

# EcoBT: Miniature, Versatile Mote Platform Based on Bluetooth Low Energy Technology

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**Abstract**—This paper describes EcoBT, one of the first wireless-sensing platforms to support Bluetooth Low Energy (BLE) as their primary communication protocol. EcoBT Super-node is a full-sized node with an on-board digital accelerometer with rich expansion ports, while EcoBT Mini is the miniature version merely  $8 \times 8 \text{ mm}^2$  in area. Included on both nodes are a digital accelerometer with programmable threshold detection for power saving, real-time clock, magnetic switches for contactless operation, and low-load DC-DC converters for low stand-by power when used in conjunction with a rechargeable Lithium-polymer battery. The use of BLE enables direct communication with a BLE-equipped smartphone, tablet, or laptop without the inconvenience of a dongle or an extra gateway device. These two platforms share the identical microcontroller unit (MCU), enabling code sharing between them with little or no porting effort. The versatility of these platforms is being demonstrated in several real-life applications ranging from temperature tracking in shipping containers and lighting control to and several wearable medical devices.

## I. INTRODUCTION

Smartphones and tablets, collectively called smartmobiles, have overtaken laptop or desktop PCs as the preferred way for end users to access wireless sensor networks (WSN). The intuitive touch-screen user interface, combined with portability and low power, has enabled the widest range of population to access computing and communication technologies with virtually no learning curve. Users have naturally come to expect these smartmobiles to be able to serve as the front-end to embedded devices such as WSNs and various home appliances. Indeed, many such research prototypes and products are now controlled by mobile apps. However, rarely are these smartmobiles directly compatible with today's WSNs; instead, they require either a dongle or a gateway, which can be inconvenient.

### A. Direct Link between WSN and Mobiles

Most WSNs today are built with wireless interfaces that are not found on these smartmobiles. The most widely used RF interface for WSNs published to date is IEEE 802.15.4, or the MAC layer under the ZigBee network protocol stack, but it has not been built in to any commercially available smartmobiles to date. Most smartmobiles are built with Wi-Fi, Bluetooth, cellular data (GPRS, 3G, or 4G), and possibly NFC and ANT+. Some specialized WSNs have been built with these interfaces, but most of them were motivated by considerations other than the need to directly interoperate with smartmobiles.

As a result, most of today's WSNs require *protocol bridging* in the form of an access point (AP), Internet gateway, or

a dongle is needed to enable the smartmobiles to access these WSNs. Dongles are inconvenient, as they are intrusive, easy to break, and incur additional power consumption, and they have always been a temporary workaround rather than a permanent, sustainable solution. Some ZigBee-WiFi APs or ZigBee-USB dongles have been built, but they are far from mainstream commercially. Moreover, such an AP becomes a potential central point of failure. Wi-Fi alone may be a candidate for WSNs, but the power and cost have been a barrier. This leaves Bluetooth as the only other interface of choice. The new Bluetooth Low Energy (BLE) subset incorporates many compelling features in terms of energy efficiency, more flexible topologies, and direct smartmobile interoperability.

### B. Size and Functionality Trade-Offs

It has been nearly impossible to build a one-size-fits-all WSN platform. WSN platforms to date have been either *full-sized* or *miniature*. A full-sized node is in the size of a USB stick or larger, a form factor that has been unchanged for nearly a decade. It exposes a prototyping area that enables easy access to the hardware signals for interfacing with external sensors and actuators. This makes it more convenient for development purpose. In some applications, data logging necessitates a high-capacity flash memory card. Thus, the expansion option can be good for not only development but also deployment as well.

A few small-sized WSN platforms have been built, but they either lack sensing device, or are lower-bounded by the  $1 \text{ cm}^3$  volume. It has become difficult to build circuit boards that are much smaller, and even more difficult to provide expansion capabilities. Therefore, essential sensors should be built on-board whenever possible, but some limited expansion capability is still needed in order to serve as a platform. It is difficult to decide which pins to expose to the expansion connectors with very limited number of signals.

### C. Technical Approach

Our approach to low power and direct smartmobile compatibility is achieved by choosing the RF standard and combining the various power-saving features of the components, including the MCU, sensing devices, and DC-DC converters. We also build the same technology in two form factors, providing designers with the most flexibility for both development and deployment.

For RF communication, we choose Bluetooth Low Energy (BLE) Technology as the communication protocol. It is not only low power but also directly compatible with smartmobiles

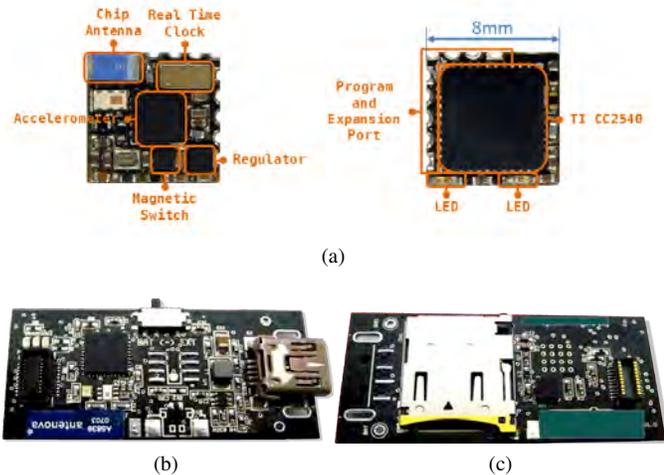


Fig. 1: Photos of (a) EcoBT Mini and (b)(c) SuperNode

while supporting security features, without requiring the use of a dongle or a gateway. Services can also be discovered dynamically.

The system components are combined in ways to enable effective power management. The MCU can be waken by a digital accelerometer with hardware threshold detection and freefall detection. The MCU can also use its built-in voltage comparator to be waken by an analog sensor. The on-board real-time clock (RTC) also supports time-based wakeup. To make sleep mode truly efficient, we choose a DC-DC converter with low quiescent current (i.e., overhead during no load condition).

Similar to EcoSpire [2], we make our platform in two sizes: a miniature node named EcoBT Mini that is merely  $8 \times 8$  mm<sup>2</sup> in area for deployment and embedding, and a larger, full-sized node named EcoBT Supernode for application development and for when storage for data logging is required. In either case, to enable contactless operation, we build magnetic switches onto the nodes.

Our contributions are that we are the first to bring a truly miniature BLE-based mote to the community. The EcoBT nodes are part of a development kit that includes software tools, libraries, and template code for smartphones and PCs. The whole kit is expected to enable the rapid development of a wide range of WSN applications that work closely with smartphones, without having to re-invent yet another hardware board with all the power management features.

## II. OVERVIEW

This section provides an overview of the key features of both EcoBT Mini and EcoBT Supernode. Fig. 1 shows their photos. We highlight the key features of the different subsystems, including the MCU, nonvolatile memory, on-board sensors, real-time clock, expansion interface, power circuitry, and antenna.

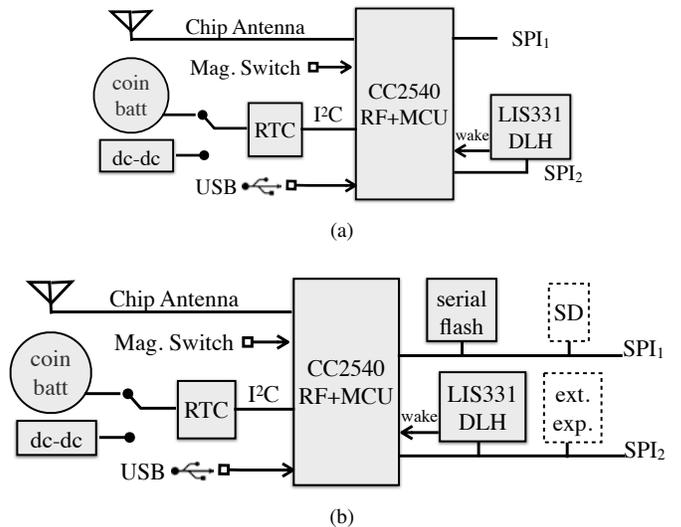


Fig. 2: Block Diagrams of the EcoBT Mini and EcoBT Supernode.

### A. Key Features

The block diagram of the EcoBT Mini is shown in Fig. 2a. Measuring  $8 \times 8$  mm<sup>2</sup>, it is the smallest, full-featured, self-contained wireless sensor node to date<sup>1</sup>. It contains not only a BLE-enabled MCU but also an on-board accelerometer, DC-DC converter or regulator, magnetic switch, and an RTC. The miniature form factor is made possible by using newly available miniature components and 4-layer PCB design. Table I compares EcoBT Mini with other miniature wireless sensor nodes.

The block diagram of the SuperNode is shown in Fig. 2b. It is built to be a multi-purpose platform. It uses the identical MCU, accelerometer, and RTC as MiniNode, making it possible to develop code on SuperNode more conveniently and then port code easily over to the MiniNode. In addition, it contains the expansion ports necessary for a wide variety of applications that are not stringently size-constrained. It includes on-board sensors and nonvolatile storage so that it is a self-contained unit that is usable even without adding any expansion modules. To meet a wide range of power options, we make the power configurable for both supplies, DC-DC converter options, and RTC power. Table II compares the features of SuperNode with other full-sized nodes. The remaining subsections describe these subsystems in more detail.

### B. MCU

The MCU on both SuperNode and MiniNode is the TI CC2540 RF-MCU system-on-chip from Texas Instruments [14]. It was chosen for the BLE protocol stack support, the 256 KB program flash size, 8 KB SRAM, built-in ADC, USB, two USARTs, DMA support, and the small package size of  $6 \times 6$  mm<sup>2</sup>. A USART is a multi-purpose controller that can be configured as either a UART or an SPI controller. The

<sup>1</sup>The Michigan Millimeter-Cube Computer is not considered the same class of wireless sensor node as it runs at a very slow speed, transmits over a very short distance, and does not contain comparable sensing or RTC features.

TABLE I: Comparison of Miniature Sensor Platforms

	EcoBT Mini	EcoSpire SimpleNode	Mica2 Dot	MicaZ OEM	Tmote mini	EPIC core	ZN1	$\mu$ Part
Size (mm <sup>3</sup> )	8 × 8 × 1.5	20 × 13 × 2	25 × 25 × 6	24 × 24 × 5	25 × 15 × 5	24 × 24 × 2	15 × 15 × 4	20 × 17 × 7
Microcontroller								
Type	CC2540	nRF24LE1	ATmega128L	ATmega128L	MSP430	MSP430	H8S/2218	rfPIC
Data mem.(KB)	8	1	4	4	8	8	12	0.064
Code mem.(KB)	256	16	128	128	48	48	128	1.2
Communication								
Radio	BLE (Integrated)	NRF24L01+ (Integrated)	CC1000	CC2420	CC2420	CC2420	CC2420	UHF(Tx) (Integrated)
Data rate	1Mbps	2Mbps	38.4Kbps	250Kbps	250Kbps	250Kbps	250Kbps	19.2Kbps
Antenna	Chip	Chip	External	External	External	Trace	External	wire
Power source								
Type	Li-Po or CR2032	Li-Po	coin cell	external	external	external	CR2	CR162x
Sensors and Peripherals								
Sensors <sup>1</sup>	A digital	A analog	T analog	Ex	Ex	Ex	T analog	L, m, T
RTC	Yes	No	No	No	No	No	Yes	No

<sup>1</sup> A = accelerometer, H = humidity, L = light, M = magnetic, m = motion, T = temperature, P = pressure, U = ultrasonic, Ex = external only (none on-board)

TABLE II: Comparison of Full-Sized Sensor Platforms

	EcoBT SuperNode	EcoSpire SuperNode	Mica2	MicaZ	Tmote Rev.B <sup>1</sup>	BTnode	XYZ Node	iBadge
Size (mm <sup>3</sup> )	42 × 20 × 2	50 × 23 × 2	57 × 32 × 6.4	57 × 32 × 6.4	66 × 32 × 6.8 <sup>2</sup>	58 × 33 × 6 <sup>3</sup>	30 × 35 × 8	55 × 40 × 8
Microcontroller								
Type	CC2540 (integrated)	nRF24LE1 (integrated)	ATmega128L	ATmega128L	MSP430	ATMega128L	OKI ARM	ATMega 103L TMS320V5416
Data mem.(KB)	8	1	4	4	8	64	32	4
Code mem.(KB)	256	16	128	128	48	48	256	128
Communication								
Radio	BLE (Integrated)	NRF24L01+ (Integrated)	CC1000	CC2420	CC2420	ZV4002 and CC1000	CC2420	ROK101007 (Bluetooth)
Data rate	1Mbps	2Mbps	38.4Kbps	250Kbps	250Kbps	1 Mbps	250Kbps	1 Mbps
Antenna	Chip	Chip	External	External	Trace	Chip	External	Module
Power source								
Type	Li-Po or USB	Li-Po	2 AA	2 AA	2 AA or USB	2 AA or Li	3 AA	
Sensors and Peripherals								
Sensors <sup>1</sup>	A digital	A analog	T analog	T	H, L, T	Ex	A, L, T	L, M, H, P, U
RTC	Yes	No	No	No	No	No	Yes	No

<sup>1</sup> A = accelerometer, H = humidity, L = light, M = magnetic, m = motion, T = temperature, P = pressure, U = ultrasonic, Ex = external only (none on-board)

MicroSD card can be accessed in SPI-compatibility mode, as is often done for WSN platforms.

### C. Nonvolatile Storage

Nonvolatile storage is available in several forms on the SuperNode: the on-chip flash of the CC2540 MCU, the on-board serial flash, and a removable MicroSD card. CC2540 that we use comes with 256 KB of program flash. With the BLE stack taking up about 100 KB, the user code can have the remaining code memory. Because the user code tends not to be overly complex, it is estimated that at least 64 KB can be used for generic nonvolatile storage. In addition, the PCB contains a 2 MB serial flash component accessible via SPI. It is meant to be the default option for a moderate amount of data logging or buffering when the MicroSD card has not been inserted. The serial flash also consumes less power than MicroSD cards do. The MiniNode can access the on-chip flash of the MCU but does not have the 2-MB on-board flash or the MicroSD card slot.

### D. On-Board Sensor

The sensor on both the SuperNode and MiniNode is the LIS331DLH digital triaxial accelerometer from STMicroelectronics [12]. It can sense acceleration in  $\pm 2$  g,  $\pm 4$  g, and  $\pm 8$  g ranges. As a digital accelerometer, it contains a built-in 12-bit ADC to do the conversion at pre-defined rates from 0.5 Hz to 1 KHz. The user can choose either SPI or I<sup>2</sup>C as the interface by pulling a hardware pin high or low. This accelerometer supports programmable *threshold detection* as well as *free-fall detection*. It allows the user to program in the high threshold and low threshold so that it can generate an interrupt when the acceleration exceeds or drops below them for over a minimum duration. They are useful for waking up the MCU upon motion triggering or putting it to sleep after an interval of inactivity. The thresholds for the three (X, Y, Z) axes can be composed conjunctively or disjunctively (i.e., AND'ed or OR'ed). Freefall is detected when all three axes detect near 0 g gravity. Threshold and freefall detections generate interrupts on different lines, and they can be very useful for motion-driven power management.

### E. Real-time Clock

Both SuperNode and MiniNode include a real-time clock (RTC) chip for keeping track of time. It is meant for several uses, including not only time stamping of collected data but also power management and security features. The SuperNode includes a jumper that allows the RTC to either share the same power source with the rest of the node or to be powered by its own dedicated coin-cell battery, which is expected to last for years and maintain the time even if the main battery is completely removed or discharged. The MiniNode's RTC shares the same power as the rest of the node; it does not currently support the option of powering the RTC with its own dedicated battery due to the lack of space.

Because the chosen RTC component requires I<sup>2</sup>C, but an I<sup>2</sup>C controller is not available on the CC2540 (it is on the CC2541 instead, which does not have USB), it must be implemented in software on both SuperNode and MiniNode. However, since this is not expected to be a very frequent operation, the extra power due to the software implementation is not expected to be a problem. The interrupt output from the RTC is triggered using its own dedicated signal rather than over I<sup>2</sup>C. If hardware I<sup>2</sup>C is desired then it is possible to replace the CC2540 with CC2541, which is pin compatible.

### F. Expansion Connectors

1) *SuperNode*: SuperNode supports an expansion port based on the Molex SlimStack board-to-board connector [9]. It is easy to connect by pressing the two PCBs together, and it is also easy to remove. Actually, a connector of each gender is mounted on each side of the PCB. This way, expansion boards can be stacked if necessary. In detail, the connector contains SPI (shared with on-board serial flash), I<sup>2</sup>C (software emulated), USB (slave), GPIO, analog inputs (either two single-ended or one differential pair) firmware programming interface, power supply to the expansion module, and UART (USART) if the second SPI is not in use.

In addition to the Molex connector, SuperNode also contains a MicroSD slot. It is implemented with a dedicated SPI port that is separate from the SPI on the Molex connector to avoid turning SPI into a bottleneck during data logging.

2) *MiniNode*: For EcoBT Mini and most miniature designs, the Molex connector takes up too much space as the expansion interface. Instead of having a standard connector or a custom flex-PCB male connector, we use the PCB edge as a female connector. That is, these are designed as vias that are cut in half and can be plugged into a "holder" consisting of posts traditionally used by jumpers. EcoBT Mini uses the pads to provided expansion port. This connector contains the following signals: USB (D+, D-), GPIO (the same pins as UART), programming pins, and SPI. The 4-layer PCB for the MiniNode with its edge connector is shown in Fig. 3.

### G. Magnetic Switches

SuperNode uses magnetic switches instead of physical ones, not because of the lack of area, but because several applications require the use of waterproof or splash-proof enclosures. We use the Murata AS-M15SAH-R [10], which disconnects the power in the presence of magnetic field, and

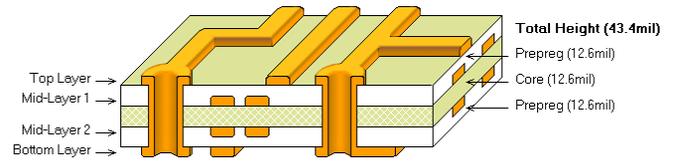


Fig. 3: MiniNode 4-layer board.

connects in the absence. We use one as a soft power reset switch and another as a user input "button."

MiniNode contains one instead of two magnetic switches. It serves as a soft power button as on the SuperNode. The MiniNode uses the TLV70033, a low-drop-out (LDO) regulator, to achieve good sleep power efficiency. Unlike the SuperNode, which allows the user to select directly powering the MCU by battery or going through the DC-DC converter, the MiniNode supports only always going through the LDO, due to the lack of space for the jumper header.

### H. DC-DC Converter Option

SuperNode includes the LTC3410 DC-DC converter to achieve low-power overhead [8]. It draws about 26 $\mu$ A in operation and < 1 $\mu$ A (including sleep mode) and < 1 $\mu$ A when shut down. It is significantly lower than that of conventional DC-DC converters by nearly two orders of magnitude. This enables the node to achieve significantly extended lifetime when its load is sleep-dominated, but it is still higher than directly connecting a battery to the MCU by an order of magnitude (1-2 $\mu$ A). SuperNode also includes a jumper that enables the MCU to bypass the DC-DC converter. By powering the MCU directly by battery, it gives the MCU an opportunity to stay in sleep mode while asserting a shut-down signal on the DC-DC converter for the rest of the node. This enables the sleep power for the entire system to drop by another order of magnitude, down to the single-digit  $\mu$ A range. One issue is that powering the MCU directly by a Lithium-polymer battery may stress the MCU as it is on higher than its tolerance range. In practice, the chip may continue to work but its longer reliability may suffer. In this case, it is recommended that the user power the system using AA or AAA batteries in series in the 3.0V (i.e., two 1.5V nonrechargeable) to 3.6V (i.e., three 1.2V rechargeable) range.

### I. Battery Charging Option

SuperNode supports the options of wired and wireless charging. For wireless charging, EcoBT using an inductive coil connected to the BQ51013 wireless power supply receiver IC from Texas Instruments [13]. It is compliant with Qi, the global interoperable standard for wireless charging developed by the Wireless Power Consortium. The receiving module rectifies the received current and converts it to a level suitable for charging Lithium-polymer batteries. The transmitting and receiving coils need to be placed fairly close to each other. Any Qi-compliant transmitter can be used as the power source.

In addition to wireless charging, the receiving module can also use wired charging when it detects an input voltage via USB or AC adapter. When charging the battery (wired



Fig. 4: Infant monitoring application

or wireless), it shuts down the DC-DC converter for higher charging efficiency and saving the charging time.

### J. Antenna

The antenna can make a great difference in terms of communication distance and power efficiency. Some version of EcoBT leaves an SMA port for an external antenna. One choice that can be used is an inverted-F microstrip antenna instead while leaving space on the PCB for an SMA connector if the user chooses the external antenna option. Another possibly better option for compact nodes is a chip antenna. Chip antennas are made with ceramic material in which RF travels at a much slower speed. This means the wavelength of a given frequency is compressed compared to air, and therefore the antenna can be made in a very compact size.

The CC2540 chip is optimized for the use in conjunction with a chip antenna. For EcoBT Supernode, we use the Antenova RUFA chip antenna [1] with a gain of about 2.1 dBi, which is considered quite high even for traditional quarter-wavelength antennas. It combines two properties of meandered line antenna and PIFA antenna. It has some performance advantages such as low profile and high gain. Because the radiation pattern of a RUFA antenna is parallel to the ground plane, this kind of feature is done to reduce the height of the antenna, even though the characteristic will produce extra parasitic parallel capacitance. We usually design the shorting stub pin to overcome it. The gain of antenna can be improved by the perfect ground. The better the ground, the higher gain of the antenna. We designed the SuperNode to have a larger ground in the back of antenna, and the distance that can connected is about to 30 m at 0 dBm based on our tests’.

EcoBT Mini, however, uses a much smaller chip antenna with 2 dBi peak gain[15], similar to consumer-grade sports heart-rate monitors. It can achieve about 10 m of communication distance at 0 dBm. It is also possible to solder on a wire as an antenna for EcoBT Mini, which can improve the gain significantly, though it may be inconvenient or unacceptable.

## III. APPLICATIONS

Our EcoBT designs have been chosen as the platform for a range of real-world applications. We now summarize each.

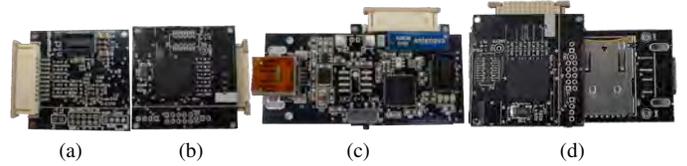


Fig. 5: Photos of ECG and SuperNode

### A. Infant Monitoring

One of the most fitting use of EcoBT Mini is in infant monitoring [5], as shown in Fig. 4. Motion monitoring with an accelerometer can be very helpful in terms of monitoring the growth of pre-term infants, detecting cerebral palsy, and calorie expenditure. The gold reference is called the Precht method, which involves a trained medical staff person visually monitoring and rating the magnitude of motion on a scale of 1-5, but it is subjective and can be inaccurate due to obstruction. Currently, those researchers use a miniature wireless sensor node but it does not last for a long time due to the lack of power management and the DC-DC converter. Our system is not only significantly smaller but also offers many more flexible options, including threshold detection. More importantly, the ability to connect directly to an iPad without a base station or a dongle is a clear advantage over the existing system that relies on an Ethernet base station connected to a laptop.

### B. Infant ECG

The infant ECG (electrocardiogram) project is done in collaboration with a pediatric cardiologist for collecting electrocardiogram data from infants up to one year of age. The current design entails connecting an ECG module via the top-side Molex connector and logging data onto a MicroSD card.

This design highlights the use of the expansion connector for a highly specialized sensing device. The ECG module is based on the TI ADS1298 ECG chip, which contains eight 24-bit ADCs (instead of a single ADC with eight channels of multiplexed input) and front-end amplifiers for collecting ECG samples. The data is accessible over SPI, which is available on the expansion connector.

In this case, the EcoBT node connects to a BLE-enabled computer that also runs a web server that provides a browser GUI and the database for logging data. Data is collected in DICOM format and can be accessed using any HTML5 browser.

### C. Smart Container

EcoBT has also been chosen as the prototyping platform for a smart container, which is a thermally insulated container whose internal temperature is monitored by EcoBT [3], [6]. The idea is that when frozen goods are to be shipped by trucks to various customers, the EcoBT would on one hand integrate with the rest of the inventory tracking system upon loading and delivery, and on the other hand monitor and log the temperature of the container. In case of abnormal temperature change, the EcoBT would alert the delivery person in real time to take remedial actions, such as replacing the malfunctioning cold



Fig. 6: Intelligent insulating shipping container based on EcoBT.

pack or close a toppled container. Before EcoBT, alternative technologies have been considered and prototyped, including the use of ZigBee and RFID.

ZigBee is a more mature wireless standard of the same class as BLE. Its Rx and Tx power are comparable to BLE, and it also has very flexible topology in terms of ad hoc mesh networking capabilities. However, ZigBee suffers from high power consumption during idle listening and the lack of direct compatibility with smartphones (smartphone or tablet). The only way for ZigBee to reduce idle-listening cost is to duty cycle its Rx by software control, but the average power is 10-100 times that of BLE. To use ZigBee, the operator must use either a custom-made ZigBee user-interface device to connect to the smart containers, or use a smartphone to connect through a WiFi-ZigBee or Bluetooth-ZigBee gateway node. The former is one additional device for the operator to carry, while the latter would not work when the container moves outside the range of the gateway. Although a third option involving the use of a ZigBee dongle on the smartphone is also possible, customers in general find dongles inconvenient, fragile, and a burden. Instead, BLE appears to have none of these problems while allowing the possibility of multi-hop relay with additional software.

Passive RFID has the advantage of even lower power than BLE – in fact, it needs no battery at all, as it operates entirely on the RF power emitted by the RFID reader. It has the advantage of requiring no battery replacement while at the same time serving as an identifying tag. However, the harvested power itself is not enough for reading a high-precision thermal couple or data logging, which consume 1 mA and tens of mA, respectively. As a result, an RFID can at best serve as an out-of-band wake-up radio to another active wireless communication device to eliminate the need for idle listening. However, in that case the cost becomes quite high: the RFID tags themselves may be inexpensive, but the readers are expensive and can serve only half of the communication purposes. Another radio in the tag and receiving device must be used to fill in the remaining functions. If ZigBee or another non-Bluetooth, non-WiFi protocol is used then it will suffer from the gateway or dongle problem discussed above, in addition to the much higher cost of the system. Therefore,

BLE has the necessary properties needed for this application.

Moreover, in the enhanced container [6], we take advantage of the proximity sensing feature of BLE to implement anti-theft features. That is, the user's smartphone acts as an authorizing tag, and if the box is opened or moved while the authorizing tag is absent, then it can consider it to be a theft and event and acts accordingly. Proximity sensing cannot be implemented easily by bridged protocols.

#### D. Lighting Control

EcoBT is being used in a lighting control system being prototyped at the authors' institution [7]. The purpose is to enable not only dedicated physical pushbuttons but also smartphones, sensors, real-time clocks, and other physical pushbuttons to be used for the purpose of lighting control. Although different wireless standards including Z-Wave, ZigBee, and even DASH7 have also targeted similar applications, BLE is the only one with direct smartphone compatibility without requiring a gateway or dongle. Even though a gateway or a dongle is necessary for remote access, requiring such a device can result in the problem of *central point of failure*. BLE will allow all these devices to connect with each other without protocol translation or bridging.

Of course, several problems with BLE are the lack of multi-hop topology and single-master restriction. That is, in paired mode, a single slave cannot be paired with multiple masters. This means if a smartphone acts as a master to a set of light switches, then it will prevent other smartphones from directly controlling the same light switches. These limitations have been removed in Bluetooth 4.1 standard, making multi-hop communication very easy to implement. At the time of this writing, however, we have implemented solutions for the 4.0 stack. First, instead of operating in paired mode, these nodes can operate in broadcast mode and overcome the topological restrictions. However, the security is more limited in this case. Another possibility is to have on-demand pairing: a smartphone pairs with a node only when necessary, and unpairs as soon as the communication is no longer needed. This will enable other potential masters to then wait for their turn to pair with the target slave. Between the two schemes, the users will be able to control a set of lights in ways they expect while achieving the effect of two-way remote.

Another feature similar to the anti-theft feature of the smart container is the use of BLE tags as an access control mechanism. This is in contrast to most existing smart homes that may automate actions but do not have concepts of individual users. BLE tags associated with individuals can also be used as input to a machine learning program to better understand the individual usage patterns and possibly automate home control in a smarter way.

#### E. Fitness

EcoBT is also suitable for health and fitness applications, including heart-rate monitors, pedometers, and blood pressure meters. In this space, ANT+ is currently the protocol of choice due to the low cost, low power, and fast connection. However, ANT+ is built into only a small number of smartphones and nearly none of the tablets. ANT+ is fast to connect to smartphones compared to Bluetooth because it is broadcast

based, but it lacks privacy and is easy to attack. BLE can connect within 10s of milliseconds, making it competitive with ANT+. Moreover, BLE is significantly lower power than ANT+ thanks to the use of connection interval. Moreover, our EcoBT Mini is possibly the smallest self-contained node for health and fitness ever built. This enables new kinds of systems to be built, including those sewn into clothing and buttons.

We have successfully constructed a BLE pedometer using just the built-in configuration without having to add any expansion modules. It takes advantage of the accelerometer with threshold detection to save power. Upon detecting each step, it transmits the event to the paired smartphone to track and display the number of steps taken.

#### F. Elderly Care

EcoBT is being applied to elderly care in the form of a fall detector. Thanks to the on-board digital triaxial accelerometer with threshold detection and freefall detection, EcoBT's MCU can remain in sleep mode by default and be woken by the accelerometer upon detecting freefall within a programmable threshold. The alert can be sent within the connection interval, which can be as short as 0.6 ms up to 20 seconds.

### IV. DISCUSSION

Our EcoBT designs represent the first step towards a platform for the Internet of Things (IoT), but it is far from perfect. In this section, we discuss the lessons we have learned from prototyping these applications above and possible trade-offs.

#### A. Power

Even though the CC2540 MCU and BLE protocol are designed to be the very energy-efficient, using a BLE chip does not automatically yield an equally energy-efficient system. Power efficiency can be improved by improving the choice of DC-DC converter and RF.

1) *Supply Voltage Conversion*: One can achieve high efficiency by connecting the MCU directly to a stable power source such as a battery, but it would preclude the use of higher voltage sources such as lithium-polymer rechargeable batteries, but conventional DC-DC converters and regulators incur non-trivial quiescent current (QC). Even the LDO recommended by TI has a QC of  $30 \mu\text{A}$ , which is still much higher than the sleep power of  $1\text{--}2 \mu\text{A}$  of the MCU. On the other hand, *hysteretic* converters have been proposed to minimize QC by sustaining sleep mode using a capacitor and turning on again when the voltage drops below a threshold. However, such converters do not result in stable voltage and are not suitable for our purposes.

One possible, somewhat aggressive way to improve the energy efficiency is to use a DC-DC converter with pass-through mode when the MCU sleeps. During active mode, the DC-DC converter outputs a voltage on the lower range (e.g., 1.8-2.2 V), which will be more efficient than running at a higher voltage, even without a regulator. During sleep mode, pass-through mode will eliminate most of the QC, but the supply voltage in pass-through mode (3.7-4.2 V) will be slightly higher than the maximum voltage of the MCU (3.6 V).

However, because the sleep current is low, the dissipated power is still very low, despite the slightly higher voltage, and it is not expected to cause much stress on most of the circuitry.

2) *RF Power*: RF consumes most of the power (instantaneous current) and energy (integrating power over time). A good antenna will be able to effectively extend battery life. This is because both the Tx power level and Rx sensitivity are programmable. A better antenna means longer RF range at the same Tx power level and Rx sensitivity; this also means it can reduce the Tx and Rx power and still achieve the same RF range as another system with a worse antenna. Therefore, we continue exploring better antenna designs in conjunction with algorithms for adjusting the RF power dynamically.

#### B. Alternative BLE Single-Chip Solutions

CC2540 is one of the "oldest" single-chip BLE-enabled MCUs. By single chip, we mean it contains not only the RF subsystem and the MCU for the protocol stack, but the MCU is also programmable by the application developer. Several other companies have made available or announced other single-chip BLE solutions. We compare these alternative solutions.

1) *Nordic nRF51822*: The Nordic nRF52811 is a single-chip BLE MCU with an ARM Cortex-M0 core with 16 KB SRAM (twice that of CC2540) and 256 KB flash [11]. One of the most notable hardware features is that its I/O pins are all remappable, which can be especially useful in the case of the miniature node with very limited room for the expansion interface. It is used in a number of designs, including several proximity tags, RFduino, the Laird BL600 BLE module with SmartBASIC, etc. The main differences with our platform are the integrated sensors and the software development environment.

Nordic provides BLE 4.1 stack (binary) supported by a threaded runtime system. Several compilers that can generate ARM code can be used and can run on various platforms. RFduino exposes a limited set of functions, while the BL600 allows the use of SmartBASIC for easier interactive experimentation. Compared to the CC2540, which requires the use of IAR's Embedded Workbench, there are many more options for the nRF51822. In fact, we have created a version of EcoBT using the nRF51822 MCU in the same layout. In our experience, it has been easier to create custom BLE profiles for the CC2540 than for the nRF51822, due to the firmware organization. Custom profiles are needed for new applications such as the smart container, ECG, and even lighting control.

2) *CSR C1010*: CSR, a well-known maker of Bluetooth ICs, offers its  $\mu\text{Energy}$  line of single-chip BLE MCUs (CSR1010) [4]. Its hardware supports remappable digital I/O pins, analog, key-scanning, and most notably, direct connection to 4.4V supply such as a lithium-polymer rechargeable batteries. CSR chips are also available in smaller packages ( $5 \times 5$  and  $4 \times 4 \text{ mm}^2$ ), making it possible to further miniaturize the whole board. In terms of software development, the  $\mu\text{Energy}$  SDK is based on a GCC compiler tool chain with a debugger. CSR has demonstrated BLE 4.1 stack and an implementation of a mesh protocol. As of this writing, we are currently designing a new system with the CSR solution, but we have not accumulated enough experience to comment on it. Issues that are of concern will include the ability to create custom profiles.

### C. Built-in Sensors

One recurring issue is whether to have built-in sensors. Many modules such as RFduino, Laird BL600, and many others are programmable BLE modules without sensors. However, we believe that sensors are very important for many applications, as standalone BLE modules without any sensors are limited to acting as beacons. Having built-in sensors makes the module ready to use. For example, TI's Simplelink SensorTag contains a gyro, accelerometer, compass, humidity, temperature, pressure, and IR, in addition to pushbuttons and LEDs, all controlled by the CC2541 MCU. In addition to these sensors, it can also act as an iBeacon at the same time. Our EcoBT contains a subset of the sensors but augmented with RTC, magnetic switch, serial flash, MicroSD card slot, and expansion interface. This means that our board can also be made ready to use while retaining expandability.

### V. CONCLUSIONS

This paper describes EcoBT, a wireless sensor platform based on the new Bluetooth 4.0 Low Energy (BLE) Technology. One of its most compelling features is the direct compatibility with BLE-enabled smartphones since iPhone4S (2011) and iPad3 (2012). Moreover, we offer two sizes to meet the requirements of most applications. The EcoBT Mini is the smallest, full-featured wireless sensor node to date.

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