EcoSense: A Hardware Approach to On-Demand Sensing in the Internet of Things

Ye Liu, Qi Chen, Guangchi Liu, Hao Liu, and Qing Yang

ABSTRACT

An Internet of Things system typically contains a large number of low-cost devices that are mainly powered by batteries and designed to operate for a relatively long period of time. Due to the stagnated battery technology, energy efficiency will still be a burning issue for future IoT systems. To achieve better energy efficiency, we propose an innovative sensor architecture called EcoSense. Unlike traditional software-based approaches (e.g., duty cycling or adaptive sampling techniques), EcoSense provides a hardware-based on-demand sensing mechanism that effectively eliminates the energy waste caused by a sensor working in sleep or standby mode. When desired events are not present, an EcoSense sensor is completely turned off to save energy (i.e., drawing zero current). When desired events occur, an on-demand connection module will harvest energy from the events and reactivate the sensor. We implemented light- and RF-driven EcoSense sensors, and evaluated their performance in real-world experiments. Experimental results show that the EcoSense technique is able to immediately detect lights and RF signals, and offers reasonable reaction distances.

INTRODUCTION

The era of the Internet of Things (IoT) is coming, and IoT is considered the next industrial revolution. A smart world will be created by IoT techniques, wherein all physical objects in everyday life will be identifiable and connected to the Internet. IoT will fundamentally change the world and make our life much more convenient, efficient, and comfortable. For example, an intelligent transportation system (ITS) could collect real-time traffic information through sensors embedded under pavements or mounted non-intrusively on roadside infrastructures [1]. In the system, sensors will collect and transmit data on demand (i.e., only when a vehicle is passing by). To ensure that a vehicle passing by is detectable, sensors must continuously sense the road, resulting in unnecessary energy waste. To address this issue, we propose a hardware approach to achieve on-demand sensing, wherein sensors are turned off if the desired event is absent.

Sensors are responsible for environment sensing and monitoring, and play an important role in an IoT system. At the early stage of IoT, low-power sensors are used to collect different types of data including temperature, light, and humidity [2]. Recently, several applications require power-hungry sensors to conduct complex sensing (e.g., video-based vehicle classification [3]). Not only the capacity but also the number of sensors are increasing at a fast pace. According to a recent report published by the Trillion Sensor Summit [4], the number of sensors had already grown from 10 million to about 10 billion from 2007 to 2013. It is projected that trillions of sensors will be deployed all over the world within a decade. With the sheer amount of sensors and various types of applications, there is no doubt that energy efficiency of sensors will still be an important problem in the era of IoT.

To save energy, sensors are usually placed in a low power consumption mode (e.g., sleep or standby mode) when the desired event is absent. For example, duty-cycled operation [5] is widely used in traditional wireless sensor networks where each sensor periodically switches between active and inactive modes. Although efficient toward saving energy in idle state, duty-cycling causes issues such as missing the detection of desired events (during the sleep mode). Another energy saving approach is called adaptive sampling, which estimates the optimal sampling frequency to minimize energy consumption on sensors while maintaining an acceptable event detection rate [6]. Nevertheless, both duty cycle and adaptive sampling based methods assume sensors are in sleep mode when they are inactive. Although low current is drawn by a sensor in sleep mode, a large amount of energy will be wasted given the huge amount of sensors in an IoT environment.

Instead of using software-based approaches, we believe energy saving on a sensor can be brought up to another level via hardware innovations. We propose a novel hardware architecture, EcoSense, to save energy by enabling on-demand sensing on a sensor. The innovative approach is different from prior works in that a sensor is completely turned off and consumes no power when the desired event is absent. The technical challenge here is to reactivate a sensor from a completely off state with the energy captured from desired events. This is challenging because any software-based approach (e.g., using internal or external timers or interrupts) will fail when a sensor completely loses its power supply. We address this challenge by introducing an on-demand con-

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Model	Manufacturer	Supply voltage (V)	Current	
			Active mode (mA)	Standby mode (μA)
MSP430F1611	Texas Instruments	1.8–3.6	0.33	2.0
MSP430F2618	Texas Instruments	1.8-3–6	0.37	0.6
C8051F930	Silicon Labs	0.9–3.6	4.1	0.75
ATmega128L	Atmel	2.7–5.5	5	80

Table 1. Power consumption of COTS microcontrollers.

nection module between a sensor and its power supply unit. This module will first harvest energy from desired events, and then connect the sensor and its power supply unit to facilitate on-demand sensing on a sensor. The energy used to activate a sensor could be harvested from the vibration generated by a moving vehicle, the sound emitted from an engine, or the RF signals sent by a wireless device. As long as enough energy is harvested from the desired events, the EcoSense technique can offer better energy efficiency on sensors.

The rest of this article is organized as follows. We describe the motivation and design sketch of the EcoSense architecture. We present a detailed circuit schematic of EcoSense along with its operating principles. Performance evaluations of EcoSense are given. We discuss the limitations of EcoSense. After discussing prevalent energy saving techniques, we conclude our work.

Motivation and Design of EcoSense

In this section, we first study the energy consumption of each component in commercial off-the-shelf (COTS) sensors. From the analysis, we draw the conclusion that a significant amount of energy is wasted on sensors running in sleep mode. Based on this observation, we propose the EcoSense architecture to improve energy efficiency on sensors.

Power Consumption Analysis

To completely understand the energy consumption of a sensor, we summarize in two tables the energy consumption of a sensor's microcontroller unit (MCU) and communication module operating in various modes. Specifically, the energy consumption levels of several COTS MCUs and radio transceivers are listed in Tables 1 and 2, respectively.

If an MCU operates in active mode, all its electronic components are fully functional. If an MCU is in standby or sleep mode, it goes into the low-power mode (LPM) of operation. An MCU usually provides various standby modes that allow a user to tailor power consumption to the application's requirements. For example, a C8051F930 MCU offers three standby modes: stop mode, suspend mode, and sleep mode. Similarly, an MSP430F1611 MCU provides LPM0, LPM1, LPM2, LPM3, and LPM4 modes. An ATmega128 MCU offers six standby modes, including the idle, ADC noise reduction, power-down, power-save, standby, and extended standby modes.

In Table 1, we provide the typical values of currents drawn by an MCU in both active and standby modes, wherein the supply power voltage is 3 V and environmental temperature is 25°C. For example, when an MSP430F1611 is in sleep mode, it is usually turned into the LPM3 mode. In this mode, the MCU's CPU, master clock, submain clock, and digitally controlled oscillator's DC generator are all disabled; however, its auxiliary clock still operates. Therefore, an internal interrupt can wake up the MCU to switch from LPM3 mode to active mode. The current drawn by an MSP430F1611 in this mode is 2.0 μA. For other MCUs (e.g., MSP430F2618, C8051F930, and ATmega128L), the standby modes in Table 1 correspond to their LMP3 mode, sleep mode (with SmartClock oscillator enabled), and standby mode, respectively.

The energy consumption levels of typical radio modules, including CC2420 and XBee 802.15.4, are provided in Table 2. Depending on the transmission power, the current drawn by a communication module in transmission mode may vary within a certain range. For example, a CC2420 draws 8.5 mA, 9.9 mA, 11 mA, 14 mA, and 17.4 mA currents when the transmission power is –25 dBm, –15 dBm, –10 dBm, –5 dBm, and 0 dBm, respectively. A radio module usually offers only one reception mode except for CC2540. A CC2540 in standard reception mode draws 19.6 mA current; however, this value goes up to 22.1 mA when a high-gain mode is chosen. Here, we only consider the currents drawn by various radio modules in a typical setting.

When a sensor is in sleep mode, both its radio

Model	Manufacturer	Supply voltage (V)	Current		
			Transmission (mA)	Reception (mA)	Power down (μA)
AT86RF233	Atmel	1.8–3.6	7.2–13.8	11.8	0.02
CC2420	Texas Instruments	2.1–3.6	8.5–17.4	19.7	20
CC2540	Texas Instruments	2.0–3.6	21.1–31.6	19.6,22.1	0.9
ZM5202	Sigma Designs	2.3–3.6	41	32	1
XBee 802.15.4	Digi International	2.8–3.4	45	50	10
XBee-PRO XSC	Digi International	3.0-3.6	265	65	45
XBee WiFi	Digi International	3.14–3.46	309	100	6

Table 2. Power consumption of COTS radio modules.

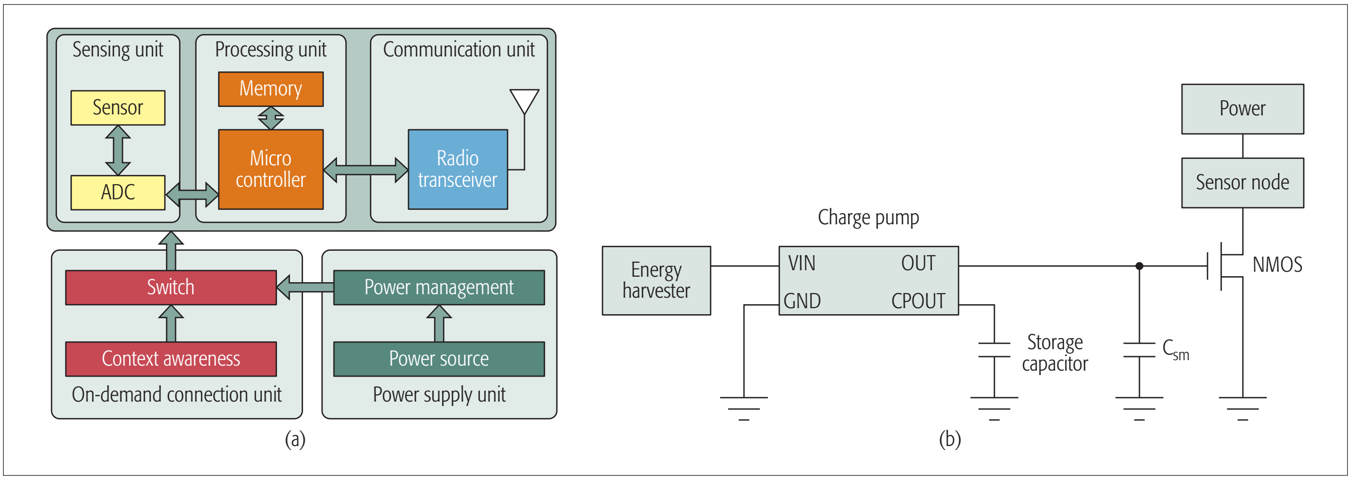

Figure 1. a) Illustration of the EcoSense architecture where the on-demand connection unit works as a bridge between the power supply unit and the sensor that consists of a sensing unit, a processing unit, and a wireless communication unit; b) circuit schematic of the on-demand connection unit where the energy harvester uses collected energy to charge the storage capacitor via a charge pump. When the storage capacitor discharges, it closes the NMOS switch and charges the smoothing capacitor C_{sm} simultaneously. When it finishes discharging, C_{sm} continues controlling the NMOS switch to ensure that the sensor and the power supply unit are connected.

module and MCU will be in the power down or standby mode. Therefore, we can use the currents drawn by an MCU in standby mode and a radio module in power down mode to calculate the energy consumption of a sensor running in sleep mode. Let I_r represent the current drawn by a sensor's radio transceiver in power down mode, U_r denote the supply power's voltage, and T be the time period of sleeping. The energy consumption of the radio transceiver in power down mode will be $W_r = U_r \times I_r \times T$. Similarly, the energy consumption of the sensor's MCU in standby mode can be computed as $W_c = U_c \times I_c \times T$ where U_c and I_c are the voltage and current of the microcontroller in standby mode. The overall energy consumption of the sensor in sleep mode can be approximated by $W = W_r + W_c$. Here, we only focus on the energy consumption of the microcontroller and radio module on a sensor, and omit that of other digital components. Based on our calculation, in a single day, dozens of millijoules to several joules of energy could be consumed by sensors in sleep mode. If the supply power's voltage is 3 V, the CC2420 and XBee-PRO XSC modules consume 5.2 J and 11.7 J per day, respectively. The MSP430F1611 and MSP430F2618 microcontrollers consume 518 mJ and 15 mJ of energy per day, respectively. Let the energy consumption of a sensor in sleep mode be 1 J per day (a conservative assumption); then one trillion sensors will waste 277,776 kWh daily. If we could eliminate this type of energy wastage for even 10 percent sensors, it would be a huge amount of energy saving.

EcoSense Architecture

Based on the previous analysis, it is critical to design a mechanism to avoid wasting energy on sensors that run in sleep mode. Our solution is a novel sensor architecture that enables a sensor to be turned off completely, rather than placed in sleep mode, if there is no desired event.

As shown in Fig. 1a, the EcoSense architecture consists of five building blocks: power supply unit, on-demand connection unit, sensing unit, processing unit, and communication unit. The power supply unit is by default disconnected from other components (e.g., the sensing, processing, and communication units). They are separated by the on-demand connection unit. Power will be provided to these components only when the switch in the on-demand connection unit is closed. The on-demand connection unit is the key component that harvests energy from desired events. The harvested energy is then used to close the switch that connects the power supply unit to the sensor. In other words, if no event occurs, the power supply unit does not provide any power to the sensor. In this way, the EcoSense architecture exhibits an on-demand sensing capability as well as zero energy consumption when a sensor is in inactive mode.

The on-demand connection unit itself should not consume any energy when the sensor is in the inactive mode. Traditionally, two types of mechanism can realize an on-demand control of a sensor. The sensor-based approach proposed in [7] senses the presence of an interesting event and triggers a sensor via an internal software interrupt. Alternatively, an external interrupt (e.g., RF signals [8]) can be used to activate a sensor. In the second approach, the sensor's radio transceiver must be in the reception mode so that the triggering RF signals can be received. Because both of the above-mentioned approaches consume energy in either detecting interested events or capturing RF signals, they do not meet the design goal.

We find that energy exists in many events and can be leveraged to control the on-demand connection unit. For example, when a light is turned on, radiant energy is generated. When water flows in a pipe, it brings either thermoelectric or vibrational energy. When wireless signals are received, electromagnetic radiation energy is available. Therefore, we employ an energy harvester in the on-demand connection module that collects energy generated from a desired event. It is worth mentioning that the energy harvested by the on-demand connection module is not necessarily the same as what is being sensed. For example, an EcoSense sensor may sense the

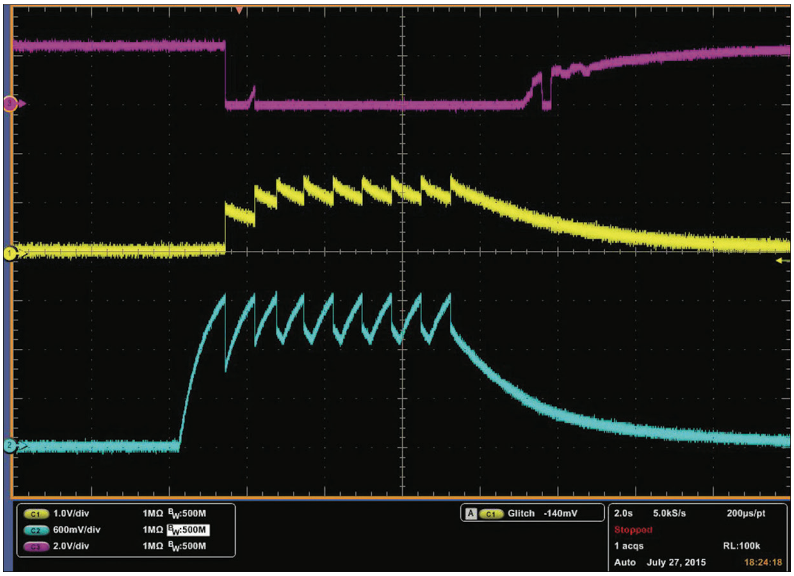

Figure 2. Voltages of the storage capacitor (blue line), smoothing capacitor (yellow line), and NMOS (purple line) captured by a Tektronix DPO7054 oscilloscope.

appearance of a target by checking its infrared sensor or camera, but be triggered by the energy harvested from the vibrations or sounds from the target. However, it is possible that the energy harvested is exactly the same as what is sensed. In the previous example, the EcoSense sensor can be triggered by the sound emitted by the target, and the same sound can be used to determine whether a target appears by the sensor.

Circuit Design and Operating Principles of EcoSense

The energy harvester in the on-demand connection module first harvests energy from a desired event and charges a capacitor. After it is fully charged, the capacitor starts discharging to control a switch that connects the power supply unit and the sensor.

Figure 1b shows the circuit schematic of the on-demand connection unit. This module includes an energy harvester, a charge pump, a storage capacitor, and a smoothing capacitor. Depending on different energy sources, a variety of harvesters can be selected such as light-, RF-, or vibration-based energy harvester. The energy output from the energy harvester is then fed into the Seiko S-882Z IC charge pump. The Seiko S-882Z IC charge pump is introduced here because the voltage of harvested energy is too low to power an electronic device; thus, the voltage needs to be increased. A Seiko S-882Z IC charge pump is a DC-to-DC converter that uses capacitors as energy storing elements to create either a higher or lower voltage power source. This particular charge pump is selected because it has an extremely low voltage requirement(e.g., 300 mV). In our experiments, we find that the proposed on-demand unit even works at a voltage as low as 260 mV. Energy output from the charge pump will be used to charge the storage capacitor. The storage capacitor then discharges energy to control the *N*-channel metal oxide semiconductor field effect transistor (MOSFET) that works as a switch between the power supply unit and the sensor.

The operating principle of the on-demand connection unit can be better explained by Fig. 2. In this figure, the voltage of each component in the on-demand connection module is measured by a Tektronix DPO7054 oscilloscope. In Fig. 2, the storage capacitor's voltage is recorded by the blue line. The charge pump OUT pin's voltage is captured by the yellow line. The purple line shows the drain-source voltage of the negative metal oxide semiconductor (NMOS) component. When a desired event happens, the energy harvester starts to harvest energy and gradually charges the storage capacitor through the Seiko S-822Z IC charge pump. When the voltage of CPOUT reaches a certain threshold (e.g., 1.8 V), the storage capacitor begins to discharge through the OUT pin. As a result, the OUT pin's voltage increases from low to high, so the NMOS switch is closed.

When the discharging process completes, the storage capacitor goes back into charging mode. Therefore, the OUT pin's voltage drops and the NMOS switch is opened. In other words, the sensor will be periodically powered on and off when the desired event is present. This will prevent the sensor from continuously sensing the desired event. To address this issue, we add a smoothing capacitor C_{sm} after the OUT pin. As shown by the yellow line, C_{sm} releases its energy when the storage capacitor is in charging mode. When C_{sm} finishes discharging, the storage capacitor will be fully charged and start to discharge again. In this way, the OUT pin provides a continuous power to the NMOS, and the sensor is powered steadily as long as the energy harvester continues to provide energy.

Because the harvested energy is only used to close a switch rather than powering a sensor, a small amount of energy is good enough to provide a long discharging time. For example, with a 4.7 μF storage capacitor, its discharging time could be as long as 16.5 s. It is also important to mention that the choice of C_{sm} highly depends on the storage capacitor. It needs to be large enough to continue releasing energy when the storage capacitor is charging.

Finally, we check the sensor's status by measuring the drain-source voltage of the NMOS. When there is no desired event, the gate-source voltage is zero, and the NMOS is in high-impedance state. Because the drain-source voltage is high, the power supply unit and the sensor are disconnected. Otherwise, the NMOS is in low impedance state and the drain-source voltage is zero (i.e., the sensor node is powered on). At this time, the sensor can perform sensing and communication tasks.

Performance Evaluation

Although the innovative EcoSense architecture facilitates energy saving on a sensor during its inactive mode, it is not clear whether such a sensor will meet the real-time requirements posed by an application. To answer this question, we first evaluate the reaction time on an EcoSense sensor, that is, the time difference from a desired event occurring to the sensor starting to work. We then investigate how long a sensor can work after a desired event is observed. Finally, we examine the reaction distances of light-driven and RF-driven EcoSense sensors.

Reaction Time and Working Duration

We fabricate the on-demand connection unit on a printed circuit board (PCB). As shown in Fig. 3, this unit is used to connect a TelosB node and its power supply component (i.e., two AA batteries). In this figure, we can see a light-driven EcoSense sensor that is triggered or turned on by lights.

Figure 4a shows the reaction time and working duration of the sensor with various storage capacitors in the on-demand connection module. The working duration is defined as how long a sensor is active after it is triggered by a desired event. When the storage capacitor is 33 pF, both reaction time and working duration are almost 0. This implies that the sensor immediately senses the environment as long as a desired event occurs and stops working once the event disappears. As the capacitance value increases, both reaction time and working duration grow accordingly. For example, the reaction times are 15 ms and 628 ms, and the working duration times are 1000 ms and 16500 ms when the storage capacitors are 47 nF and 4.7 µF, respectively. We also note that the working duration is always much larger than the reaction time. It means a short charging time provides a long discharging time, which is opposite to the cases where harvested energy is used to directly power a sensor. Based on our experiments, it usually takes a couple of hours for the harvester to collect enough energy to power a sensor to work for a few seconds.

Reaction Distance

Figure 4b shows the reaction distances given different light sources. We first use three cell phones to trigger the light-driven EcoSense sensor. For Apple iPhone 5 and 6 Plus, the reaction distance is about 70 cm. The performance of a Samsung Galaxy S5 is much better than that of iPhones (i.e., it provides a 170 cm reaction distance). We then place the sensor in an office, and turn the lamp on and off. The sensor always reacts to the lamp whenever it is turned on. The office ceiling is about 5 m high, but we believe the actual reaction distance could be much larger than that. Finally, we place the sensor in a football field at night and trigger it via a car's headlights. The reaction distances for low-beam lights and high-beam lights are 18 and 87 m, respectively. Because the sensor indeed reacts to a car's headlights, it operates exactly the same as if it is in standby mode. The difference is that an EcoSense sensor does not consume any energy when there is no car's headlight; however, a regular sensor in standby mode still consumes a certain amount of energy.

In addition to the light-driven EcoSense sensor, we implement an RF-driven EcoSense sensor. In this sensor, the energy harvester is implemented by a five-stage modified Dickson charge pump presented in [9]. It converts the AC power received from an RF antenna to DC power and increases its voltage. The harvested energy is then provided to the Seiko S-882Z IC charge pump in the on-demand connection module. To emulate an RF event, we adopt an Agilent N5182A signal generator that generates

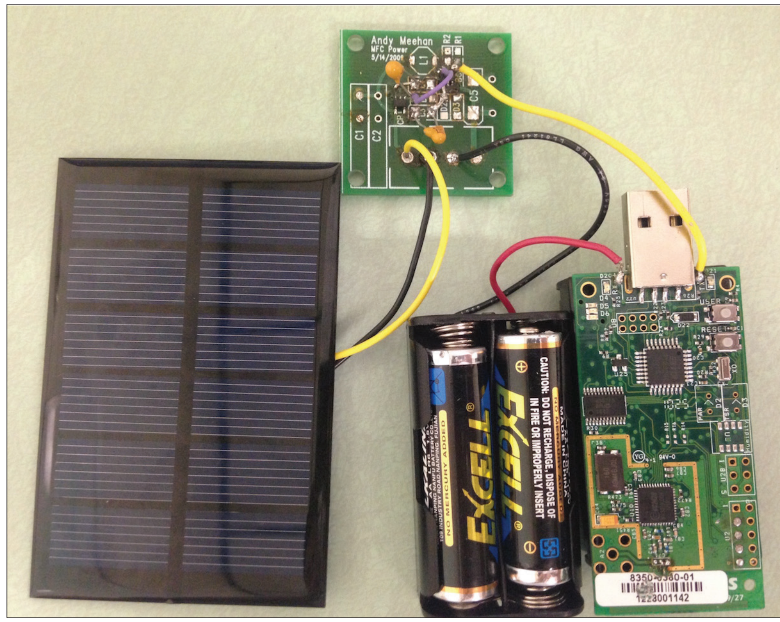

Figure 3. Prototype of a light-driven EcoSense sensor that consists of a solar panel, an on-demand connection module, a TelosB sensor, and two AA batteries as the power supply.

RF signals at the frequency of 540 MHz. Figure 4c shows the reaction distances given different transmission powers used by the Agilent N5182A to transmit RF signals. The reaction distance increases when the transmission power gets stronger. When the transmission power is 17 dBm, the sensor is able to detect RF signals that are 10.34 m away. When the transmission power is reduced to 8 dBm, the reaction distance is still 3.3 m. We also compare the reaction distances to the theoretical values computed based on the free-space path loss model. A good match between the reaction distances and theoretical distances can be observed in this figure.

Discussion

In this section, we discuss the limitations of the proposed technique and point out the scenario(s) where it is applicable. Due to the short reaction distance, only sensors near the desired event(s) will be triggered and start to work. This will cause challenges in realizing multihop networking among sensors. Therefore, the EcoSense technique can only be applied to sensors that are connected to a backbone network. For example, it can be implemented on the reduced function devices (RFDs) in a Zigbee network or the non-clusterhead sensors within a cluster. In this way, when EcoSense sensors are triggered, they will transmit their sensing data to full function devices (FFDs) or clusterheads, which will relay and forward the data to the destination.

The EcoSense technique leverages the energy in desired events to activate a sensor; that is, if enough power can be harvested from any form of energy generated by the event, an EcoSense sensor will be triggered. In some cases, the energy associated with a desired event may be too weak to be collected by the energy harvester, or the energy may not even exist. To address this problem, we rely on the always-on nodes in the network (e.g., the FFD nodes in a Zigbee network or clusterhead nodes) to send activation signals (e.g., RF signals) to remotely turn on EcoSense sensors to collect their sensing data. In summary, EcoSense sensors are polled only when there is no or limited energy generated by the desired events.

The working duration of an EcoSense sensor is mainly determined by the amount of energy available in desired events, i.e., longer the desired event, longer the working duration. In some cases, we may want a sensor to work for a relatively long period of time. Therefore, it is critical to enhance the proposed EcoSense architecture to support longer working durations on sensors, which is considered our future work.

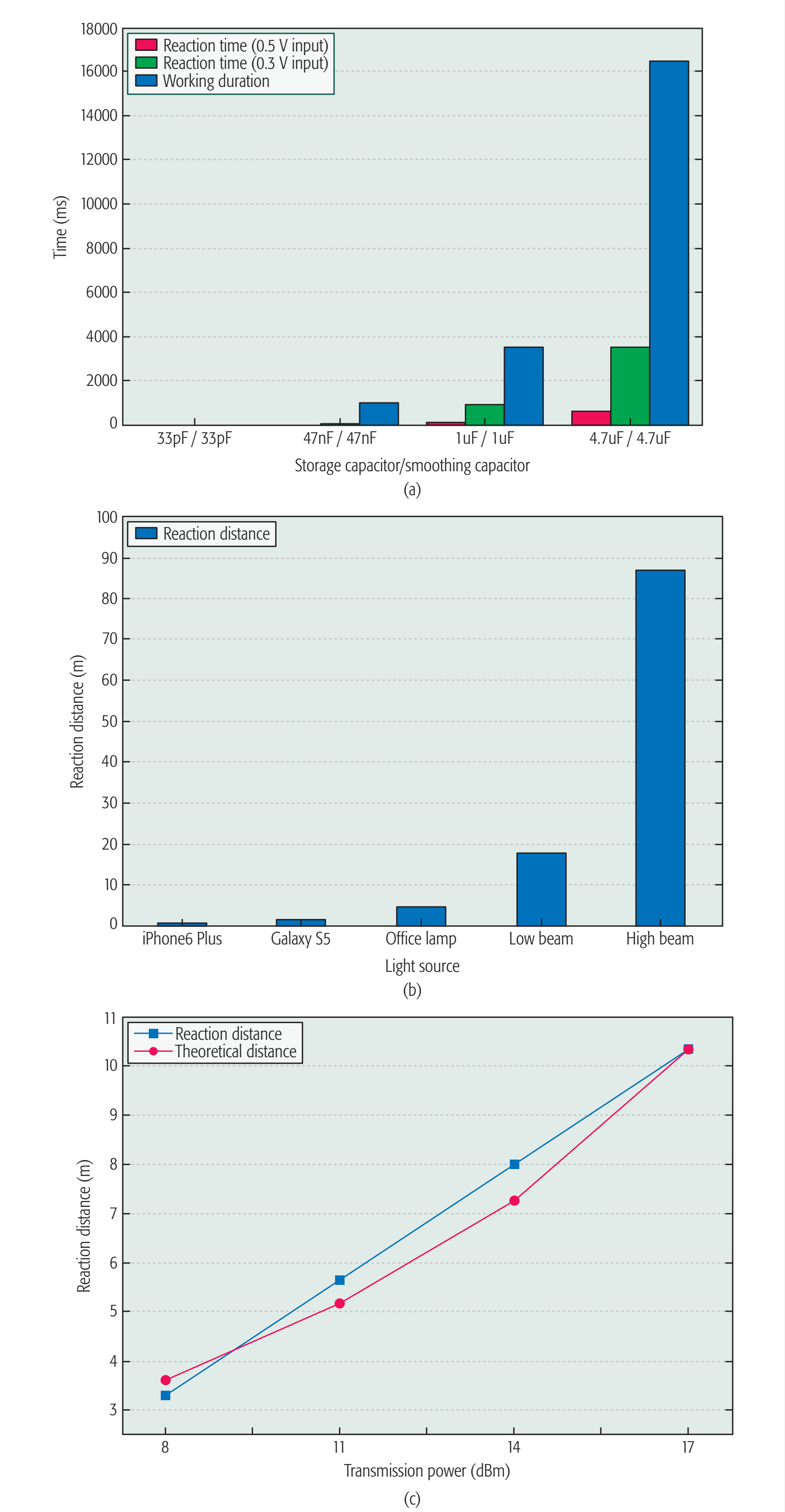

Figure 4. a) Reaction time and working duration of an EcoSense sensor with various storage and smoothing capacitors; b) reaction distances of the light-driven EcoSense sensor with different light sources; c) reaction distances of the RF-driven EcoSense sensor with various RF transmission powers.

Related Work

In the past decade, we have witnessed a growing interest in energy saving techniques for low-power sensing systems. In the following, we briefly survey previous works about this research subject.

Duty Cycle MAC Protocol. Duty cycle medium access control (MAC) is an important mechanism to reduce the energy consumption by a wireless communication module. This type of method can be categorized into three groups: synchronous, sender-initiated asynchronous, and receiver-initiated approaches. In synchronous duty cycle MAC protocols [5], sensors switch their radio transceivers on and off according to a common schedule. In the sender-initiated asynchronous approach (e.g., X-MAC [10]), sensors switch on their radio transceivers independently and employ low-power listening (LPL) to monitor channel activities. In the receiver-initiated asynchronous duty cycle MAC approach (e.g., RI-MAC [11]), wakeup beacons are used to remotely turn on a sensor's radio component. Different from the above-mentioned methods, a SmarSense sensor is activated on demand and thus avoids unnecessary wake-ups.

Radio Triggered Wake-Up Technique. Radio-triggered wake-up techniques enable a sensor to communicate on demand [8, 12]. If a sensor wants to transfer a packet to another node, it first sends an RF signal via a wake-up transmitter. When the wake-up receiver of a neighboring node captures this signal, it generates an interrupt to switch itself from sleep mode to active mode. With this technique, a node keeps sleeping until it needs to communicate with others. Therefore, the energy waste caused by idle listening is eliminated. EcoSense differs from these works in that it not only supports on-demand communication but also on-demand sensing. EcoSense draws zero current when a sensor is in sleep mode, which further reduces energy consumption.

Energy Harvesting. In recent years, ambient energy harvesting attracts lots of attention. Trinity [13] is an indoor sensing system that harvests energy from airflow produced by a heating, ventilation, and air conditioning (HVAC) system. E-WEHP [14] presents a digital TV signal powered embedded sensor platform. A multi-band simultaneous power harvesting system is proposed in [15] that can harvest RF energies at 900 MHz, 1800 MHz, and 2.45 GHz. Energy harvested in these systems is used to power sensors, which is different from energy being used to control a switch in the EcoSense architecture.

Conclusion

In this article, we propose the EcoSense — a novel sensor architecture — to minimize energy consumption on a sensor. Compared to traditional approaches, an on-demand connection module is introduced to control the connections between a sensor and its power supply unit. The module acts as a bridge between the power supply and the sensor. This bridge is set to disconnected by default (i.e., no current is drawn by the sensor). When desired events occur, the energy harvester collects the energy associated with the events and wakes up the sensor by connecting it to the power supply unit.

We implemented two types of EcoSense sensors and evaluated their performance regarding reaction times, working duration, and reaction distance. Results show that the capacitances of the storage and smoothing capacitor affect both reaction time and working duration. Given a small storage capacitor, the reaction time is almost zero. The reaction distance is relatively short (e.g., less than dozens of meters), which implies that the proposed technique is only applicable in short-range applications. We believe a new direction of saving energy on sensors in IoT is opened, and more hardware-based energy efficiency techniques are expected in the future.

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Biographies

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We implemented two types of EcoSense sensors and evaluated their performance regarding reaction times, working durations, and reaction distances. Results show that the capacitances of the storage and smoothing capacitor affect both reaction time and working duration.