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 mm^3 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 (648mm^3 in volume) without batteries, or × 7mm (1cm^3 in volume) with the battery. Eco is also available in an alternative form factor, called Eco-Stick, which measures 22mm × 9mm × 3.5mm (693mm^3 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.

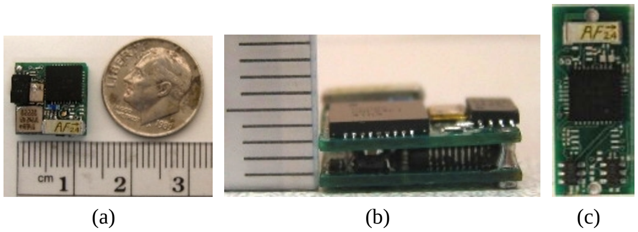


Fig. 1. Photos of Eco. (a) top view (b) side view (c) Eco-Stick.

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

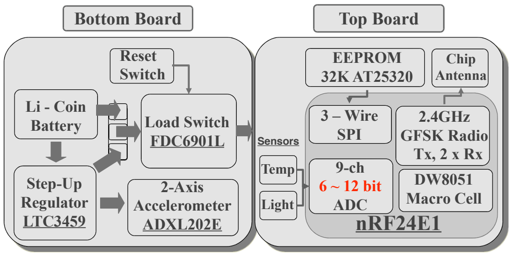


Fig. 2. Hardware architecture of Eco node.

of the four limbs, and thus four Eco nodes must operate in a coordinated 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 1cm^2, with a thickness of about 6mm, weighing under 5 grams. The total volume should be about 1cm^3 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

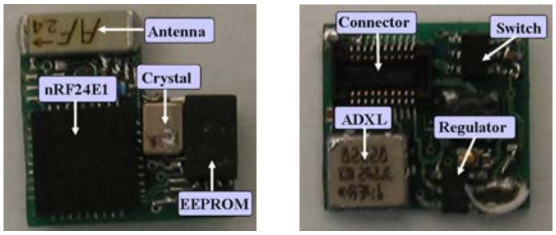
The power consumption of the Eco node is constrained from above by the physical size, since small batteries can deliver very limited current and voltage. The wireless transmission distance imposes a lower bound on the RF power consumption. For the infant monitoring application, the range is at least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



(a) Top board: micro-controller and radio board

(b) Bottom board: sensor and power board

Fig. 3. Two boards of Eco from top and bottom views.

Device	Mode	Operation	Current
Radio	TX	$-$5dBm,10Kbps	6.8mA
		$-$20dBm,1Mbps	8.8mA
		$-$10dBm,1Mbps	9.4mA
		$-$5dBm,1Mbps	10.5mA
		0dBm,1Mbps	13mA
Radio	RX	one channel,1Mbps	19mA
		two channels,1Mbps	25mA
Radio	Stdby		16μA
MC	Active	Supply current for ADC	0.9mA
		Supply current for MCU	3mA
MC	Stdby		2μA
EEPROM	Active		4mA
	Stdby		0.3μA
ADXL202E	Active		1mA

Table 1. Current draw of Eco node @3V and 16MHz.

The nRF24E1 is a 2.4GHz RF transceiver with an embedded 8051-compatible microcontroller (DW8051) [7]. The microcontoller 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 by 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 microcontoller 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-maintain regulation below V_{IN} (at reduced efficiency).

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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 <1µA.

The LTC3459 is offered in a low profile (1mm) 6-pin SOT-23 (ThinSOT™) package allowing a tiny footprint for the total solution.

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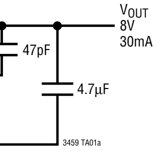
(a) Eco with the CR1225 (48mAh) battery (b) Eco-Stick with the CR2447 (1000mAh) battery

Fig. 4. Eco and Eco-Stick with batteries.



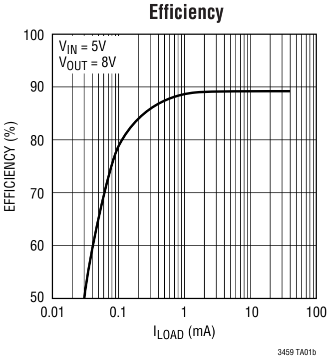


Fig. 5. Efficiency vs. output load current of LTC3459.

imum gain is 0.8dBi.

Table 1 shows the average current draws of each device in different operation modes. At the maximum output power level and transmission data rate, Eco consumes 55mW. In Standby mode, Eco consumes only 60μA. Mode transition from Standby to Active TX or RX takes 202μs. To save power, we always set the EEPROM in Standby mode except when Eco boots up.

3.2. Sensor and Power Board

Fig. 3(b) shows the sensor and power board. The power system of the Eco node consists of a Lithium Coin battery (CR1632) [8], a step-up switching regulator (LTC3459) [9], a load switch (FDC6901) [10], and a power path switch. As shown in Fig. 4, the battery is connected on the bottom side of the sensor and power board. The Eco node uses the CR1632 battery, whose nominal output voltage and capacity are 3V and 125mAh, respectively. Also, the Eco-Stick can accommodate higher capacity batteries such as CR2354 (560mAh) and CR2477 (1000mAh). In order to supply stable power to the Eco, we use the step-up switching regulator. 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 operating in Eco's current range of 5mA to 30mA, as shown in Fig. 5.

Eco supports two power configuration schemes. The first is that all components are powered by the switching regulator. In the second scheme, only the acceleration sensor and the embedded AD converter are powered by the switching regulator, while everything else is powered directly by the battery. In the first scheme, the Eco node can always be operating at stable 3V regardless of the voltage drop of the battery. However, because the switching regulator itself is lossy and the peak switching current (55mA) is much higher than the recommended continuous current draw of the battery (0.2mA), the battery will be drained very quickly. In the second scheme, because most of the components are powered directly by the battery without the regulation overhead, a longer battery life time can be expected. However, the performance of the Eco node such as transmission power level degrades as the battery's output voltage drops. Also, as the output voltage of the battery decreases, the Eco node consumes more current than shown in Table 1. In order to guarantee the accuracy of data, the acceleration sensor and AD converter should still be powered by the switching regulator. The power configuration scheme can be selected by the power path switch on the sensor and power board.

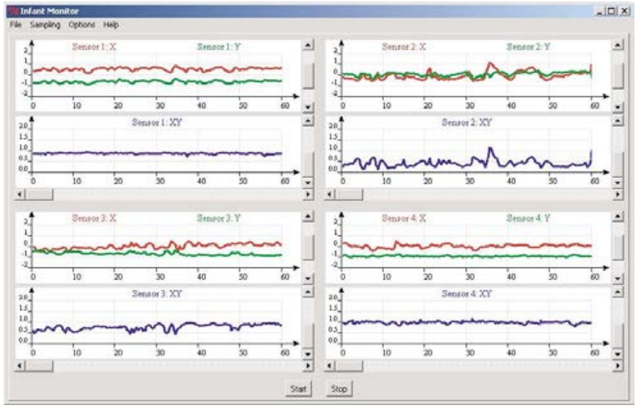


Fig. 6. The GUI showing four-channel motion data in real-time.

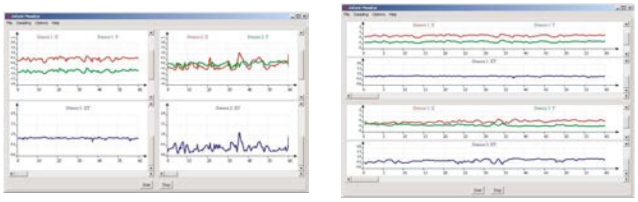


Fig. 7. The GUI showing two-channel motion data in a horizontal or a vertical layout.

The ADXL202E is a dual-axis accelerometer. It measures acceleration ranging from -2g to $+2$g. 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.

4. SOFTWARE DESIGN

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.

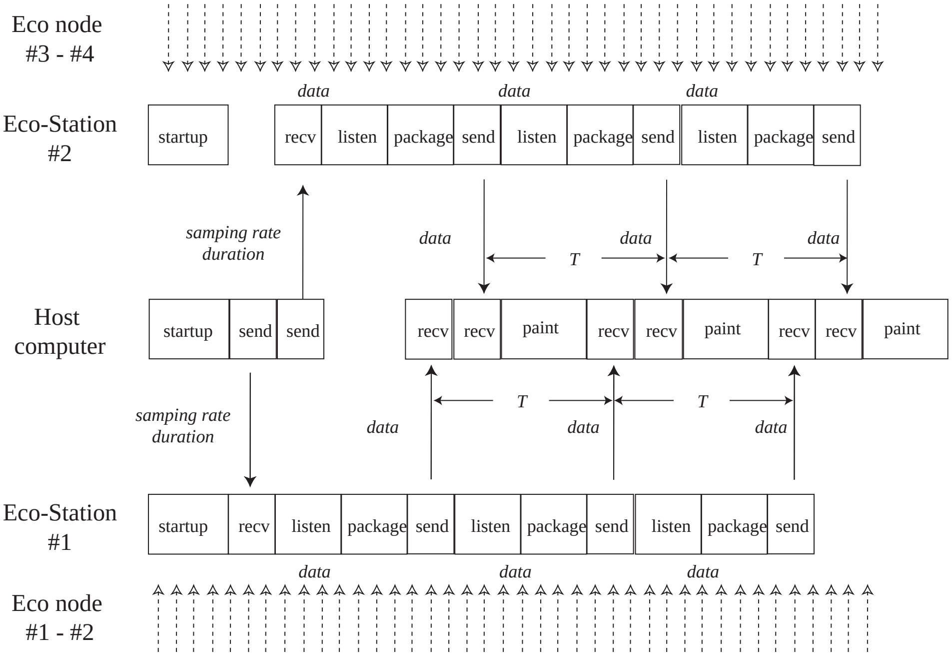


Fig. 8. Host / Eco-Station / Eco node communication sequences.

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.

Once an Eco-Station receives the initial startup commands from the host computer, it immediately starts listening to the two Eco nodes it is assigned for a period of time. After having received multiple data packets from both Eco nodes, the Eco-Station computes the average values of the motion data on each Eco node, and sends them in a single data packet to the host computer. The same *listen-package-send* 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 × 6mm thick = 2944 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-

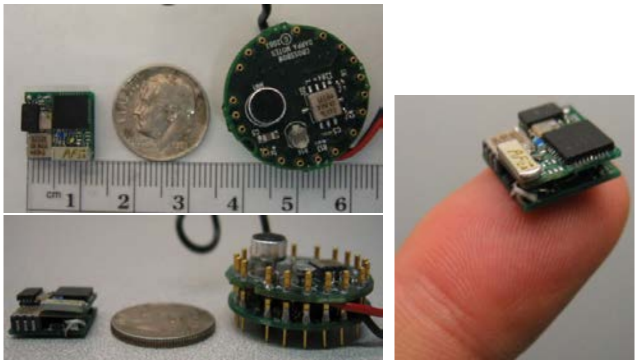


Fig. 9. Size comparison: an Eco, a dime, and the MICA2-DOT. Also shown is an Eco on an adult index finger.

	Mode	Eco	MICA2-DOT	MICAz
Processor	Active	3mA	8mA	8mA
		@16Mhz @3V	@4Mhz @3V	@7.37 @3V
	Sleep	$< 2\mu A$	$< 15\mu A$	$< 15\mu A$
Radio	Tx	13mA	16.8mA	14mA
	Pout/Data Rate	0dBm / 1Mbps	0dBm / 38.4Kbps	0dBm / 250kbps
	Rx	19mA	10mA	19.7mA
	Sensitivity	−90dBm / 1Mbps	−98dBm / 38.4Kbps	−90dBm
	Sleep	N/A	$1\mu A$	$20\mu A$
Total	Active Tx	16mA (48mW)	24.8mA (75mW)	22mA (66mW)
	Active Rx	22mA (66mW)	18mA (58mW)	27.7mA (83.1mW)
	Sleep	$< 2\mu A$	$< 16\mu A$	$< 16\mu$
Flash	Write	N/A	15mA (Max. 30mA)	15mA (Max. 30mA)
	Read	N/A	4mA (Max. 10mA)	4mA (Max. 10mA)

Table 2. Power Comparison: Eco vs. MICA2-DOT vs. MICAz

	Eco node	MICA2-DOT	MICAz
Program Memory	32KB EEPROM	128KB Flash	128KB Flash
Data Memory	4KB SRAM, 128B SRAM	4KB SRAM	4KB SRAM
External Memory	None	512KB Flash	512KB Flash
ADC	9×12-bit	6×10-bit	6×10-bit
Radio Channels	128	4/50	83
RF Power	−20 to 0dBm	−20 to +5dBm	−10 to 0dBM
Data rate	250Kbps, 1Mbps	38.4Kbps	250Kbps
Outdoor Range	35ft	500ft	30ft
Battery	3V Li Coin	3V Li Coin	2 AA batteries

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

Part Number	Description	Cost (US$)
nRF24E1	MCU & Radio Chip	$5.20
TXS-3225	16Mhz Crystal	$3.00
AT25320AY	32K EEPROM	$0.87
P8090SCT	Switch	$0.57
LTC3459	Step-Down Regulator	$5.75
PCD1664CT	$4.7\mu H$ Inductor	$1.40
FDC6901	Load Switch	$0.87
, 5602 Plug	Male Connector	$7.20
5602 Receptacle	Female Connector	$7.20
ANT-25-CHP	Chip Antenna	$3.25
CR1225	Battery	$1.84
	Inductors	$2.25
	Capacitors	$1.24
	Resistors	$0.54
Subtotal		$42.18
	PCB	$15.00
Total		**$57.18**

Table 4. Material cost of the Eco node

arate sensor board must be added, making the MICA2-DOT even larger and heavier.

5.2. Power Consumption

Table 2 compares the power consumption of Eco, MICA2-DOT, and MICAz. In Tx mode, Eco consumes less power than others, although its data rate is faster. In Rx mode, Eco consumes 12mW more power than MICA2-DOT and almost the same power as MICAz. However, because the data rate of Eco is the highest, Eco has the lowest energy per bit. In fact, Eco uses 1/13 as much energy as MICA2-DOT to receive the same amount of data. For more realistic comparison, we actually measured the battery lifetimes of Eco and MICA2-DOT. In this experiment we used a 560mAh Li-Coin battery and set both of them to 50% Tx duty cycle and 0dBm transmission power. According to our measurement, MICA2-DOT lasted 3.18 hours, whereas Eco lasted 7.56 hours. This measurement result shows that Eco is 2.38 times more battery-efficient than MICA2-DOT.

5.3. Performance

Table 3 compares the performance of the Eco node, MICA2-DOT, and MICAz. Both MICA2-DOT and MICAz have a larger size of program memory and an external 512KB flash memory for data acquisition. Although Eco has less memory, this is not a significant drawback. Because Eco is originally designed for real-time monitoring, it transmits data to its base station instead of storing in the local memory. Also, writing data into the flash memory consumes significant power (45mW), almost the same power as transmit. MICA2-DOT can transmit over a longer distance than Eco, because of its lower center frequency and higher RF power. However, the transmission range of Eco is almost the same as that of MICAz.

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-

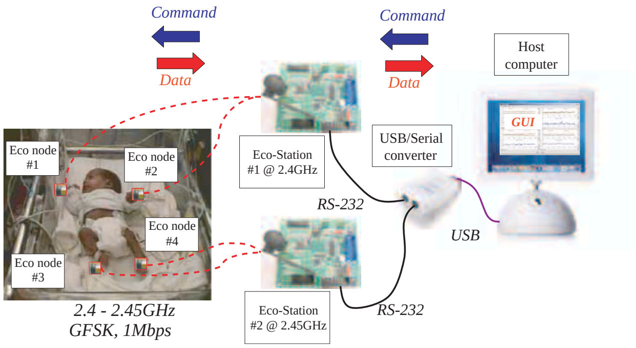


Fig. 10. Setup of the Infant Monitoring application.

quency 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.

Acknowledgments

This work was supported in part by NIH Grants HD26939, UCI GCRC Grant M01 RR00827, NSF CCR-0205712, and a Printronix Fellowship. The authors would like to thank Dr. Andrei Shkel for providing the material costs of building the prototype Eco nodes and Eco-Stations. The authors also thank Kensho Iwanaga, the physicians and nurses of UCI, Dept. of Pediatrics, and Neonatal Intensive Care Unit under the direction of Dr. Feizal Waffarn.

8. REFERENCES

[1] "ADXL202E," `http://www.analog.com/UploadedFiles/Data_Sheets/567227477ADXL202E_a.pdf`.

[2] "ActiWatch," `http://www.minimitter.com/Products/Actiwatch/`.

[3] "MICA2DOT Wireless Microsensor Mote," `http://www.xbow.com/Products/Product_pdf_files/Wireless_pdf/6020-0043-04_A_MICA2DOT.pdf`.

[4] "nRF24E1: 2.4GHz Transmitter/MCU/ADC," `http://www.nvlsi.no/files/Product/data_sheet/nRF24E2rev1_2.pdf`.

[5] "LINX," `http://www.linxtechnologies.com/images/products_cat/antennas/series/chip_antennas/ant-24-chp_data_guide.pdf`.

[6] "AT25320A," `http://www.atmel.com/dyn/resources/prod_documents/doc3347.pdf`.

[7] "DW8051 Macrocell," `http://www.synopsys.com/products/designware/docs/i/DW8051.pdf`.

[8] "CD1632," `http://www.renata.com/content/tabbedlithium/2pinshorizontal.pdf`.

[9] "LTC3459 High Efficiency Synchronous Step-up Regulator," `http://www.linear.com.cn/pdf/3459.pdf`.

[10] "FDC6901," `http://www.fairchildsemi.com/ds/FD/FDC6901L.pdf`.

[11] "MICAz wireless measurement system," `http://www.xbow.com/Products/productsdetails.aspx?sid=101`.