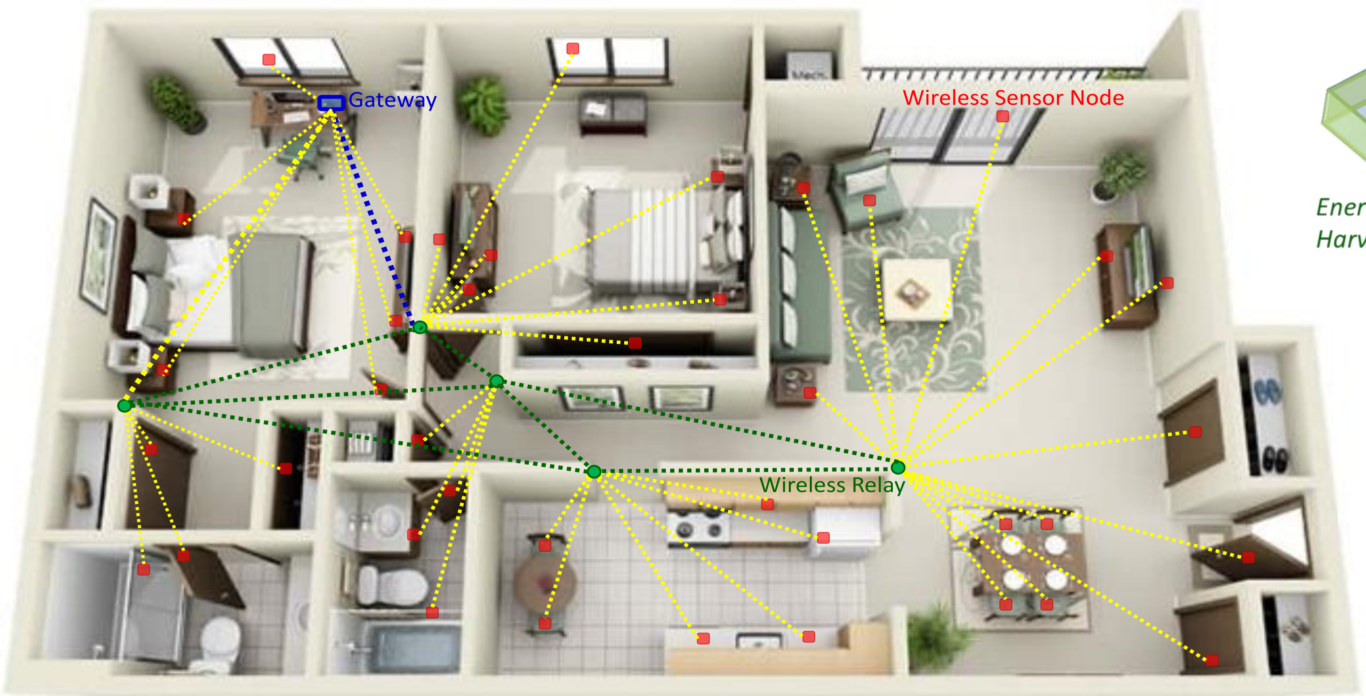
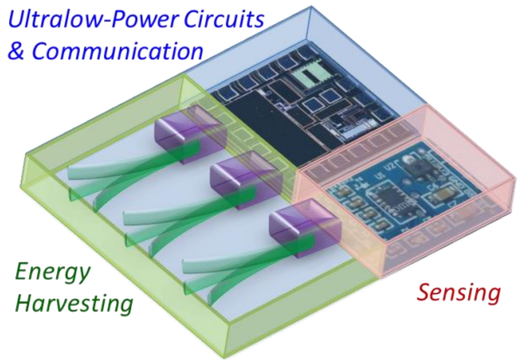
Transforming Ordinary Buildings into Smart Buildings via Low-Cost, Self-Powering Wireless Sensors & Sensor Networks

2016 Building Technologies Office Peer Review





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Philip Feng, Ph.D., philip.feng@case.edu
Case Western Reserve University

Project Summary

Timeline:

Start date: 10/01/2014

Planned end date: 09/30/2014

Key Milestones

1. Design Energy Harvesting ASIC; 12/31/2014
2. Tapeout ASIC and Test Circuit; 6/30/2015
3. Complete Sensor Node; 9/30/2015

Key Partners:

Intwine Connect	

Budget:

Total Project $ to Date:

- DOE: $405,356.59
- Cost Share: $60,309.76

Total Project $:

- DOE: $749,990
- Cost Share: $103,012

Project Outcome:

The objective of this project is to design and demonstrate a low-cost, compact, easy-to-deploy, maintenance-free sensor node technology, and a network of such sensors, which enable the monitoring of multiphysical parameters and can transform today's ordinary buildings into smart buildings with environmental awareness.

We have developed the proposed the sensor node, and have integrated it with the network, and are making solid progress on development and commercialization objective is to create prototypes for our target products.

Purpose and Objectives

Problem Statement: A low-cost solution is needed in transform today's ordinary buildings into smart buildings. Battery-Powered wireless sensors require periodic replacement of battery (high maintenance cost) and generate large amount of battery waste at end of lifespan (environmental threat). Our technology can address these issues.

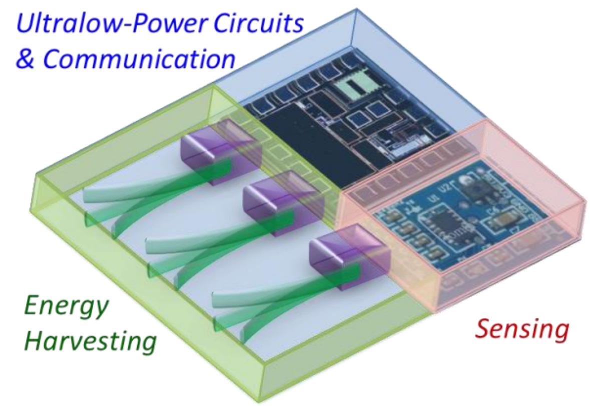
Target Market and Audience: Our technology allow BEMS integrators to provide highly competitive smart building solutions to end customers. The BEMS market is $2.4 billion in 2015, and advanced sensor market is $1.2 billion in 2016.

Impact of Project:

1. The final product of this project is a low-cost, compact, easy-to-deploy, maintenance-free sensor node technology, and a network of such sensors,
2. The technology developed can enable the monitoring of multiphysical parameters and can transform today's ordinary buildings into smart buildings with environmental awareness, and is expected to take a substantial market share in the smart sensors for BEMS.
   a. Near-term outcomes: alpha prototype complete and start formulating business plan based on the developed technology.
   b. Intermediate outcomes: beta prototype complete and validated with independent third party/potential customer.
   c. Long-term outcomes: startup company established and product taking a large BEMS market share.

Approach

Approach: We leverage high-efficiency energy harvesting and ultra-low power circuits to achieve self-powering wireless temperature sensors.



Key Issues: The key issue is to generate sufficient power from harvesting the vibration energy from the environment, and minimize the energy consumption in the sensor operation.

Distinctive Characteristics:

The uniqueness of our energy-harvesting technique is that we focus not just on steady vibrations, but also on harvesting energy from all the transient vibrations such as door closing.

The uniqueness of our ultra-low power design is that it can minimize power consumption during normal operation, and use the most energy-efficient scheme for wireless data transmission.

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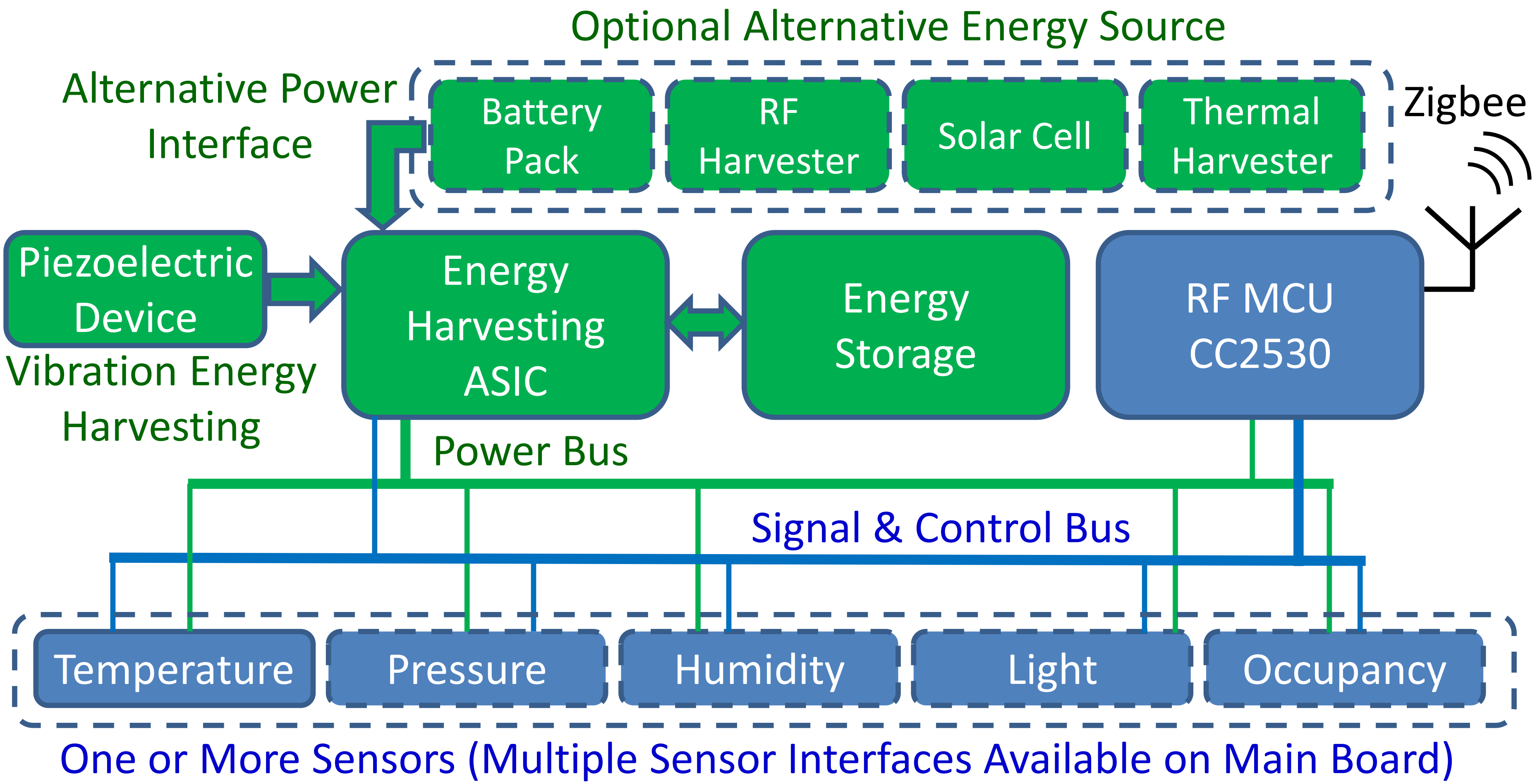
Approach: System Architecture for the Sensor Node



Progress and Accomplishments

Accomplishments: We have achieved:
Self-powering sensor nodes, harvesting vibrational energy in indoor environments.
Wireless connectivity through standard ZigBee network.
Self-powering wireless temperature sensing using the sensor node and network.
See *Quarterly Breakdown* for more details.

Market Impact:

1. To ensure & accelerate impact, the technology is timely disseminated through peer-reviewed publications, conference presentations, and patent applications. In addition, business plans are developed based on the technology and we have actively participated in many business competitions, and have achieved ***surprisingly successful*** results.
2. The actual impacts ***exceed*** the planned impacts, in that the business competitions based on the developed technology has been ***highly successful***. See *Quarterly Breakdown* for more details.

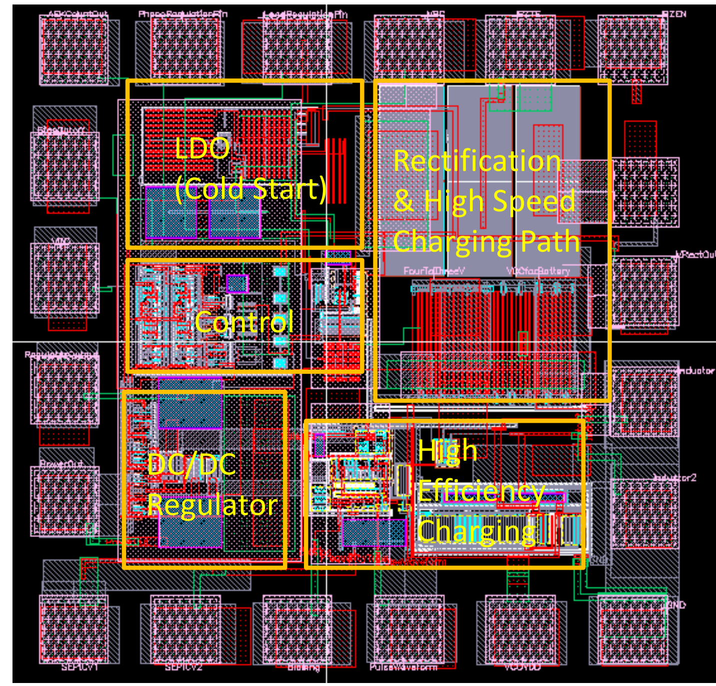
Awards/Recognition: See *Quarterly Breakdown* for more details.

Q1 Progress and Accomplishments

We have completed the design of the Application Specific Integrate Circuit (ASIC), a key enabling component, for this application.

High Speed Charging Path
High Efficiency Charging Path

Block Diagram of ASIC



Layout of ASIC for Tapeout

Q1 Progress & Accomplishments Toward Commercialization

- IP: the 1st patent on this project is being filed, more disclosures in prep.
- PI's students' team won *2015 Clean Energy Challenge* at CWRU.
- Team selected to compete in Chicago for 2015 Clean Energy Challenge.

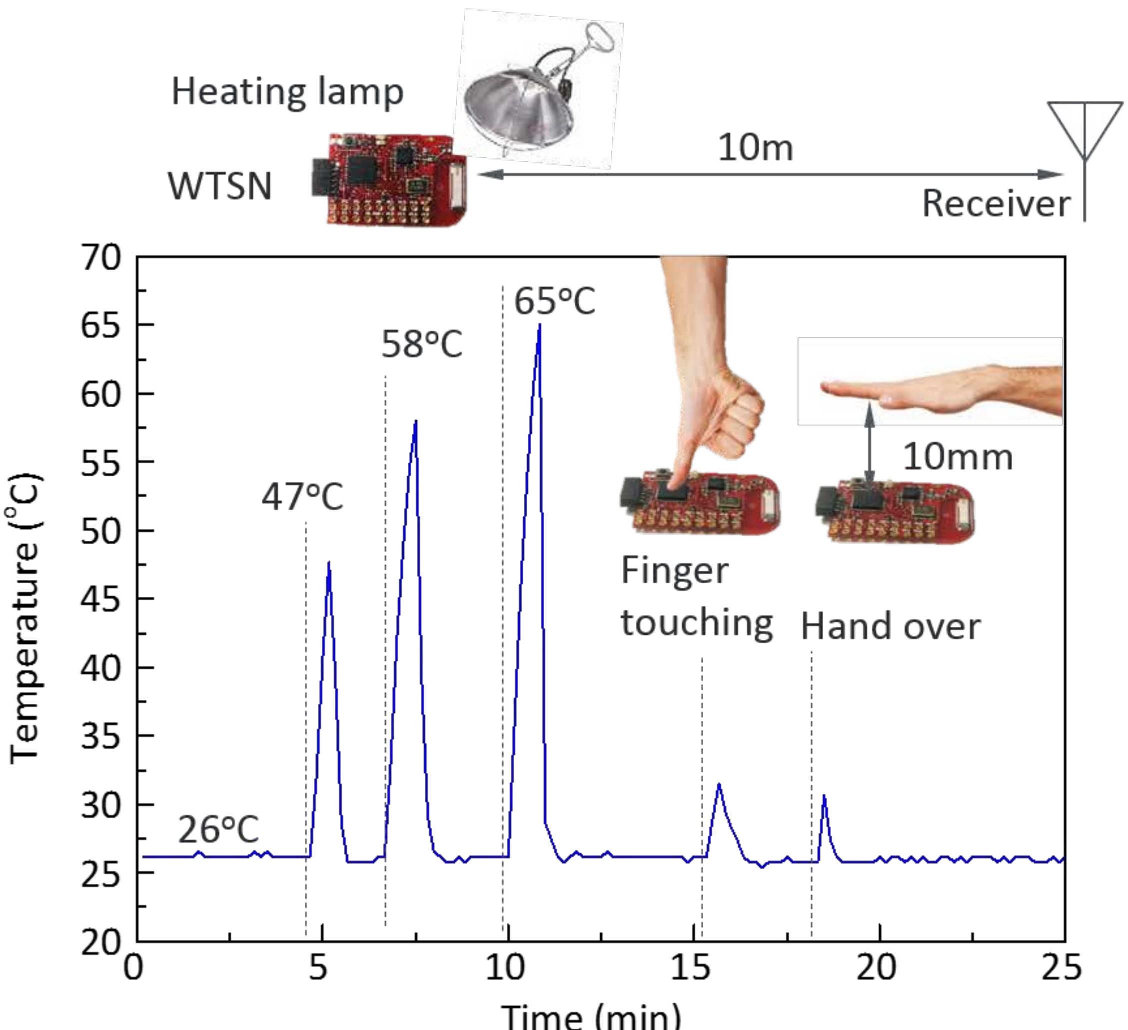
Interdisciplinary CWRU Team (for the Chicago competition) Included:

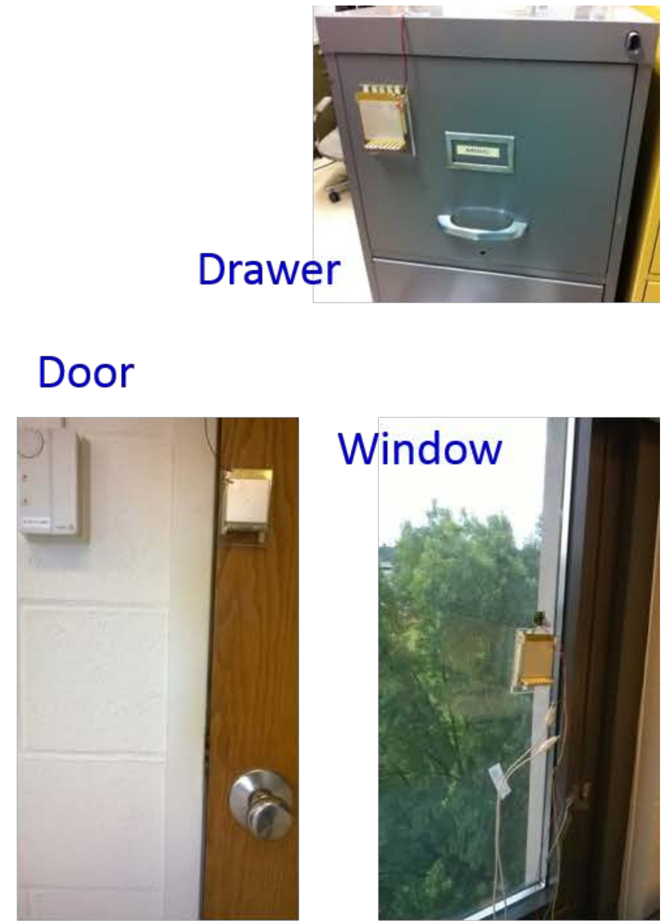
- Engineering
- Business
- Economics
- Materials Science

Q2 Progress and Accomplishments

We have demonstrated wireless temperature sensing by using a commercial wireless sensor entirely powered with our piezoelectric harvester.

We also completed the calibration of different vibrational surfaces for PZE energy harvesting.





Q2 Awards/Recognition

The work in demonstration of wireless temperature sensing powered by PZE vibrational energy harvesting) is accepted in and presented at the IEEE International Frequency Control Symposium (IFCS 2015), the flagship IEEE conference in electromechanical resonant transducers,
The full-length publication is published in the conference proceedings.

Based on his work during this part of the project, high school student Robert Gray (under the supervision and support from Dr. Peng Wang & Dr. Philip Feng) has won the Grand Prize at this Spring's Northeastern Ohio Science & Engineering Fair (NOSEF), ranking the 1st place for the Engineering category at NOSEF, receiving plaques and certificates from CSA, SPIE, and Parker Hannifin.

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Q2 Progress & Accomplishments Toward Commercialization

- Clean Energy Challenge 2015 (Clean Energy Trust, Chicago, IL)
  - 14 cleantech startups from seven Midwestern states competed for $1MM in early stage investment funding—our student team (1 Ph.D. student working on this project plus a few undergrads) made to the one of the only 5 student team finalists
  - The event has sold-out crowd of 400 included clean energy investors, entrepreneurs, and innovators—as well as Illinois Governor Bruce Rauner
  - NREL investor event validated market interest
  - Venture groups from BASF, GE, LG, Siemens and Saudi Aramco all expressed strong interest
  - Extensive feedback from mentors and judges (Energy businesses and VCs)

Clean Energy Challenge 2015 Chicago, IL

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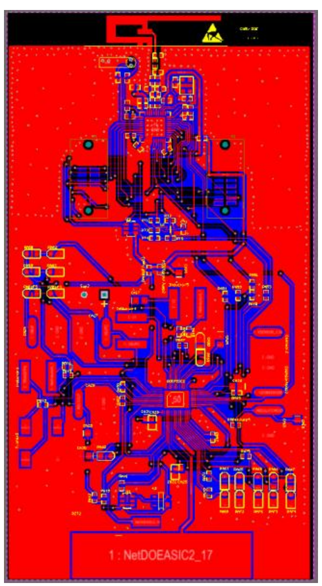
Q3 Progress and Accomplishments

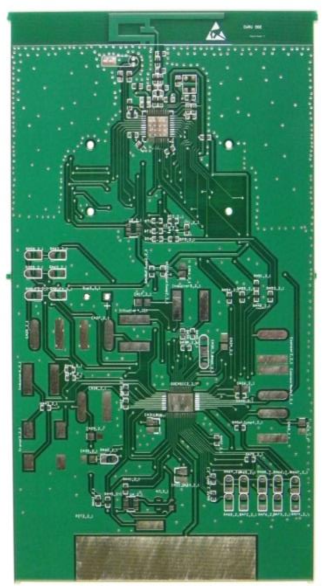
- We have completed the circuit design and produced printed circuit board for the sensor node.
- We also received the ASIC from tapeout and completed the testing
- We further completed the sensor node and fully verified its functionality using external power.

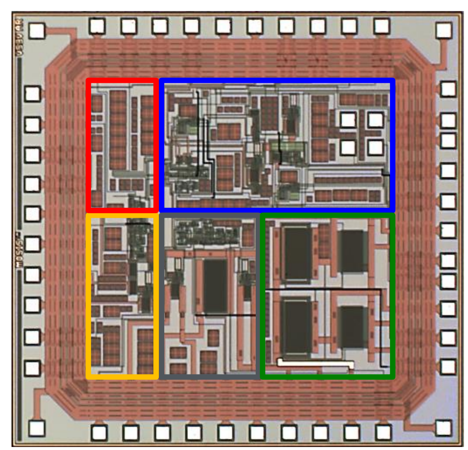
Externally-Powered Sensor Node

Intwine ICG Gateway

Wireless Transmission of Temperature Reading







ASIC Chip Received from MOSIS

LDO (Cold Start)

Control

Rectification and High Speed Charging

High Efficiency Charging

DC/DC Regulator

Q3 Awards/Recognition

The work has been accepted by the 18th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers'15), the leading international conference in electromechanical transducers, energy harvesters, and novel sensor systems, as a Poster Presentation. Team members traveled to the conference and presented the work.

Battery-Less Wireless Temperature Sensors via Harnessing Household Vibration Energy

Peng Wang[1*], Xu-Qian Zheng[1], Ran Wei[1], Aman Nair[1,2], Robert Gray[1,2], Zenghui Wang[1], Philip X.-L. Feng[1*]

[1]Electrical Engineering, Case Western Reserve University, Cleveland, OH 44106, USA

[2]Hawken Upper School, Gates Mills, OH 44040, USA

[*]Emails: peng.wang9@case.edu; philip.feng@case.edu

CASE SCHOOL OF ENGINEERING
CASE WESTERN RESERVE UNIVERSITY

IEEE Advancing Technology for Humanity

Abstract & Overview

We report on experimental demonstration of a wireless temperature sensor node (WTSN) powered by a piezoelectric (PZE) resonant energy harvesting system. The energy harvesting circuit collects and stores the energy generated by a piezoelectric resonant transducer into a capacitor, and uses the stored energy to power the temperature sensor and its associated signal processing circuits for wireless signal transmission. The resulting WTSN transmits measured temperature data over a distance of 10m, in real time, and consumes ~4µW to ~13µW power (for transmission intervals from 10min to 10s, respectively), supplied entirely by the PZE resonant energy harvester. Such self-powered WTSNs, when integrated with building energy management system, can enable low-cost transformation of ordinary buildings into energy-efficient smart buildings.

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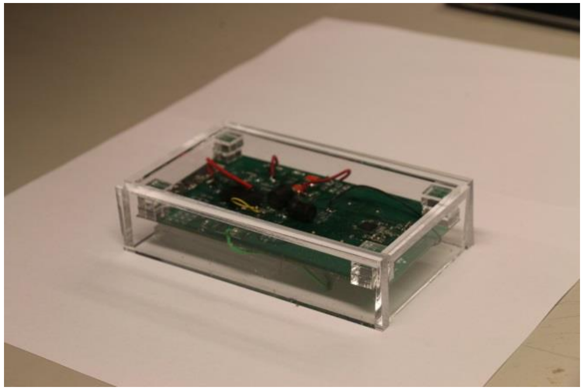
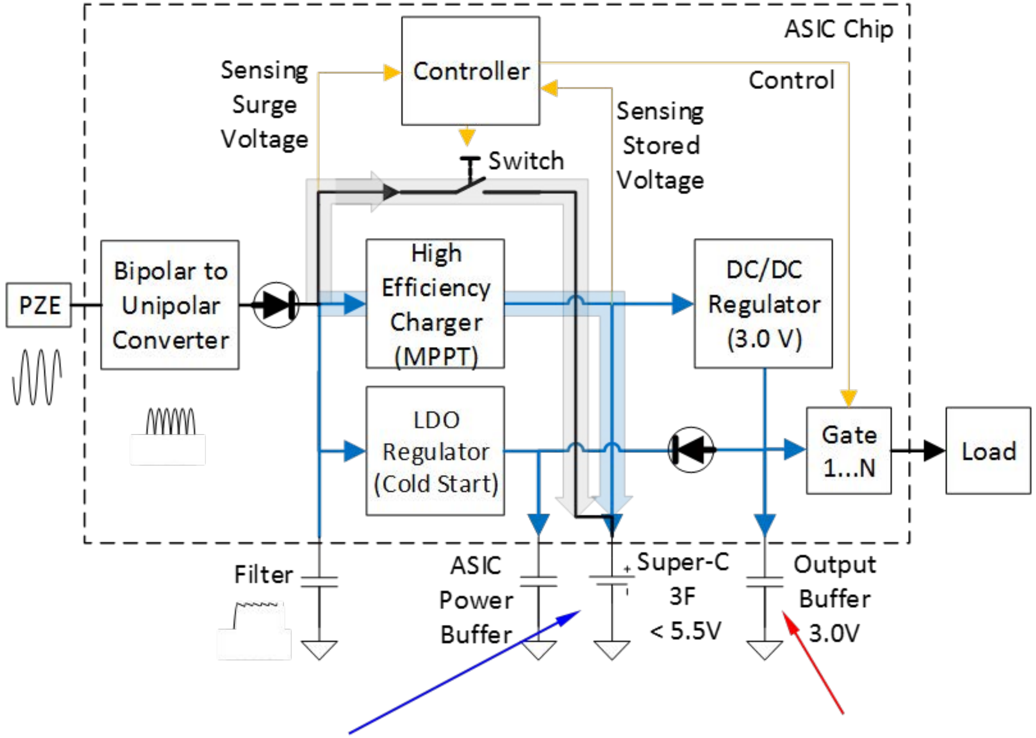
Q4 Progress and Accomplishments

- We have completed assembled the self-powering wireless sensor node.
- We established wireless connection between the sensor nodes and ZigBee gateway.
- We demonstrated self-powering wireless temperature sensing.



Verifying Energy-Harvesting &Ultra-Low Power Operation



Voltage on the super capacitor reflects the total stored energy.
When vibrational energy is harvested, it shows as an increase in
When energy is used to charge the output buffer, it shows as a decrease in voltage.

Voltage on the output buffer shows how the sensor node consumes energy.
When the ZigBee chip performs wireless data transmission, a sudden drop in voltage is seen.
When the voltage fall below a threshold, the ASIC will charge it (from the super capacitor)

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Verifying Energy-Harvesting &Ultra-Low Power Operation

15 minutes of data

Voltage on the Output Buffer

ZigBee Idle Power (No Transmission): slowly drain the voltage on output buffer

Data used for calculation (see next slide)

ASIC charges the output buffer (from super capacitor) when voltage below a threshold

ASIC charges the output buffer (from super capacitor) after each transmission

Data Transmission (Every 10 min): sudden voltage drop (energy consumed)

Voltage on the Super Capacitor

Energy Harvesting Events (4 such events during the 15 minutes)

Minimal voltage drop outside the charging cycles

ASIC extracts energy from super capacitor to charge output buffer

ASIC extracts energy from super capacitor to charge output buffer after each transmission

Verifying Energy-Harvesting &Ultra-Low Power Operation

- We calibrate the power consumption from the measured voltage drops
  - Wireless transmission (data from the drop at 72.4 min):
    - V_{begin}=2.828V, V_{end}=2.503V, $\Delta E=\Delta(0.5CV^2)=8.66\times10^{-4}$J
    - Average power consumption=8.66×10^{-4}J/10min=1.44µW
  - Idle power (data from 67.74min to 69.80min)
    - V_{begin}=2.957V, V_{end}=2.761V, $\Delta E=\Delta(0.5CV^2)=5.60\times10^{-4}$J
    - Average power consumption=5.60×10^{-4}J/(69.80min-67.74min)=4.53µW
  - Total power consumption
    - 1.44µW+ 4.53µW=5.98µW
- Test shows that the complete sensor node exceeds the requirement specified in the SOPO (power consumption 7.4µW when the transmission is one per 10 min)

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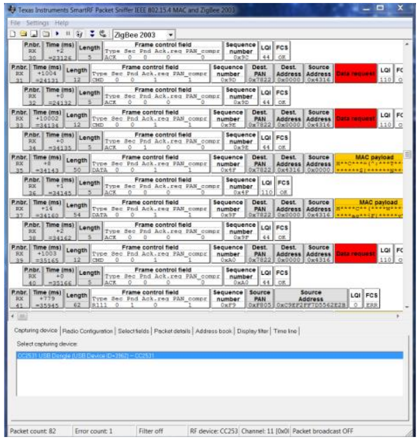
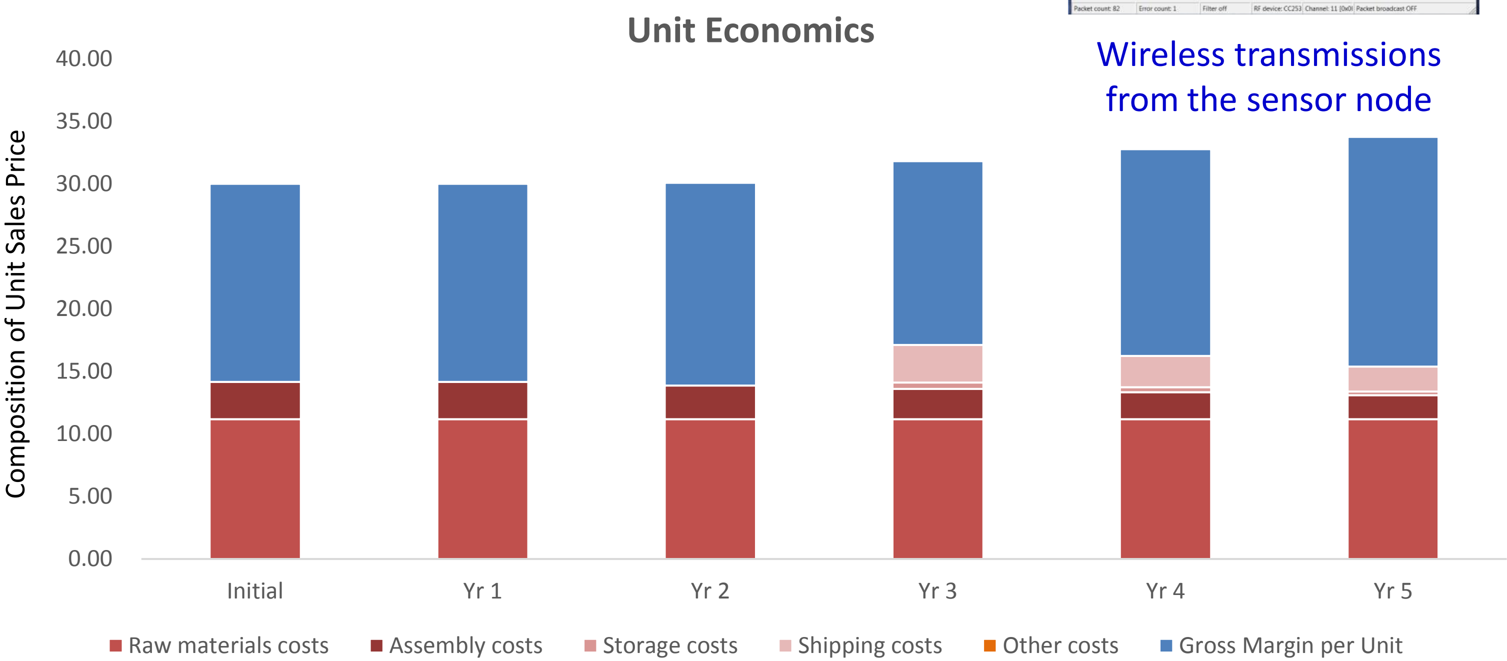
Q5 Progress and Accomplishments

- We have tested wireless functions between the emulator and ICG, which are verified to function as intended.
- We have completed market analysis.



Wireless transmissions from the sensor node



Estimate of unit economics (cost , sales, margin) for the first 5 years after product launch

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Q5 Awards/Recognition

- We have been awarded the Ohio Third Frontier Technology Validation and Start-up Fund (TVSF) as an supplementary resource for validating our self-powering wireless sensor technology and product.

Ohio Third Frontier
Innovation Creating Opportunity
www.OhioThirdFrontier.com

- Our paper "A Self-Powering Wireless Temperature Sensor Node with Low-Power Application-Specific Integrated Circuit (ASIC) and Vibration Energy Harvester" has been accepted for Lecture presentation at the 2016 IEEE International Symposium on Circuits & Systems.

ISCAS 2016
MONTREAL CANADA
IEEE International symposium on circuits and systems
MAY 22 - 25

Q5 Progress & Accomplishments Toward Commercialization

- Our startup based on the technology developed under this project, *CrystalE*, has been making substantial progress towards securing venture capital and commercializing the technology:
- During Q5, the team has already:
  - Won 1st place in Case GLEI Clean Energy Business competition
  - Will attend as finalist in Allegheny CleantechUp competition (3/16/2016)
  - Will attend as finalist in 2016 Clean Energy Trust Challenge (4/12/2016)
  - Will attend as finalist in 2016 Rice Business Plan Competition (4/14/2016)(500+ startup teams around the world competed for the 42 finalist position in the competition)

2015

Case Western Reserve University | Great Lakes Energy Institute — 2nd Place

Finalist — + Clean Energy Trust

2016

Case Western Reserve University | Great Lakes Energy Institute — 1st Place

Finalist — Allegheny CleantechUP

clean energy trust — Finalist

Finalist — RBPC 2016 Rice Business Plan Competition sponsored by Insperity

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Project Integration and Collaboration

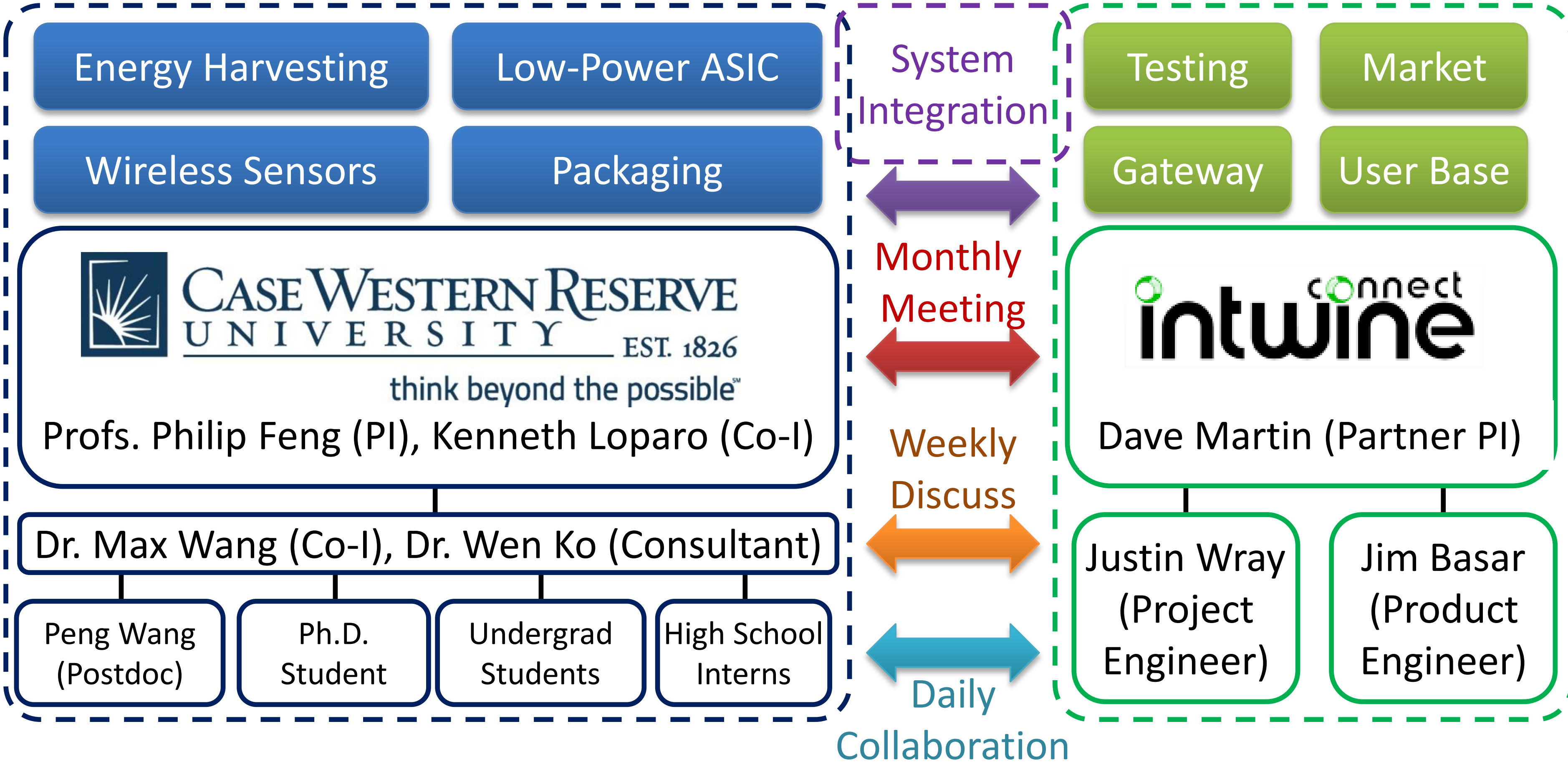
Project Integration: The CWRU team and the Intwine team are both located on CWRU campus (within the same set of interconnected buildings), and have regular meetings to coordinate the progress and make synergetic efforts towards solving technical challenges.

Partners, Subcontractors, and Collaborators: (more in following slides)

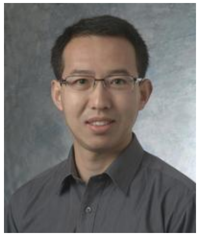
- We work closely with Intwine Connect in both technology development and commercialization effort.
- We work closely with Great Lakes Energy Institute (GLEI) in business plan development and competitions.
- We work with Case Master in Engineering Management (MEM) program in product development and market analysis.
- We work with Case Office of Research and Technology Management (ORTM) in IP management and securing additional resource for technology validation.

Communications: see quarterly details.

Team Management Plan

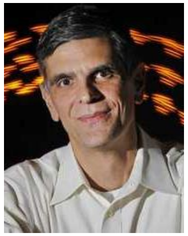


Technical Team



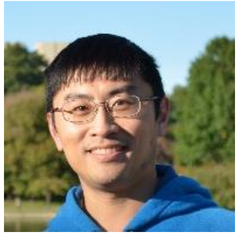
Philip Feng
PI, Case

Kenneth Loparo
Co-PI, Case



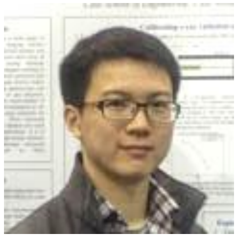
Dave Martin
Co-PI, Intwine

Postdoc/Ph.D.



Max Wang

Peng Wang



Xuqian Zheng

Engineer	Jim Basar	Ryan May	Justin Wray	Ran Wei
Undergraduate	Amanda Jaworski	Eric King	Christopher Herbst	
High School Intern	Aman Nair	Robby Gray	Geoffrey Miller	

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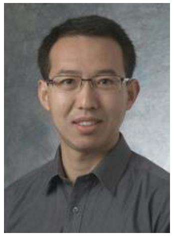
Commercialization Team

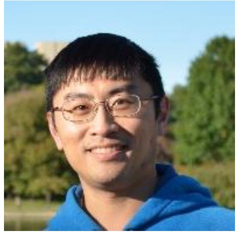


Philip Feng

Mindy Baierl

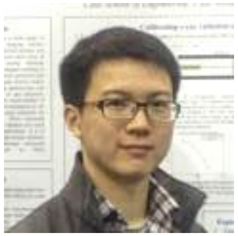
Alexis Abramson

Postdoc and Ph.D. Student



Max Wang

Peng Wang



Xuqian Zheng

Undergraduate (Business and Management)

Billy Littlefield

Alicia Chang

Jeffrey Brown

Advisors & Partners

Ali Ahmed
Cisco

Bob Sopko
Blackstone

Gordon Yonel
Entrepreneur

Roger Saillant
Fowler Center

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Next Steps and Future Plans

Next Steps and Future Plans: (more details in following slide)

- Device
  - Implement compact design in circuit board, smaller energy harvester
- Wireless Function Design
  - Programing on both sensor node and ICG for low-power automated pairing and data transmission
- Commercialization
  - Contact business partners, showcase demonstration prototype

Next Steps and Future Plans

REFERENCE SLIDES

Project Budget

Project Budget: FY2015 numbers are End-of-Year numbers as of 9/30/2015. FY2016 numbers are Project-to-Date numbers as of 1/31/2016 (corresponding to the "Total Project $ to Date" numbers in the Summary Slide).
Variances: Overall the expense follows the original planned budget and the project plan has not been modified.
Cost to Date: See table below.
Additional Funding: N/A

Budget History

10/1/2014– FY 2015 (past)		FY 2016– 9/30/2016 (current)		FY 2017 – N/A (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
308,657.19	56,260.42	405,356.59	60,309.76	N/A	N/A

Project Plan and Schedule

Project Schedule		
Project Start: 10/1/2014		Completed Work
Projected End: 9/30/2016		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned) use for missed
		Milestone/Deliverable (Actual) use when met on time

	FY2015				FY2016				FY2017			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Q1 Milestone: Circuit Design												
Q2 Milestone: Energy Harvester												
Q3 Milestone: ASIC Tapeout and Test												
Q4 Milestone: Prototype Sensor Node												
Q1 Milestone: Sensor Node Programming												
Current/Future Work: Sensor Node Testing												
Q3 Milestone: Packaging/Market Analysis												
Q4 Milestone: System Testing/Commercialization												