Eco: Ultra-Wearable and Expandable Wireless Sensor Platform

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Abstract

Eco is a self-contained, ultra-wearable and expandable wireless sensor platform under 1cm^3. Previous platforms make trade-offs between size or expandability. Eco achieves both with a novel flex-PCB expansion connector for digital/analog I/O, firmware programming, and battery charging. It can be folded up without obstruction or clipped off if expandability is no longer needed. Only 15% the volume of Mica2DOT, Eco has the same size as the nonexpandable μPart node but with several times more memory, processing and communication speeds. A separate data aggregator and a development/base-station board enable Eco nodes to form a high-performance body sensor network for pre-term infant monitoring and interactive dance.

1 Introduction

Many wearable wireless sensor systems have similar-looking architectures. To reduce unnecessary redundant design effort, modular, expandable platforms have been proposed [2, 3, 5, 7, 10]. They include snap-on connectors to make the interface pins accessible. End users can customize the platform by simply swapping in another board with a different sensing device or performance. Unfortunately, expandable platforms today are still relatively bulky for many body area network applications. On the large side, PASTA [10] includes a 180-pin connector plus CF socket, and measures 6.5cm by 4.5cm which is larger than the Mica2 mote. On the smaller side, the Spart [11] with on-board devices and an expansion connector measures 17mm×35mm not including battery, but it is still not small.

Expansion capabilities are often the first to be eliminated, since they occupy a nontrivial amount of nonfunctional volume. Eliminating connectors can also reduce layout and assembly complexity. For instance, the smallest Smart-Its, called μPart, is 1cm^3 in volume but without apparent expandability [1]. However, by spinning a new board for each application, a simple layout change can introduce many new problems [2], especially RF, and the efficiency of miniature antennas is extremely sensitive to their distance to other components and ground. Additional considerations include separation of power and ground lines for digital and analog subsystems. This approach often results in much duplicate effort at the low level.

To address these problems, we propose a new ultra-compact, expandable development platform called Eco for wearable wireless sensing applications. Previously, we designed Eco primarily to be small, lightweight and wearable by a pre-term infant. The latest design is now even smaller while including a novel flex-PCB connector. It exposes all available digital and analog I/O pins on the MCU, plus pins for serial communication and firmware programming, and battery charging. The flex-PCB is durable and can be folded up alongside the sensor node when not in use without taking up volume. It can be clipped off if expandability is no longer needed. Because it is manufactured as part of the PCB, it incurs no extra assembly cost or part cost. We show the effectiveness of our approach by interfacing Eco with a variety of sensing devices. In addition, the Eco platform also includes a separate data aggregator board and a development/base-station board. They enable Eco nodes to form a high-performance body sensor network. The combination of expandability and ultra-small form factor is expected to make Eco an attractive platform for developing and deploying many body area network applications.

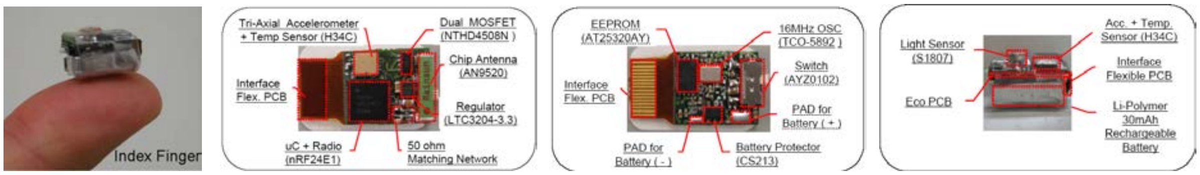
2 Platform Design

The Eco platform consists of the Eco sensor node, the Data Aggregator, and the Development/Base-Station Board.

2.1 Eco Sensor Node

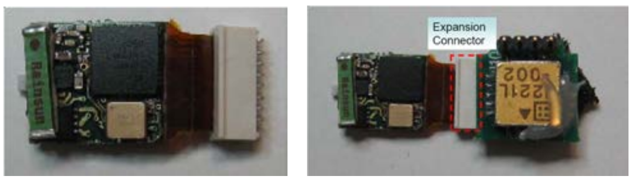
The Eco sensor node (Figure 1.) consists of four subsystems: MCU/Radio, Sensors, Power, and expansion port.

MCU/Radio nRF24E1 is a 2.4GHz RF transceiver with an embedded 8051-compatible MCU (DW8051) [6]. The MCU has a 512-byte ROM for a bootstrap loader, a 4KB RAM for the user program, SPI (3-wire), RS-232, and a 9-ch. ADC. The ADC is software-configurable for 6–12 bits



(a) On the finger (b) Top view (c) Bottom view (d) Side view

Figure 1. Photos of Eco node.



(a) Exp. port w/connector (b) Exp. sensor board

Figure 2. Photos of Eco's expansion port w/connector and expansion sensor board.

Table 1. Pin out for Eco's expansion port.

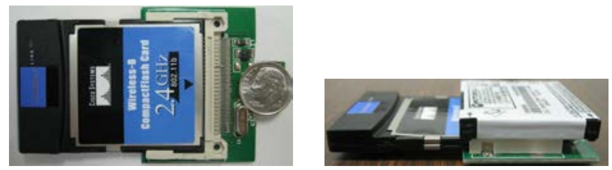
Num	Description	Num	Description
1	Digital I/O 0	9	SI (SPI)
2	Ground	10	SCLK (SPI)
3	RVDD (Regulator)	11	CS (SPI)
4	Digital I/O 1	12	BVDD (Battery)
5	Digital I/O 2	13	Analog Input
6	TXD (RS232)	14	SO (SPI)
7	RXD (RS232)	15	Ground
8	Digital I/O 3	16	VDD (3.3V)

of resolution A 32KB serial (SPI) EEPROM stores the application program. The nRF24E1's 2.4GHz transceiver uses a GFSK modulation scheme with 125 frequency channels that are 1MHz apart. The maximum RF output power is 0dBm at the maximum data rate of 1Mbps. The RainSun chip antenna (AN9520) measures 9.5mm(H) $\times$ 1.5mm(W) $\times$ 1mm(H) and has a maximum gain of 1.5dBi.

Sensors Eco has a 3-axial acceleration sensor, Hitachi-Metal's H34C (3.4mm $\times$ 3.7mm $\times$ 0.92mm). It measures acceleration from -3g to $+3$g and temperature from 0 – 75°C while consuming 0.36mA at 3V in active mode. Eco also has a light sensor (S1087).

Power Eco's power subsystem includes a 3.3V regulator (LTC3204-3.3V), battery protection circuitry, and a custom 30mAh rechargeable Li-Polymer battery (12mm(L) $\times$ 10mm(W) $\times$ 5mm(H)). LTC3204 (2mm $\times$ 2mm) is a low noise regulated charge pump regulator that outputs 3.3V. Its maximum output current is 50mA and average efficiency over a Li-Polymer battery's output range (3.0V – 4.2V) is 80% at the maximum output current. To measure the actual battery capacity, we continuously discharge it at constant 30mA and it lasts 1.5 hours. This translates into 45mAh.

Expansion Port Eco's expansion port has 16 pins as listed in Table 1, including 4 digital I/Os, one analog input, SPI, RS232, 3.3V output, and voltage input for a regulator and battery charging. This port enables Eco to interface with other sensing devices such an image sensor, gyroscope, pressure sensor, or compass. We can charge the battery and program the EEPROM via this expansion port. Fig. 2 shows the port connector and an expansion board for the Eco node.



(a) Top View (b) Side View

Figure 3. Photos of Data Aggregator.

2.2 Data Aggregator

The Data Aggregator (Fig. 3) consists of a TI MSP430 16-bit MCU, an nRF2401A 2.4GHz transceiver, a WCF CompactFlash 802.11b card, and a 700mAh Li-Polymer battery. The 802.11b card consumes a maximum of 250mA at 3.3V, and the entire Data Aggregator consumes $<$300mA at 3.3V. It collects data from all the Eco sensor nodes through the 2.4GHz transceiver and then transmits aggregated packets over UDP or TCP to a wireless access point connected to a host computer.

2.3 Development/Base-Station Board

Fig. 4 shows the Eco Development board. It includes a Freescale 16-bit MCU (MC9S12NE64), programmer circuitry, debugging serial port, battery charger (LTC4504), nRF2401A RF module, and RJ-45 Ethernet port. This board can serve as an EEPROM programmer, debugger, battery charger for the Eco sensor node, or as a base station for Eco nodes with a 100Mbps interface to the host computer.

3 Evaluation

We evaluate the Eco in terms of size and weight, radio performance, and power consumption/battery lifetime.

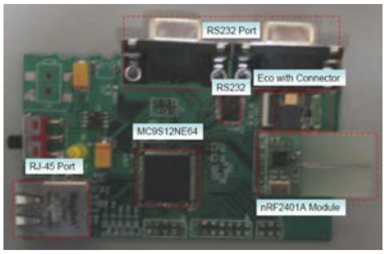
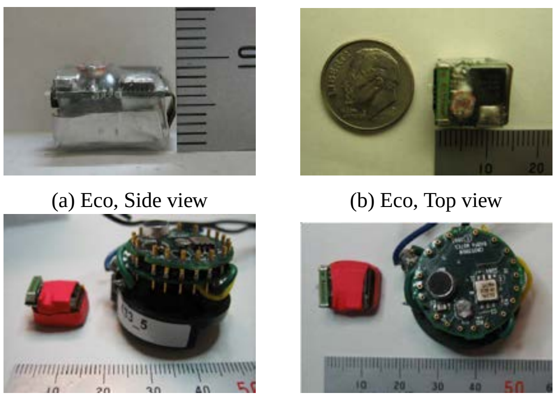


Figure 4. Photo of Development/Base-Station Board.



(a) Eco, Side view

(b) Eco, Top view

(c) Eco v. MICA2DOT (Side)

(d) Eco v. MICA2DOT (Top)

Figure 5. Dimensions of Eco and Size Comparison with MICA2DOT.

Also, we compare Eco with MICA2-DOT [5] from Crossbow. It is the quarter-sized, smallest of the "Berkeley mote" family, currently the most widely used wireless sensor platform.

3.1 Size and Weight

Eco is the first to achieve possibly the world's smallest form factor for a wireless sensor node without sacrificing expandability and performance. It measures only 13mm $\times$ 10mm $\times$ 8mm = 1040mm^3 including a battery and weighs under 2grams. In comparison, the smallest Crossbow mote, the MICA2DOT, measures 25 mm in diameter $\times$ 6mm thick = 2994 mm^3 excluding the battery, or $\times$ 14.5mm thick = 7144 mm^3 including the battery holder. The μPart node has a specified volume of 1cm^3, but it does not appear to have an expansion capability, and it uses a transmit-only UHF radio at 40 Kbps with a loop antenna whose volume is not included in the 1cm^3. The μPart uses the Microchip PIC12F675 MCU with 1.4KB internal flash, 64 bytes data SRAM, and 128 bytes of internal EEPROM.

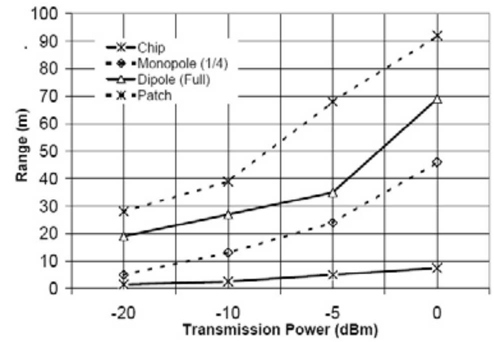


Figure 6. Transmission Power Level vs. Radio Range: Chip, 1/4-wave monopole, full-wave dipole, and patch antennas

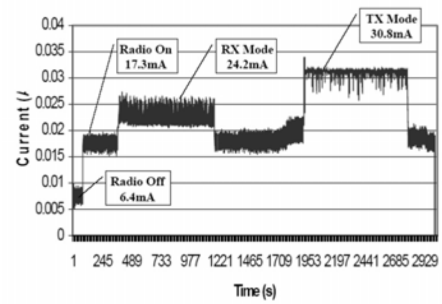


Figure 7. Power Profile of Eco.

3.2 Radio Performance

We evaluate the radio performance in terms of the radio range and sustainable data rate using a pair of Eco sensor nodes (a transmitter and a receiver) in an outdoors environment. We first measure the distance between two sensor nodes where the packet error rate drops down to 50% at each transmission power levels. Also, we repeat the same measurement for four different types of antennas: a chip (Rainsun's AN9520, 1.5dBi), 1/4-wave monopole (Antennafactory's ANT-2.4-CW-RCS, 2dBi), full-wave dipole (DLink's ANT24-0400, 4dBi), and patch (TRENDNET's TEW-IA06D, 6dBi). The results (Fig. 6) show that the radio range is highly dependent on the type of antenna. To measure the maximum data rate of Eco, we set the data rate to 1Mbps and transmission power level to 0dBm. The measured maximum data rate is about 800Kbps.

3.3 Power Consumption and Battery Life

Fig. 7 shows the power profile of Eco, when the supply constant is 3.3V. Eco consumes 30.8mA in transmit mode (0dBm, 1Mps), 24.2 mA in receive mode, 6.4mA in standby

(a) Interactive dance (b) Infant monitoring

Figure 8. Wearable applications for Eco platform.

mode. Also, with a 30mAh battery, Eco's battery lifetime is about 4 hours when the duty cycle is set to 50%.

4 Applications

We have applied the Eco platform to interactive art performance [8] and spontaneous motion monitoring of pre-term infants [9].

We used the Eco platform for interactive art performance. Fig. 8(a) shows a dancer wearing Eco nodes and a waist-pack data aggregator, which transmits real-time data for the dancer's motion, body temperature, heart beat, and even surrounding images. The base station converts the data stream into MIDI format before sending to a host computer running Max/MSP and Jitter [4], which are widely used commercial software packages for interactive music, video, and special effects synthesis in real time. This adds a whole new dimension to dance performance and empowers the dancers by extending their control to the stage and props. In this application, the Eco platform enables to implement the truly wearable wireless body sensor network (BSN) and collects data from multiple types of sensing devices using the same expansion port. Also, Eco's high bandwidth realizes fast collection of a non-trivial amount of data from those sensing devices. In addition, the WiFi-equipped data aggregator contributes to achieving high scalability, which is essential for group dance performance.

Fig. 8(b) shows the application of the Eco platform to monitoring spontaneous movement of pre-term infants. One way to help them grow in weight and bone strength is to apply assisted exercise, although it must be closely monitored to ensure the infants are not adversely assisted. Therefore, doctors need monitoring methods that are non-invasive and unobtrusive. Eco's small form factor and light weight enable infants to wear sensor nodes on their limbs so that doctors can monitor their movement in real-time in a cost effective way without the inconvenience of wired sensors or inaccuracy of vision based techniques.

5 Conclusions and Future Work

The Eco wireless sensor platform combines the ultra-wearable form factor with expandability, two factors that are crucial to the success of body sensor networks. Originally designed to be worn by pre-term infants, Eco is even more wearable by anyone than most other sensor nodes. It packs high wireless performance into possibly the world's smallest form factor while offering a novel flex-PCB expansion port general enough for many wearable applications. As miniaturization poses design challenges, the Eco platform enables a variety of new applications in body sensor networks to be not only prototyped but also deployed with little additional effort. One direction for future work is a cellular phone based data aggregator that will enable data to be collected from the body-area Eco nodes more easily and conveniently. The cellular phone can also relay the data to the base station or laboratory.

References

[1] M. Beigl, C. Decker, A. Krohn, T. Riedel, and T. Zimmer. μparts: Low cost sensor networks at scale. In *Ubicomp 2005*, 2005.

[2] A. Y. Benbasat and J. A. Paradiso. A compact modular wireless sensor platform. In *IPSN*, 2005.

[3] N. Edmonds, D. Stark, and J. Davis. MASS: Modular architecture for sensor systems. In *IPSN*, 2005.

[4] Max/MSP. `http://www.cycling74.com/products/maxmsp.html`.

[5] MICA2DOT. `http://www.xbow.com/Products/productsdetails.aspx?sid=73`.

[6] Nordic VLSI. 2.4GHz RF tranceiver with a 8051 microcontroller. `http://www.nvlsi.no/index.cfm?obj=product&act=display&pro=79`.

[7] B. O'Flynn, S. Bellis, K. Delaney, J. Barton, S. O'Mathuna, A. M. Barroso, J. Benson, U. Roedig, and C. Sreenan. The development of a novel miniaturized modular platform for wireless sensor networks. In *IPSN*, 2005.

[8] C. Park, P. H. Chou, and Y. Sun. A wearable wireless sensor platform for interactive art performance. In *International Conference on Pervasive Computing and Communications(PerCom)*, March 2006.

[9] C. Park, J. Liu, and P. Chou. Eco: an ultra-compact low-power wireless sensor node for real-time motion monitoring. In *IPSN/SPOTS 05*, pages 398 – 403, April 2005.

[10] B. Schott, M. Bajura, J. Czarnaski, J. Flidr, T. Tho, and L. Wang. A modular power-aware microsensor with $>$ 1000x dynamic power range. In *IPSN*, 2005.

[11] TecO/University of Karlsruhe. TecO particle devices. `http://particle.teco.edu/devices/`.