ECO: AN ULTRA-COMPACT LOW-POWER WIRELESS SENSOR NODE FOR REAL-TIME MOTION MONITORING

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ABSTRACT

ECO is an ultra-compact wireless sensor node. Only 648 mm³ in volume and weighing under 1.6 grams, ECO was initially designed to monitor the spontaneous motion of preterm infants over 2.4GHz radio links at the maximum data rate of 1Mbps. The compact form factor and low power consumption also make ECO nodes highly suitable for many other applications, including medicine, environmental monitoring, new computer-human interface, and ambient intelligence. This paper describes the hardware and software designs of the second generation ECO nodes and the host interface. We also present an evaluation and comparison against other popular sensor nodes in the similar class.

1. INTRODUCTION

Wireless sensor nodes (WSNs) have received wide attention recently across many application areas, ranging from medical and clinical research, structural health monitoring in civil engineering, to mission-critical industrial and military applications. Wired sensors have been available for a long time, but wires are often cumbersome and expensive to install and maintain. Making these nodes small, wireless, and low power will not only make it more convenient for data acquisition and environmental monitoring, but also open up new applications. However, it is challenging to make WSNs consume very low power, low cost, communicate reliably at high speed, and be packed in a lightweight, small form factor.

As a motivating application, consider the problem of monitoring preterm infants. One way to help these preterm infants grow in weight and bone strength is to apply assisted exercise. This entails helping the babies move their arms and legs as a way to stimulate their spontaneous physical movement. Although assisted exercise is effective for many such preterm infants, it must be closely monitored to ensure the infants are not adversely assisted. As a result, a bed-side device that is minimally invasive and can measure their spontaneous movement is needed.

Currently these preterm infants are monitored at least three different ways. The first is by direct observation, which is mainly qualitative and has several obvious drawbacks with manual monitoring. The second is either 2D or 3D motion analysis based on images taken by cameras. While also noninvasive, image-based motion analysis techniques fail to pick up small movements and can be obscured by clothing or blankets. The third is to attach sensors directly to the infant’s limbs. Currently, wired sensors can be made small, thanks to devices such as the ADXL202E dual-axis accelerometer (5mm × 5mm × 2mm) [1]; however, the wires are cumbersome, because the infant already has many other wires attached. Besides, long wires can easily introduce noise to the data.

Several other sensor nodes today are available with different trade-offs. The ActiWatch [2] is a wearable motion sensing and data logging device that records the motion data to be processed later. It is cordless, but it does not have an RF unit. It does not interfere with other medical instruments, but real-time monitoring is not possible. Weighing 17.5g, the ActiWatch is also too bulky for premature infants. Another sensor node, the Mica “Mote,” is capable of wireless transmission. The smallest of the Mote, MICA2-DOT (MPR500) [3], is 25mm in diameter and 6mm in height, which is still 2.9 times as large as the required size. It is designed for sporadic event detection rather than real-time monitoring. Also, for the Mote to perform motion sensing, a separate sensor board must be connected to its expansion port, making the device even larger.

This paper presents two designs of our second generation, ultra-compact wireless sensor node, called ECO, to meet the requirements specified by medical researchers. The standard ECO node is 12mm × 12mm in surface area, × 4.5mm thick (648mm³ in volume) without batteries, or × 7mm (1cm³ in volume) with the battery. ECO is also available in an alternative form factor, called ECO-Stick, which measures 22mm × 9mm × 3.5mm (693mm³ in volume). Unlike previous WSNs, ECO has a data rate of up to 1Mbps, much higher than similar sized WSNs. Furthermore, the frequency hopping feature enables multiple ECO nodes to simultaneously transmit to multiple receivers without sacrificing response time or bandwidth. This paper first reviews the specification, followed by the hardware design, software design, and a detailed evaluation and comparison.

2. REQUIREMENTS SPECIFICATION

The requirements specification for ECO can be divided into functional and timing specification, power constraint, and physical constraints, including size, weight, and cost.

2.1. Functional and Timing Specification

As a single node, ECO performs a simple task: it takes a sample from the X-Y accelerometer for 10–100 times per second, and transmits the data over the wireless link to one or more receivers connected to a host computer. One ECO node is required on each
of the four limbs, and thus four Eco nodes must operate in a co-ordinated manner. All Eco nodes should synchronize to the same clock and take samples at the same time. In addition, they should perform communication scheduling at different times so that the nodes do not interfere with each other. Even though this system is designed for “real-time” monitoring, the actual latency constraint is somewhat flexible. For this purpose, a 3-second latency (from sensing to transmitting) was chosen as a practical timing constraint. A longer latency will provide more flexibility in communication scheduling and opportunities for power management, but a shorter latency is desirable for the user.

An Eco-Station is the interface between the Eco nodes and the host computer. It receives data over the wireless link from one or more Eco nodes, one at a time. Then, it sends the data to the host computer over Ethernet or USB. Depending on the total number of nodes, sampling rate, and latency, multiple Eco-Stations may need to be used. Each Eco-Station can define its own frequency hopping sequence to work with its set of Eco nodes.

2.2. Size and Cost Constraints

Because Eco nodes are to be worn by preterm infants, they must be small enough in order not to impede their spontaneous motions. According to the medical researchers, the desired surface area of the sensor node should be around 1cm², with a thickness of about 6mm, weighing under 5 grams. The total volume should be about 1cm³ including batteries. The 1cm width is based on the width of such an infant’s limb, although the length can be longer. A slightly more relaxed specification for the physical dimensions of Eco is 1cm × 2cm × 6mm in order to accommodate a larger battery. The target cost of each Eco node is US$50.

2.3. Power Constraint

The power consumption of the Eco node is constrained from above by the physical size, since small batteries can deliver very limited current and voltage. The wireless transmission distance imposes a lower bound on the RF power consumption. For the infant monitoring application, the range is at least one meter.

3. HARDWARE DESIGN

Fig. 2 shows the block diagram of Eco’s hardware architecture. The standard Eco node consists of (1) the microcontroller and radio board and (2) the sensor and power board. Eco-Stick integrates both onto a single board.

3.1. Microcontroller and Radio Board

Fig. 3(a) shows the microcontroller and radio board. It consists of the nRF24E1 [4], a chip antenna [5], a 32K EEPROM(AT25320A) [6], and a 20-pin connector.

The nRF24E1 is a 2.4GHz RF transceiver with an embedded 8051-compatible microcontroller (DW8051) [7]. The microcontroller has a 512-byte ROM for a bootstrap loader and a 4KB RAM for the user program that is loaded from an external serial EEPROM via the bootstrap loader. It also has 256 bytes of RAM, which is used for data memory with a portion of the 4KB program memory. In addition, the microcontroller has one SPI (3-wire), one RS-232 port, and a 9-channel AD converter. The bit resolution of the AD converter is software-configurable from 6 bits to 12 bits.

The 32KB serial EEPROM is to store the application program and parameters. It is connected to the nRF24E1 via SPI as shown in Fig. 2. When the nRF24E1 is powered up, the bootstrap loader loads the user program from the EEPROM to the program memory. Also, user-configurable parameters such as transmission power level, AD converter resolution, and node ID number are stored in the EEPROM.

The transceiver on the nRF24E1 uses a GFSK modulation scheme in the 2.4GHz ISM band. It has 125 different frequency channels that are 1MHz apart and supports frequency hopping among them. It takes less than 200µs to switch from one frequency channel to another. The unique feature of this transceiver is that it supports simultaneous data reception on two frequency channels. When we use one frequency as a main channel, we are also able to receive data from the subsidiary channel that is 4MHz apart from the main channel. The maximum RF output power is 0dBm at the maximum data rate of 1Mbps. The output power, data rate, and other RF parameters can be set from software.

We use a chip antenna to radiate RF signals. It is a compact and high-performance 2.4GHz antenna. Its SMD type package measures only 6.5mm(H) × 2.2mm(W) × 1.0mm(H) and its max-
The LTC3459 offers Burst Mode operation with a fixed peak current, providing high conversion efficiency over a wide range of load currents. During start-up, inductor current is controlled preventing the inrush surge current found in many boost converters. In shutdown the output is disconnected from the input and quiescent current is reduced to <1 µA.

### Features Description

#### 2.5V to 10V Micropower Boost

The LTC3459 is an internal synchronous rectifier for boost converter intended for low power, size constrained portable applications. The LTC3459 can be powered from 1.5V to 5.5V. The output is programmable via an external divider between 2.5V and 10V. Although the part is primarily intended for boost applications, V OUT will operate above 10V when using a boost converter.

#### Inrush Current Limiting

The LTC3459 offers Burst Mode operation with a fixed peak current, providing high conversion efficiency over a wide range of load currents. During start-up, inductor current is controlled preventing the inrush surge current found in many boost converters. In shutdown the output is disconnected from the input and quiescent current is reduced to <1 µA.

#### Output Disconnect in Shutdown

In shutdown the output is disconnected from the input and quiescent current is reduced to <1 µA.

#### Burst Mode

Burst Mode is a registered trademark of Linear Technology Corporation.

#### Small OLED Displays

This switching regulator generates a constant 3V regardless of the battery's actual output voltage. We have carefully chosen the regulator whose conversion efficiency is highest (around 90%) when the output voltage is 8V. This switching regulator is used to power the small OLED displays.

#### LCD Bias

This switching regulator is also used to power the LCD bias, ensuring stable power to the LCD.

#### PDAs

This switching regulator is also used to power PDAs, ensuring sufficient power for the device.

#### General Purpose Micropower Boost

This switching regulator is used for general purpose micropower boost applications, providing stable power for various devices.

#### Ultralow Quiescent (10 µA)

This switching regulator is known for its ultralow quiescent current (10 µA), making it suitable for battery-powered devices.

#### Small Solution Size

With its small solution size, the LTC3459 is ideal for applications requiring minimal space.

#### VIN Range: 1.5V to 5.5V

The VIN range of the LTC3459 is from 1.5V to 5.5V, allowing flexibility in power input options.

#### Internal Synchronous Rectifier

The internal synchronous rectifier reduces power loss, improving efficiency.

### Application Examples

- **Supercap Charging**
- **Small OLED Displays**
- **LCD Bias**
- **PDAs**
- **General Purpose Micropower Boost**
- **Ultralow Quiescent (10 µA)**
- **Small Solution Size**
- **VIN Range: 1.5V to 5.5V**
- **Internal Synchronous Rectifier**

### Power Configuration Scheme

The power configuration scheme can be selected by the power path switch on the sensor and power board.

The ADXL202E is a dual-axis accelerometer. It measures acceleration ranging from ±2g to ±2g. It has both PWM (pulse-width modulation) and analog output. We sample this accelerometer's analog output using the nRF24E1's embedded AD converter. The power consumption of the ADXL202E is less than 3mW.

### Graphical User Interface

This section highlights the features of the software on the host computer and the communication mechanism between the host computer and the RF receiver called the Eco-Station.

#### 4.1. Graphical User Interface

The entire control and data acquisition of all Eco nodes is coordinated by a graphical user interface (GUI) running on a host computer. Currently the GUI can control up to four Eco nodes simultaneously. Clicking the “Start” button causes all Eco nodes to start data acquisition immediately, and the GUI starts plotting the data in real-time, as shown in Fig. 6. The duration, sampling rate and other parameters can also be defined prior to starting the experiment. After the experiment is finished, the motion data from all Eco nodes can be saved to a file. The same GUI can also be used to display previously saved data.
4.2. Communication between Host and Eco-Station

By default, the GUI is divided into four panes, plotting the motion response sensed by the four Eco nodes. Each pane is further divided into separate X and Y magnitudes over time on the top half, and the magnitude of the combined X-Y vector over time on the bottom half. The GUI also supports customization of the layout to show the motion data from only one, two, or three Eco nodes. This feature is useful when not all four sensors are used, or if the physician wants to focus on specific sensors (e.g., arms or legs only). Fig. 7 shows two layouts (horizontal and vertical tiling) for plotting the same data from two sensors.

In the current design, we need a separate 2.4GHz RF transceiver called Eco-Station to relay control and data packets between Eco nodes and the host computer. The nRF24E1 evaluation board serves as the Eco-Station that can listen to two RF channels simultaneously. We use two Eco-Stations to listen to up to four Eco nodes. The communication link between the Eco-Station and the host computer is wired RS-232. More details of the application setup can be found in Section 6.

Fig. 8 illustrates the communication sequences of the host computer, two Eco-Stations, and four Eco nodes. On startup, the host computer sends commands to both receivers to set the sampling rate and the total duration of the experiment. Then, the host starts waiting for incoming data from the first and second Eco-Stations. Upon receiving the data packets, the GUI on the host computer will plot the motion data on all four Eco nodes in real-time. The same recv-recv-paint cycle repeats until the experimental duration expires. The microcontroller on the Eco-Station board also ensures that the total period of each listen-package-send cycle is equal to the sampling period (the inverse of the sampling rate). The listen-package-send cycle on the second Eco-Station is interleaved with the same cycle of the first Eco-Station, such that in each sampling period the host computer can receive data from both stations sequentially, as shown in Fig. 8.

Each Eco node simply keeps acquiring one sample of the motion data and sending it to its designated receiver wirelessly. Usually the raw sampling rate of the Eco node is much higher than the sampling rate that is required by the Infant Monitoring application. As a result, the listen stage on the receiver can always capture multiple packets of data from each Eco node.

5. EVALUATION

In this section we evaluate Eco in terms of size and weight, power consumption, and performance. MICA2-DOT and MICAz [11] from Crossbow are used for comparison. MICA2-DOT is the quarter-sized wireless sensor node, the smallest of the Mote family. MICAz is the new ZigBee series in the 2.4GHz ISM band.

5.1. Size and Weight

Size is one of the significant limitations in designing wireless sensor nodes. For unobtrusive monitoring, the sensor node should have a small form factor, especially in the medical applications such as activity and vital sign monitoring of the human body. Eco’s dimensions are \(12 \times 12 \times 4.5\,\text{mm}^3 = 648\,\text{mm}^3\). As shown in Fig. 9, Eco is 4.5 times smaller than MICA2-DOT, whose size is 25mm in diameter \(\times 6\,\text{mm thick} = 2944\,\text{mm}^3\) excluding the battery. The weights of the Eco node and MICA2-DOT are 1.6g and 3g, respectively, without batteries. In fact, the MICA2-DOT contains a temperature sensor only. In order to use an accelerometer, a sep-
Table 2. Power Comparison: Eco vs. MICA2-DOT vs. MICAz

Table 3. Performance Comparison: Eco vs. MICA2-DOT vs. MICAz

Table 4. Material cost of the Eco node

5.4. Cost

Wireless sensor nodes are sometimes expected to be disposable, especially in medical applications. Therefore, low cost is another important issue. Table 4 shows the material cost of the Eco node. The total material cost of the Eco node is $57.18 in small quantities. We expect to be able to meet the target $50.00 price tag in larger quantities. In comparison, the price of MICA2-DOT and MICAz is more than $300 each.

6. INFANT MONITORING WITH ECO NODES

This section describes the setup of the Infant Monitoring application using Eco nodes as motion sensors. The setup is shown in Fig. 10. Up to four Eco nodes can be attached to the arms and legs of the infant. The Eco nodes communicate with the Eco-Station receivers via the 2.4GHz RF channel at a maximum data rate of 1Mbps. We use two nRF24E1 evaluation boards as Eco-Stations to collect data from the four Eco nodes. Each nRF24E1 chip can listen to up to two frequency channels. Although it supports dynamic switching between different channels, the 200µs frequency switching overhead will limit the sampling rate of the entire system. Therefore we use two Eco-Stations to listen to up to four Eco nodes simultaneously. The first Eco-Station’s frequency is set to 2.4GHz, and it listens to two Eco nodes that transmit data at 2.4GHz and 2.4GHz + 8MHz. The second Eco-Station’s fre-
frequency is shifted to 2.45GHz, and it communicates with the other two Eco nodes at 2.45GHz and 2.45GHz + 8MHz.

The two Eco-Stations are connected to a host computer running a graphical user interface program showing the motion of the infant’s arms and legs in real-time. The host computer sends control, timing, and power management commands to the Eco-Stations. These commands are then distributed to the Eco nodes to start data acquisition. The motion data collected by the Eco nodes are transmitted to the Eco-Stations. Each Eco-Station then packages the data from the two nodes and forwards them to the host computer in real-time.

The nRF24E1 evaluation board currently supports communication with the host computer over a serial link. In case the host computer is not equipped with multiple serial ports, extra serial ports can be made available by attaching a USB/Serial converter to the host computer.

7. CONCLUSIONS

This paper presents the Eco data acquisition system consisting of a set of Eco nodes, Eco-Stations, and software on the host computer. The Eco node is possibly the world’s smallest, low-power wireless sensor node in its class, capable of taking vibration data and transmitting wirelessly in real-time to the Eco-Station, which provides the up-link to the host computer. Much of the novelty with the Eco design lies in the ultra-compact form factor of the Eco node hardware, which consists of a microcontroller/RF board and a sensor/power board. This stacking design enables the hardware to occupy a small footprint while reducing data noise and critical path. The serial interface to the EEPROM also reduces switching and power. Coordinated by the Eco-Stations, the Eco nodes also exploit frequency hopping and communication scheduling to maximize bandwidth utilization while reducing or eliminating RF interference.

Eco nodes are naturally applicable to cases where the ultra-compact form factor is essential. The first application is in monitoring the spontaneous movement of preterm infants. Today’s available wireless or cordless sensors are too bulky that they impede the motion of these infants. We believe our Eco nodes are not only suitable for infant monitoring but also many other moving subjects where low-power and compactness are a must. The ability for multiple Eco nodes to support simultaneous, real-time data acquisition also makes Eco a versatile research tool for ambient intelligence. Eco nodes can be configured for various applications by replacing accelerometers with other types of sensors (light, temperature, sound, etc), without significantly changing the current design. This paper reports only a small sample of a large collection of interesting research topics. One future direction is exploring trade-offs between data buffering, low-jitter, and fast response. Eco nodes also make an ideal platform for studying low-power ad-hoc networks. The wireless communication mechanism of Eco is capable of supporting more sophisticated protocols using TDMA and frequency hopping, which will enable dynamic construction of networks on a larger scale.

8. REFERENCES