Research Performance Final Report

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Project Type: Cooperative Agreement

Title: Passively-Powered Adaptively-Located Flexible Hybrid Sensors

Prime Recipient: PARC, a Xerox Company

Prime Recipient Type: Large Business

Prime Recipient DUNS number: 11-221-9014

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Section I: Project Technical Summary

Executive Summary

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 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 label can be equipped with a variety of printed and conventional sensors for building energy optimization, including lighting, occupancy, temperature, humidity, motion, and air quality. A key advantage of this system is its ability to automatically locate multiple sensor nodes to within 0.5 m (at a 5-m read distance) for simplified commissioning, as well as its interoperability with a wide range of existing BMS hardware and software. This enables automatic sensor reconfiguration and recommissioning, which is an important cost reduction driver. Moreover, the sensors are compatible with low-cost-, high-throughput roll-to-roll manufacturing, further reducing system costs. Upon successfully developing, manufacturing and deploying the system with optimized control, it can lead to annual primary energy savings >280 TBtu in offices, and up to ~1850 TBtu in combined offices and residences. The technology is based on PARC innovations in small antenna design, efficient RF energy capture, and flexible electronics. PARC is a leader in flexible hybrid integration similar to what is used in current RFID tags, which will provide a low-cost system in a flexible form factor. Our team member, Energy ETC, is a leader in supplier-agnostic BMS deployments, and will design the commissioning and deployment procedures to maximize system interoperability. The project will result in a demonstrator that will provide temperature and humidity data and will be wirelessly integrated into PARC's BMS.

Summary of Work

A block diagram of the system developed in the project is shown in Figure 1. The system is built around the RF hub, which provides power to the sensor nodes, receives data from them, and relays that data to the building management system (BMS). The sensor nodes are flexible "peel-and-stick" labels comprising an energy-harvesting antenna and rectifier for receiving RF power from the RF hub and converting it to DC and storing the received energy on a capacitor, a data antenna used for transmitting sensor data back to the RF hub, a microprocessor/transceiver to control the system, and a set of sensors. In the project, a combined temperature/humidity sensor was used. The RF hub transmits and steers RF power at 915 MHz to the sensor nodes. As power is received, the energy storage capacitor on the sensor nodes is charged. When its voltage is high enough, the microprocessor/transceiver is activated. It reads data from the sensors and transmits it back to the RF hub at 2.45 GHz. The RF hub then encodes the data and transmits it to the BMS over WiFi. The system is agnostic as to the BMS protocol. Both MODBUS and a SQL-based system compatible with higher security encoding were implemented. In addition to sensor data, the sensor node can measure and report the power seen by the antenna and rectifier. Sensor localization is achieved by cross-referencing the variation in received power with RF transmission angle.

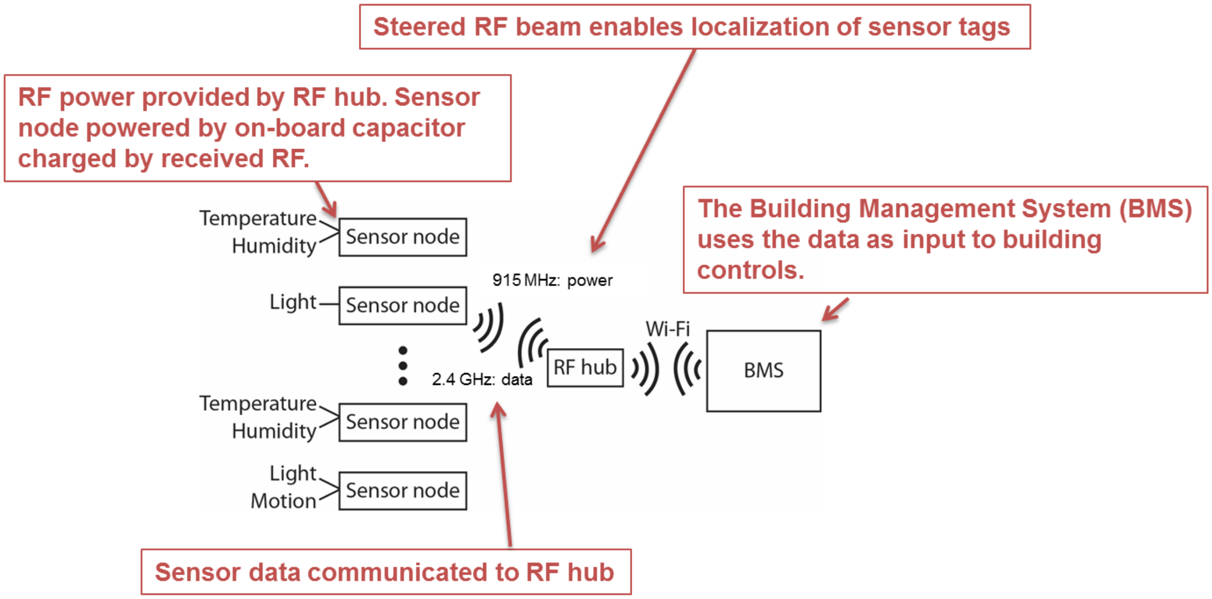

Figure 1 System diagram

To validate the concept, the system was built using conventional printed circuit board (PCB) technology. A custom set of antennas and a rectifier were designed to maximize energy harvesting efficiency. Photos of this test system are shown in Figure 2. The RF hub was implemented using benchtop instruments, development kits, and custom-designed transmission antennas.

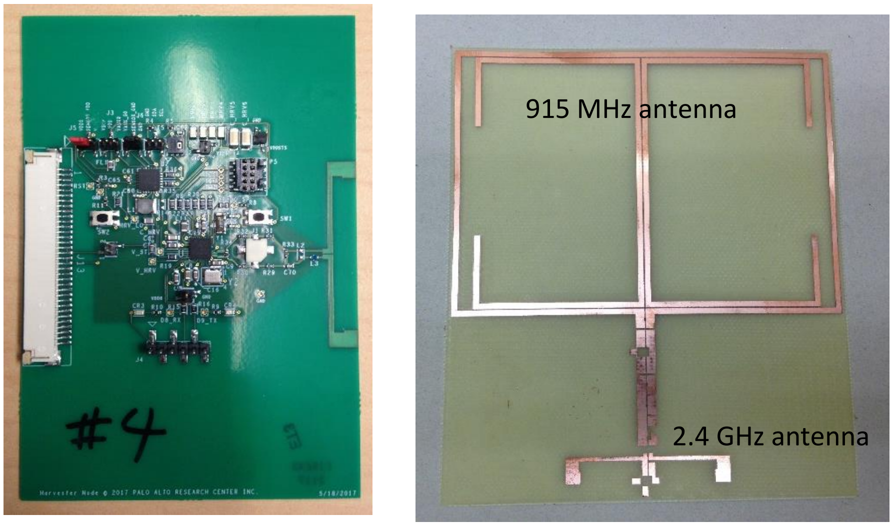

Figure 2 Sensor label PCB (left) and antennas (right)

Using this system, all basic functions were validated. The sensor was successfully charged with RF power over a distance of 10m and both humidity and temperature data were relayed back. Figure 3 shows a photo and data from these tests.

After confirmation of the ability to transmit and convert RF power and read, transmit, and relay sensor data, we designed and fabricated the RF hub unit. The RF hub is shown in Figure 4. It consists of 4 panels with 3 antennas each forming a phased array designed to steer the RF source beam around 360° at an average interval of 8°.

To validate the ability of the system to locate sensor tags based on received power as the transmitted power is steered we tested the individual antenna arrays at distances of 5 m, 8 m, and 10 m in a variety of scenarios.

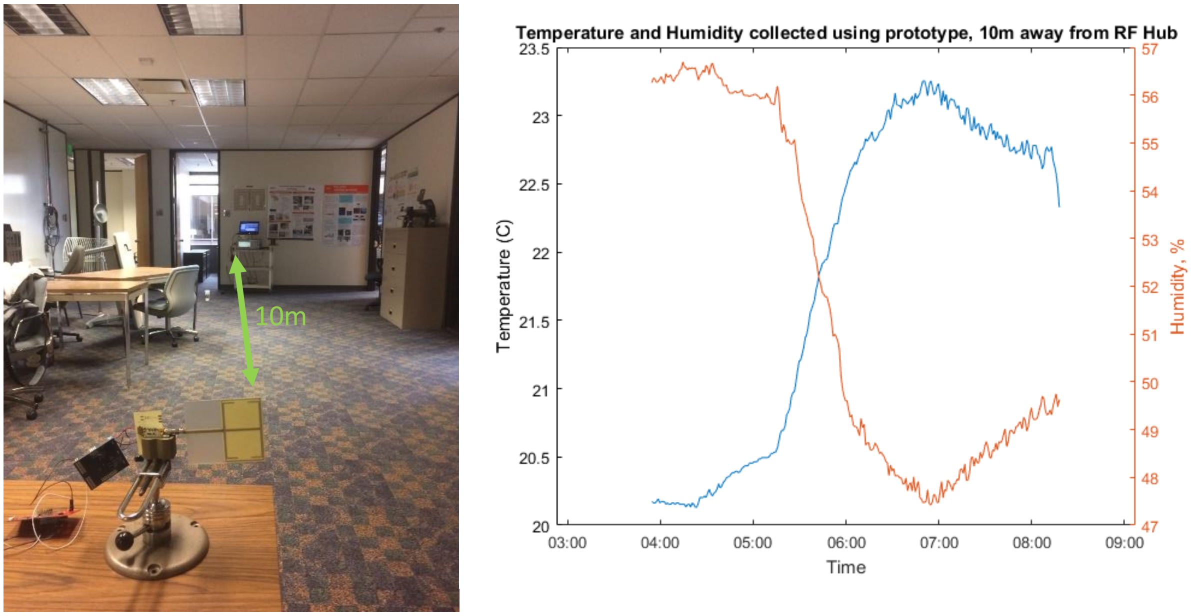

Figure 3 Sensor tag transmitting data over 10 m

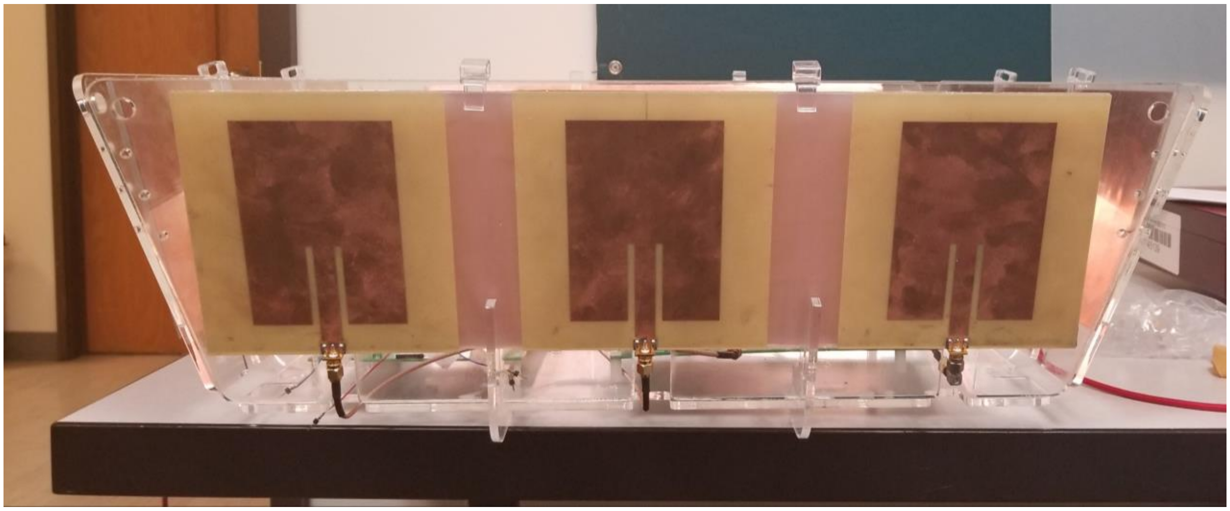

Figure 4 Photo of completed RF hub

5-m tag distance

At 5-m, the system achieved the target lateral localization resolution of 0.5 m.

Figure 5 shows measurements of the received power at the tag at a 5-m distance. In this test, the transmitted beam is steered by the hub from -45˚ to 45˚ at 10˚ increments. The power peak at the location of the tag is clearly evident. Figure 6 shows the received power at a tag moved laterally across a wall, also at a 5m distance, with the source beam fixed at 0 ˚ heading. Again, the decrease in power as the tag is moved from center is clear.

Figure 7 shows received power at the tag for different tag positions as the beam angle is swept. While there are some false peaks due to reflections, the primary peaks correlate to the tag position and demonstrate 0.5-m resolution. The locations of tags positioned at -2m, -1.75m, and -1.25m are clearly distinguishable.

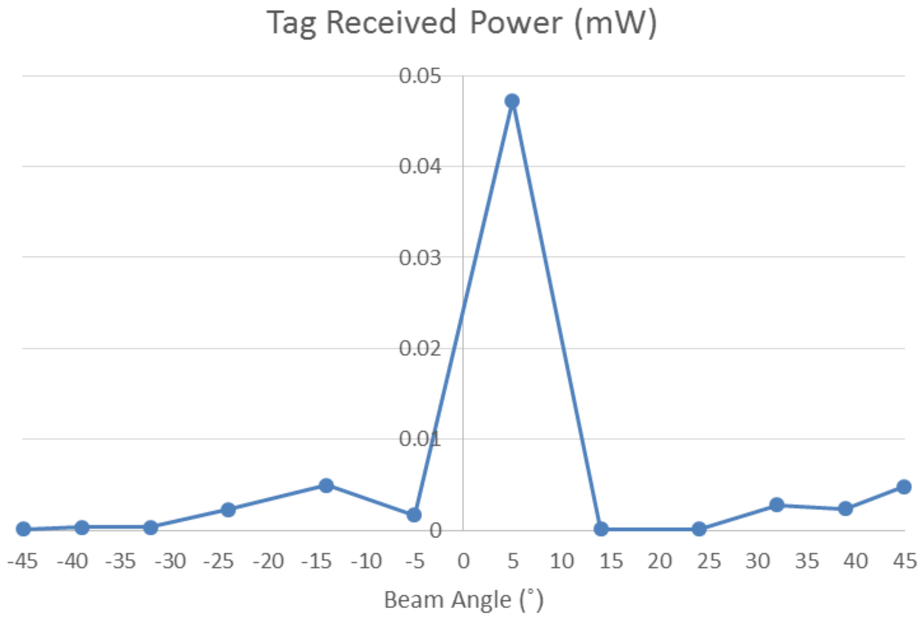

Figure 5 Tag received power at 5 m with fixed tag position at ~0˚.

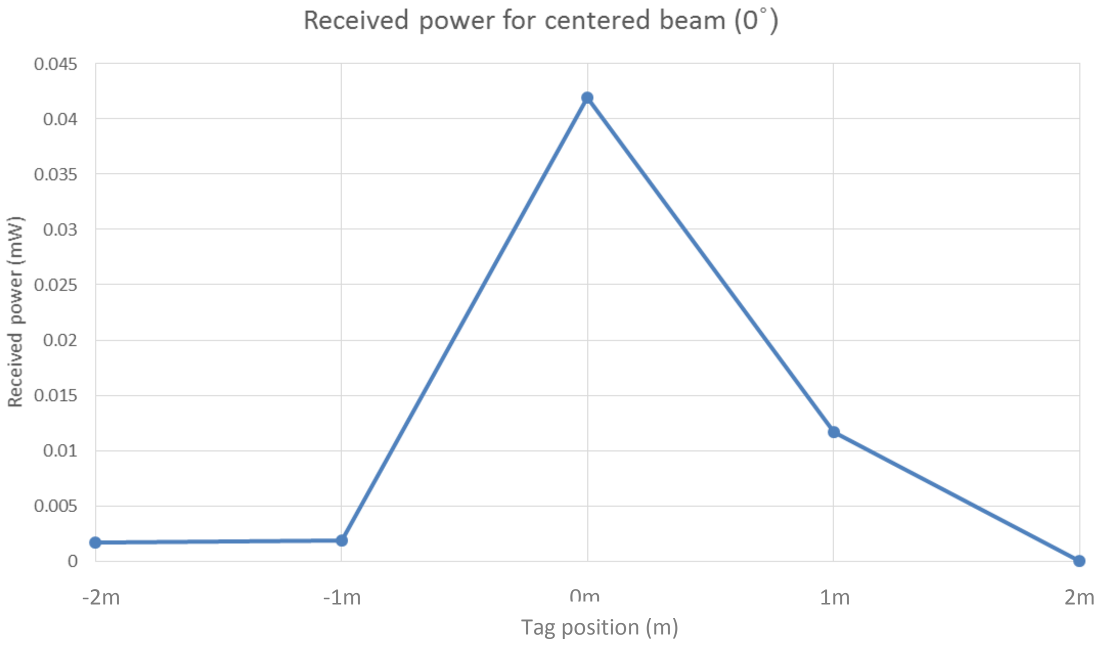

Figure 6 Received power at 0˚ beam transmission for tags positioned at -2m, -1m, 0m, 1m, and 2m laterally.

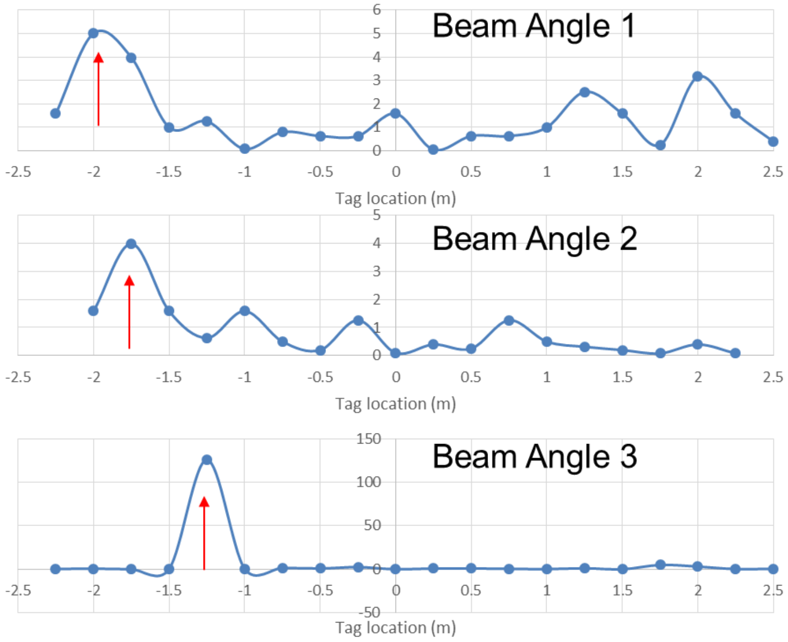

Figure 7 Received power peaks for multiple tag positions as the source beam is swept at 5-m distance. Resolution of better than 0.5m is seen in this case.

8-m tag distance

The room in which the measurements were taken was large enough to allow an 8-m maximum distance. Although there is no 8-m target, the 5-m measurements were repeated at 8-m. Figure 8 shows the results of sweeping the source beam for varying tag positions. Tag positions at -1.5m, -1.0m and -0.5m are distinguishable, showing 0.5-m resolution. Here, however, reflections from the side wall showed larger false peaks for tags located near the wall. The magnitude of the reflected signals is in some cases larger than the direct signal. These spurious signals may provide false sensor location information. This can be addressed in several ways. More complex localization algorithms, optionally with machine learning techniques, can aid in discrimination of true from false signals. These would include detailed mappings of beam angle sweeps to sensor locations. This scope of this project did not allow for sufficient data to be collected to train such algorithms. However, additional measurements are planned to explore this after the conclusion of the project. Another approach would be to create a set of rules for sensor placement that could reduce the likelihood of significant impact of reflections. This could be implemented as user instructions, or as confidence weightings in the location interpreter inside the building management control system. Finally, if multiple sensors are located within a room, comparison of location signals among them can provide additional input to the localization algorithm that can be used to predict reflections.

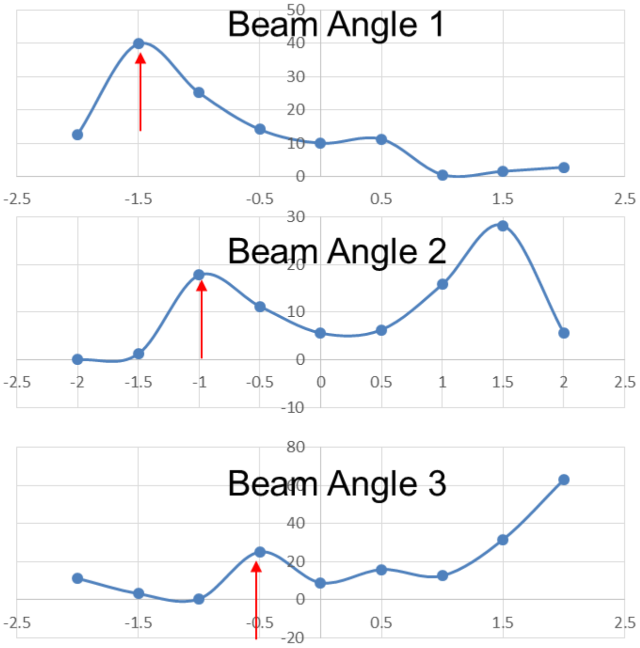

Figure 8 Received power peaks for multiple tag positions as the source beam is swept at 8-m distance. Resolution of better than 0.5m is seen in this case. Resolution of 0.5 m is evident.

10-m tag distance

To complete the testing, the system was moved to a larger room (the PARC cafeteria) that allowed measurements at 10-m distance, the targeted distance for the project. Figure 9 shows evidence of localization to 0.5-m (better than the target of 1.0-m) for two pairs of tag locations. As in the previous cases, the received power peaks clearly shift as the tag is moved. Here, again, there is some evidence of reflection from the side walls. In this set of measurements, the reflected signals are significantly lower than the true signals. This gives added confidence that a set of placement rules or algorithms that includes room wall locations can mitigate the impact of reflections.

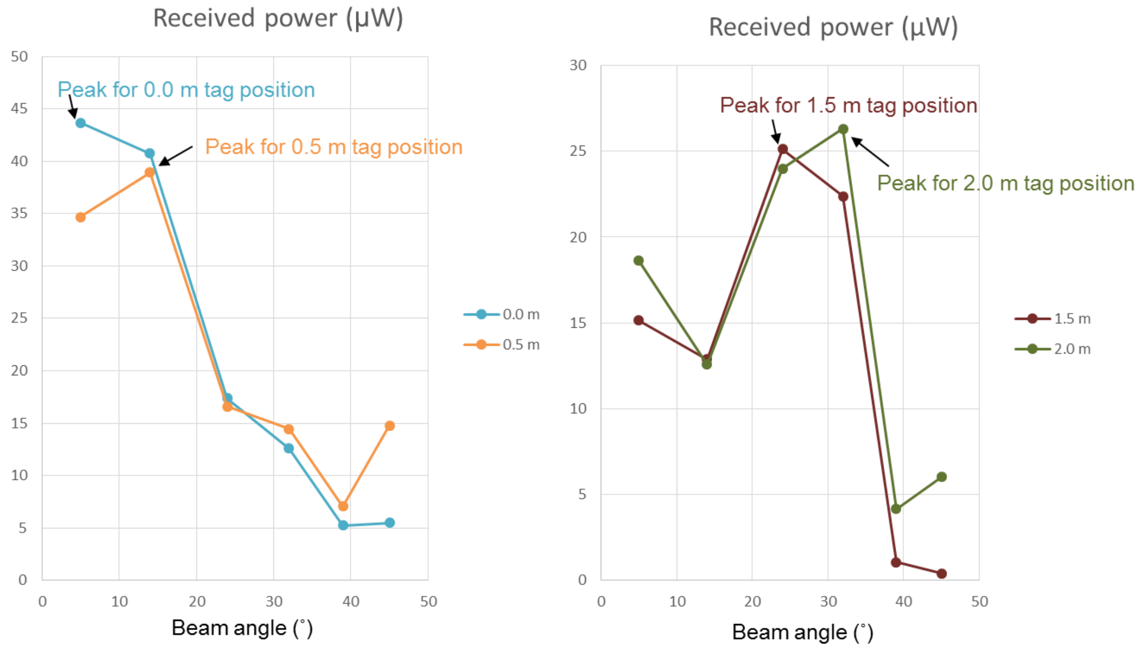

Figure 9 Power measurements at 10-m distance for two pairs of tag locations. Here, 0.5-m resolution is achieved between 0.0 m and 0.5 m locations, and between 1.5 m and 2.0 m locations.

With the system fully validated, we proceeded to redesign the sensor label for flexible-hybrid electronics (FHE) fabrication. FHE is a technique for making low-cost flexible electronics systems based on printing interconnect on polymer substrates and attaching discrete electronics components. The discrete components are electrically connected using printing or an anisotropic conductive adhesive (ACA). For this project, we used a PARC fabrication system that uses screen printing of silver for the interconnect and extruded anisotropic conductive paste (ACP) for component connection.

The completed FHE circuit is shown in Figure 10. Unfortunately, although we were able to verify most circuit functions, we were ultimately unable to get the complete circuit to operate. The primary reason for this was our use of an updated microprocessor/transceiver component in the FHE circuit. We expected the new version of this component to be directly compatible with the previous version and it had advantages of fewer pins (32 instead of 44) which would improve robustness and yield and lower power consumption, which would enable a faster sampling rate and/or a longer power transmission distance. We learned that the updated component was not backwards compatible and all firmware had to be rewritten. We expended significant time and effort porting the code, but were still unable to get the system to function correctly. During this process, we learned that the newer version was poorly supported by the manufacturer and on the user forums.

After careful consideration, we opted to redesign the system using a Flex PCB technology instead of FHE. We decided instead to fabricate the final system in a commercial flexible PCB ("Flex PCB") technology. Our primary concern with this fabrication route is its higher cost. However, after careful analysis, we were able to establish that the Flex PCB sensor label would be able to achieve compelling cost for commercial systems. We also reasoned that a commercial system could still be realized in FHE for reduced cost.

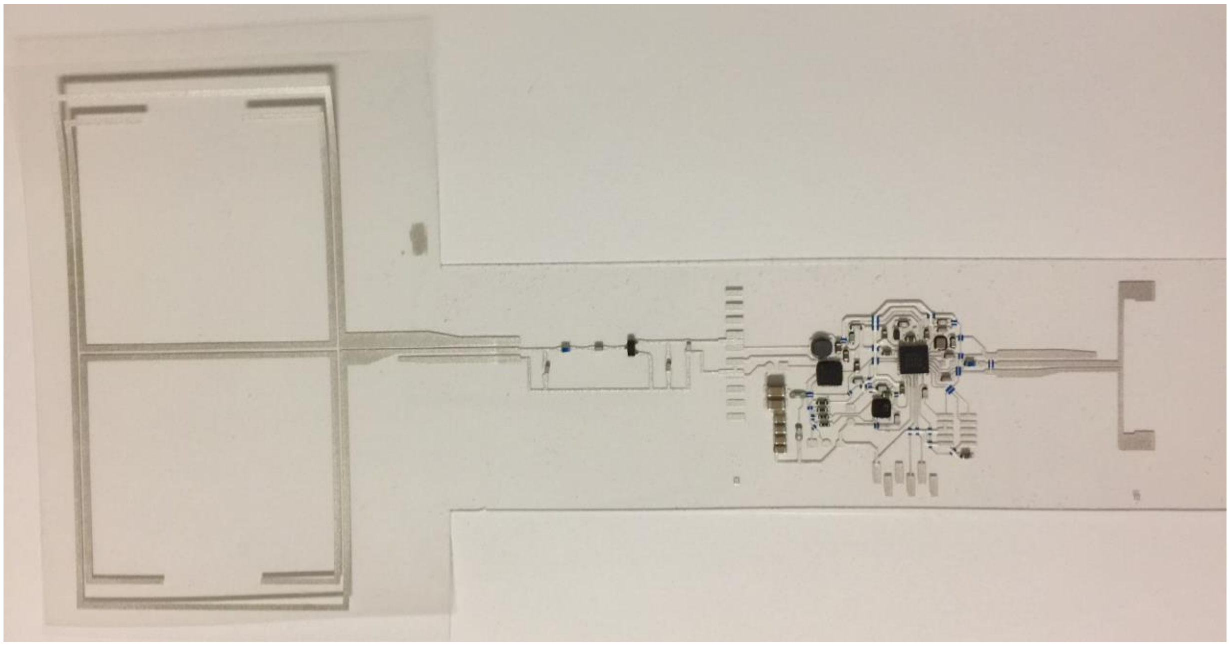

Figure 10 Assembled flexible sensor label

Flex PCB is a commercially available electronics manufacturing technology that uses similar fabrication techniques to conventional rigid PCBs but on flexible polyimide substrates. As with conventional PCBs, plated copper is etched to form traces and components are attached with solder. Multilayer interconnect is available.

A comparison of FHE and Flex PCB technologies is shown in Table 1. The primary advantage of FHE is its potential for lower cost. However, as there is no existing manufacturing infrastructure, it is not available at scale, so this advantage is currently theoretical, though it is likely to be realized in the next few years.

Another advantage of FHE is its improved flexibility as compared to Flex PCB technology, deriving from its use of direct-die attach instead of solder and the compatibility with bare silicon dies and even thinned dies. For this project, however, we are not using bare dies, and at our target bend radius of 10 cm required by the application, there is no advantage for FHE. Furthermore, the availability of multiple interconnect layers in Flex PCB provides a significant benefit for this system. With multilayer PCBs, we can design a ground plane behind the rectifier. This improves the efficiency of the rectifier and reduces its sensitivity to its dielectric environment, in particular the material onto which the “peel-and-stick” sensor is affixed. On prototyping scales, Flex PCBs are significantly more expensive than conventional FR-4 PCBs. At large manufacturing scales, however, the cost difference is significantly reduced.

Table 1 Comparison of Flexible Hybrid Electronics and Flex PCB fabrication technologies

Flexible Hybrid Electronics (FHE)	Flex PCB
Printed silver interconnect and direct-die attach on PEN substrate	Etched copper and solder on polyimide substrate
Lower cost	Higher cost
Pre-manufacturing	Commercially available
Extremely flexible	Flexible well below 10 cm project target
Ground plane increases complexity and cost	Ground plane available

Figure 11 shows a photo of the completed Flex PCB circuit will all components mounted. The circuit was flexed up to a bend radius of ~5 cm with no change in the resonant frequency, indicating no change in performance. This is better than the 10 cm bend radius targeted in the project.

The Flex PCB circuit was successfully tested. At a distance of 5m from the RF source, the tag receives a calculated 0.1 mW of power. This charges the storage capacitors and, when they are fully charged, the sensor tag begins sampling the temperature and humidity sensors as well as the received power, and transmits the data over the Bluetooth Low Energy (BLE) link.

Figure 11 Photo of completed Flex PCB circuit

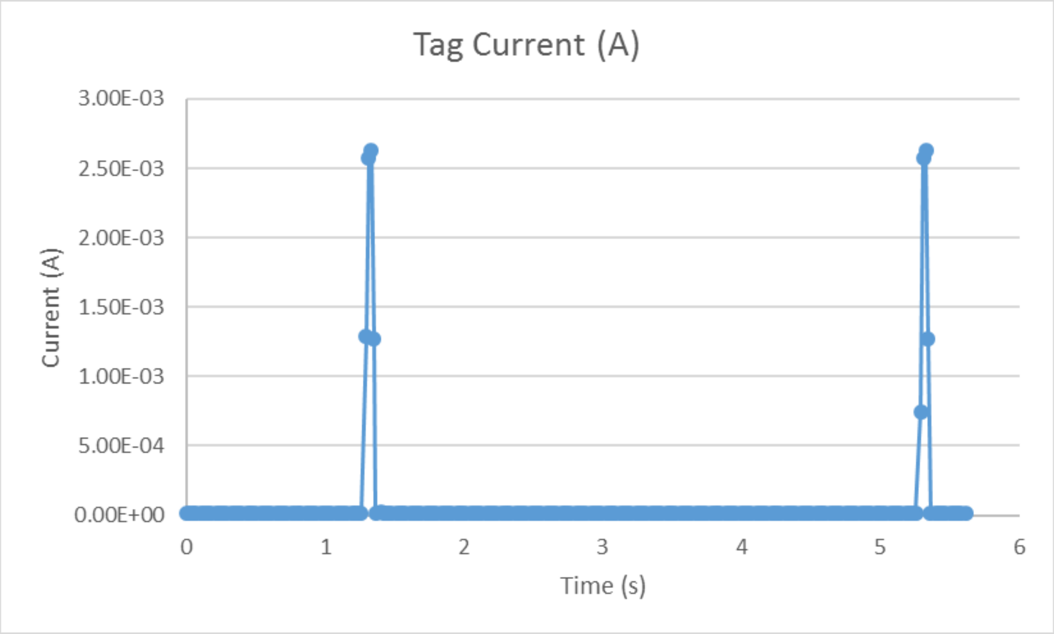

Figure 12 Current consumption of sensor label microprocessor during data transmission events.

Based on experiment, the tag requires 50 µW to operate, which is available at a distance of 7.3m. This is the maximum distance from the RF hub that a sensor label can be placed. At a distance of 10m, the received power is only 20 µW. We were not able to verify functionality at this distance. We are still investigating why the original prototype was able to operate at this distance and the flexible version is not. It is likely because of the higher efficiency of the PCB-based rectifier. Nevertheless, as discussed below, our cost model assumes a room size of 45 ft x 45 ft to achieve the target payback time. This size room can be covered at a distance of 6.9m from a central RF hub. Therefore we expect the achieved result to be sufficient for the application.

Figure 12 shows the measured current consumption of the flexible sensor label with periodic data transmission. The system was programmed to measure and transmit data every four seconds in this configuration. An extremely low sleep current consumption of 17 µA was achieved. Each peak in the figure represents a sampling and data transmission event. Temperature, humidity, and received power data are broadcast for receipt by the RF hub. The peak current during these events is 2.6 mA with a duration of ~100ms. The total integrated charge consumption for one event is 0.15 mC. The sensor label has 840 µF storage capacitance. The microprocessor can operate from 2.4V to 3.9V. Thus, when fully charged, the total usable stored energy is 4 mJ and stored charge is 1.26 mC. This charge can allow >8 samples per full charge. With a sampling period of 5 minutes, the system can operate for 35 minutes on a single charge.

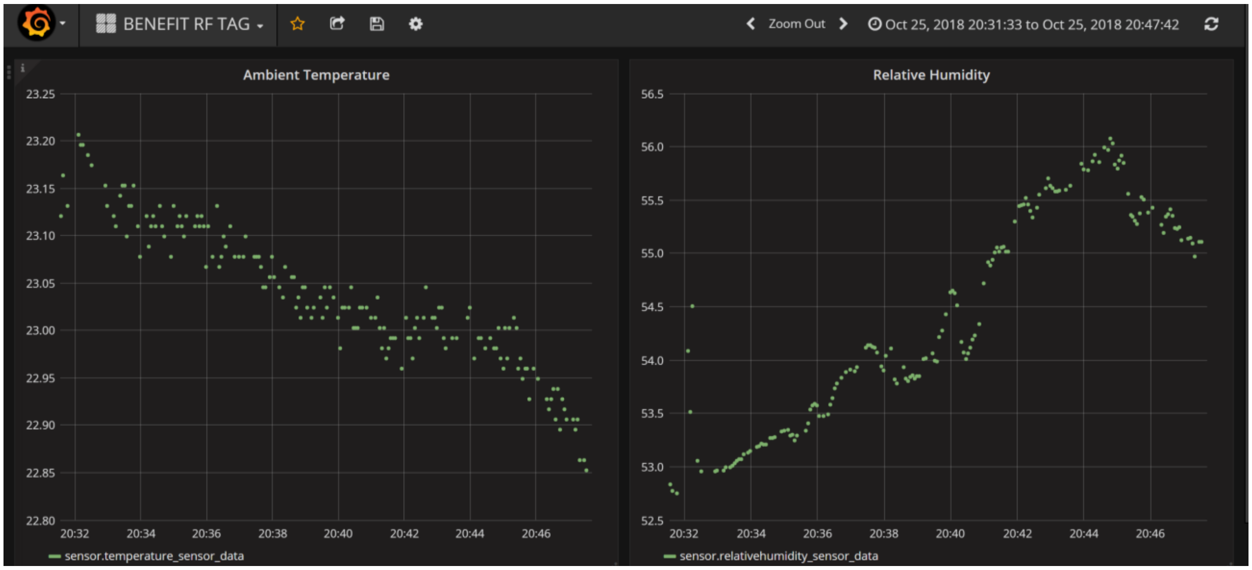

Figure 13 BMS-compatible temperature and humidity data streamed from Flex PCB tag displayed on cloud-based graphing tool.

Technology Transition Activities

Project work also included in-depth market and product hypotheses development and a detailed technoeconomic analysis. The technology was found to have compelling potential in a range of markets across commercial and residential buildings. Open office plan buildings were selected as a first target market as they leverage several advantages of the technology. In particular, they are large spaces with variable temperatures, they are difficult to sensor with conventional technology, and they are reconfigurable with movable walls.

Technical development in the current project has yielded a functioning demonstration system consisting of flexible sensor tags that are powered by RF power at 915 MHz from a remote RF hub and can read and report temperature and humidity information to the building management system at PARC via a Bluetooth low energy (BLE) link to the RF hub followed by encoding in the MODBUS protocol or as InfluxDB data, and transmission via WiFi, and a system for automatic tag localization based on received RF power from steered power transmission from the hub. The system is designed to be interoperable with as many building types and operating environments as possible.

For field testing in the first target market of open office plan buildings, the following additional development is needed. Details of these plans have been described in the Commercialization Plan delivered as part of the project.

1. The system design should be refined and optimized for the open office plan environment.
2. To make the hardware system attractive, robust, and user-friendly for field testing at external sites, thoughtful industrial design for the hub packaging should be implemented.
3. Additional work is required to build control loops that can incorporate the sensor data and to optimize building operations based on their input.

4. Techniques must also be developed for utilizing variable sensor location data in building management system software.

The technoeconomic analysis yields compelling cost model technology. The project target was a 2 year payback time. However, industry feedback indicated a 1 year payback would be more desirable. As summarized in Table 2, payback times of 1 year or less are possible for the target market.

Table 2 Payback time for several fabrication and use case scenarios

Fabrication	**FHE**		**Flex PCB**		**Flex PCB**	
Area/hub	**40 ft x 40 ft**		**40 ft x 40 ft**		**45 ft x 45 ft**	
Sensors/hub	35	20	35	20	35	20
Payback time	1.0 y	9 m	1.3 y	11 m	**1.0 y**	**9 m**

Section II: Work Accomplished Against Technical Objectives

Project milestones and completion dates are listed in

Table 3. All milestones were completed as planned with the following exceptions.

Milestone 3.2.1

All components of this milestone were achieved except for the rectifier efficiency of 70%. With extensive research and simulation, it was determined that a 70% efficiency was not a reasonable target for the system. The maximum measured rectifier efficiency achieved in the project on the Flex PCB system was 42%, which is in fact high for this type of rectifier.

Milestone 5.11
Milestone 5.3.1

While a sensor tag was successfully fabricated in FHE, the final deliverable used commercial flexible PC (Flex PCB) fabrication instead for reasons descripted in Section I. While this increases the cost of the final system somewhat, the final payback time remains below 1 year, which is extremely attractive for the target market. All milestone metrics were met except the 70% rectifier efficiency, as explained above. The tag operated successfully at up to 7.5m distance, sufficient to satisfy the target application.

Table 3 Project milestones and completion dates.

Milestone Number	Milestone Description	Anticipated Start Date	Anticipated Completion Date	Actual Start Date	Actual Completion Date
M1.1.1	Antenna with dimensions ≤5-cm-by-9-cm with gain 2 dB demonstrated and fully characterized (impedance, gain, radiation pattern).	10/1/2016	12/31/2016	10/1/2016	12/31/2016
M1.2.1	PCB with all electronics complete. Basic functionality demonstrated: rectifier and charge pump deliver DC supply voltage to components, program successfully compiled and executed on microcontroller, temperature and humidity sensor successfully read with at least 6-bit resolution and values validated to within 20% of precision external sensors.	11/1/2016	2/28/2017	10/1/2016	1/31/2017
M1.3.1	PCB with revised electronics completed. Basic functionality demonstrated: rectifier and charge pump deliver DC supply voltage to components, program successfully compiled and executed on microcontroller.	5/1/2017	7/31/2017	5/1/2017	6/30/2017
M2.1.1	Mono-directional RF hub electronics completed. Basic functionality demonstrated: program successfully compiled and executed on microcontroller; RF power successfully transmitted and measured at a distance of 5 m; modulated RF signal received and demodulated.	10/1/2016	1/31/2017	11/1/2016	1/31/2017
M2.2.1	Multi-directional RF hub design completed.	4/1/2017	6/30/2017	4/1/2017	6/30/2017
M2.3.1	Multi-directional RF hub electronics completed. Basic functionality demonstrated (programmability of microprocessor established).	7/1/2017	8/31/2017	7/2/2017	8/31/2017
M2.4.1	Firmware programming complete and basic functionality of code verified in hardware-in-the-loop demonstration in preparation for system test in subtask 3.2. Localization to within 1-m at 10-m	8/1/2017	10/31/2017	7/1/2017	12/31/2017

	read distance established in simulation.				
M3.1.1	Basic functionality verified and RF power measured at 5-m from RF hub. Sensor label reading of temperature and humidity values and encoding and transmission on RF signal demonstrated. Performance data collected for input into design revision (Subtask 1.3).	3/1/2017	4/30/2017	3/1/2017	4/1/2017
M3.2.1	System will achieve target specifications: read distance ≥10 m, positional accuracy ≤0.5 m with 5-m read distance and ≤1 m with 10-m read distance, rectifier efficiency >70%, successful transfer of 10-bit data from two sensors on tag to hub achieved.	11/1/2017	12/31/2017	11/1/2017	12/31/2017
M4.0.1	Interoperability and commissioning plan complete. Plan will include specifications of minimum building management system requirements as well as communications and software protocols.	10/1/2016	12/31/2017	11/1/2017	12/31/2017
Go/No-Go #1	Demonstration of basic functionality in conventionally-manufactured system, together with achievement of Milestone 3.2.1 targets. Results will include at a minimum successful reading of data at a distance of 10 m. Preliminary commercial feasibility demonstrates a payback period of no more than 3 years.	10/1/2017	12/31/2017	10/1/2017	12/31/2017
M5.1.1	Flexible hybrid implementation of sensor electronics complete. Bend radius of 10 cm achieved. Rectification efficiency >70% demonstrated.	10/1/2017	6/31/2018	10/1/2017	11/26/2018
M5.2.1	Data will be successfully transferred from the RF hub to BMS in preparation for the full system test of Subtask 5.3.	1/1/2018	3/31/2018	8/1/2017	10/31/2017
M5.3.1	Flexible hybrid system will achieve comparable performance to the conventionally fabricated system tested in Task 3.2 or will achieve target electrical specifications: read distance ≥10-m, positional accuracy ≤0.5-m with 5-m read distance and ≤1-m with 10-m read distance, successful transfer of 10-bit data	7/1/2018	9/30/2018	10/1/2017	11/27/2018

	from two sensors on tag to RF hub, and from RF hub to BMS achieved. Rectification efficiency >70% demonstrated.				
M6.1.1	The IP management plan signed by all relevant parties and approved by BTO prior to project start.	10/1/2016	12/31/2016	8/10/2016	8/10/2016
M6.2.1	TEA skeleton laying the groundwork for a system-level cost completed.	1/1/2017	3/31/2017	1/1/2017	3/31/2017
M6.2.2	First version of completed TEA complete including estimates of all constituent costs.	4/1/2017	6/30/2017	4/1/2017	6/30/2017
M6.2.3	TEA refined with updated costs based on system design. TEA will achieve a 3-year payback for at least one potential application.	7/1/2017	12/31/2017	7/1/2017	10/31/2017
M6.3.1	Status update and overview of study to be completed as part of Milestone 6.3.2, including any findings and learning stemming from market research thus far delivered.	4/1/2017	6/30/2017	1/1/2017	3/31/2017
M6.3.2	Competitive landscape survey and value chain mapping complete. Comparative advantages and key features of technology being developed identified.	1/1/2017	9/30/2017	1/1/2017	9/30/2017
M6.3.3	Preliminary commercialization strategy complete.	10/1/2017	12/31/2017	10/1/2017	10/31/2017
M6.4.1	Determine internal or external resources that will serve as the T2M lead for the project.	9/1/2016	12/31/2016	9/1/2016	10/1/2016
M6.4.2	T2M Draft Plan outlining roadmap for advancing BTO funded technology toward commercial viability. Plan should detail 2-year roadmap and identify key T2M issues for future analysis.	1/1/2017	3/31/2017	1/1/2017	3/31/2017
M6.4.3	Revised T2M Plan incorporating feedback received from DOE on Draft Plan submitted under 6.4.2 delivered.	4/1/2017	12/31/2017	4/1/2017	12/31/2017
M7.1.1	TEA refined with updated costs based on expected first product	1/1/2018	6/30/2018	1/1/2018	6/20/2018
M7.2.1	First product hypothesis description complete. Preliminary post-project financing and transition plan presented, including initial markets of entry, expected business model, target partners, identified financing needs for next steps and potential funding sources, outreach plan to	1/1/2018	3/31/2018	1/1/2018	3/31/2018

	customers, partners, and/or investors based on anticipated maturity of technology, market sector, commercialization strategy, key technological risks and mitigations, and next steps and actions with associated timeline.				
M7.2.2	Present at quarterly review meeting a refined transition plan and progress made securing transition partner.	4/1/2018	6/30/2018	4/1/2018	6/30/2018
M7.2.3	Final report on transition.	7/1/2018	9/30/2018	7/1/2018	9/30/2018

Section III: Successes and Challenges

The project was extremely successful as attested to by a number of key accomplishments:

- Achievement of a projected payback time of 1 year or less for the target application
- Demonstration of very low power electronics that can sense and report temperature and humidity (and other parameters as needed) without a battery
- Demonstration of remote RF power of sensors
- Communication of sensor data to the BMS
- Demonstration of the ability to locate sensors based on received power from the swept RF beam
- Fabrication of flexible PCB sensor label prototypes compatible with “peel-and-stick” deployment

The project was also faced with challenges. We switched our choice of microprocessor/transceiver two times, leading to the project falling somewhat behind schedule, though we were able ultimately to essentially complete the final deliverables. Both decisions were based on sound reasoning. In the first case, we found that the previously chosen component, which PARC had used successfully for years previously, was senescent and had poor BLE support. We also had a number of reliability problems with the system. The second change because our newly chosen part had just been released and the specific functions we required were not yet reliable. The timing of this change led to our not having sufficient remaining time or funding to complete a functional FHE version of the sensor tag. This was a major reason for pivoting to a Flex PCB implementation.

Section IV: Lessons Learned and Best Practices

The best practice for fabricating a flexible system is to first prototype as a conventional FR-4 PCB and then implement the exact system in the flexible technology. In this project we made substantial changes to the system between the conventional and flexible versions that we believed were straightforward and would not lead to challenges. However, this assumption was incorrect and led to the project falling behind schedule.