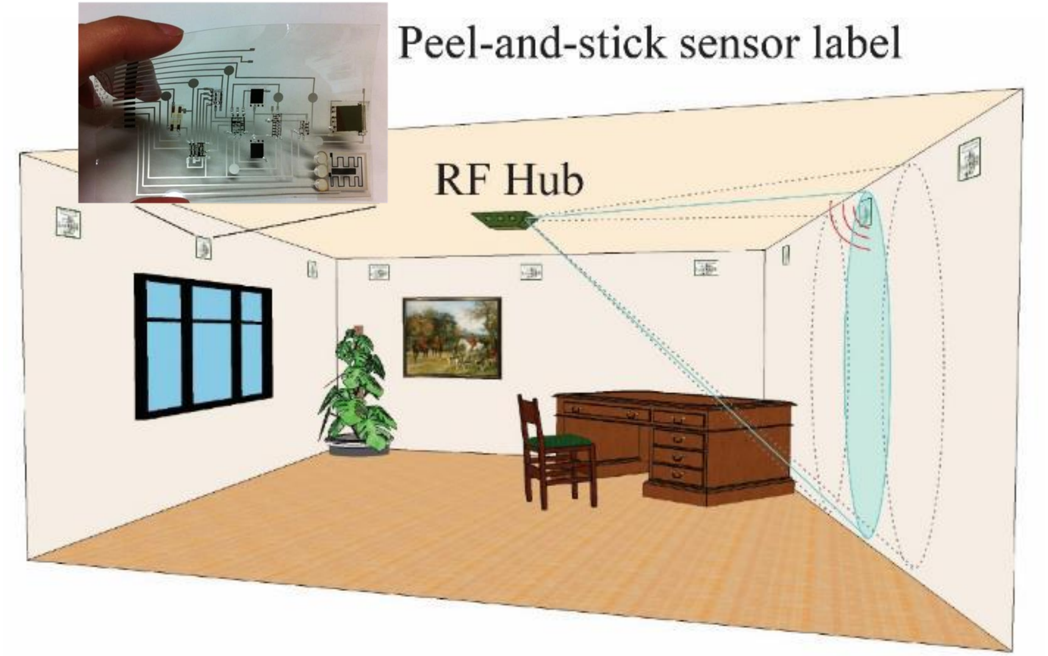
U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Passively-Powered Adaptively-Located (P-PAL) Flexible Hybrid Sensors



Performing Organizations: Palo Alto Research Center, Inc. (PARC) & Energy ETC
PI: David Eric Schwartz, Area Manager
(650) 812-4733 David.Schwartz@parc.com

Project Summary

Timeline:

Start date: 10/1/2016

Planned end date: 9/30/2018

Key Milestones

1. Milestone 1; 12/31/2017 – Demonstration of system with conventional hardware (complete)
   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 from two sensors on tag to RF hub, and from RF hub to BMS. Preliminary commercial feasibility demonstrates a payback period of no more than 3 years.
2. Milestone 2; 9/30/2018: Demonstration of full system
   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 from two sensors on tag to RF hub, and from RF hub to BMS achieved. Rectification efficiency >70% demonstrated.

Budget:

Total Project $ to Date: $822,004

- DOE: $657,221
- Cost Share: $164,783

Total Project $:993,858

- DOE: $795,086
- Cost Share: $198,772

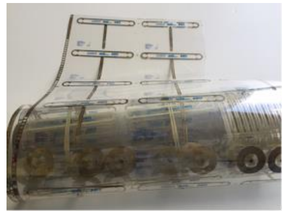
Key Partner:

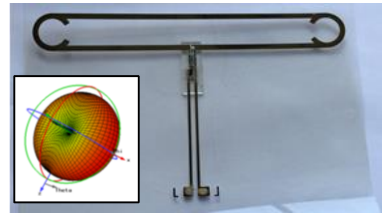
Energy ETC

Project Outcome:

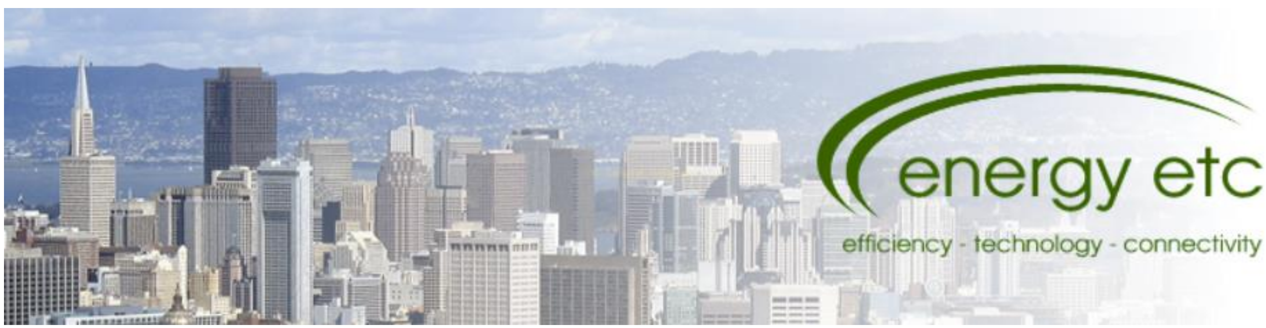
Facilitation of fine-grained building sensing via low-cost enabled by RF powered self-locating peel-and-stick sensors to enable reductions in HVAC power consumption

Team





- David Schwartz, PI; Clinton Smith; Shabnam Ladan
- Leading research institution practicing open innovation
- Deep expertise in printed and flexible electronics
- Broad capability in electronics, algorithms, sensor systems, and RF



- Rick Costanza
- Building controls system integrator
- Specialization in cloud-based, supplier-agnostic BMS software
- Provides interoperability support and field-testing sites

Challenge

Commercial buildings generally have just **one** temperature sensor per zone

Up to 30% energy savings are available with more building sensors: up to 1,800 Tbtu/yr

BUT

Hardware, installation, and commissioning costs are prohibitive

A system of 10 temperature/humidity sensors to cover a room can cost $2,700-$4,000 installed.

Siemens, 2012, "Building Automation – impact on energy efficiency."

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Buildings generally have just **one** temperature sensor per zone

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P-PAL is a self-commissioning, remotely-powered wireless sensor system

Siemens, 2012, "Building Automation – impact on energy efficiency."

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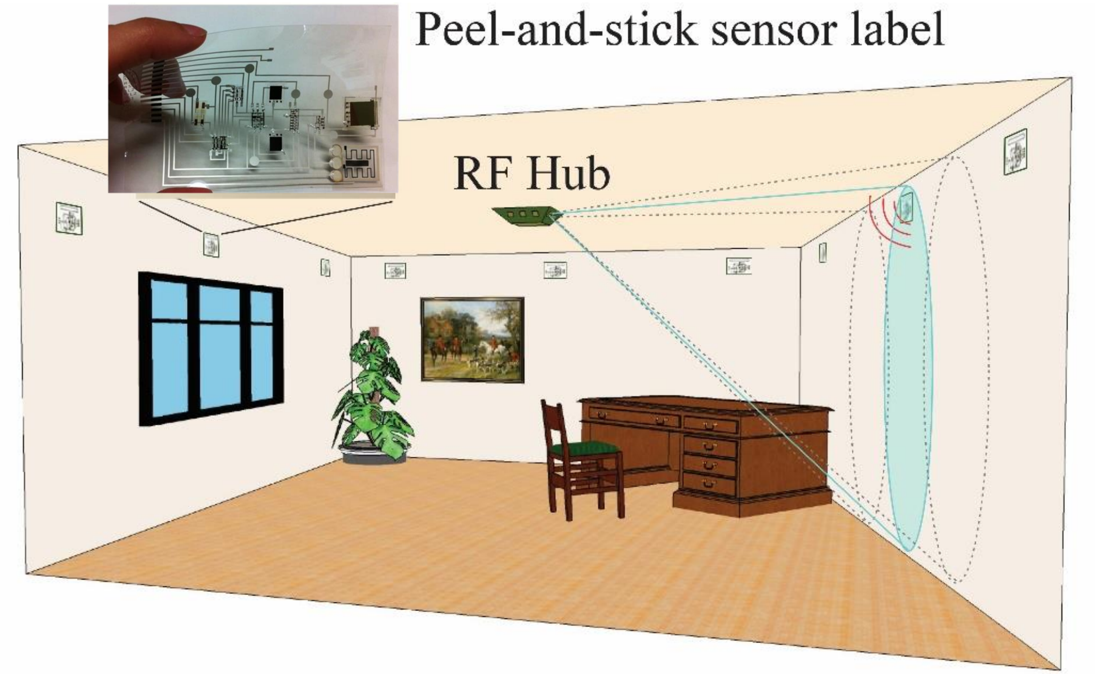


- Leverages PARC's flexible-hybrid electronics fabrication capability
- Project work includes:
  - Development of sensor tag electronics
  - RF power delivery
  - Tag localization techniques
  - BMS integration

P-PAL is a self-commissioning, remotely-powered wireless sensor system

Advantages

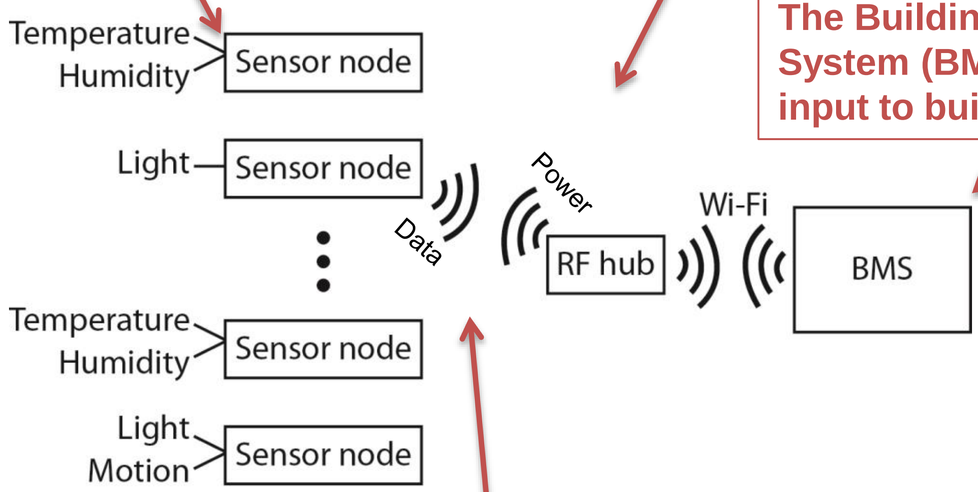
- **Peel-and-stick** form factor, based on flexible-hybrid electronics (FHE) technology for easy plug-and-play installation.
- **Remote power** delivery, based on PARC's unique printed high-efficiency antennas, eliminating battery costs, limited battery lifetime and charge, and light harvesting.
- **Wireless communication** to building management systems, based on Energy ETC's system-agnostic platform, for reduced installation cost.
- **Self-locating sensors** to within 0.5-m, via PARC's steered antenna topology, for reduced commissioning cost, and enabling automatic sensor recommissioning upon replacement.
- **Adaptability** to multiple sensors of different types (temperature, humidity, light, occupancy, air quality, etc.), for customizability.

System architecture

Steered RF beam enables localization of sensor tags

RF power provided by RF hub. Sensor node powered by on-board capacitor charged by received RF.

The Building Management System (BMS) uses the data as input to building controls.



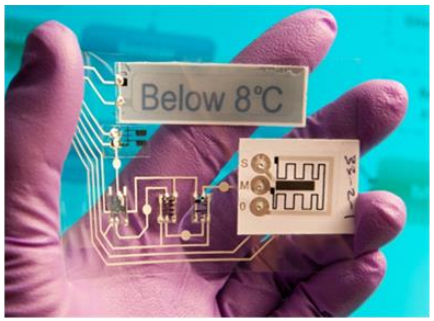
Sensor data communicated to RF hub

Background: Flexible-Hybrid Electroncs (FHE)

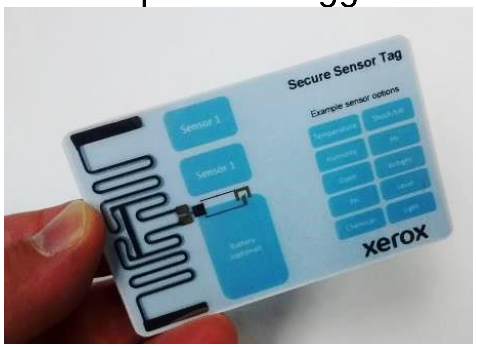
Fully Printed

Hybrid printed/conventional

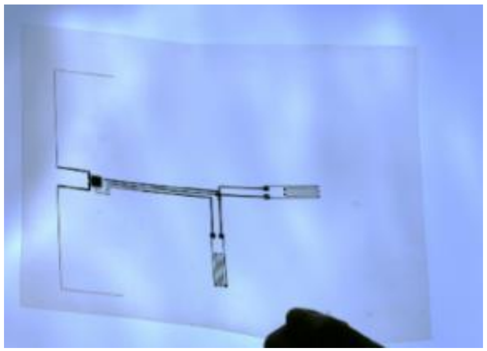
Temperature tag



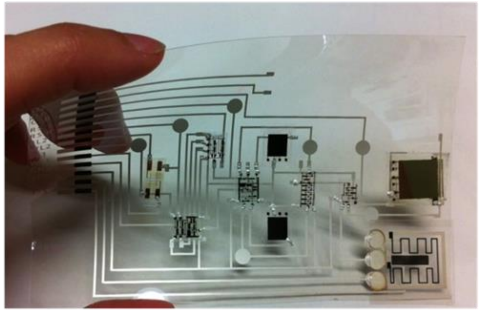
Temperature logger



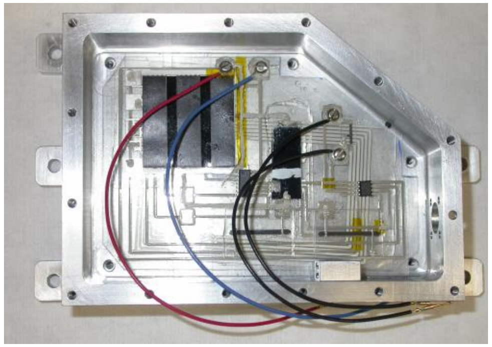
2-axis strain sensor



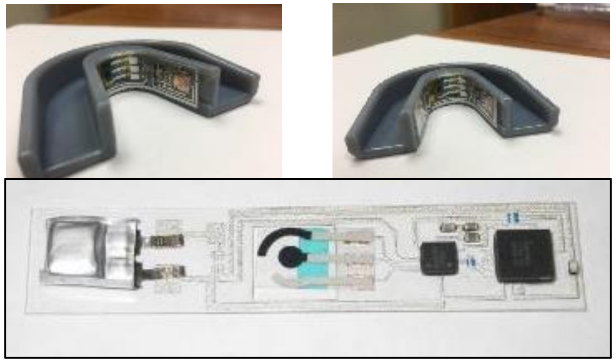
Time-temperature dose tag



Temperature/light sensor system



Mouth guard biosensor



Impact

<u>**Key differentiators:**</u>

- **Ultra low cost hardware**
  - FHE fabrication
  - Use of common RF frequency bands
- **Ease of installation/commissioning**
  - Battery-free RF power
  - Peel-and-stick form factor
  - Self-localization
- **Interoperability**
  - MODBUS over WiFi
  - Easily adapted to other protocols
- **Adaptability**
  - Compatible with multiple sensor types

Cost Model

- Detailed cost model including multiple scenarios and hardware, manufacturing, & labor cost
- Cost/10 sensors ~$200 (as compared to $2,700-$4,000)
- Payback time 2.1 - 3 years in most commercial installations and < 2 years in residences

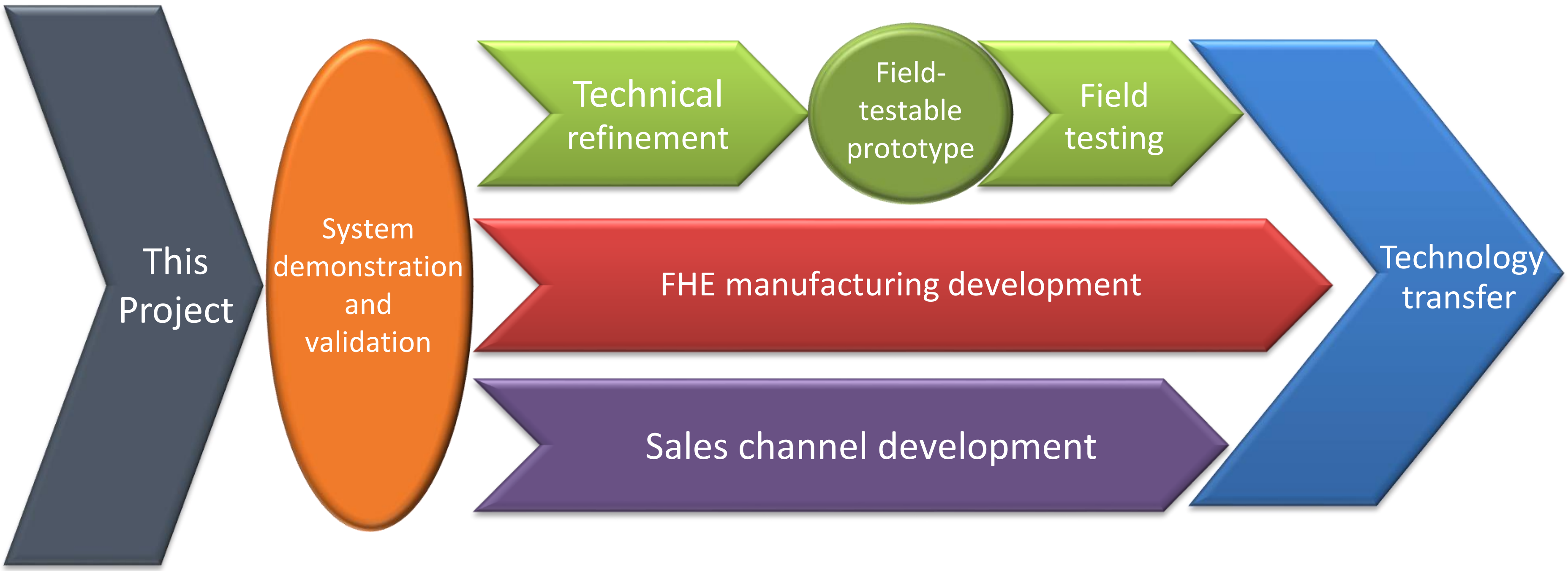
Commercial

	Heating and Cooling					Lighting	
Labor rate	**Low**	**Low**	**High**	**High**	**Cost scenario**	**Low**	**High**
Power availability	**Yes**	**No**	**Yes**	**No**			
Cost/sensor tag ($)	$8.46	$8.46	$8.46	$8.46		$8.46	$8.46
Area covered by RF hub (sq ft)	400	400	400	400		400	400
Sensors/RF hub	10	10	10	10		10	10
RF hub installed cost (wireless) ($)	$120.75	$215.75	$164.75	$339.75		$164.75	$339.75
Sensor cost per RF hub ($)	$ 84.63	$ 84.63	$ 84.63	$ 84.63		$ 84.63	$ 84.63
System cost per area ($/sq ft)	**0.51**	**0.75**	**0.62**	**1.06**		**$ 0.62**	**$ 1.06**
Baseline energy use (kWh/sq ft/y)	8.0	8.0	8.0	8.0		2.3	2.3
Energy cost ($/kWh)	$0.104	$0.104	$0.104	$0.104		$0.104	$0.104
Baseline energy cost ($/sq ft/y)	$0.83	$0.83	$0.83	$0.83		$0.24	$0.24
Projected energy savings (%)	30%	30%	30%	30%		13%	13%
Energy cost savings ($/sq ft/y)	$0.250	$0.250	$0.250	$0.250		$0.031	$0.031
Simple payback (y)	**2.1**	**3.0**	**2.5**	**4.3**		**20.0**	**34.1**

Residential

	Heating and Cooling	
Cost scenario	**Low**	**High**
Cost/sensor tag ($)	$8.46	$8.46
Area covered by sen	400	400
Sensors/RF hub	10	10
RF hub cost ($)	$68.50	$68.50
Sensor cost per RF h	$ 84.63	$ 84.63
System cost per are	$0.38	$0.38
House size (sq ft)	1500	1500
System installed cos	**$574**	**$574**
Baseline energy use	9463.9	9463.9
Energy cost ($/kWh	$0.127	$0.127
Baseline energy cos	$1201.92	$1201.92
Projected energy sa	30%	30%
Energy cost savings	$360.57	$360.57
Simple payback (y)	**1.6**	**1.6**

Realization Strategy



Project overview

Tag design and verification
- Data communication over 10 m
- Localization to 1 m at 10 m and 0.5-m at 5 m

Flexible hybrid implementation
- Layout and screen complete
- Rectifier and antenna assembled and being tested

BMS integration
- Data communication already demonstrated

RF hub design and verification
- Power transmission over 10 m
- Communication to BMS via MODBUS over WiFi

RF hub redesign
- Components complete
- Mechanical assembly underway

Received power measurement
- Measurement, encoding and communication with data

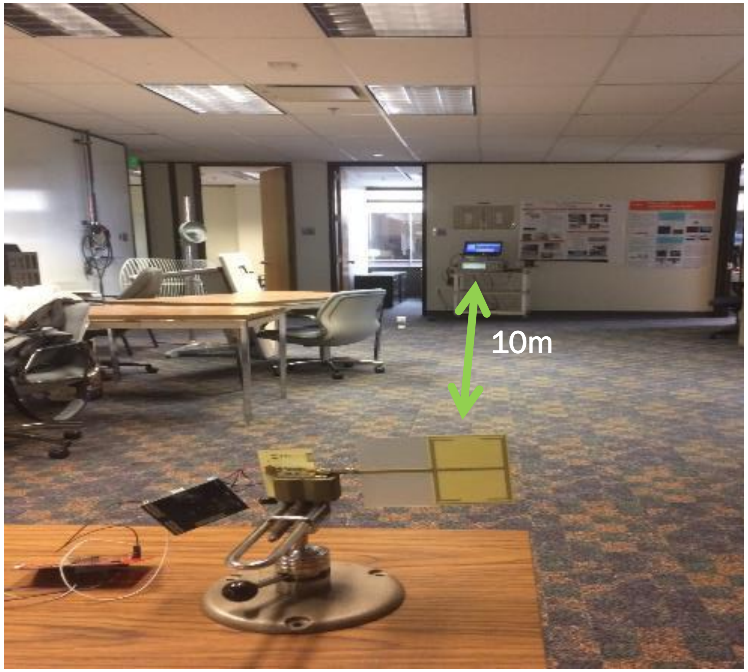
Localization algorithm development
- Basic algorithm complete
- Additional data to be collected for algorithm refinement

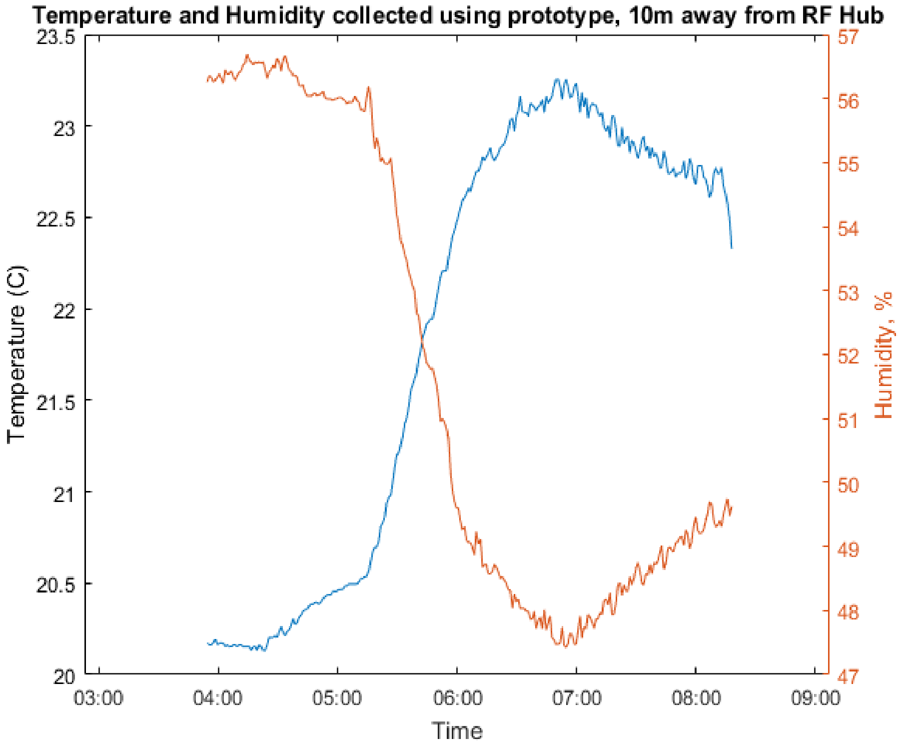
Firmware programming
- Sensor tag microcontroller programming complete
- RF hub programming nearly complete

Current status:

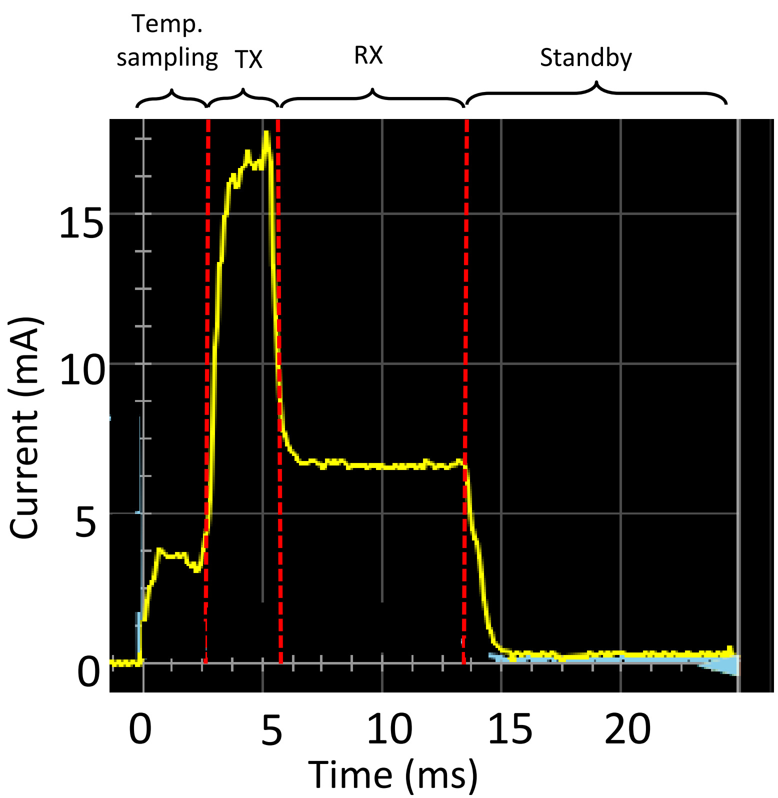
- ❖ Have demonstrated system using conventional hardware
- ❖ Implementing flexible hybrid sensor tag
- ❖ Data communication to BMS established
- ❖ Building final version of RF hub (electronics completed, firmware and mechanics nearly completed)

Power and data transmission over 10 m





Power consumption profile (preliminary)

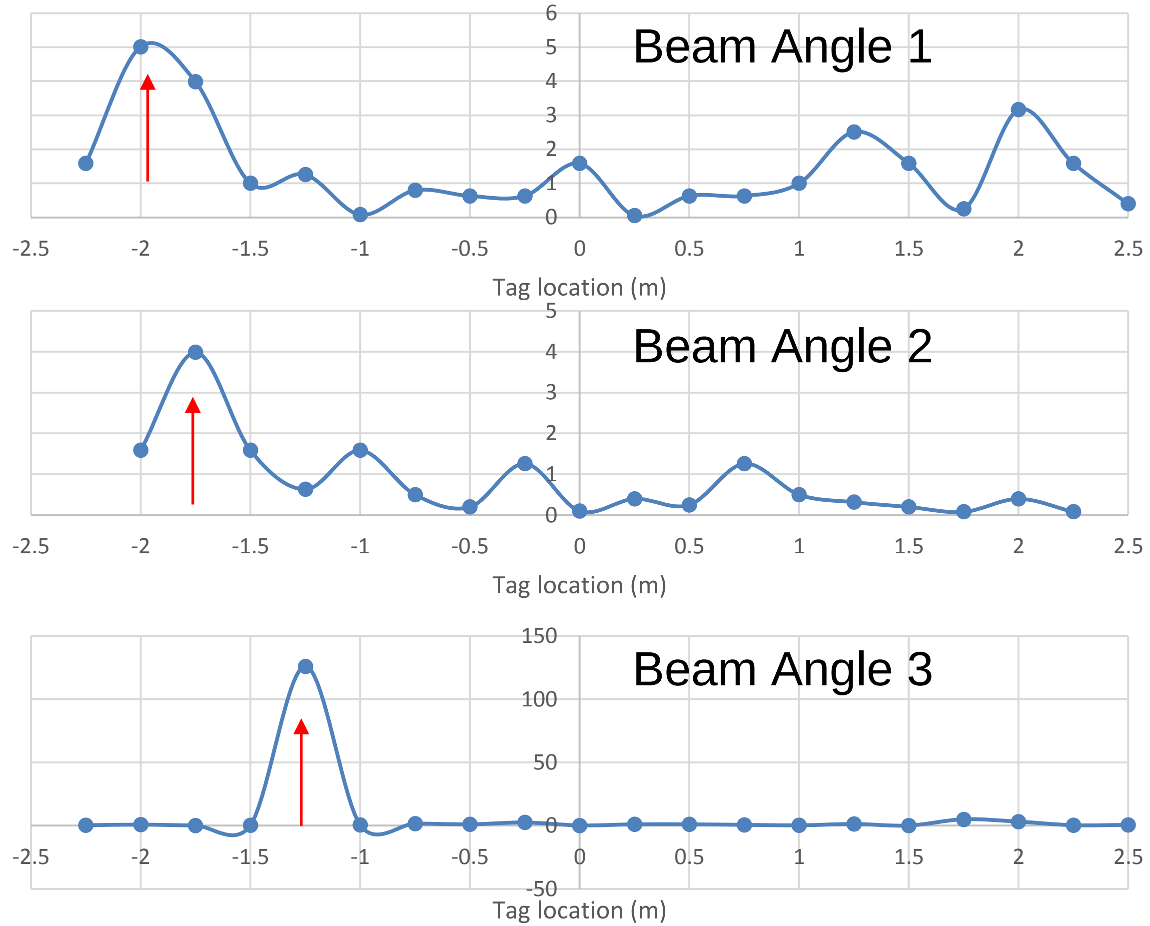


Phase	Current	Duration	Energy
Turn on	--	--	500 µJ
Temperature sampling	4 mA	2.5 ms	33 µJ
TX	16 mA	3.5 ms	184 µJ
RX	6 mA	11 ms	217 µJ
Total			834 µJ

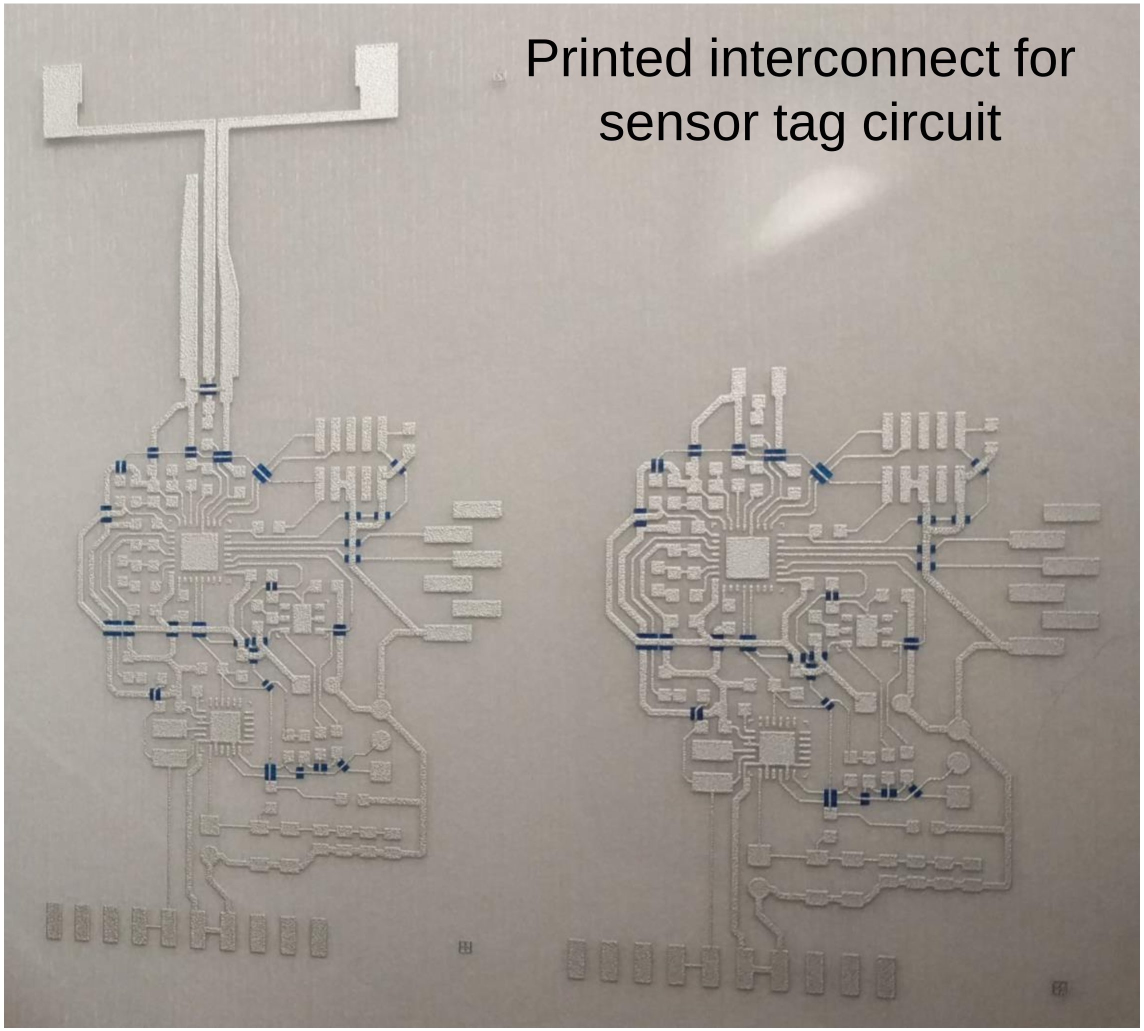
Energy required at the sensor for one measurement cycle	Charging power available	Charging time required
834 µJ	11.7 µW	71 s

Tag Localization at 5-m distance

- Plots show tag in different positions for fixed beam angle
- Localization to 0.5 m is demonstrated in this case
- Also have demonstrated localization at 8 m and 10 m

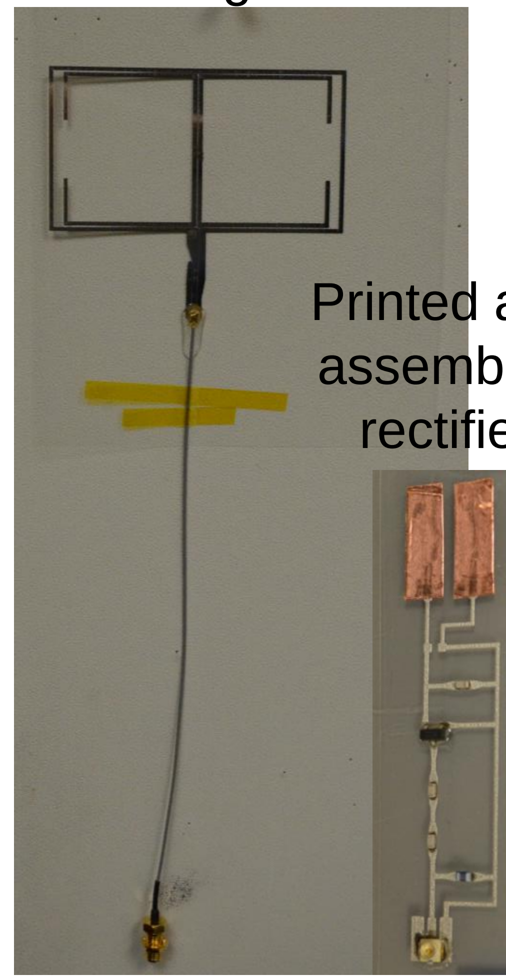


Flexible-Hybrid Implementation Progress



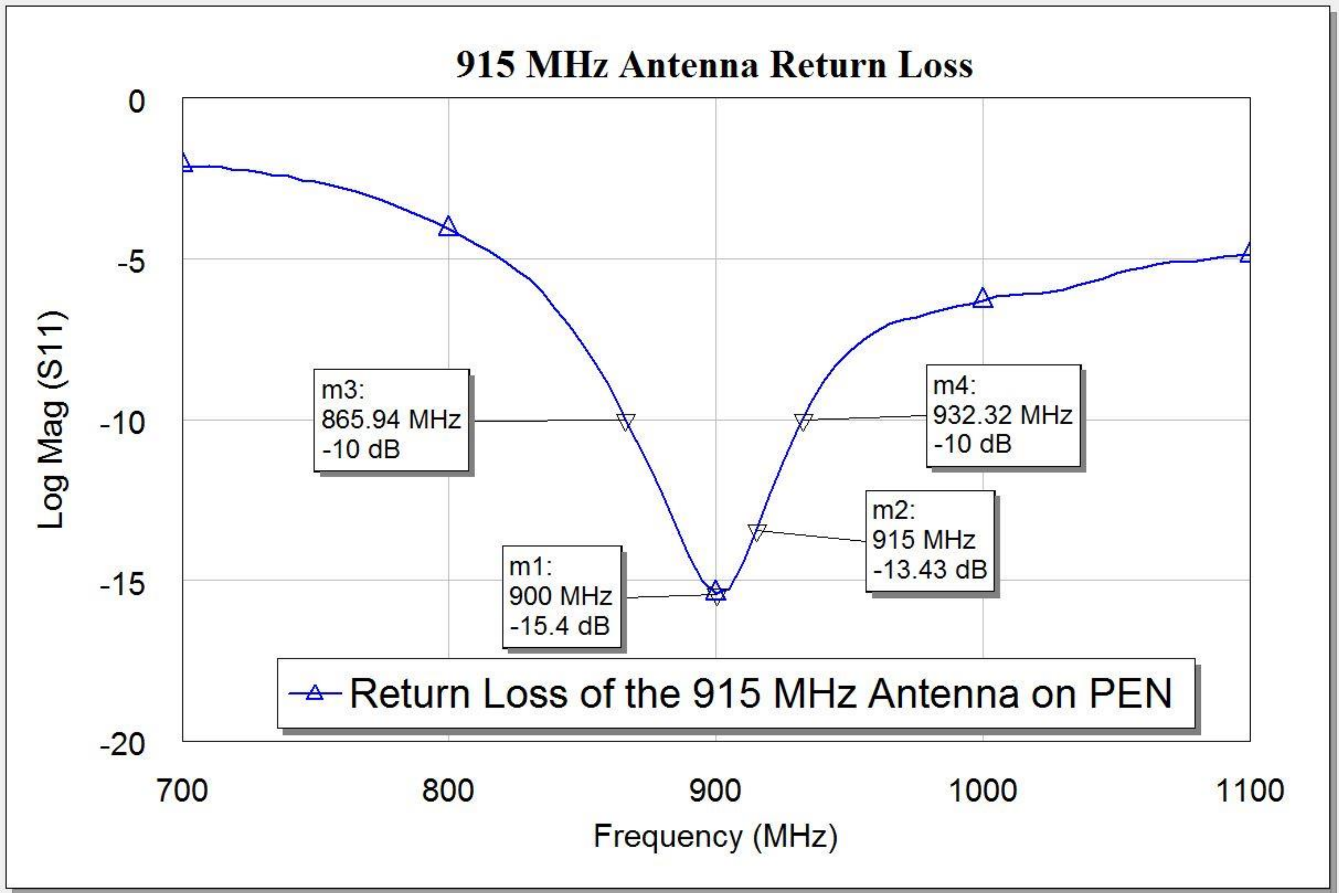
Printed interconnect for sensor tag circuit

Printed energy harvesting antenna



Printed and assembled rectifier

Preliminary measurements



Stakeholder Engagement

- Technology is still in early stage – developing first lab-scale prototype system
- Working with energy etc to ensure system is interoperable
- Engaging with major BMS hardware and service providers as well as Energy ETC to seek input into desirable characteristics as well as input into cost model
- Working with the NEXTFLEX manufacturing institute, PARC's parent company, xerox, and other major players to ensure FHE manufacturing is available
- Demonstration of energy savings in field trials critical to success. Initial field tests at PARC facility. Working with Energy ETC to identify and engage with field test sites.

Remaining Project Work

- **Flexible-hybrid tag implementation**
  - Goal: Flexible hybrid system will achieve comparable performance to the conventionally fabricated system
  - Status: Design and print layout complete; fabrication and initial testing underway
- **Final RF hub implementation**
  - Goal: RF hub that can transmit power 360˚, receive data from multiple tags, transmit data to BMS
  - Status: Electronics complete; firmware nearly complete; integration underway
- **Final demonstration**
  - Goal: 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 from two sensors on tag to RF hub, and from RF hub to BMS
  - Status: Integration of software with PARC BMS complete; preliminary localization algorithm demonstrated; will refine localization, power management, high-level system application during testing with FHE system

Thank You

PARC, Energy ETC

David Eric Schwartz, Area Manager (PARC)

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REFERENCE SLIDES

Project Budget

Variances: Some funding was moved to BP1 (2016-2017) from BP2 (2018) to cover redesign work and transfer of Milestone 5.2.1 to BP1

Cost to Date: $822,030 total cost

Additional Funding: There are no additional funding sources

Budget History					
10/1/2016– FY 2017 (past)		FY 2018 – 9/30/2018 (current)		FY 2019 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$657,247	$164,783	$137,839	$33,989	N/A	N/A

Project Plan and Schedule

- Start date: 10/1/2016; Planned end date: 9/30/2018
- All milestones achieved on or ahead of schedule
- Go/No-Go; 12/31/2017 – Demonstration of system with conventional hardware (Passed)
- Future work: Completion of flexible hybrid tag and demonstration of full system

Task		Description	eam memb	dget Peri	1															2								
				Project Mo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0		**Management**																										
1		**Sensor tag electronics development**	PARC																									
	1.1	Antenna design, modeling, fabrication					M1.1.1																					
	1.2	Sensor tag electronics design and fabrication on PCB							M1.2.1																			
	1.3	Design revision												M1.3.1														
2		**Transceiver development**	PARC																									
	2.1	Design and fabrication of monodirectional transceiver						M2.1.1																				
	2.2	Design of multidirectional transceiver											M2.2.1															
	2.3	Fabrication of multidirectional transceiver													M2.3.1													
	2.4	Implementation of localization algorithm															M2.4.1											
3		**System testing**	PARC																									
	3.1	Test and verify system with monodirectional transceiver									M3.1.1																	
	3.2	Test full system																	M3.2.1									
4		**Interoperability assessment and commissioning plan**	Energy ETC																M4.0.1									
5		**Flexible hybrid integration and testing**	PARC																									
	5.1	Flexible hybrid implementation																							M5.1.1			
	5.2	Integration into PARC building management system																				M5.2.1						
	5.3	Testing of full system																										M5.3.1
6		**Market Transformation Plan I**	PARC/ EETC													M6.1.3			M6.2.2									
	6.1	Intellectual Property					M6.1.1																					
	6.2	Technoeconomic Analysis (TEA) and Cost Model								M6.2.1			M6.2.2						M6.2.3									
	6.3	Market Discovery											M6.3.1			M6.3.2			M6.3.3									
	6.4	Technology to Market (T2M) Plan					M6.4.1			M6.4.2									M6.4.3									
7		**Market Transformation Plan II**	PARC/ EETC																									
	7.1	Technoeconomic Analysis (TEA) and Cost Model																							M7.1.1			
	7.2	Transition Activities																				M7.2.1			M7.2.2			M7.2.3

Current status