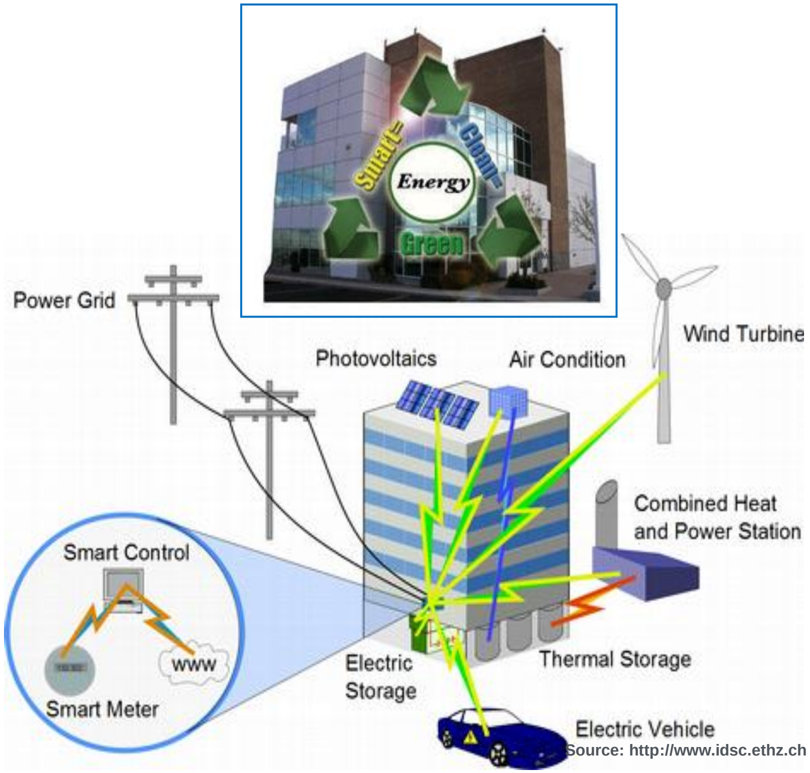
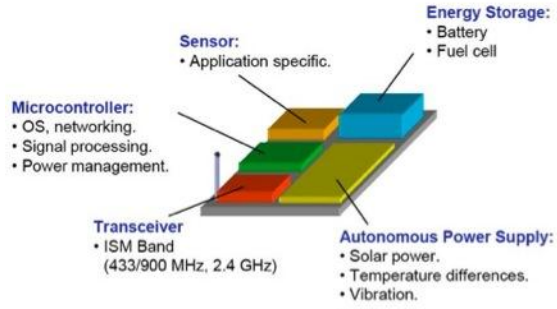
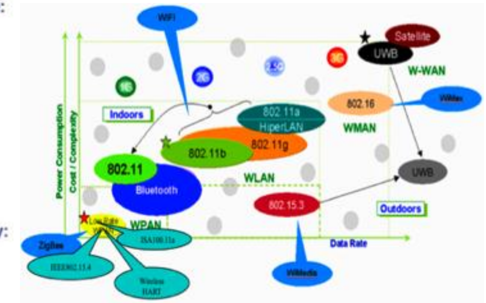
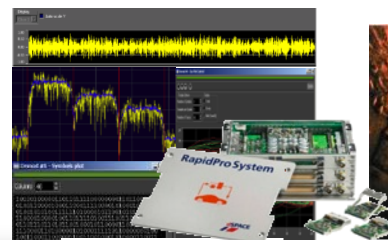
Low-cost Wireless Sensors for Building Monitoring Applications

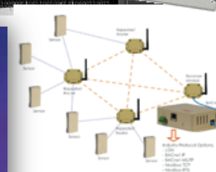
2014 Building Technologies Office Peer Review

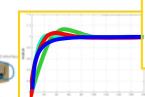


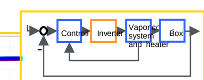


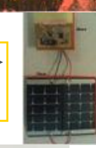












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Project Summary

Timeline:

Start date: September 2013

Planned end date: 2015

Key Milestones

1. Develop requirement specification for low cost wireless sensors by looking at regulatory and standards-based requirements - 12/31/13
2. Draft report on the low-power communication techniques and characterization of the communication scheme - 6/30/14
3. End-to-End demonstration of fully integrated self-powered wireless sensor platform for building monitoring - 9/30/14

Budget:

Total DOE $ to date: $950K

Total future DOE $: $500K

Target Market/Audience:

The market is all commercial buildings and the audience includes buildings retrofit solution providers, OEM sensors and equipment manufacturers. The technology is also applicable to several sectors - Vehicles, Industrial, Health

Key Partners: TBD. Currently in discussions and demonstrations with industry partners

Project Goal:

Develop and deploy low-cost wireless sensors for building monitoring to realize energy savings through optimal control of building subsystems.

The goals are:

- Low-power wireless communication driven by energy harvesting techniques
- Retrofit-friendly devices with minimal maintenance.
- Multi-sensor platform tailored for building monitoring needs
- Leverage additive, roll-to-roll manufacturing techniques to enable rapid adoption

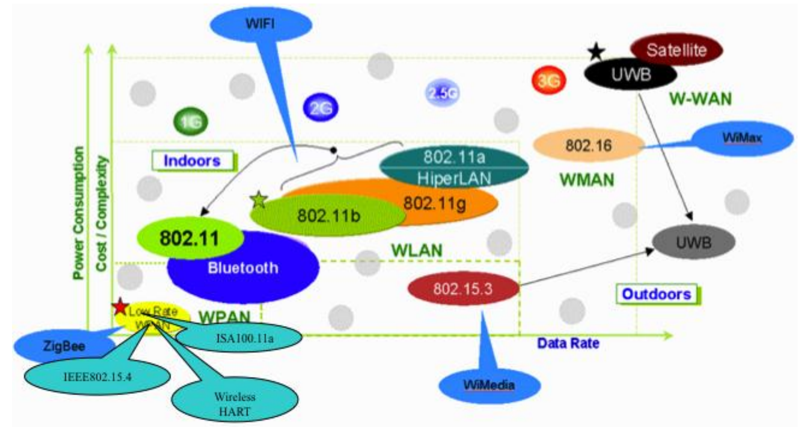
Purpose

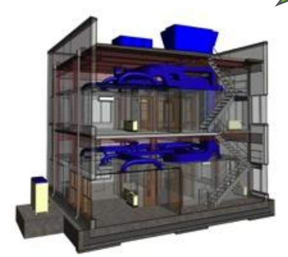
- **Problem Statement**:
  - Buildings consume up to 40% of the energy produced in the US
  - Sensors and controls have demonstrated potential to reduce building energy consumption by 20–30%
  - Savings can be realized only by retrofit solutions that have a 1-2 year payback, which facilitate adoption
  - There is a technology gap in wireless sensors for reliable self-powering mechanisms – Key is to leverage ultra low-capacity batteries (<5mAh) that can be driven by energy harvesting devices(indoor photovoltaic and waste heat)
  - New modulation techniques and additive manufacturing friendly wireless sensors have to developed to realize the vision
  - **The project addresses the gap by developing wireless technology and system-level integration to enable energy-harvesting wireless sensors with significant range to reduce networking infrastructure requirements and roll-to-roll manufacturing compatible**

Objective

Develop wireless sensors featuring:

- Low-power communication scheme
- Reduced infrastructure cost of networking through increased range
- Thin-film batteries powered by energy harvesting solutions
- Multiple relevant sensors in a single platform
- Path towards standards
- Additive, roll-to-roll manufacturing compatible





Advanced sensors and controls have the potential to save 20-30% energy consumed by buildings.

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Target Market and Audience & Impact of the Project

Target Market and Audience:

- All residential and commercial buildings.
  - **Small and medium commercial buildings** – improved control of energy providing opportunity for 6-8 quads of energy savings potential
  - **Large commercial buildings** – improved control of energy use optimization, and diagnostics of large equipment with 8-9 quads of energy savings potential
- Building automation system and equipment manufacturers for OEM integration
- Technology adaptable to various sectors including ***Health, Process, Manufacturing, Vehicles, and Energy***

Impact of Project: The project envisions reducing the cost barriers to deploying advanced sensors in buildings to enable optimization of energy usage. The project will develop and demonstrate low-cost wireless sensors for buildings applications along with path towards additive, roll-to-roll manufacturing techniques.

- <u>Near Term</u>: Demonstrate end-to-end technology and identify path towards low-cost manufacturing.
- <u>Intermediate Term</u>: Identify partner(s) for commercialization and deployment tailored to specific building applications
- <u>Long Term</u>: Demonstrate energy savings realized by widespread adoption of the low-cost sensors within buildings

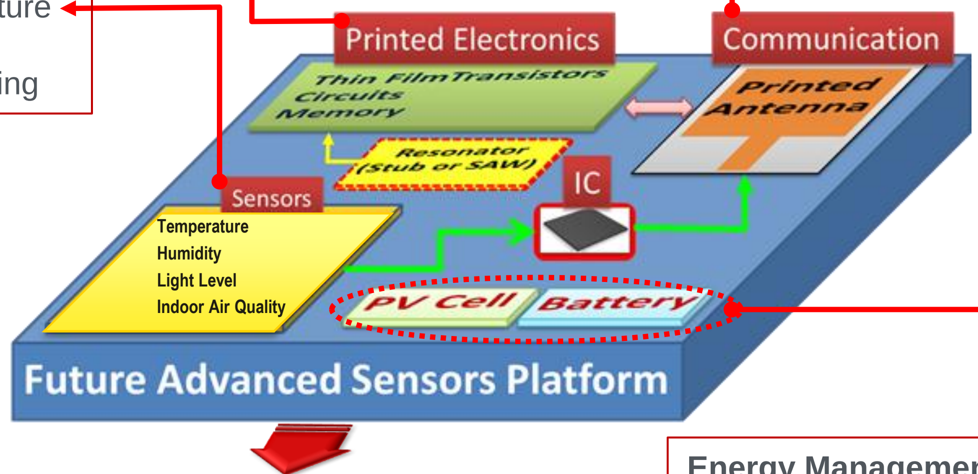
Approach – Multifunctional Wireless Sensors

Current wireless sensor Platform: $150-$300/node → Proposed Advanced Sensors Platform: $1-$10/node

Core Components
- High performance thin films
- Low temperature integration
- R2R processing

Preliminary Investigations

Extensive Capabilities at ORNL
- Modeling
- Design
- Test and Measurements



Four Key Elements of Technology:

1. Low-power Wireless Communication
2. Thin-film Battery and Indoor Photovoltaics
3. Sensor(s) Integration into Thin-films
4. Integrated System Design

Market Potential
- Prospects of New market
- Enhanced Functionality

Energy Management Technologies
- Extensive know-how at ORNL
- Resources required to target low temperature material/device development

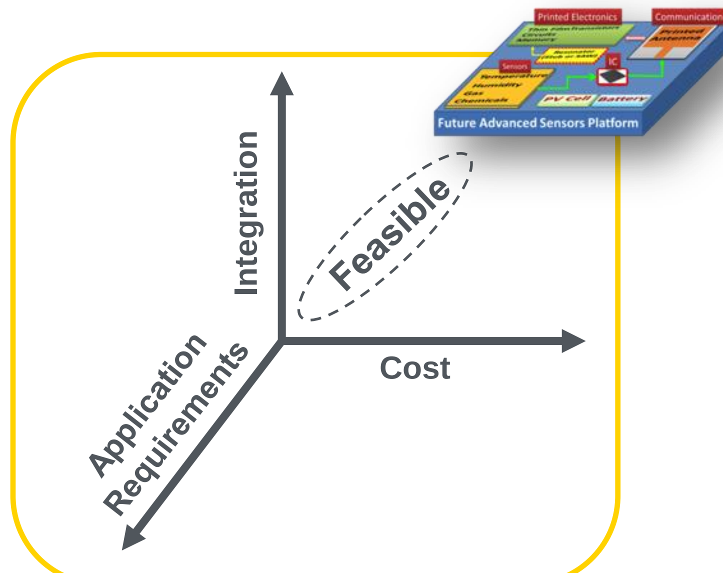
Demonstrate path towards additive roll-to-roll manufacturing techniques

Sensor Requirements for Building Monitoring

Impact on Buildings Technology
Advanced sensor, control technology brings big growth to building energy management market:

- **Market Growth**: 17% compound annual rate to become a $2.14 billion industry by 2020(Lux Research)

- Non-Orthogonal Multi-dimensional requirements for low-cost wireless sensors
  - Application Requirements: Data Rate, Sensor Accuracy, Sampling Rate, Battery, RF communications
  - Integration Requirements: Materials, Functionality, Device/Sensor Integration, Regulations
  - Cost: Low-cost, Manufacturing Infrastructure
- ASHRAE Standards 90.1, 90.2, 55, 62.1, and 189.1
- IECC, IBC, and NFPA 5000 code.



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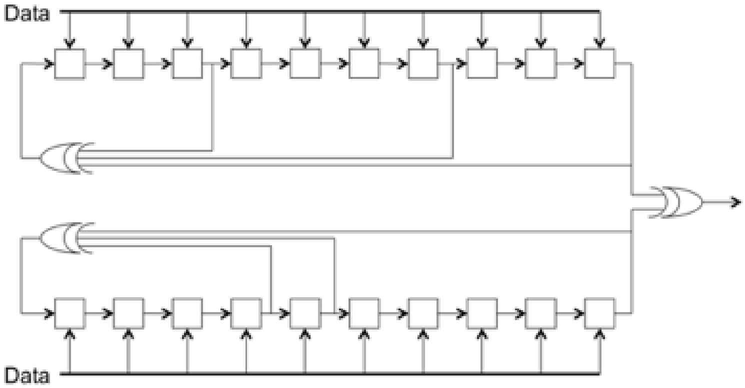
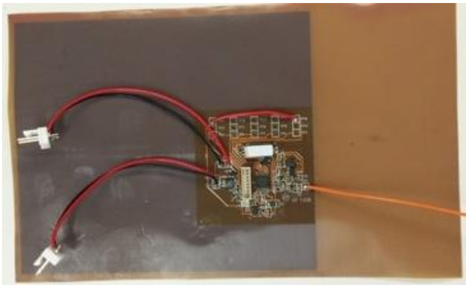
Low-power Communication Scheme

- Data of 20 bits to preload registers
- Generates over 1 million “orthogonal” shifted Gold codes
- Spread Spectrum length of 1023 bits to deliver the 20 bits (51:1 expansion) – 30dB Gain
- 1 W performance from a 1 mW transmitter
- Smaller battery, low current operation
- Relaxed tolerance 2KHz vs. 40Hz for 40bps
- Bandwidth recovery - CDMA



Transmitter Frequency	433.92 MHz
Transmitter Power	+5 dBm
Receiver Sensitivity	-145 dBm
Chipping Rate Data rate	2000 BPS 40 BPS



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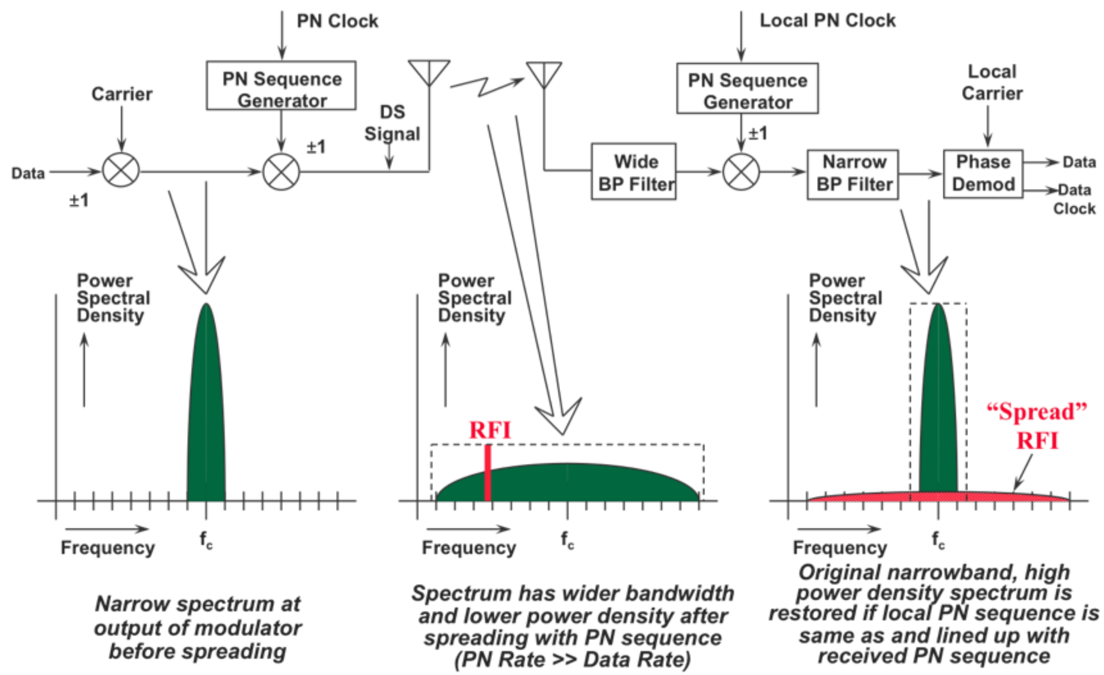
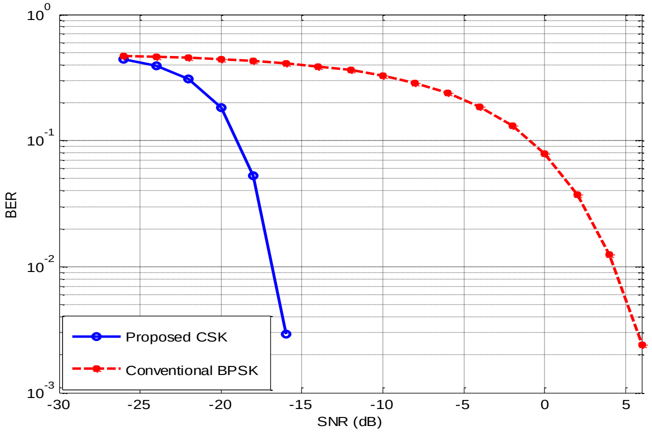
Scalable Solution - Spread Spectrum

- COTS low-power wireless network
  - ~20-30mA per TX
  - 2.4GHz, 10-100mW output power
  - Rx sensitivity: -95dBm
  - Processing gain: ~9dB (16)
  - Range: 100-300m
  - Bi-directional communication (TX-RX)
- ORNL platform
  - ~3-5mA per TX
  - 433MHz, 1-5mW output power
  - Rx sensitivity: -140dBm
  - Processing gain: ~30dB (1023)
  - Range: 1000-1500m
  - Uni-directional communication (TX)
- Theoretically accommodates more than a million simultaneous transmitters (orthogonal codes)
- Multi-user simulations currently underway to assess performance
- CDMA techniques can allow simultaneous usage to recover most of the expanded bandwidth





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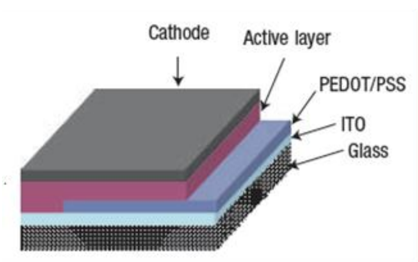
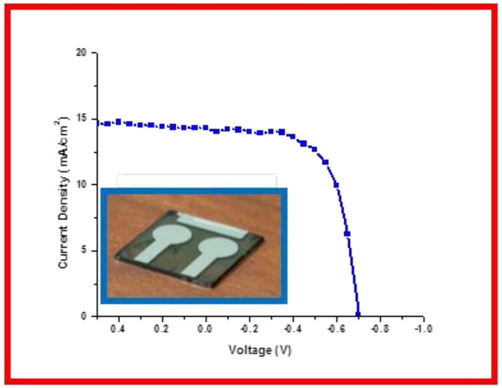
Energy Harvesting and Thin Film Batteries

Organic Photovoltaic Device

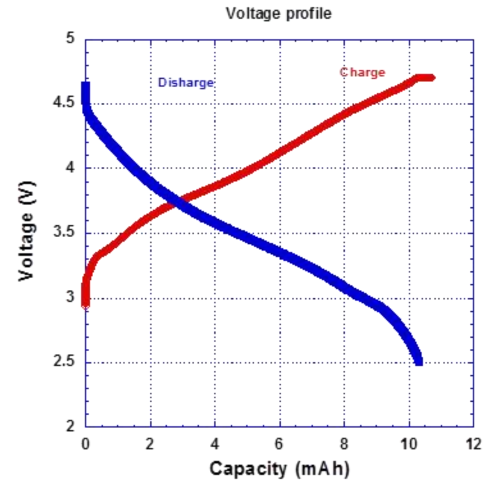




Device Performance	
Efficiency (η)	6.3%
Fill Factor (FF)	64%
Short Circuit Current Density (J_{sc})	14.1 mA/cm²
Open Circuit Voltage (V_{oc})	0.7 V

Flexible thin-film energy harvesting solutions will enable peel-and-stick wireless sensors that are self-powered

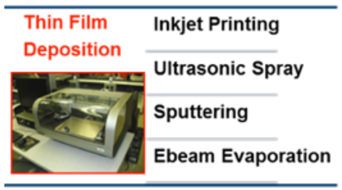
Small Form Factor Li-polymer Battery: Pouch Cell

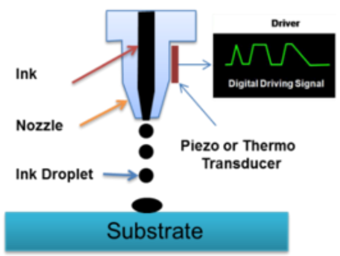


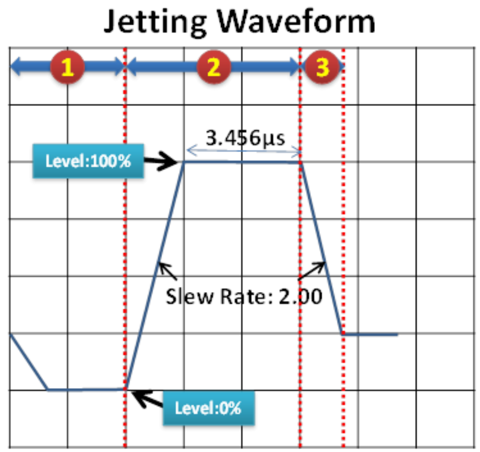
- The pouch cell offers a simple, flexible and lightweight solution to battery design.
- Lithium ion battery poses high energy density and offers a flexible and lightweight solution to system design.
- Solid electrolyte like LiPON, screen printed on same substrate

Characterize the Bulk Conductivity

- **Inkjet Printing of Ag**

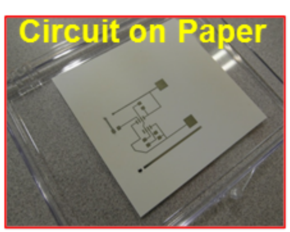


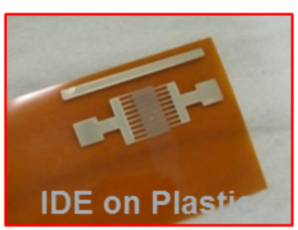




1. Fluid chamber at maximum volume
2. Main drop ejection phase
3. Recovery phase

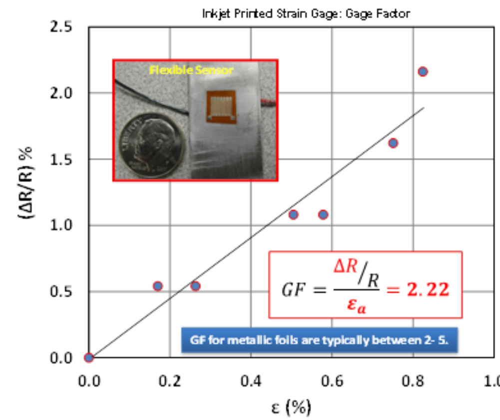
- **Line width control below 100μm established (Path towards 25μm)**



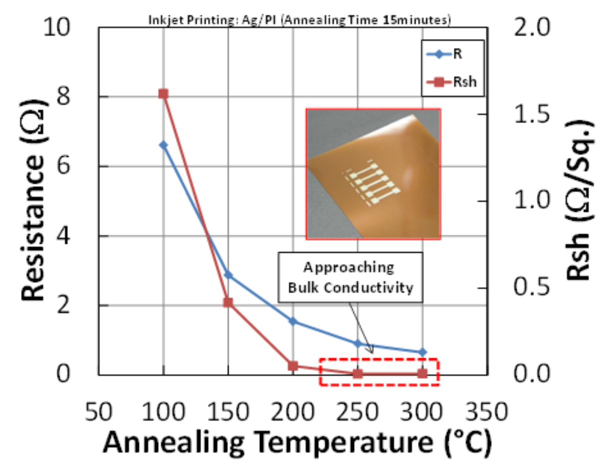


- **Additive Integration on Paper, Plastic, Ceramic, and Rubber**

- **Printed Metal Performance**



- **Mechanical Integrity: Gauge Factor comparable to Metallic Foils**



- **Printed Metal Conductivity approaches the Bulk value**

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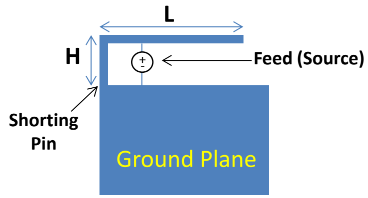
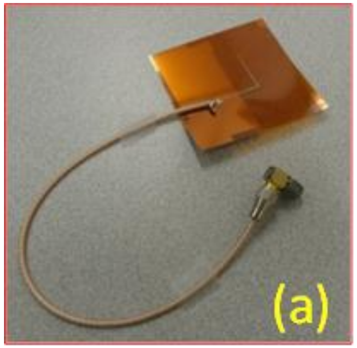
Printable Antenna Development

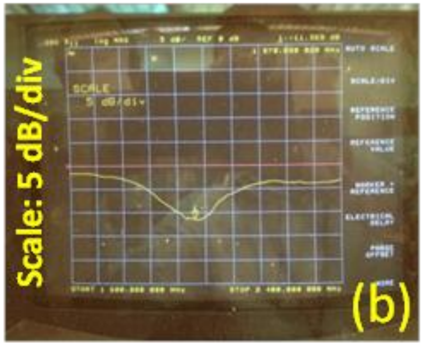
- Printable, flexible antennas for operation in ISM frequency bands
- Printable dielectric, metals, and nanomaterials for optimal radiation pattern for producing thin-profile conformal antenna

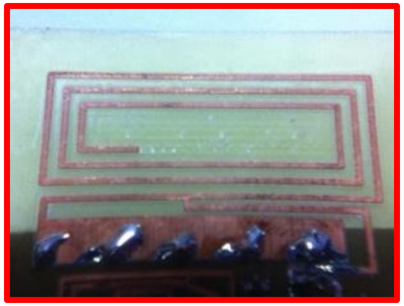
Antenna Design: 433 MHz

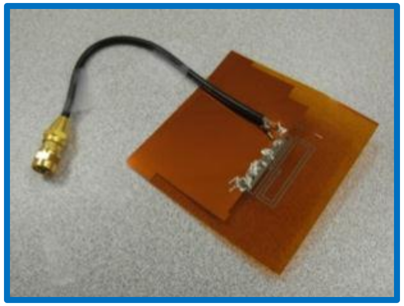
- "Inverted F" design
- Dimensions 16 by 27 mm
- Better than 10 dB return loss over 5 MHz

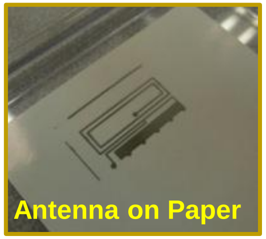












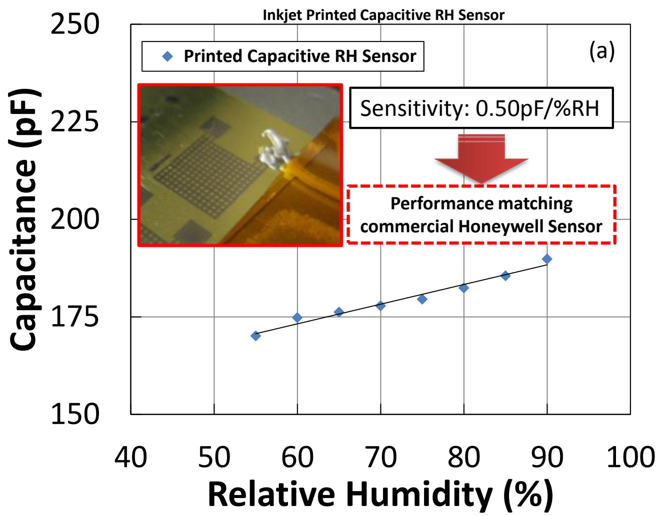
Path towards Low Cost, Ultrawideband Antenna Technology

Antenna Design: 2.45 GHz

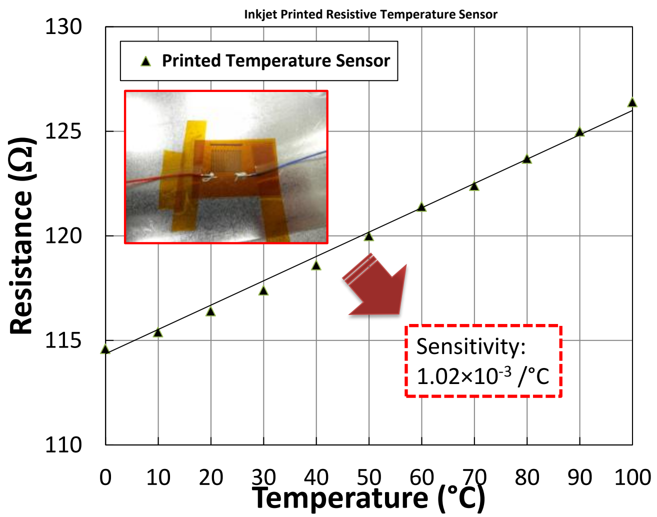
- Printed High Frequency Monopole Antenna
- Return loss below -10dB easily achieved
- Addressing demands for small size, ease of fabrication, tunability, and low cost for short-range applications.

Thin Film T and RH Sensors

- Humidity sensor with a resolution of ±2% RH



- Low temperature metal thin film temperature sensor



RH Sensor

- Integration on 5-125µm thick PI films
- Mesh Electrode: Additive Integration eliminates masking, photo, and etch steps
- High Performance matching RH commercial sensors

Temperature Sensor

- Linear Thermal Response from Printed Temperature Sensor
- Resistance can be controlled by Line Definition control: No mask redesign step

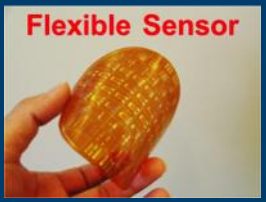
Unique Approach- Advanced Manufacturing

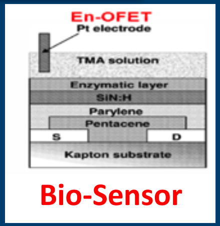
Material Innovations to Manufacturing Technology

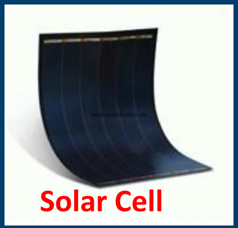
ORNL's R&D Platform

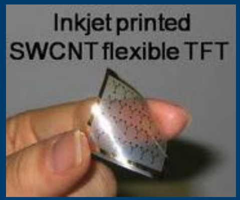
- Materials
- Printing Technology
- Device Integration
- Test & Measurements

Advanced Devices









Current wireless sensor Platform: $150 $300/node

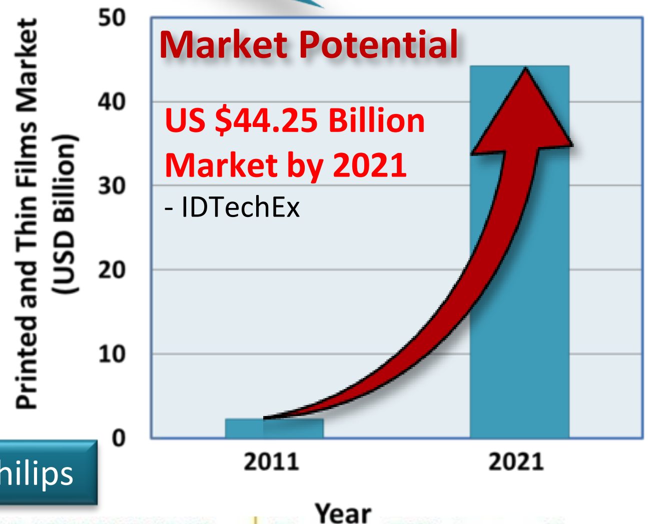
Proposed Advanced Sensors Platform: $1 $10/node

Key Technology improvements

→ **Low-power wireless**

→ **Multifunctional sensor**

→ **Advanced materials**



Driving Industries: SHARP, HP, Plastic Logic, Dow Chemical, DuPont, FlexTech, Philips

Progress and Accomplishments

Lessons Learned: Thin-film antennas are not suitable for attaching to metallic surfaces requiring specific deployment protocols. Component placement on printed silver over thin-films is incompatible with regular soldering approaches.

Accomplishments:
- Successfully demonstrated low-power wireless sensor that is self-powered using an indoor photovoltaic source and thin-film batteries that can operate successfully overnight without light source
- Demonstrated thin-film sensors printed using inkjet printing of silver
- Multi-user analysis of DSSS/CSK communication scheme
- Experimental data collected to demonstrate adequate performance for buildings applications
- Path towards integration of additional sensors (IAQ, Occupancy) into the platform

Market Impact:
- Reduce the cost barrier to deploying advanced sensors and controls to optimize energy usage (improve by 20-30%) with in buildings.
- Demonstrations to potential industrial partners and engaging in discussions tailored for building monitoring applications
- Multi-functional devices realized using additive, roll-to-roll manufacturing techniques.

Awards/Recognition: Two Invention Disclosures

Project Integration and Collaboration

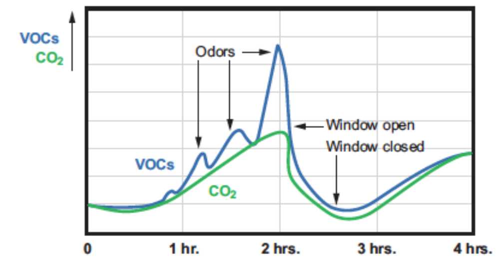
Project Integration: The project is led by ORNL and the team includes experts from wireless networks, materials processing, battery manufacturing, and buildings technology. The team is currently in discussion with sensor and flexible circuits manufactures, building HVAC equipment manufactures, lighting manufacturers, and energy service contractors.

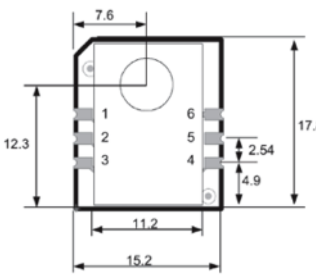
Partners, Subcontractors, and Collaborators: The project team is working with University of Tennessee to develop optimal antenna designs, thin-film transistor design, and flexible photovoltaic cell development. We are actively engaging in discussions with industrial partners mainly to identify use cases for incorporating low-cost sensors into their business strategy.

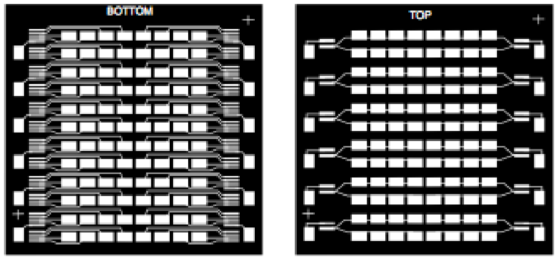
Communications: The work is presented at ISA, IEEE and AVS forums. Several publications are currently underway to disseminate the results

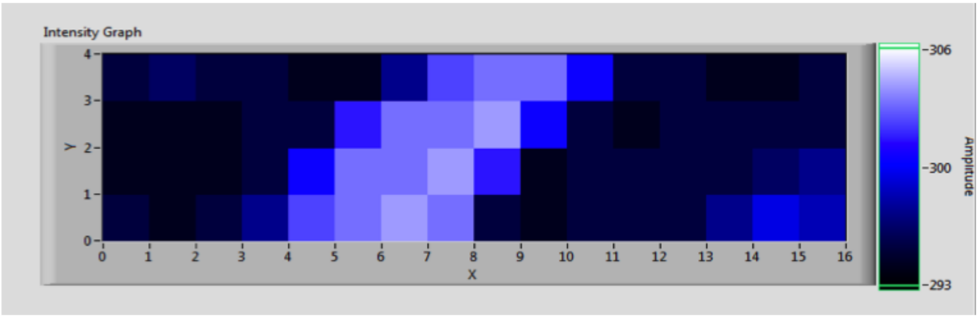
Next Steps and Future Plans

- Leverage low-cost printable manufacturing techniques for manufacturing sensors
- Develop sensors for
  - **Indoor Air Quality (IAQ)**: Low-temperature processing approaches using metal oxide semiconductors
    - Algorithms on receiver side for post processing
  - **Occupancy**: Low-cost, low-power pyroelectric sensor arrays for providing full scene images
    - Algorithms for post processing to identify "number of occupants"
- Characterization of sensor reliability, response times, and calibration requirements
- Outreach and Partnerships









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REFERENCE SLIDES

Project Budget

Project Budget: $200K (FY13), $750K (FY14).
Variances: none
Cost to Date: $350K
Additional Funding: None

Budget History					
FY2013 (past)		FY2014 (current)		FY2015 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$200K	$0K	$750K	$0K	$500K	$0K

Project Plan and Schedule

Project Schedule												
Project Start: 10/1/2012		Completed Work										
Projected End: 9/30/2015		Active Task (in progress work)										
		Milestone/Deliverable (Originally Planned) use for missed milestones										
		Milestone/Deliverable (Actual) use when met on time										
	FY2013				FY2014				FY2015			
Task	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Q1 Milestone:Scoping study to develop requirements for low-cost, low-power wireless sensors												
Q4 Milestone: Prrof of Concept demonstration of low-cost, low-power wireless sensors for building monitoring												
Q1 Milestone: Develop requirement specification by looking at regulatory and standards-based requirements												
Q2 Milestone: Draft report on sensor characterization and feasibility study of multi-array sensors												
Current/Future Work												
Q3 Milestone: Draft report on the low-power communication techniques and characterization of the communication scheme developed by ORNL												
Q3 Milestone: Design specification of thin-film battery and harvesting solution & manufacturing considerations												
Q4 Milestone: End-to-End demonstration of fully integrated ORNL wireless sensor platform												