 Voltage on the storage capacitor and at the output of the rectifier circuit as the sensor label is charged. RF power is turned on at 5 s. At 30 s the energy harvesting IC exits cold-start mode and activates its high-efficiency internal boost converter. At 100 s, power is connected to the MCU. At 105 s temperature and humidity data are transmitted to the hub.

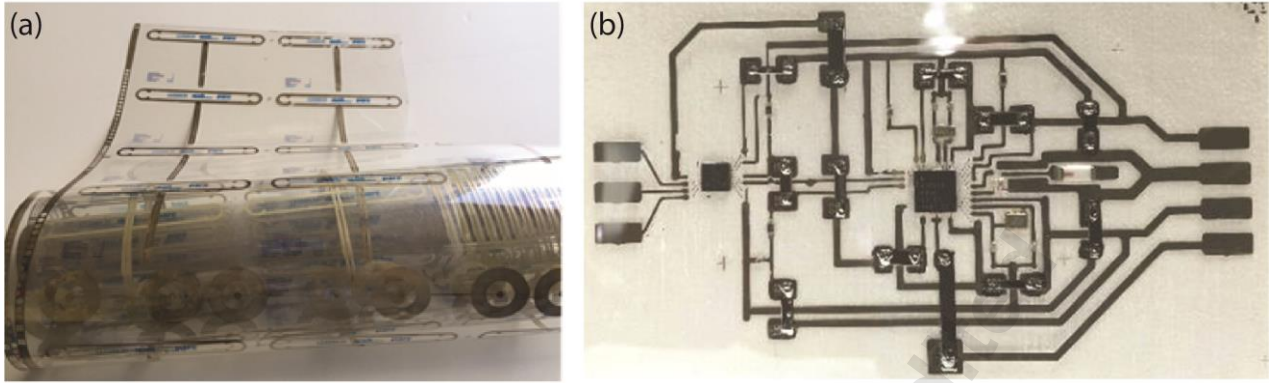


Figure 5 (a) Roll-to-roll printed antennas and (b) flexible-hybrid electronics (FHE) circuit printed at PARC

Accepted Manuscript Not Copyable

Table 1 Sensor tag energy consumption

Stage	Current	Duration	Energy
Turn on	--	--	1.5 mJ
I2C Communication			160 μ J
Sensor (RH or T) sampling	4 mA	2.5 ms	33 μ J
TX	16 mA	3.5 ms	120 μ J
RX	6 mA	11 ms	217 μ J

Accepted Manuscript Not Copyedited