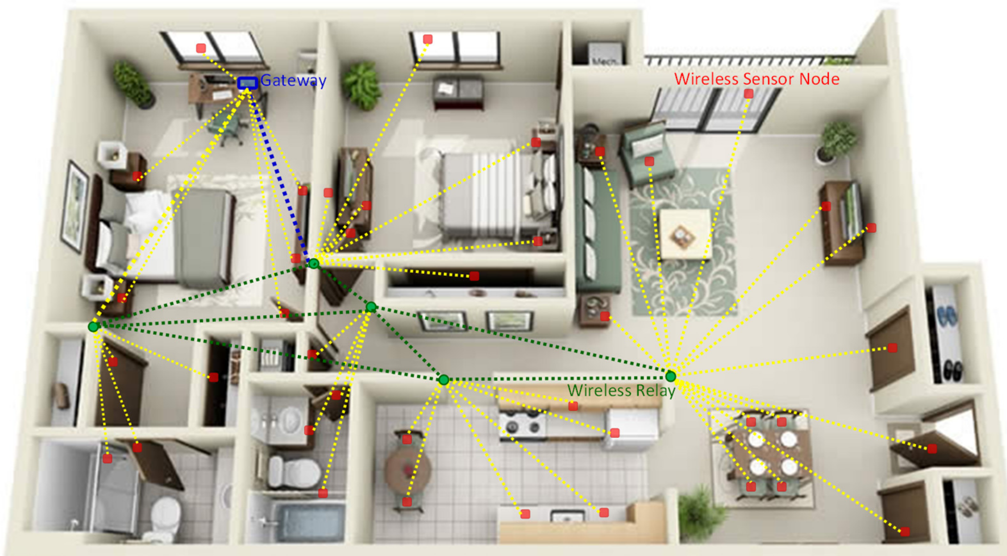
– Final Scientific Report –

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



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EXECUTIVE SUMMARY

The execution of this project has led to: (i) design and demonstration of a *low-cost*, *compact, easy-to-deploy*, *maintenance-free* sensor node technology, and a network of such sensors, which enable the monitoring of building parameters and can *transform today's ordinary buildings into smart buildings* with environmental awareness; (ii) in partnership with Intwine, prototype products that have smaller volume, higher efficiency, and *much lower cost* (in *both manufacturing and maintenance*) than the baseline technology and today's state-of-the-art.

This research has added understanding to the area of energy harvesting, wireless sensors, and smart sensor networks. The research has led to a number of publications in the public domain, as well as technical presentations in various formats in different international conferences (see 7. Key Achievements), adding knowledge to the area of vibrational energy harvesting, power management, ultralow-power circuits, and wireless sensor network. This funded research has also demonstrated technical effectiveness and economic feasibility for the technologies investigated in this research. The energy harvesting scheme, circuit design, and wireless sensing functionalities developed in this project are being patented, and a startup company (CrystalE) has been formed to bring this technology to market. The business startup team has been in discussion with a number of venture capitals and potential commercialization partners, and attended 2017 Consumer Electronics Show (CES) to showcase the technology developed.

1. INTRODUCTION AND BACKGROUND

1.1 Background

Case Western Reserve University (CWRU) is a top-ranked research university with excellent academic reputation (12^{th} among private institutions and 24^{th} overall in science and engineering research expenditures). It is based upon the 1967 federation of a renowned 'tech' university, the Case Institute of Technology (famous for physics, chemistry, engineering and applied sciences, founded 1880) and the Western Reserve University (reputed for medicine, nursing, arts & sciences, founded 1826). CWRU has 16 Nobel Prize winners (a remarkable record given its small size), including physicist Albert Michelson and chemist Edward Morley who won the very first Nobel Prize in science for American. CWRU is at the center of the intellectually stimulating 'University Circle', just east of Cleveland, OH, with neighbors including the Cleveland Clinic, University Hospitals of Cleveland, Louis Stokes Cleveland Department of Veteran's Affairs Medical Center, Cleveland Institute of Music, the Cleveland Hearing & Speech Center, the Cleveland Museum of Art, the Cleveland Museum of Natural History, the Severance Hall (home of the Cleveland Orchestra), and the Cleveland Play House.

The Case School of Engineering today (evolved from the reputed Case Inst. Tech.), despite its tiny size (108 faculty), has all major research programs ranked in top 50 and several in top 20. The school's strategic initiatives have been focused on Energy, Advanced Materials, and Human Health. Particularly the school has been internationally renowned in areas including biomedical engineering, polymers and macromolecules, ceramics, electromechanical engineering, renewable energy, micro/nanoscale and implantable technologies. The school has created the Great Lakes Energy Institute (GLEI) to build an energy focus around related research. Since its inception in 2008, GLEI has enabled a 4-fold increase in energy research (with a 42% proposal success rate). GLEI, working with over 100 faculty and 100 industry partners, has raised over $60M for innovative research on cutting-edge energy technologies. The success has gained national attention. We are in the top 5 leading Department of Energy (DOE) ARPA-E awards.

In this proposed project, the strong collaboration between CWRU researchers and engineers at Intwine Connect LLC, which has a research lab located on CWRU campus, combines unique expertise from both sides and accelerates the development of technologies and prototypes that would be transformative for building energy management with unprecedented awareness and intelligence. The team's key technological components include: (i) Self-powering via spectrally-engineered high-efficiency vibration energy harvesters [1-3] that are integrated with low-cost, robust supercapacitors; (ii) Innovative power management via application-specific integrated circuits (ASICs) [4,5] for ultralow-power sensing and wireless communication (such ASICs have already been applied to implantable biomedical devices for human health applications with very stringent power budget [5]); (iii) The strong partnership between CWRU and Intwine enables us to leverage the extensive knowledge, experience, and customer base of Intwine to facilitate customer-orientated development and commercialization of the proposed technology.

CWRU is surrounded by industrial leaders in energy and has a long history of delivering technologies to market. Ohio has wealth of local manufacturing resources that provide a distinctive advantage in prototype development and scale-up. CWRU has a proven Technology Transfer Office managing 200+ invention disclosures, 35+ transactions, multiple patents and four to five start-ups per year. CWRU is integrated into the nationally recognized Northeast Ohio entrepreneurial ecosystem focused on energy, working collaboratively with organizations such as NorTech, TBEIC, and JumpStart.

1.2 Project Goals

The goals of this project are to: (i) 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; (ii) in partnership with Intwine, prototype and develop target products that have smaller volume, higher efficiency, and *much lower cost* (in *both manufacturing and maintenance*) than the baseline technology or today's state-of-the-art.

1.3 DOE Impact

Funding from BENEFIT (DE-FOA-0001027) allows us to accelerate the development of the energy harvesting systems and building energy management system (BEMS) from TRL 2 to TRL 6. Prior funds from VA and NIH (for PI's collaborative research on self-powering medical implants toward long lifetime, at TRL 1-2) have facilitated fundamental research of the devices and circuits, paving way for this project. The DOE funding provides additional scientific and entrepreneurial resources necessary to translate the self-powering microsystems from medical to energy-efficiency applications and to purchase the electronic components necessary to incorporate it into a BEMS. The novel self-powering wireless sensor system is transformational in its ability to cost-effectively expand the use of sensors, enhancing data granularity in installed systems and expand the use of BEMS to small commercial buildings contributing to DOE-BTO's goal to deliver 50% primary energy savings by the year 2030.

1.4 Relevance and Outcomes

1.4.1 Description of the Proposed Technology

We propose to develop *low-cost, easy-to-deploy, self-powering* wireless sensor nodes, and integrate them with existing solutions into wireless sensor networks, to *transform today's mainstream civilian buildings to next-generation smart buildings*. Each sensor node (Fig. 1) includes energy-harvesting components (which convert the vibrational motion of its mounting surface into electricity stored in supercapacitors), multiphysical sensor components, and an ultralow-power wireless communication unit. The sensors communicate with a powered hub unit (we use the Intwine Connect Gateway (ICG), a mature product from the partner Intwine Connect, LLC) intermittently while constantly harvesting and storing energy, maintaining *always-on operation without external energy input*. These sensors *can be installed by the end users* (requiring no professional service) in a *100% non-intrusive way* by mounting onto existing surfaces with tapes, stick-and-peel labels, or alike. The proposed wireless sensor node can be implemented in any existing home or office and requires minimal maintenance, while providing granulated information (*e.g.* temperature) to enable energy efficient operation.

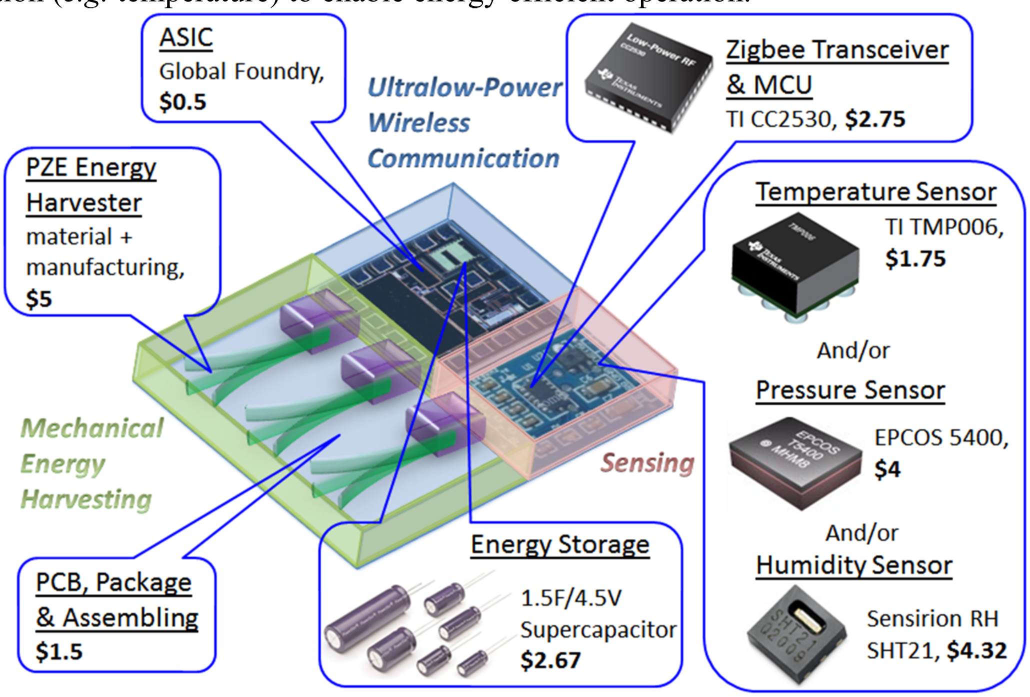


Fig. 1: The proposed low-cost sensor node and its components (with price/estimated cost).

1.4.2 Applicable DOE Targets

The proposed project directly address the goals and objectives by providing a solution with a *new type of self-powering sensor system*, with *low-cost* sensors that can be easily installed, commissioned, and operated to communicate to a centralized system. It utilizes *non-proprietary* communication protocols by employing well-established ZigBee technology (based on IEEE 802.15 standard), which is designed for *low power*, *low data rate*, and *secure* wireless transmission. The proposed solution has the following merits:

1. *Interoperability*. The proposed sensor nodes can *work seamlessly within any existing control solutions* by adopting the open ZigBee protocol and utilizing commercially available ZigBee components, for wireless integration with the ICG (which use the same wireless components and

protocol) to connect with existing computer systems and mobile devices.

2. <u>Scalability</u>. The proposed solution is *compatible with mass production*, and maximizes the use of existing commercial components to *minimize development cost and risk*. The sensor network can also *easily be scaled* to fit buildings with different sizes and layouts, through the mesh-topology nature of ZigBee wireless network.

3. <u>Deploy-ability</u>. The proposed system requires *minimal effort in installation and initialization*, which can all be performed directly by the end user. The self-powering nature *eliminates the requirement for on-going commissioning or maintenance*, such as battery replacement.

4. <u>Availability and Flexibility</u>: The proposed solution uses the open IEEE 802.15 standard and utilizes commercially available ZigBee components for *non-proprietary, secure wireless communication*. In fact, this *open-source hardware solution* with *modular design* allows users to fully customize the sensor node by choosing different components: *e.g.* the user can choose to use a different ZigBee chip, or even a wireless solution other than ZigBee.

5. <u>Affordability</u>: The proposed system can be *manufactured with low cost* by integrating existing mature technologies under an optimized design for self-powering sensor applications. ***The estimated production cost for each sensor node can be as low as ~<u>$15</u>*** (Fig. 1), which corresponds to ***a total saving of <u>$1.4M-4.2M</u>*** for a typical small town, when compared with existing wireless sensing solutions. The *installation requires minimal effort and cost*: no wiring is needed, and the sensors can be applied to any household surface using included tape. The self-powering nature *minimizes the cost and maintenance required for ongoing operation*, with ***an average annual cost saving of <u>$160k-270k</u>*** for a small town (Table 1).

1.4.3 Expected Outcomes

We expect this project to lead to an end-product of wireless sensor system that is ready for mass production and commercialization. The system includes one or more self-powering wireless sensor nodes for in-building monitoring, and optional ZigBee relay units for operation in large buildings. The sensor nodes integrate seamlessly with Intwine's existing products (specifically the ICG) and form a complete *low-cost* solution to energy efficient building operation.

1.5 Project Concept and Feasibility

The technical feasibility of the proposed solution is based on two key expertise: (i) *self-powering* via vibration energy harvesting, and (ii) *ultralow-power* wireless communication.

<u>Vibration Energy Harvesting</u>*:* The proposed sensor node uses piezoelectric (PZE) material-based mechanical resonators to harvest the vibrational energy of the hosting surfaces. Mechanical vibrations are prevalent in buildings. They can be transient (closing doors), or lasting, from seconds (sink grinder), to minutes (microwave), hours (drying machine), even all day long (refrigerator, HVAC). Such energy is almost always wasted. The typical frequency range of indoor vibrations is 40–200Hz, ideal for mm- to cm-sized mechanical resonators [6].

Piezoelectric materials can directly convert mechanical vibration into electrical charges and voltage. Figure 2a-2c illustrates our prior work on demonstrating resonant energy harvesters *operating in ambient conditions*. The mm-sized piezoelectric devices (Fig. 2c) harvest vibration energy from a small pump and easily power a blue LED, *outputting >250μW per cantilever*.

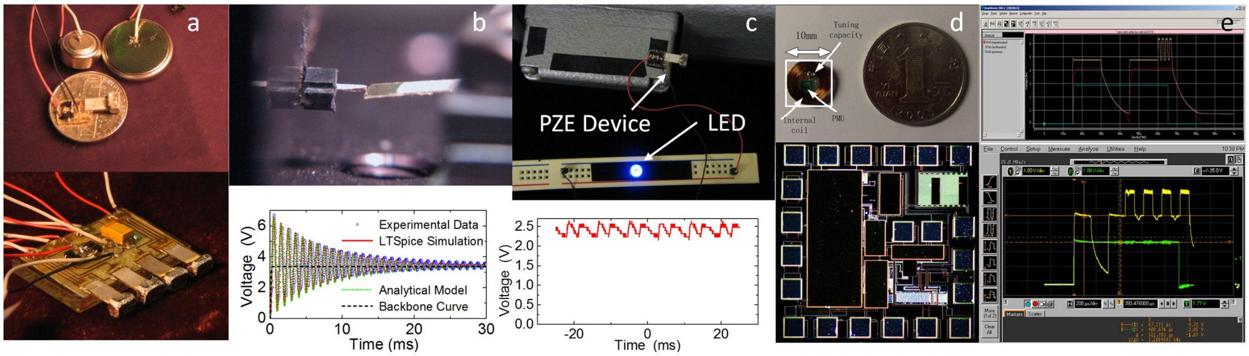


Fig. 2: Examples of established results in prior work. (a) A PZE energy harvest and an array. (b) Transient and (c) lasting vibration test image and data. (d) ASIC die images. (e) Simulation and measured ASIC circuit response.

We have estimated available vibrational power from various indoor items and measured selected surfaces using commercial accelerometers [7].

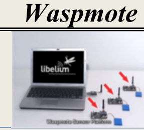
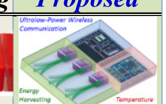
Ultralow-Power Wireless Communication: The power input from the energy harvester is handled by an ASIC which manages the energy utilization and storage. In prior work we have developed an ASIC for low-power operation of wireless medical implants (Fig. 2d & 2e), which consumes a ***miniscule power of just 15pW*** in listen mode [5], paving way for proposed work.

To minimize cost and risk, in proposed work we used TI CC2530 ZigBee chip for ultralow-power secure wireless communication. For indoor environmental monitoring, the average power consumption is estimated to be 4µW [8], and the energy harvested from typical household surfaces is sufficient for typical daily operations of the wireless sensor nodes.

1.6 Innovation and Impacts

1.6.1 State of the Art

Table 1: Comparison of Different Wireless Sensor Systems and the Proposed Approach

Wireless Sensor Systems		*Waspmote*	*Plugwise*	*MEMSIC*	*TI Sensortag*	*Proposed*
						
Installation		Complicated (8×2 hrs)	Limited (AC power)	Applicable to any surface	Applicable to any surface	Any surface that vibrates
1 Sensor Node Cost/Price:		$225	$163	$112	$25	$15
1 Home system (10 sensor + 1 gateway)	Acquire Cost	3,534	1,915	1,420	$550	$450
	Maintenance Cost	77	110	120	$108	0
	Payback Time	8.3	4.9	3.7	1.4	0.9
1 Small Business System (100 sensor + 1 gateway)	Acquire Cost	$23,784	$16,585	$11,500	Not scalable for larger network (based on Bluetooth technology)	$1,800
	Maintenance Cost	$1,825	$2,000	$3,000		$0
	Payback Time	7.5	5.5	5.8		0.4
1 Small Town (1000 Homes + 50 Small Businesses)	Acquire Cost	$4,723,200	$2,744,250	$1,995,000		$540,000
	Maintenance Cost	$167,750	$210,000	$270,000		$0
	Payback Time	8.1	5.1	4.2		0.7

In Table 1 we summarize the commercially available indoor wireless sensor systems and compare them to the proposed solution. The cost for each sensor node and different sized systems, as well as the annual maintenance cost and the payback time are compared.

1.6.2 Innovation of Proposed Approach

The proposed approach leverages the energy harvesting capability of piezoelectric devices, the ultra-low-power and wide-range wireless communication of the open ZigBee system, and the advanced power management of our ASIC design, to offer a *low-cost* solution for improving building energy efficiency. The clear comparative advantages are:

1. Low cost to manufacture: The proposed system can be *manufactured at low cost* by integrating existing technologies under an optimized design for self-powering sensor applications. ***The estimated cost for manufacturing each wireless sensor node is as low as ~$15*** (Fig. 1).

2. Facile to install: No wiring is needed, and the sensors can be applied to any vibrational surface with tapes that's easy to apply/remove and efficiently transduces vibrations. The user interface allows one-man installation of the entire system, ensuring all nodes are within the wireless range, and notifies users when a ZigBee router (relay) is needed, especially for large homes/offices/retailers.

3. Minimal cost to operate: The self-powering sensor nodes require no battery or other external power supply, and the ZigBee wireless network is capable of automated re-establishing wireless connection in the event of individual node failure. Such self-sustained operation minimizes the maintenance cost and effort.

1.6.3 Potential to Advance the State-of-the-Art

The proposed solution can advance the state-of-the-art by significantly reducing the energy and cost required for long-term operations. All the existing products require external power supply, in the form of batteries or domestic power, which imposes maintenance cost in addition to limitations in deployment. The clear advantage of the proposed system is *maintenance-free operation*, in addition to *low acquiring cost* and *facile installation process*.

2. PROJECT PLANNING

2.1 Statement of Project Objectives

The research 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 develop the sensor node and network via engineering and integration of existing technologies, including high-efficiency mechanical energy harvesting, and ultralow-power integrated circuits (ICs) for sensing and wireless communication. Through integration and innovative power management via specifically designed low-power control circuits for wireless sensing applications, and tailoring energy-harvesting components to indoor applications, the target products *have smaller volume, higher efficiency*, and *much lower cost* (in *both manufacturing and maintenance*) than the baseline technology. Our development and commercialization objective is to create prototypes for our target products under the CWRU-Intwine collaboration.

2.2 Technical Scope Summary

Develop a fully functioning prototype sensor node, with self-powering capability and wireless communication compatibility. This includes:

1. Complete application-specific integration circuit (ASIC) design with ultralow-power performance verified through mixed-signal simulation.
2. Optimize piezoelectric (PZE) energy harvester module with power generation meeting requirements.
3. Prototype ASIC chip and circuit board with designed functionality and power consumption. Demonstrate remote temperature sensing
4. Complete prototype self-powering wireless sensor node with designed function, verified in various indoor conditions.

Develop a fully functioning prototype wireless sensor system, with sensor nodes, wireless relays, and a central hub unit interfacing with control systems. Develop and implement a technology to market strategy and commercialization plan to move the product to market-readiness. This includes:

1. Verify communication and remote programming functions
2. Test all functions with actual sensor nodes and ICG and relay(s)
3. Package all the components into a consumer friendly prototype device. Complete the market analysis and the commercialization plan including target customers, target costs, potential US manufacturers and potential jobs created.
4. Test prototype system in at least 3 different indoor settings. Contact US manufacturers for production of components and packaging. Identify and contact a minimum of 3 commercialization partners

2.3 Work Breakdown Structure

PHASE 1 – SENSOR NODE DEVELOPMENT

Task 1: Develop a Prototype Self-powering Wireless Sensor (Month 1−Month 12)

Task Summary: We develop a non-proprietary prototype sensor node in this task. Starting with a pre-prototype made of generic and developer components, we sequentially replace each part of it with the components we specifically develop for this project. The objective is to develop the energy harvesting module, design and produce the ASIC, and assemble the components into a fully functioning prototype. The final deliverable is a wireless sensor composed of a piezoelectric harvester, an ultralow power ASIC, a temperature sensor, and a wireless module. All hardware and software solutions developed through this project remain open source and nonproprietary.

Subtask 1.1: Circuit Design (Month 1−Month 3)

Subtask Summary: Design the ASIC with primary focus on energy storage/management for ultralow-power wireless sensor operation (energy conversion/storage/allocation). We perform: (1) schematic design, (2) presimulation (including behavior, logical, and transistor simulation) to validate the design concept, (3) layout design, (4) postsimulation (including analog and logical simulation).

Milestone 1.1 (Month 3): ASIC design finished.

Subtask 1.2: Energy Harvester Implementation (Month 1−Month 6)

Subtask Summary: We optimize the PZE module for indoor energy harvesting. We calibrate its harvesting power on various household surfaces, and use it to power a commercial wireless sensor to demonstrate self-powering wireless temperature sensing.

Milestone 1.2 (Month 6): PZE energy harvester completed. We demonstrate wireless sensing by using a commercial wireless sensor entirely powered with our piezoelectric harvester. For this demonstration, the commercial wireless sensor requires 7.4μW when the wireless transmission rate is set at 1 transmission/10min.

Subtask 1.3: Circuit Implementation (Month 3−Month 9)

Subtask 1.3.1: Mainboard Development

Subtask 1.3.2: Tapeout ASIC

Subtask Summary: Upon receiving the packaged ASIC, it is installed on the mainboard together with all the other components to demonstrate wireless sensing capability.

Milestone 1.3 (Month 9): The deliverable is a functioning sensor node (less the PZE module).

Subtask 1.4: Sensor Node Integration (Month 9−Month 12)

Subtask Summary: Integrate the PZE module (Subtask 1.2) with the main board (Subtask 1.3), and establish self-powering wireless operation of the prototype sensor node.

Milestone 1.4 (Month 12): A self-powering, fully functional wireless sensor node is demonstrated. It (1) generate and store sufficient energy; (2) read the sensor (baseline: 1 reading/10 min); and (3) transmit sensor reading to the Intwine Connect Gateway (ICG).

PHASE 2 – SYSTEM DEVELOPMENT, INTEGRATION, AND TECHNOLGY TO MARKET

Task 2: Prototype a Wireless Sensor Network toward Product (Month 13−Month 24)

Task Summary: Develop and test non-proprietary and open-source wireless sensing system. Integrate the self-powering wireless sensor from Task 1 to the ICG. Distribute under the Creative Commons License BY-NC-SA. All the detailed research results and published papers and reports are available for download.

Subtask 2.1: Function Design (Month 13−Month 15)

Subtask Summary: Communication schemes between the ICG and the sensor node are established and developed in this task The CWRU team performs programming on the developed sensor node to communicate with the ICG. The Intwine team provides ICG hardware and programming support to ensure communication functionalities.

Milestone 2.1 (Month 15): Wireless functions between the emulator and ICG are verified to function as intended.

Subtask 2.2: Function Implementation (Month 13–Month 18)

Subtask Summary: Test and debug the communication and programming functions between the actual sensor node and the ICG.

Milestone 2.2 (Month 18): All wireless functions beyond simple sensing (including self-guided installation, self-adjustable sensing, remote programming*)* on actual sensor nodes are verified to function as intended.

Subtask 2.3: Components Packaging (Month 13–Month 21)

Subtask Summary: Develop physical enclosure and mounting mechanisms.

Milestone 2.3 (Month 21): Fully functioning, packaged final product. The sensor node can be easily handled by end users, and have clear brand identity.

Subtask 2.4: Full-System Testing (Month 22-Month 24)

Subtask Summary: Full-system tests in various indoor settings.

Milestone 2.4 (Month 24): Fully tested system ready for production/commercialization. The full system includes the wireless sensor node (developed in this projected), the wireless relay unit (developed in this project), and ICG (for purpose of developing and demonstrating the sensor node; the sensor node also is compatible with other similar systems). The wireless sensor node is self-powered (but also have interfaces available for other power sources such as solar cell and battery pack), and is connected wirelesses to the ICG. The sensor node includes a temperature sensor, but is compatible with other types of physical sensors (humidity, light, *etc.*). The sensor node, the optional wireless relay unit (for larger buildings), and the ICG form a final, highly customizable system that is available as a household product

Task 3: Technology to Market Strategy & Commercialization Plan (Month 12–Month 24)

Task Summary: The technology-to-market strategy and commercialization plan is developed in this task. All hardware and software solutions developed through this project remain open source and nonproprietary. We distribute under the Creative Commons License BY-NC-SA. Peer-reviewed publications (journal and conference papers) and patent publications (application, granted patents) are available on the publishers' websites.

Subtask 3.1: Develop Market Strategy (Month 13–Month 21)

Subtask Summary: Conduct a market analysis of potential sales and evaluation of potential US jobs created by commercialization. Identify target range for total system cost.

Milestone 3.1 (Month 21): Market analysis completed. Target costs and job creation analysis included in deliverables.

Subtask 3.2: Develop Commercialization Strategy (Month 13−Month 21)

Subtask Summary: Identify at least three potential firms for commercialization

Subtask 3.3: Develop Technology to Market Strategy (Month 19−Month 24)

Subtask Summary: Identify potential US manufacturers of required system components.

Milestone 3.3 (Month 24): US manufacturers and commercialization partners identified and contacted.

2.4 Milestones Summary Table

Table 3: Milestones Summary

Recipient:	***CWRU & Intwine Connect LLC***						
Project Title:	*Transforming Ordinary Buildings into Smart Buildings via Low-Cost, Self-Powering Wireless Sensors & Sensor Networks*						
Task #	**Task/ Subtask**	**Milestone Type**	**Milestone #**	**Milestone Description**	**Milestone Verification Process**	**Anticipated Date**	**Anticipated Quarter**
1.0	Develop a Prototype Self-powering Wireless Sensor						
1.1	*Circuit Design*	*Mile-stone*	*1.1*	*Circuit design of the ASIC and circuit board ready*	*Verification of circuit functionality with Cadence.*	*Month 3*	*Quarter 1*
1.2	*Energy Harvester*	*Mile-stone*	*1.2*	*Piezoelectric energy harvester optimized*	*Output of harvester verified with electrical measurements*	*Month 6*	*Quarter 2*
1.3	*Circuit Implemen-tation*	*Mile-stone*	*1.3*	*ASIC prototype fabricated in foundry; circuit board and other electrical components made*	*Remote sensing tested for the sensor node using alternative power input*	*Month 9*	*Quarter 3*
1.4	*Node Integra-tion*	*Go/ No-Go*	*1*	*Prototype sensor node complete, interfacing electrical components with the harvesting module*	*Remote sensing tested for the sensor node using PZE energy harvester onboard*	*Month 12*	*Quarter 4*
2.0	Prototype a Wireless Sensor Network toward Product						
2.1	*Function Design*	*Mile-stone*	*2.1*	*Programming for the sensor node functions communication schemes*	*Verification of communication using TI development tools*	*Month 15*	*Quarter 5*
2.2	*Function Implemen-tation*	*Mile-stone*	*2.2*	*Completing testing designed local and remote functions for sensor node and ICG;*	*Verification of sensor functions and wireless communications between the sensor node and ICG*	*Month 18*	*Quarter 6*
2.3	*Compo-nents Packaging*	*Mile-stone*	*2.3*	*Production of the end-product package for all the components in the wireless sensor system*	*Verification of compatibility and functionality of the package with every component in the system*	*Month 21*	*Quarter 7*
2.4	*Full-System Testing*	*Mile-stone*	*2*	*Full scale testing in various indoor configurations and operation conditions*	*Demonstration of the complete system in realistic settings; all components ready for production.*	*Month 24*	*Quarter 8*
3.0	Technology to Market Strategy & Commercialization Plan						
3.1	*Function Design*	*Mile-stone*	*3.1*	*Market analysis completed.*	*Target costs and job creation included in deliverables*	*Month 21*	*Quarter 7*
3.2	*Function Implementation*	*Mile-stone*	*3.2*	*Develop Commercialization Strategy*	*Identify at least three potential firms for commercialization*	*Month 23*	*Quarter 7*
3.3	*Components Packaging*	*Mile-stone*	*3.3*	*Identify potential US manufacturers of required system components*	*US manufacturers and commercialization partners identified and contacted.*	*Month 24*	*Quarter 8*

2.5 Project Management

The PI (Feng) is responsible for the project and is the primary contact for the DOE Program Manager. To facilitate a seamless collaboration between CWRU and Intwine, the PI and the Co-Is (Loparo, Martin, Wang) function as the leadership team to leverage the combined expertise and the unique skill sets on both sub-teams to develop an innovative, synergistic multidisciplinary group. The leadership team sets the tone for the collaborative efforts, ensures development goals are met, and facilitates paths to market. The leadership team has been meeting monthly to discuss research progress, team performance and address pressing issues. ***Intwine engineering offices and laboratory facilities are located on CWRU campus***; this greatly facilitates the collaboration and enhance the project development. Regular meetings were highly focused and action oriented, and occured *in person* on the CWRU campus. Co-I Ken Loparo works routinely with the Intwine team through several other ongoing collaborative projects, and has developed an effective and productive working relationship.

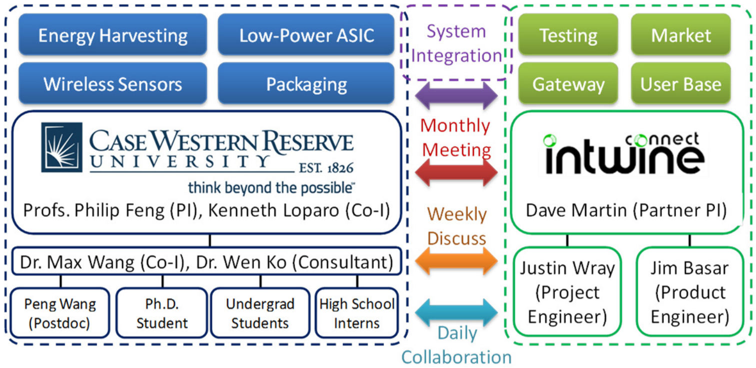


Fig. 3: Team organization and management plan.

The full project team (Fig. 3) includes 3 faculty, 2 research associates, a few Ph.D. students and multiple opportunities for undergrad and high-school interns. The project team is co-located on CWRU campus, making it perfect to have face-to-face meetings. The team uses a private cloud-based site for internal use to share data, discussions, reports, publications/literature, agendas. Access is limited to team members and information is treated as confidential. The full project team met regularly (weekly or biweekly) to review progress, technical challenges, tasks and plans, *etc*. Quarterly reports have been published highlighting specific tasks and milestones. An annual summary is published and reviewed by the entire team including the DOE Program Manager. The team presents and publishes key findings at program review and other important conferences in the research field.

2.6 Market Transformation/Commercialization Plan

Market Analysis: According to Commercial Buildings Energy Consumption Survey (CBECS), commercial buildings represent 19% of US energy consumption. Small commercial buildings, less than 50,000 square feet, comprise over 50% of the buildings. Managing energy for buildings is an emerging, high growth market forecasted to include \$3.2 billion in advanced sensors by 2025 (Navigant Research "Advanced Sensors for Intelligent Buildings"). The market for building energy management systems is new, highly fragmented and growing rapidly. The value chain (see Fig. 4) is evolving as the market grows and contains a mix of small start-up companies and large established brands throughout. Successfully commercializing novel sensors requires established relationship with end-users, an understanding of their energy management goals, data analytics, BEMS development, installation and support. CWRU is partnering with Intwine Connect LLC to help navigate this complex and dynamic market, integrate the novel sensors into a BEMS and maintain customer relationships. Intwine Connect, LLC is an independent company that develops hardware, software and services for Cloud-based monitoring, management and utilization of business-critical performance data. The company's mission is to be the best at collaborating with customers to provide an end-to-end solution that connects electronic devices to businesses and end users via user-friendly, real-time, two-way communications. The company is focused on deploying its end-to-end energy management platform to meet the needs of retail energy providers, regulated utilities, and commercial building and multi-family residential owners and operators.

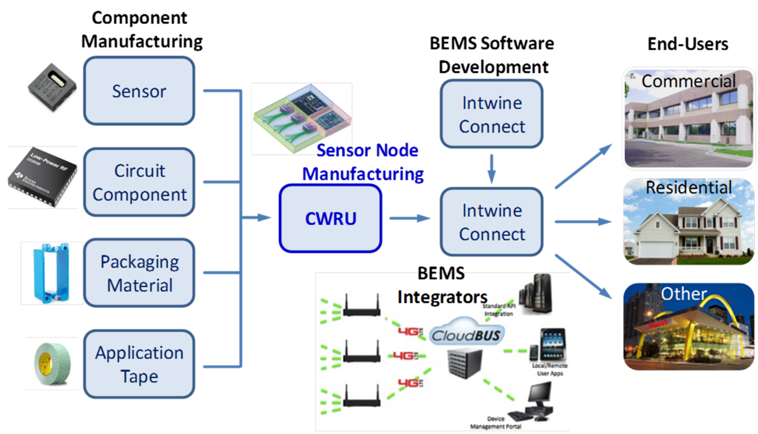


Fig. 4: Value chain and path toward market and end users.

The company's primary product is its ICG, which provides both lower-level, physical-layer gateway functionality and upper-level protocol translation functionality for the Cloud, "Internet of Things" (IoT) and Machine-to-Machine (M2M) applications. The gateway, combined with proprietary software and user-defined interfaces, is the technology backbone that enables customers to connect proprietary and standard monitoring and measuring devices to create smart buildings, "the connected home" in an ecosystem of third-party devices – devices that have not previously been connected. Intwine helps integrate the novel sensors into a BEMS that can be readily packaged, distributed and supported in the initial target market: small commercial buildings. CWRU and Intwine have collaborated on multiple projects and have a working agreement already in place to support research and development projects.

Product Development Plan: The novel sensors described in this project are developed using readily available components from US suppliers. One key component, the PZE material, are to be manufactured locally in Cleveland by Channel Products Inc. and MTC ElectroCeramics, both of which are leading manufacturers of piezoelectric materials, and both have had close relationship to CWRU for more than half a century (*e.g.* the many collaborative work they co-authored with Prof. W. Ko, the Consultant on this project).

The development plan includes a prototype in the Year 1 that can be modified to include customer requirements (size, design and functionality) when integrated into a user friendly energy management system. The prototype can be further refined based on feedback from customers willing to validate the technology in live applications. The refined prototype and input from local component vendors are the basis for a manufacturing specification. The sensor technology can be manufactured by a spin-out company/by Intwine under license from CWRU.

2.7 Project Personnel

Philip Feng (PI, CWRU) is currently an associate professor in EECS. He is an electronic engineer and experimental applied physicist with expertise in novel multiphysical sensors with MEMS/NEMS, ultralow-power nanoelectronics, and their integration with mainstream CMOS ICs and advanced materials. Feng obtained his Ph.D. (2007) for developing ultra-high frequency (UHF) NEMS with low-noise technologies for single-biomolecule sensing, under the supervision of Michael Roukes. During 2007-2010, Feng was a Staff Scientist/Project Leader at the *Kavli Nanoscience Institute* (KNI) of Caltech, where he also served as the Co-PI (for a 3-phase DAPRA

Project) leading a team of engineers and physicists. Since joining CWRU in 2010, Feng has been named a *T. Keith Glennan Fellow* (2012) for excellence in integrating research and teaching (2012), has received an *Innovation Incentive Award* from Louis Stokes Cleveland Medical Center of the Department of Veterans Affairs (2011), and the *Mihajlo "Mike" Mesarovic Award for Extraordinary Impact* (awarded biannually) (2013). In 2013, Feng has been selected as "one of the nation's 81 brightest and creative young engineers" (30 to 45 years old) to participate in the *National Academy of Engineering (NAE)'s 2013 U.S. Frontier of Engineering Symposium* (USFOE). In March 2014, he was selected as 1 of the only 2 awardees for *NAE's Grainger Foundation Frontiers of Engineering Grants* for advancing interdisciplinary research. Feng is also a recipient of the *NSF CAREER Award*, and the recipient of the *Case School of Engineering Graduate Teaching Award*, and the *Case School of Engineering Research Award*. Along with his Ph.D. students, he has received 4 Feng has >100 peer-reviewed papers (with >3600 citations in recent years), >30 invited lectures/tutorials at peer-reviewed conferences/workshops, >35 invited seminars at renowned research institutions in US/Europe. He has 6 issued and >5 pending patents. Feng serves diligently on a number of technical committees in *IEEE* (*IEDM, Transducers, UFFC-IFCS, NANO*, *NEMS*), *AVS*, and *MRS*.

Kenneth Loparo (Co-I, CWRU) is the Nord Professor of Engineering and chair of EECS department (also holds appointments in BME and MAE) in Case School of Engineering. He has received numerous awards including the Sigma Xi Research Award for contributions to stochastic control, the John S. Diekoff Award for Distinguished Graduate Teaching, the Tau Beta Pi Outstanding Engineering and Science Professor Award, the Undergraduate Teaching Excellence Award, the Carl F. Wittke Award for Distinguished Undergraduate Teaching and the Srinivasa P. Gutti Memorial Engineering Teaching Award. He was associate dean of engineering from 1994 - 1997 and chair of the Department of Systems Engineering from 1990 -1994. He is an IEEE Fellow. He has numerous patents, >200 archival publications, and has served as the PI on over $25 million in industrial and government funding. A key recent thrust of his research interests is focused on sensors and wireless sensor networks, especially the design of distributed autonomous control systems, advanced signal processing for monitoring, tracking, control and decision-making in engineered & physiological systems [9-13].

Dave Martin (Co-I, Intwine) is founder, president and CEO of Intwine Connect, LLC. Since founding Intwine Connect in 2008, Mr. Martin has been instrumental in defining the company's primary platform technology, developing and implementing an end-to-end solution that connects electronic devices to businesses and end users via real-time, two-way communications, and solidifying and implementing key partnerships with organizations such as the Schools of Medicine and Engineering at CWRU, the Northeast Ohio Public Energy Council (NOPEC), the Verizon Innovation Program, and American Electric Power (AEP). Martin is also a managing partner of Victory Sales, which sells semiconductors and related products, and provides dedicated, customized service and support to electronics manufacturers. Martin has a bachelor's degree in management science from Westminster College, and an MBA from CWRU.

Zenghui (Max) Wang (Co-I, CWRU) is a senior research associate in EECS. His research expertise spans the physics and engineering of micro/nanoscale sensors and advanced materials. He earned a Ph.D. (2010) in Physics from University of Washington, for building an ultra-high frequency NEMS resonator with an individual single-walled carbon nanotube for sensing of mono-atomic-layer surface adsorption. Wang has published over a dozen of research articles in high-impact journals, including *Science*, *Nature Nanotechnology*, *Nature Scientific Reports, Nano Letters, ACS Nano*, and

Applied Physics Letters, and his publications have been highly cited by peer researchers in the field. He has received a number of awards for his research work since when he was a graduate student. Wang has given more than a dozen invited talks and seminars, at peer-reviewed conferences, and at research universities. He is a member of IEEE, MRS, AVS, and APS.

Postdoctoral Researchers: Peng Wang.

Ph.D. Students: Xu-Qian Zheng, Ran Wei.

Other Graduate Students: Swetha Maluvadu Ravi, Jonathan Colon, Andrew Ritosa, Mohammad Saiful Islam.

Undergraduate Students: Liuming Zhao, Amanda Jaworski, Eric King, Christopher Herbst, Billy Littlefield, Alicia Chang, Jeffrey Brown, Yutong Liu, Anran Zhang, Yuzhang Zhao, Ben Brucker, Jonathan McCandless, John Stockmann.

High School Students: Aman Nair, Robby Gray, Geoffrey Miller, Sears Schulz, James Swingos.

3. SENSOR NODE DEVELOPMENT

We have developed the sensor node under this project. Below we describe the technical details of the sensor node including design philosophies and operation principles, as well as circuit models.

3.1 1st Generation Prototype

System Block Diagram: Fig. 5 shows the block diagram of the wireless temperature sensor node (WTSN) system. It includes a PZT resonant energy harvester, a full-wave-bridge rectifier, an ASIC prototype, and an RF module with a microcontroller integrated with a temperature sensor. The full-wave rectifier is built with Schottky diodes, with a total voltage drop of 0.7V. A 50nF capacitor is used as a filter, and the harvested energy is stored in a 100µF capacitor.

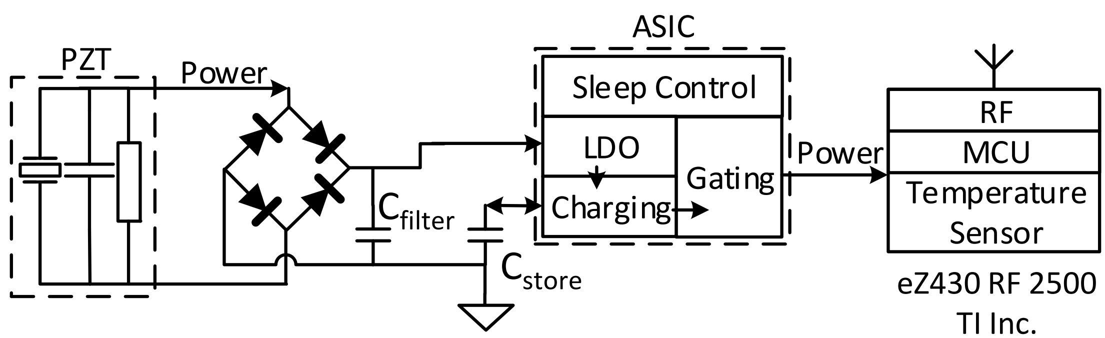


Fig. 5: System diagram of the wireless temperature sensor node (WTSN).

PZT Transducer Design: The PZT transducer takes the form of cantilever-shaped resonator (15mm×12mm×200µm), laser machined to have an optimized dimension. The PZT part extends ~2/3 of the total cantilever length for minimizing the undesirable charge redistribution effect. Once made, the PZT transducer is mounted on the vibration source (a small pump) that has been characterized using a 3-axis accelerometer (ADXL325, Analog Devices, Inc.). We then fine-tune the resonance frequency of the PZT cantilever (Fig. 6) to match that of the vibration source through adjusting the proof mass, a piece of low-melting-temperature metal attached at the end of the cantilever. Upon fine tuning, the optimized PZT transducer can output up to 96µW (measured with a 51kΩ load resistor) with a peak acceleration of 1.5g at the pump surface.

Wireless Network: Wireless connection (over ZigBee network) is established between the WTSN (front-end device) and a receiver (access point, AP) connected to a data-taking computer.

Wireless Transmission Range: To estimate the wireless transmission range, we calculate the RF signal attenuation over distance, wireless link budget, and power budget on the sensor node.

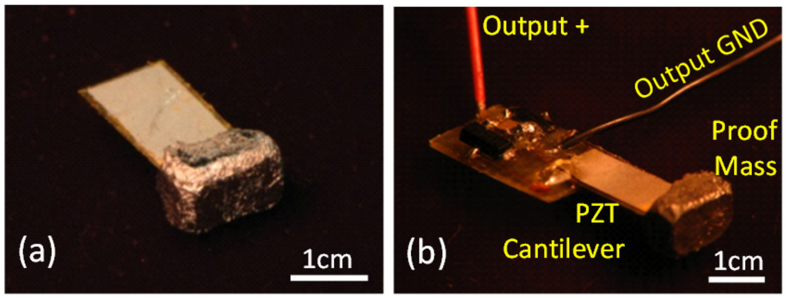


Fig. 6: PZT transducer mounted on a surface. (a) Front view. (b) Side view.

The wireless signal attenuation can be generally described by the Friis equation: the received power P_R at a distance d is:

$$P_R = P_T G_R G_T (\lambda/4\pi)^2/d^{\,n}. \quad (1)$$

Here, P_T is the originally transmitted power at the source, G_R and G_T are the gains of the transmitting (TX) and receiving (RX) antenna respectively, λ is the EM wavelength, and n is an environmental parameter (n=2 in free space; here we use n=2.2, typical value for most indoor settings). In our experiment, both the transmitter and receiver (eZ430RF2500 and CC2500) have an average gain of 1dBi, the receiver sensitivity is -104dBm at 2.4kBaud 1% packet error rate, and λ=0.1227m at 2.445GHz. Fig. 7a shows wireless range d vs. the transmitter output power P_T as calculated using Eq. (1), with available settings on the CC2500 indicated by square dots.

The link budget is analyzed by calculating the difference between the received signal power, P_R, and the sensitivity of the receiver. In a practical design of link budget, additional output power has to be added to the output power predicted by Friis equation. Sufficient link budget can reduce the RX power consumption and data packet loss rate. Fig. 7b shows the link budget for a typical indoor transmission distance d=10m.

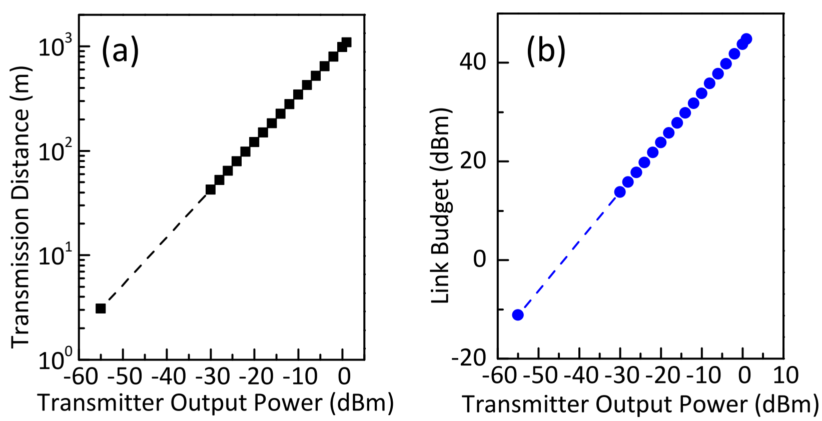


Fig. 7: Wireless transmission analysis results. (a) Calculated wireless transmission range as a function of transmitter output power. (b) Calculated RF link budget for wireless transmission over 10m using CC2500. The dots represent available configurations in the CC2500.

Temperature Sensor: The temperature sensor used in this study is a silicon (Si) bandgap temperature sensor integrated in the microcontroller (MSP430F2274) of the eZ430RF2500 module, and is read by an on-chip 10-bit ADC converter.

PZT Transducer Characterization: We characterize the PZT transducer in both frequency and time domains. In the frequency domain measurement, the transmission loss is measured with a network analyzer (Agilent 4395A) as shown in Fig. 8a. In the time domain measurement, we deflect the cantilever by a fixed amount, and then suddenly release it. The PZT cantilever then undergoes a 'ring down' oscillation which decays over time, and its voltage output is measured with an oscilloscope (Fig. 8b).

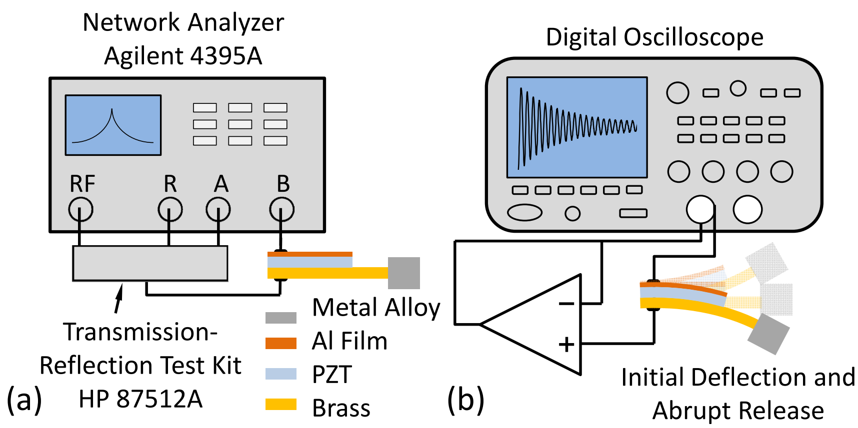


Fig. 8: Schemes for characterizing the PZT cantilever. (a) Frequency domain measurement. We measure the S_{21} parameter to identify the cantilever resonance frequency from its frequency-dependent transmission loss. (b) Time domain measurement. We measure the 'ring down' oscillations of the PZT cantilever using an oscilloscope (with an amplifier).

PZT Harvester Assembly and Installation: The complete WTSN is shown in Fig. 9a, and the inset picture shows the prototype ASIC die. The fully assembled WTSN, once characterized, is mounted on the pump surface as shown in Fig. 9b. The PZT transducer energy harvester is fixed on the pump using 7036 Blanchard Wax (J.H. Young Company) for optimized mechanical coupling.

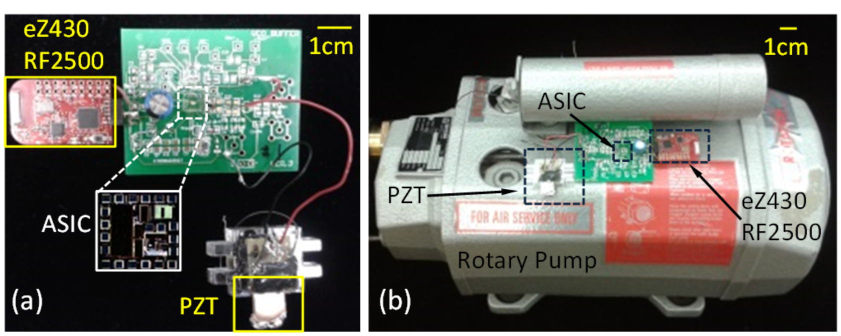


Fig. 9: System assembly. (a) The WTSN. (b) WTSN mounted on the pump.

WTSN Power Consumption Characterization: We characterize the transient power consumption of the eZ430RF2500 front-end device. As shown in Fig. 10, we power the WTSN with a battery pack, and connect a 68Ω resistor in series. This allows us to estimate the current (and thus power consumption) in the WTSN by using a digital oscilloscope (TDS1012C-EDU, Tektronix) to monitor the voltage drop across the resistor.

During the characterization, the WSTN is in the normal operation mode. It reads the environmental temperature with the built-in temperature sensor, and sends the readings wirelessly to the wireless access point (AP, another eZ430 RF 2500 unit) connected to the data-taking computer (Fig. 10).

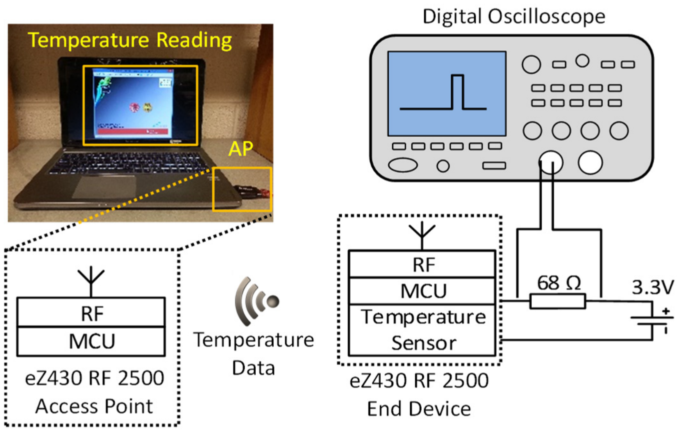


Fig. 10: Scheme for measurement of transient power. A small resistor of 68Ω is connected in series with the power input to the WTSN (the wireless end device), which wirelessly communicates with the wireless access point (AP).

Wireless Temperature Reading: Once the WTSN is characterized, we demonstrate wireless temperature sensing powered entirely by vibration energy harvesting. The experimental setup is the same as shown in Fig. 10, except that the battery pack is replaced by the PZT energy harvesting system, and the current-monitoring resistor (and the oscilloscope) is removed. While the PZT transducer remains fixed on the pump throughout the experiment, the remaining part of the WTSN is tested under different temperature settings and wireless environments.

The different settings/environments include ambient open space in the lab (room temperature controlled by thermostat), on top of a hotplate (HP131725, Thermo Scientific Inc.), underneath a heat lamp, and inside two ovens with metal enclosures (model 1410 and 1410MS, VWR International, LLC.). A separate digital temperature sensor (Caliber IV Digital Hygromter, Western Humidor, Inc.) is used as a reference. During the experiment, the WTSN wirelessly transmits the temperature reading to the wireless access point (AP) once every 10s, and the data is logged by the data-taking computer connected to the AP device (similar to the scheme during WTSN power consumption characterization, as shown in Fig. 10). The access point is located 10m away from the WTSN for the open space/heat lamp measurements, and 2m away during the oven/hotplate measurements.

PZT Transducer Characterization: The PZT transducer is characterized using the methods shown in Fig. 6. The results for both measurements are shown in Fig. 10. From the frequency domain transmission/reflection measurement (Fig. 11a), we clearly observe the mechanical resonance of the PZT transducer exemplified as a sharp 'heart beat' curve feature on top of a slowly-varying frequency dependent back ground. The data show that our fine tuning results in good frequency matching of the cantilever to the vibration source (120Hz).

The result from the time domain measurement is shown in Fig. 11b. The data are fit to the ring-down curve of a damped harmonic oscillator:

$$a(t) = a_0 + A\exp\left(-\frac{\pi f_{res} t}{Q}\right)\sin\left(2\pi f_{res} t + \phi\right), \tag{2}$$

where $a(t)$ is the time-dependent amplitude of the vibration, a_0 is the offset of the response, A is the initial amplitude, f_{res} is the resonance frequency, Q is the quality factor, and ϕ is the initial phase. From the fitting we extract the resonance frequency f_{res} and quality factor Q of the PZT cantilever. The results show excellent agreement with the frequency domain measurement, and again verify the precise tuning of the cantilever frequency.

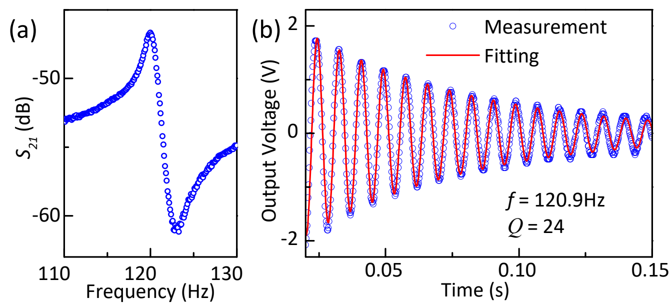


Fig. 11: Characterization of the resonant PZT cantilever energy harvester. (a) Frequency domain measurement. (b) Time domain data and fitting. *Blue Circles*: Raw data. *Red Curve*: Fitting of the data according to Eq. (2).

Power Consumption of WTSN: The power consumption of the WTSN is measured using the methods as shown in Fig. 10. The measured current (and calculated power consumption) during one active transmission event (~30ms long) is shown in Fig. 12a. The peak power is around 55–65mW, and lasts about 2ms. Outside this ~30ms 'active' window, the idle power of the WTSN is about 4μW, which sets the 'baseline' of the average power consumption. Based on these measured values, we estimate the overall average power consumption of the WTSN with different transmission intervals (Fig. 12b). Example values are also shown for 10s (13μW) and 10min (4μW) transmission intervals, both of which are well within the PZT power output of 96μW.

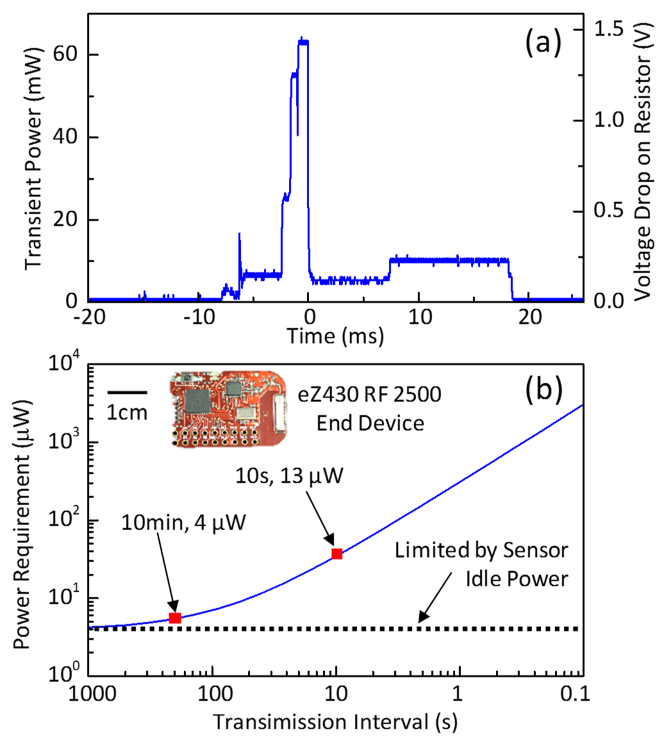


Fig. 12: Calibration of power consumption of the WTSN. (a) Measured current in a WTSN during one transmission event (~30ms). (b) Average power consumption as a function of transmission interval.

Wireless Temperature Reading: Fig. 13 shows examples of the wirelessly transmitted temperature data. Fig. 13a shows the measurement performed when the temperature sensor is placed inside an oven, with the oven temperature going through four setpoints (26°C, 29°C, 36°C, and 42°C) with 20min duration at each setpoint. During this measurement, the wireless receiver (AP) is located at 2m away from the WTSN. Fig. 13b shows the measurement when the WTSN is placed underneath a heat lamp, showing fast response of the temperature sensor when the lamp is turned on and off. We also increase the heating duration ('on' time of the heat lamp) during each heating event, resulting in increasing temperature reading from the WTSN. With the open space setting (no metal enclosure), the wireless transmission distance is increased to 10m in this measurement.

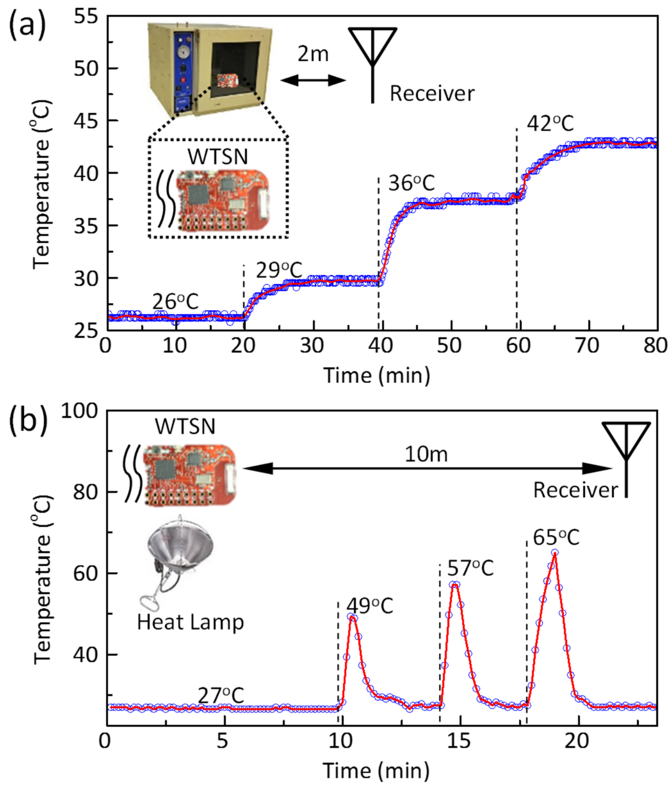


Fig. 13: Wireless temperature sensing in real time. (a) Temperature sensing from inside an oven. (b) Temperature sensing underneath a heat lamp. *Blue Circles*: Raw data. *Red Curves*: Smoothed data. Vertical dashed lines indicate changes in temperature setpoint.

In summary, we have demonstrated a wireless temperature sensor node (WTSN) powered by a PZT resonant transducer that scavenges vibration energy and supplies ~10 to ~100µW to the circuits. The system is fully characterized, and the power output of the PZT is sufficient for normal operations of the WTSN. We have further demonstrated real-time wireless temperature sensing under different experimental settings, with the signal transmission over a distance up to 10m.

3.2 2nd Generation Prototype

Architecture of the Sensor Node: The complete sensor node consists of an energy harvester, energy management ASIC, energy storage unit, sensors, and RF module (Fig. 14). The energy harvester is a piezoelectric (PZE) device, converting vibration energy from environment to electricity. The energy storage is a super-capacitor (in test we use a 3F super-capacitor). The ASIC controls the power supply for each sensor individually with a tunable voltage, under the request from the MCU or the Co-Processor. The ASIC also provides a stable power output for a timing unit (such as RTC or low-power MCU), while powering off other components individually to minimize system idle power.

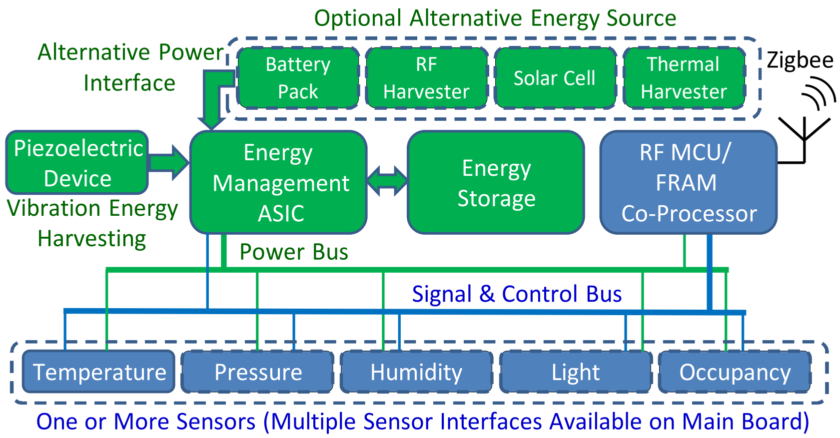


Fig. 14: System architecture showing both core components (detailed described below) and optional items (additional sensors, alternative energy sources).

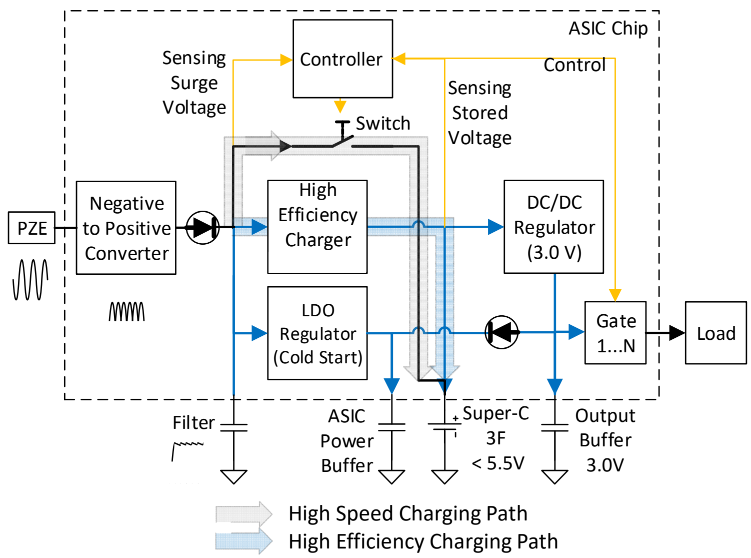
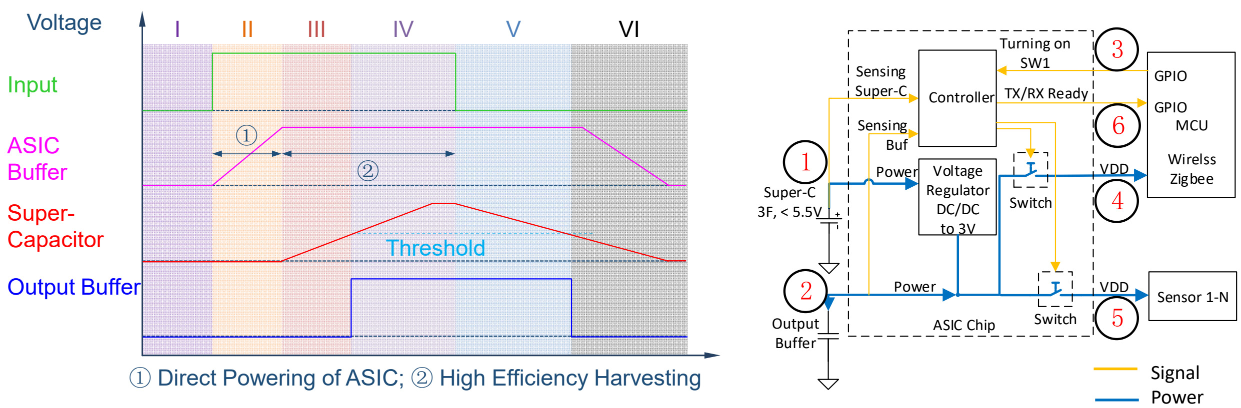


Fig. 15: ASIC modules. Blue/grey arrows: energy flow; yellow ones: signal flow. Some off-chip components (inductors etc.) are not shown. The ASIC has: a. A bipolar to unipolar voltage conversion module; b. A module for starting the ASIC and then the sensor node from 0 stored energy onboard (cold start); c. A high efficiency harvesting module for converting energy input with a wide range of voltage levels into stored energy on the device; d. A high speed charging module for fast converting transient energy input with a large voltage into stored energy on the device; e. An output regulator that ensures stable power output to all the components on the sensor node, over a wide range of stored energy level; f. A logic control unit that turns on and off the different components on the sensor node for optimized energy efficiency.

***Application-Specific Integrated Circuit (ASIC) Design and Test Results*:** The ASIC is the key enabling component of this WSTN. It consists of several modules (Fig. 15). These modules are self-contained and can thus be further upgraded individually. The most important modules include: (1) a negative to positive voltage converter (NVC), which rectifies the AC input from the PZE vibration energy harvester; (2) a high efficiency energy conversion/storage module, which uses the rectified energy input to charge the supercapacitor (the energy storage unit), and maintains a high charging efficiency; (3) a cold-start unit that allows the ASIC to start under initial power input, with zero stored energy onboard (which include a low dropout (LDO) regulator and other components), (4) a DC/DC regulator (in the demonstration as a single-ended primary-inductor converter (SEPIC)) that maintains the voltage output (to other components on the sensor node, *e.g.*, sensor, wireless transceiver, *etc.*) at constant level to ensure proper and low-power operation of the entire node; and (5) other on-chip components and interconnects, such as controllers, switches, and diodes.



Input from Energy Storage		Input from MCU	Output			
Super-C Ready (> 0.5V)	Output Buffer Ready (>3.0V)	Enable Sensors	To Zigbee (V)	To Sensors (V)	TX/RX Ready	System Idle
1	1	1	3.0	3.0	1	0
1	1	0	3.0	0.0	1	0
1	0	1/0	2.0-3.0	3.0/0.0	0	0
0	1/0	1/0	0.0	0.0	0	1*

Fig. 16: System timing diagram, system logic connections, and logic table of the ASIC, showing its operation principle. The proper operation of the entire sensor node requires the ASIC controller unit to manage the power state (on or off) of the other components on the sensor node depending on the charging status of the supercapacitor and the output buffer (as shown in the logic table). To achieve this, as shown by the numbered circles in the upper right plot, the controller monitors the voltages on the supercapacitor and the output buffer using comparators (1&2). Each energy storage unit is considered ready if its voltage reaches the designated threshold voltage (0.5V for the supercapacitor and 3.0V for the output buffer), and when so the ASIC will respond to the MCU request (3) to power up the other components (sensors, wireless transceiver etc.) (4&5). The ASIC also notifies the ZigBee module when there is sufficient energy for RF transmission (6).

Timing Diagram: Here we describe the operation cycle of the ASIC (Fig. 16). The ASIC begins with dormant state (I) when there is no input energy. The initial energy input (II) is used entirely to power the ASIC before powering any other components on the sensor node, during which the cold start module is used to charge the ASIC power buffer (in the test we use a 100nF capacitor). With continued power input (III), the ASIC starts to charge the 3F supercapacitor through the high efficiency charging module (arrowed part 1). Once the supercapacitor is charged (IV) beyond the threshold voltage (0.5V), the ASIC starts to use the stored energy to power all the components on the sensor node (arrowed part 2) through an output power buffer (in the test we use a 1mF capacitor maintained at 3V). When vibration energy input stops (V), the entire sensor node (including the ASIC itself) operates out of the energy stored in the supercapacitor. The ASIC gradually drains the energy stored in the supercapacitor to keep the output power buffer at 3V to maintain the sensor node operation. The super capacitor (3F) stores the harvested energy, and when fully charged (4.5V), the stored energy (30J) is sufficient for ~2 months of operation (~60 days at 6μW, assuming no leak in super capacitor; even with leak it is sufficient for > 1 month). When there is no energy input for an extended time beyond this (VI), the super capacitor voltage will fall below the threshold (0.5V). The ASIC then reports the status to the gateway, shuts off the other components on the sensor node, and finally enters dormant state (idle). Below we discuss the construction of the individual modules in the ASIC, and their designed performance.

NVC and Active Diode: The AC output from the PZE harvester first goes through the NVC (Fig. 17a) and an active diode (Fig. 17d). The converter is designed to have minimal voltage drop, making the rectification much more efficient than using p-n junction diode or Schottky diode. This is achieved by including three different rectification paths in parallel (Fig. 17a): (1) a transistor bridge. The PZE output is used to directly drive the gate of transistors. When the PZE output is >0.7 volts, the transistors are fully turned on and the voltage drop across them (V_{DS}) is very low (~20mV). (2) An active diode full-wave bridge. When the PZE output is <0.7V (so the transistors in (1) do not turn on), the active diodes (biased using the on-board voltage source) efficiently rectifies the input with minimal voltage drop (~20mV). (3) A Schottky diode half-wave bridge. When the PZE output is <0.7V, and there is no energy stored on the node (so the active diode bridge in (2) does not turn on), this allows the AC output from PZE be rectified with ~100mV voltage drop. The rectified outputs from (1) and (2) goes through an active diode to ensure directional current flow; when there is no energy on board it is basically open circuit, and the Schottky diode (3) directly powers the cold start module.

The merit of this design comes from its nearly-zero voltage dropout (little wasted energy) in most cases and its self-controlling nature which eliminates complex control circuit (simplicity and high reliability). Since the NVC is bidirectional, an active diode is used to direct the energy from the PZE harvester to the next stage on ASIC.

We have experimentally verified the transistor bridge design. The test result (Fig. 17c) shows that it efficiently converts the bipolar input from the PZE harvester (green curve; applied across the V_{in+}/V_{in-} ports in Fig. 17a) to a unipolar output (red curve, measured at the V_{out} port in Fig. 16a), with only ~10mV drop, fulfilling the designed function. We have also tested the active diode (Fig. 17e), and the results show that over the entire designed working range of input (2-3V above ground), the voltage drop is ~20mV, achieving the designed goal of having a minimal voltage drop (orders of magnitude lower than typical Si p-n junction diode: 600-700mV, Fig. 16e red arrow).

Cold Start Function: To quickly start the ASIC with the initial energy input (when there is zero stored energy onboard), a cold start unit is used to directly charge the ASIC power buffer from the rectified power output. It has a low dropout (LDO, Fig. 18) regulator to prevent high voltage from damaging the circuit components (as the PZE output can be as high as 10s of volts). The LDO regulates the rectified output to a constant 3V. The LDO is biased by an on-chip voltage reference, which is turned off when there is no energy input to save power. The voltage reference has a bias current as low as 7nA. The current consumption of the LDO is 1μA when operating and much less than 1pA when bypassed (when the ASIC power buffer is charged from the output buffer, phase IV in the timing diagram). The cold start also has a voltage booster to upconvert low voltage inputs in case of low-level vibrations.

The design ensures that the LDO operates entirely out of the input from PZE (no stored energy on board). Figure 10c shows the circuit schematic and test results: as designed, over a large input range (2-5V) the LDO output is maintained at ~3V, or the input, whichever is smaller (input higher than 5.9V is handled by the high speed charging).

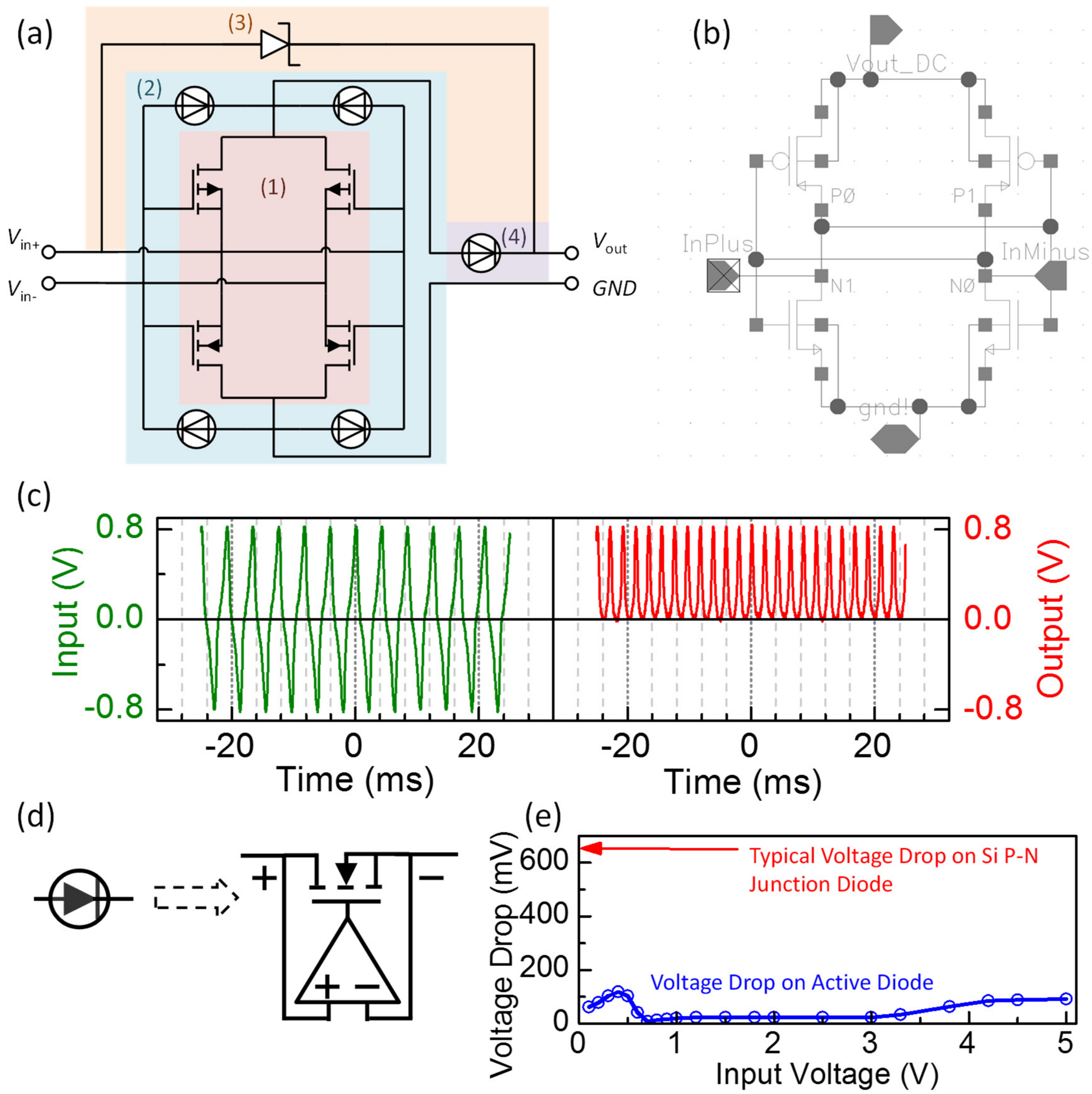


Fig. 17: NVD and active diode. (a) The NVC design with its components color boxed: (1) the transistor bridge; (2) the active diode bridge; (3) the Schottky diode; (4) the active diode. (b) The circuit design for the transistor bridge. (c) Measured result for the full-wave rectifying bridge circuit in (b) biased directly by the input voltage (showing bipolar input being converted to unipolar output). (d) Schematic for the active diode. (e) Measured voltage drop across active diode, showing 10mV-level voltage drop over a large input range.

High Efficiency Charging: With continued input from the PZE harvester, once the voltage on the ASIC power buffer reaches 3V the high efficiency charging function engages to store the rectified energy input into the supercapacitor. In order to achieve the highest possible efficiency, the rectified output voltage needs to be maintained at 1/2 of V_{OC} (open load output voltage) of the PZE harvester. On the other hand, the voltage on the supercapacitor is determined by the energy stored in it, and generally does not equal to the desired value ($V_{OC}/2$). To address this, a fly-back interface (or a boost converter) is used to isolate the rectified PZE output from the supercapacitor. A closed loop control unit maintains the output voltage from the rectification components at the optimized point by adjusting the working duty cycle of the fly-back interface (Fig. 19a). Additionally, to avoid overcharging, a series of diodes are used to ensure the voltage on the supercapacitor does not exceed

5.5V. The simulation results are shown in Fig. 18b. The tunable clock generators and SEPIC are developed from a recent work [9], with further reduced power consumption (lower bias current).

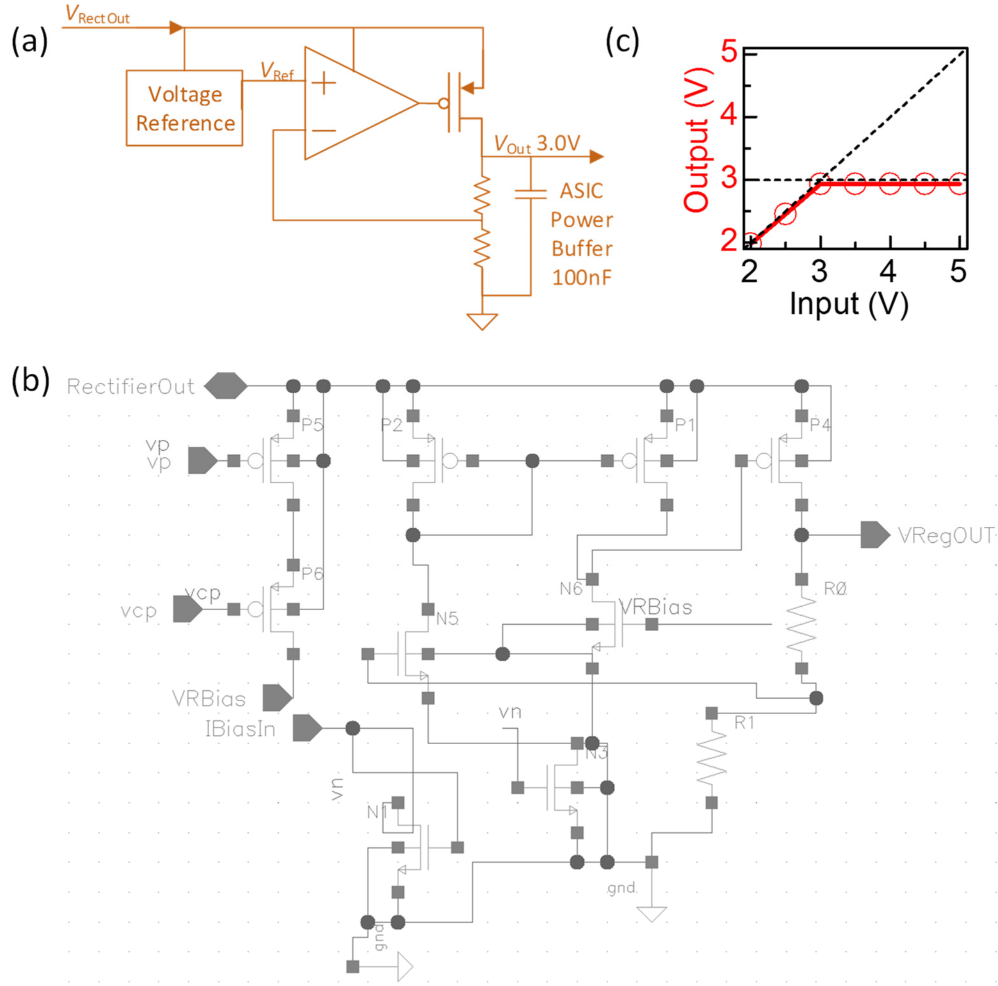


Fig. 18: Cold start and the test of LDO. (a) Schematic and (b) circuit design of the LDO. (c) Measured data of the LDO in the cold start module, showing any higher voltage input is successfully regulated to the desired output level (3V).

Fig. 19c (corresponding to an individual fast switching cycle in Fig. 19b) shows that the key part in the high efficiency charging module, the boost converter, upconverts the low input voltage to a sufficient value to charge the supercapacitor. The duty cycle of the "clock signal" can be adjusted to achieve optimal operation.

High Speed Charging: This is the other mode of charging operation. When there is a surge in the input power, the ASIC activates its high speed charging function to collect as much energy as possible in a short period of time, by opening up a high-capacity bypassing charging path to directly connect the input power with the supercapacitor, circumventing the high efficiency charging path (grey path in Fig. 15). The schematic of the high speed charging path is shown in Fig. 20a. This function is activated when the rectified output of the energy harvester exceeds 5.9V. Below this threshold value, this function remains dormant (and all the power input is handled by the high efficiency charging path as described above), and the relevant components consume only pA level current (as verified by simulation Fig. 20b).

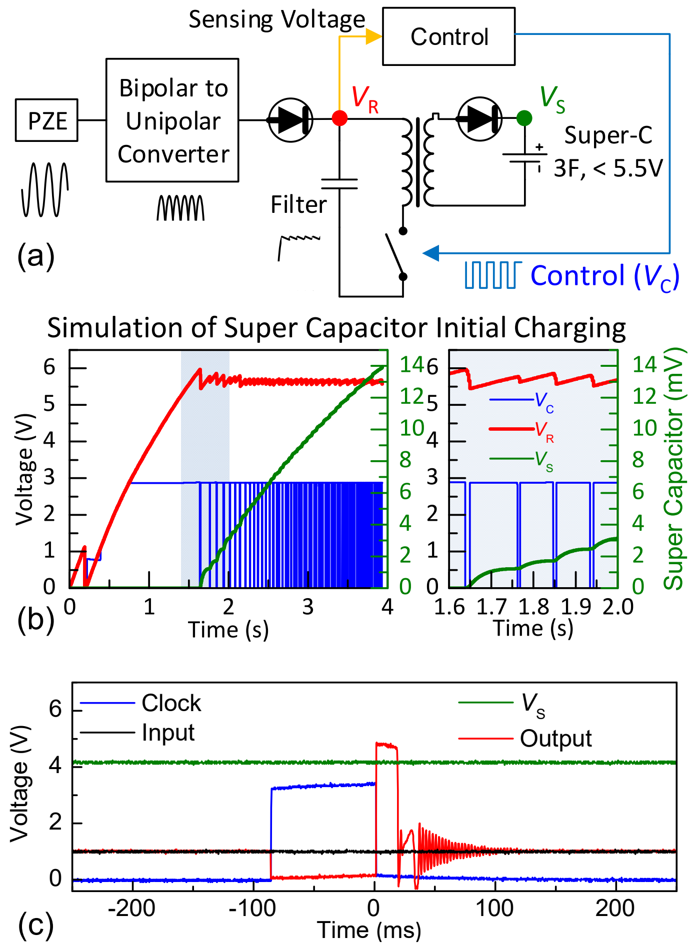


Fig. 19: High efficiency harvesting module design. (a) Circuit schematic. (b) Simulation of circuit behavior (shaded area further zoomed). *Red*: input from PZE device. *Green*: output to super capacitor. *Blue*: control signal. (c) Measured result of a single switching event in the booster converter (high efficiency charging).

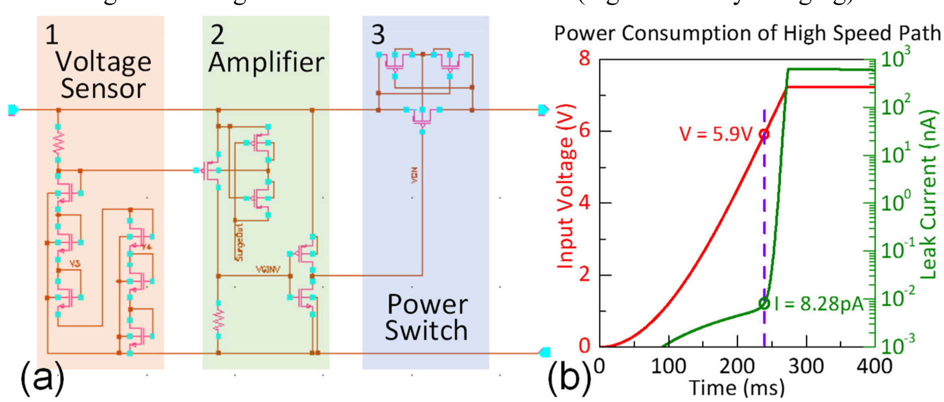


Fig. 20: High speed charging. (a) Circuit schematic. (b) Simulation results showing fast charging and minimal energy consumption (*red*: input from PZE harvester; *green*: current on high speed charging components, which turns on at the time indicated by the dashed line).

DC/DC Regulator: Once the supercapacitor voltage is above the threshold voltage (0.5V), the ASIC uses this stored energy to power the rest of the sensor node by charging the output buffer (100µF capacitor). A single-ended primary-inductor converter (SEPIC) is used to maintain the charging voltage for the output buffer at 3.0V (Fig. 21a). The charging stops as the buffer voltage reaches 3V, and resumes when it falls below 2V. The energy supplied by the output buffer (when discharged from 3V to 2V) is sufficient for two consecutive wireless transmissions, and the fast recharging (less than 0.2s to recharge from 2V to 3V) can enable continuous transmission of the sensor node when required (Fig. 21b).

Test results of the DC/DC regulator (Fig. 21c) shows that in a wide range of DC inputs (representing super capacitor voltage), the SEPIC output (at which it charges the output buffer) remains at 3.0V, as designed.

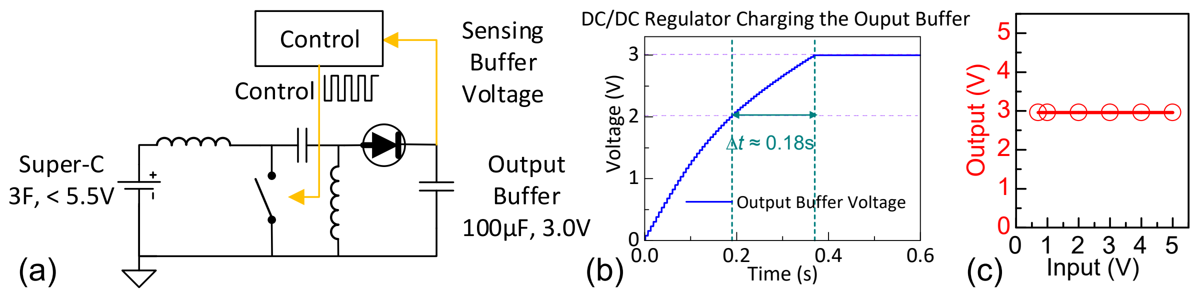


Fig. 21: DC/DC regulator. (a) Schematic of the module. (b) Simulation of charging output buffer from 0V, showing fast replenishment of energy. (c) Output voltage of the DC/DC regulator over a range of input voltage, showing the output voltage remains stable over a large range of input (that is, supercapacitor voltage).

ASIC Prototype: The actual ASIC is shown in Fig. 22, with the functional modules highlighted (total area: 2mm×2mm). We describe the experimental results of the different ASIC functions below.

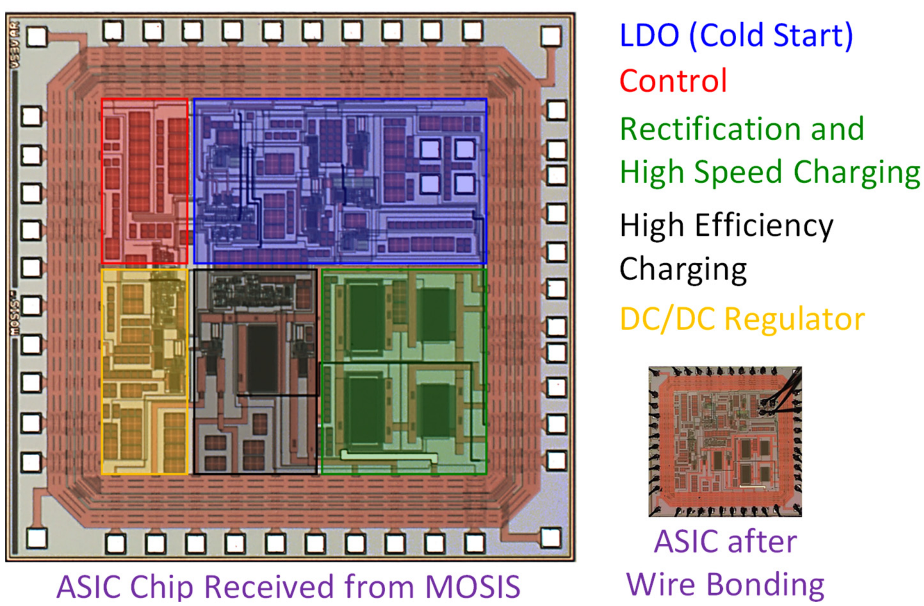


Fig. 22: Actual ASIC die from tape out. Small image: ASIC after bonding.

Circuit Board Prototype: The complete WSN circuit board (Fig. 23) has two main parts: (1) RF/sensor: ZigBee MCU (TI CC2530), peripherals (clocks, power buffers, RF pathways/antenna, *etc.*), and temperature sensor (TI TMP102); (2) Energy harvesting/ storage: ASIC (wired-bonded), peripherals (inductors, *etc.*), the super capacitor/output buffer capacitors, and PZE interface. In this development-board version (31 mil thick FR4 PCB chosen for antenna and impedance matching), all ASIC pins are fanned out for testing and further development. The final product version is substantially miniaturized by redesigning the circuit board and removing the test ports.

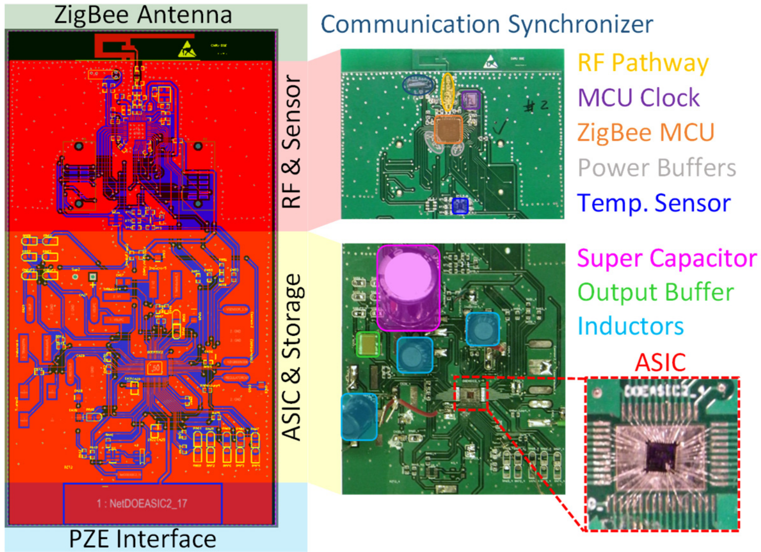


Fig. 23: Design and assembled product of the mainboard. Fan-out image: ASIC wire-bonded on the PCB.

Energy Harvester and Complete Sensor Node Prototype: The completely assembled WSN includes circuit board (with all components installed), PZE energy harvester, and enclosure. The ZigBee MCU wirelessly communicates with Intwine Cloud Gateway (ICG, acting as ZigBee coordinator). Transmitted readings are plotted by a computer (Fig. 24).

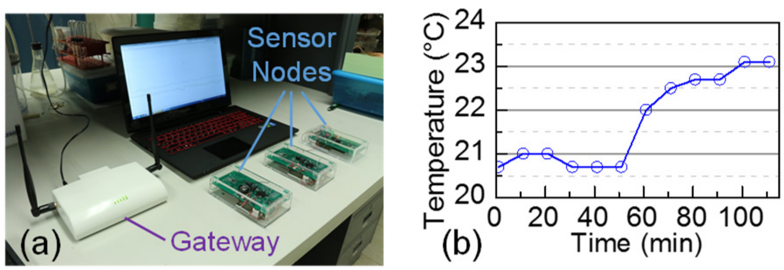


Fig. 24: Demonstration of vibration-powered wireless sensing. (a) Experiment setup. (b) Wirelessly-transmitted sensor reading over ~2 hour.

Vibration-Powered Wireless Sensing: We power the WSN's PZE by gently tapping it, which induces transient vibrations in the PZE harvester. The transmission rate is set to be one per 10 min. During sensor operation, we monitor the voltage on the supercapacitor and output buffer (both replaced by a 1mF capacitor during the experiment to obtain accurate measurement of voltage change) to calibrate energy harvesting/consumption. Figure 25 shows measured data over ~2 hour of continuous operation, entirely powered by vibration energy harvesting. By monitoring voltage decrease on the output buffer (top red curves in both plots), we estimate the total power consumption, which equal the static power (slow decrease) plus the wireless transmission (sudden drops averaged over time), to be ~6μW. The calculation is as follows (Fig. 25 bottom, C=1mF):

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=5.60×10-4J/(69.80min-67.74min)=4.53μW

Total power consumption

1.44μW+ 4.53μW=5.98μW

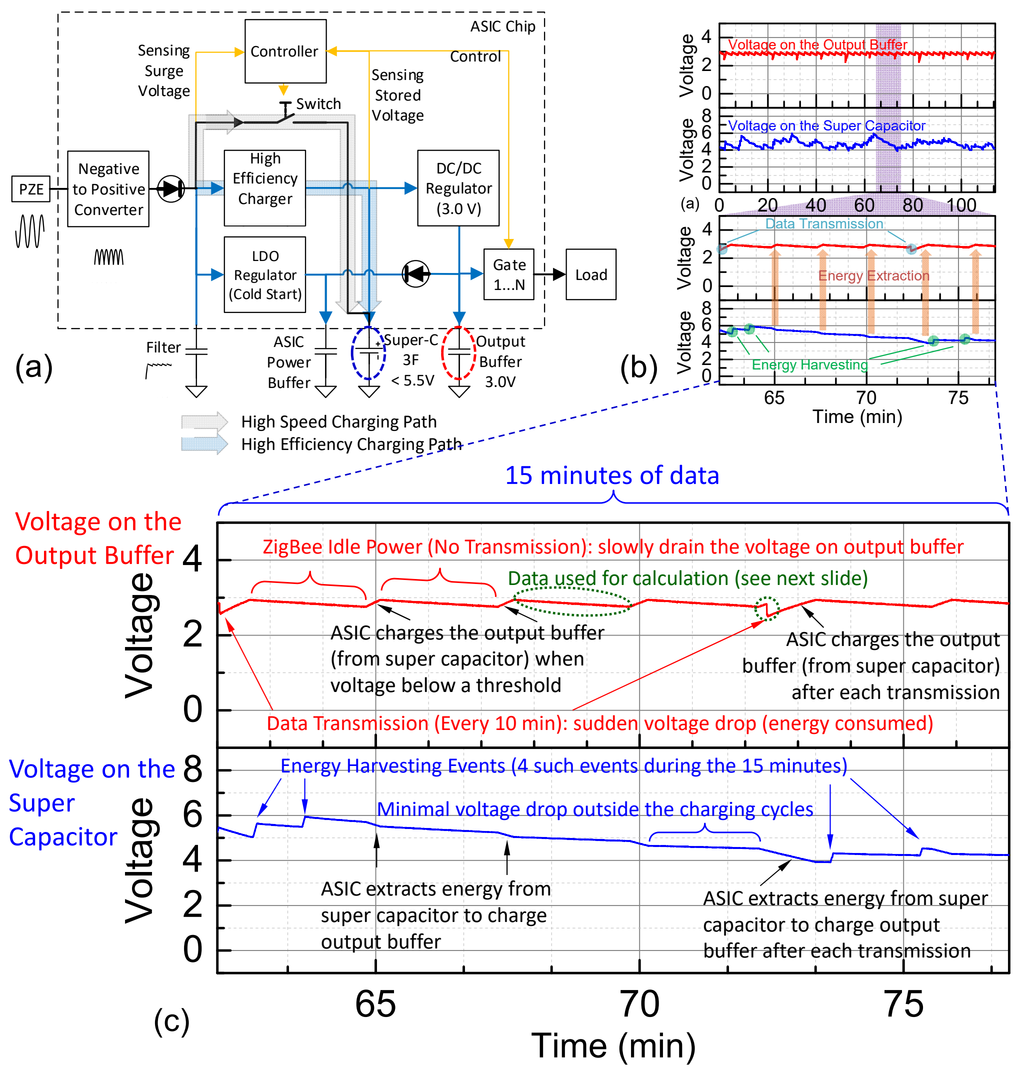


Fig. 25: Top: Measured power consumption of the WSN prototype. (a) Schematic of the WSN showing which capacitor voltages are measured experimentally (blue and red dashed ovals, colors corresponding to those in the data plots). (b) Data over ~2 hour and a zoomed-in segment of ~15 minute data. The output buffer voltage reflects the power consumption; wireless transmission show as sharp dips (such event consumes a sizable amount of energy). The super capacitor voltage shows the total energy stored. The usage (downward part) is replenished by energy harvested from vibration (upward part). (c) Zoomed-in data with detailed explanation (~15 minutes). As DC/DC regulator charges the output buffer using the energy on the super capacitor (energy extraction), the output buffer voltage (top red curve) increases while the super capacitor voltage (bottom blue curve) decreases. Bottom: Real-time data as in (d) above with detailed explanation, showing energy harvesting and wireless sensing. From the data one can calculate power consumption of the entire sensor node to be ~6μW.

4. Wireless Sensor Network

The team has established and developed the communication schemes between the ICG and the sensor node. The team has developed the wireless scheme to pair the sensor node with the ICG gateway, and the method to transmit temperature and voltage readings to the ICG, which minimize the energy consumption by reducing the amount of unnecessary wireless transmission while keeping the required functionality of the network (without breaking any standard ZigBee protocols or definitions). The entire programming is based on the published standard ZigBee wireless standards and remains open source and nonproprietary. A Schematic of the topology of the ZigBee network based on ICG and wireless sensors developed in this project is illustrated in Fig. 26 below (actual field test were implemented in similar indoor environments):

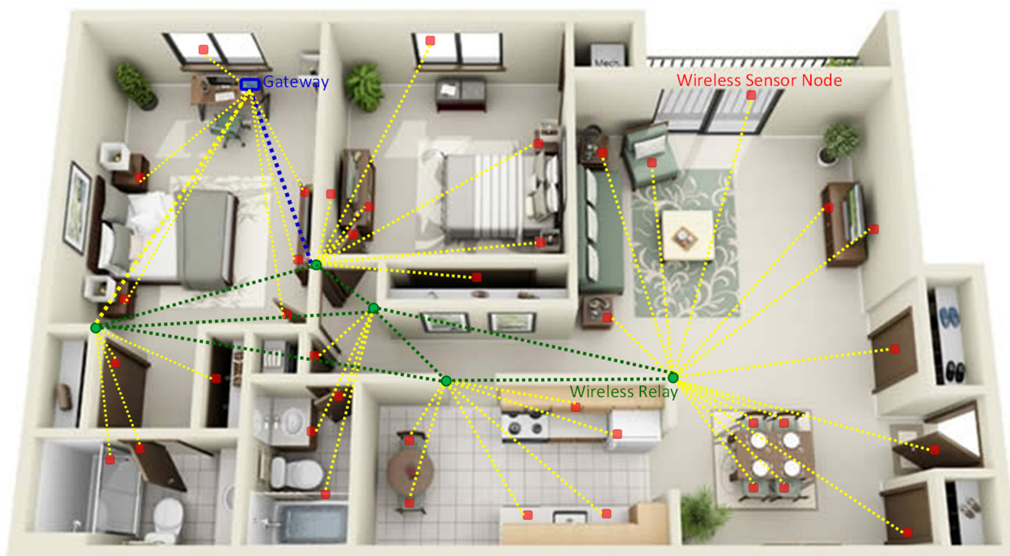


Fig. 26: Illustration of the wireless sensor network developed in this project based on ZigBee protocol. Red dots denote the self-powering energy harvesting wireless sensor nodes. Green dots illustrate optional wireless relays for better signal transmission. Blue rectangle represents the ICG gateway. Yellow dotted lines are data links between the wireless sensor nodes and relay/gateway, and green dotted lines are wireless relay paths. Blue dotted line shows the connection between gateway and a relay.

Shown in the illustration, red dots denote the self-powering energy harvesting wireless sensor nodes. Green dots illustrate optional wireless relays for better signal transmission. Blue rectangle represents the ICG gateway. Yellow dotted lines are data links between the wireless sensor nodes and relay/gateway, and green dotted lines are wireless relay paths. Blue dotted line shows the connection between a gateway and a relay.

5. Market Strategy and Commercialization Plan

CrystalE is founded by graduate students and alumni of Case Western Reserve University. The mission of our company is to enable maintenance-free sensor networks through energy harvesting, thereby helping building owners save money. The core technology we are utilizing is developed by Prof. Philip Feng's group at the Department of Electrical Engineering and Computer Science of Case Western Reserve University under a research grant from the U.S. Department of Energy. Below we describe in detail the products, including target costs, contacted manufacturers of components, firms for commercialization and the number of jobs created.

5.1 Potential Applications and Markets

Technologies related to Internet of Things (IoT) are experiencing exponential growth these years. Sensors are becoming more commonplace, and most require battery power. This creates a disposal issue as the batteries age. Additionally, the periodic changing of batteries not only creates high cost in maintenance, but also requires more human capital for end users. We see potential of our technology not only for sensors of BEMS, but also a variety of other fields, where frequent maintenance is not favorable.

5.2 Market Size

By selling sensor nodes for BEMSs, the potential market of our product majorly lies on the market size of BEMS and the number of buildings that are more demanding for easy-to-deploy and nearly-maintenance-free sensors. In 2015, the global total addressable market of BEMSs was $2.4 billion and is project to be as high as $55 billion in 2024, according to a report from Navigant research. We focus on small-to-medium sized commercial buildings, which make up 91% (4.8 million) of all buildings in the commercial sector.

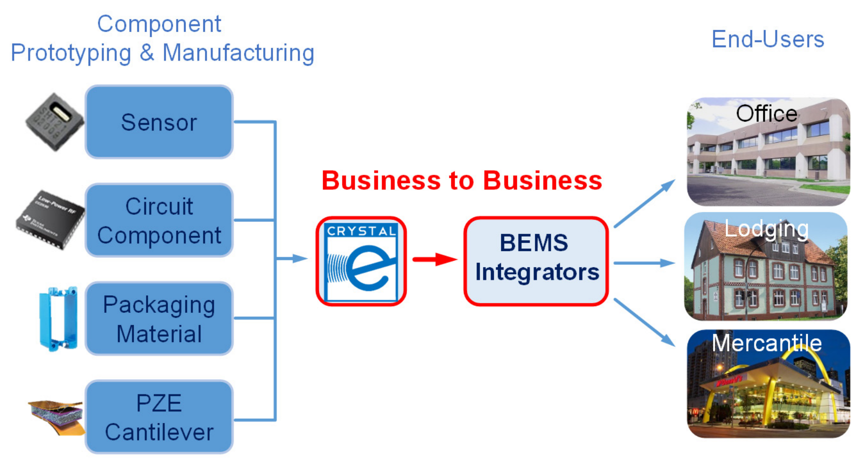


Fig. 27: Business model illustration. We serve as sensor supplier for BEMS integrators.

5.3 Business Model

As illustrated in Fig. 27, CrystalE empowers BEMS (Building energy management systems) integrators to provide their customers (building owners, managers) with an efficient and non-cumbersome way to keep their buildings smart. This is done by supplying CrystalE sensor nodes to companies like Johnson Controls, Siemens, and Schneider Electric that are the major suppliers in its target market. The business shall grow from the early collaboration with Intwine Connect to demonstrate the functionality and feasibility of our technology. Once the product is well established, we shall contact the above-mentioned system integrators to discuss about testing our sensor node out in their systems. Then, once the test results are well received, we can start being a sensor node supplier for these companies. CrystalE is a business to business company that earns money by selling sensors to BEMS integrators to satisfy end user needs.

5.4 Potential Markets

Beyond buildings, our sensors create new revenue streams for additional markets too. Energy harvesting sensors are a potential value-added feature for building materials and household appliance manufacturers. Manufacturers could pre-install sensors on their windows, window frames, roof materials, vent outlets, refrigerators, air conditioning systems, home theater speakers or embed in sofa cushions, seat pads, mattress pads, floor mats and carpets prior to shipment or installation. In vehicles, our low-cost, easy-to-install, low maintenance sensors, powered through the engine/wheel motion in the vehicle, could be deployed to align seatbelt warnings with occupancy or self-regulate temperature based on passenger occupancy. Adhered to forklifts or in plant vehicles and powered through the mechanical motions of the machines, our self-powered sensors could provide tracking and location services. Embedded in seats, our sensors could help theaters, concert halls or even theme parks identify and capitalize on empty seats or parking spaces.

5.5 Potential Jobs Creation

Based on a few assumptions on sales and costs, CrystalE shall reach a total revenue of $1,584,045 on Year 5, corresponding to a gross profit of $876,105 and a net income of $321,105. By using 25% of the revenue to pay the salary of internal jobs and taking the job created through sensor production into consideration, it is estimated to be up to 55 full time U.S. jobs created by Year 5.

5.6 Sensor Node Manufacturing

We have also contacted a few firms for manufacturing the sensor node. The firms include Cleveland Circuits for PCB printing, Versitec Manufacturing for PCB printing and product assembly, and Morgan Advanced Materials or Channel Technology Group for purchasing the piezoelectric material and cantilever for energy harvesting. The overall material and manufacturing cost of each sensor node on the early stage should be below $15.

5.7 Competitor Analysis

The field of advanced sensors is very diverse and has many options for different applications. Most current options involve either wired-in or battery powered sensor nodes. Companies like Lord MicroStrain and Civionics develop sensors for high-end performance with multiple sensors on a node and have a subsequently high installed cost. This prohibits larger scale projects.

Other companies like Monnit and Centralite have lower cost nodes that do fewer functions but can have you replacing the battery every 1 to 2 years. With a few hundreds of these sensors, you find yourself paying for them repeatedly by sending someone to go out and install a new battery.

CrystalE is located right in the sweet spot with a low installed cost and extended component lifetime.

Our closest competitor is EnOcean that makes a connected device with a different energy harvesting system. They employ an electromagnetic transducer technology that charges when you press a button on the node. They are used for simple wireless switches for things like lights, remote controls, or consumer electronics. Ideal sensors are powered by AAA batteries that are advertised to last for 15 years.

6. KEY ACHIEVEMENTS

A number of products/outcomes/achievements have been developed/derived under the Award and technology transfer activities. Specifically:

Publications:

1. Peng Wang, Robert Gray, Zenghui Wang, and Philip X.-L. Feng, "A Wireless Temperature Sensor Powered by a Piezoelectric Resonant Energy Harvesting System", *Proceedings of 2015 Joint Conference of the IEEE International Frequency Control Symposium & European Frequency and Time Forum*, 316-319, Denver, CO, April 12-16 (2015). Also presented as *Oral Presentation*.

2. Peng Wang, Xu-Qian Zheng, Ran Wei, Aman Nair, Robert Gray, Zenghui Wang, and Philip X.-L. Feng, "Battery-Less Wireless Temperature Sensors via Harnessing Household Vibration Energy", *18th International Conference on Solid-State Sensors, Actuations and Microsystems (Transducers 2015)*, Anchorage, AK, June 21-25 (2015). Presented as Open Poster.

3. Peng Wang, Xu-Qian Zheng, Zenghui Wang, and Philip X.-L. Feng, "Self-Powering Wireless Temperature Sensor Node", *2016 Hilton Head Solid-State Sensors, Actuators and Microsystems Workshop*, Hilton Head Island, SC, June 5-9 (2016). Presented as Open Poster.

4. Shiquan Fan, Liuming Zhao, Peng Wang, Ran Wei, Xu-Qian Zheng, Zenghui Wang, and Philip X.-L. Feng, "A Battery-Less, 255 nA Quiescent Current Temperature Sensor with Voltage Regulator Fully Powered by Harvesting Ambient Vibrational Energy", *IEEE International Symposium on Circuits and Systems (ISCAS 2017)*, Baltimore, MD, May 28-31 (2017). Accepted as Poster Presentation.

5. Shiquan Fan, Liuming Zhao, Ran Wei, Li Geng, and Philip X.-L. Feng, "An Ultra-Low Quiescent Current Power Management ASIC with MPPT for Vibrational Energy Harvesting", *IEEE International Symposium on Circuits and Systems (ISCAS 2017)*, Baltimore, MD, May 28-31 (2017). Accepted as Oral Presentation.

6. Shiquan Fan, Xu-Qian Zheng, Ran Wei, Jeffrey S. Pulskamp, Ryan Rudy, Ronald G. Polcawich, and Philip X.-L. Feng, "mm-Scale and MEMS Piezoelectric Energy Harvesters Powering on-Chip CMOS Temperature Sensing for IoTs Applications". *19th International Conference on Solid-State Sensors, Actuations and Microsystems (Transducers 2017)*, Kaohsiung, Taiwan, June 18-22 (2017). Accepted as Poster Presentation.

Inventions/Patent Applications:

1. "Self-Powering, Easy-to-Deploy, Low-Cost Multiphysical Sensors for Smart Building and Environmental Monitoring", CWRU Invention Disclosure 2014-2672; Provisional Patent Application, No. 62/090085.

2. "Devices and Application Specific Integrated Circuits Technologies for Harvesting and Storage of Unconventional Vibration Energy in Ordinary Buildings", CWRU Invention

Disclosure, In Preparation, 2017.

3. "Device-Circuit Integration and Packing Techniques for Low-Cost, Self-Powering Wireless Temperature Sensors", CWRU Invention Disclosure, In Preparation, 2017.

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[2] R. Wei, A. Nair, P. X.-L. Feng, "Spectrally Selective Mechanical Energy Scavenging from Ambient Vibrations for Solid-state Lighting", *Sensor & Actuat. A-Phys. under review* (2014).

[3] Z. Wang, R. Wei, P. Wang, W. H. Ko, P. X.-L. Feng, "Self-powering, easy-to-deploy, low-cost multiphysical sensors for smart building and environment monitoring", *CWRU Invention Disclosure* No. 2014-2672 (2014).

[4] P. Wang, D. Sun, S. J. A. Majerus, S. B. Lachhman, S. X. Li, M. S. Damaser, C. A. Zorman, P. X.-L. Feng, W. H. Ko, "Implantable pressure telemetry device with thin film micropackage", in *Proc. EMBS* (2013).

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[7] Acceleration measured with commercial accelerometer (Analog Devices ADXL325). Harvested mechanical power estimated for commercial PZE (MIDE Volture V22BL, http://www.mide.com/pdfs/Volture_Datasheet_001.pdf)

[8] Calculated for TI CC2530 assuming 1 transmission/receiving every 10min (http://www.ti.com/lit/an/swra292/swra292.pdf).

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