Experimental Characterization of a Low Power Device for IoT Applications: micro.sp©

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***Abstract*—The paper investigates the transmission characteristics of a low power device, named micro.sp©, patented by STE Industries, to be used for Internet of Things (IoT) applications where battery duration is a critical aspect and the transmitted information is organized in messages composed by a limited number of bits. The technical characteristics of micro.sp© are compared with those of Bluetooth low energy (BLE) devices, which appears as the main competing short range wireless technology. Experimental results show that micro.sp© can be considered an enabling technology for the implementation of very low consumption short-range devices (according to ETSI definition). To give some examples, measurements have revealed that assuming to transmit few bytes every 30 seconds, a micro.sp© device can work for more than 30 years with the same coin battery, more than double the time of the BLE devices.**

I. Introduction

In 2013 the number of connected objects has been of about 10 Billion with a forecast of 50 Billion for the year 2020. This growth will be driven by the Internet of Things (IoT) paradigm, which is expected to stimulate the deployment of a huge amount of applications requiring the use of small devices with computation and connectivity capabilities [1]–[3].

In the IoT paradigm, the concept of *smart* objects plays a crucial role, since the use of ICT technology can enhance the perceived utility of normal objects and transform them into interactive elements able to provide services and monitor the surrounding environment [2]. It is interesting to note that IoT objects belong to the broader class of Cyber-Physical Systems (CPS), which can be defined as physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core. CPS and, of course IoT, are expected to be cutting-edge in several important sectors of the everyday life, such as transportation, health-care, manufacturing, agriculture, energy, defence, aerospace and buildings [4], [5]. The design and implementation of the Internet of Things (or CPS) presents several technical challenges. Specifically, since smart objects must have the capability to connect themselves to the Internet and among each other, the use of wireless technologies is mandatory [6]. To this regard, the communication technologies operating at a short range, like those enabling wireless personal area networks (WPANs) or embedded systems, play a very important role. Although IoT includes devices with very different capabilities, it is worth noting that in most relevant cases the communication technologies to be adopted are characterized by the following similar requirements: low or very low energy consumption; reduced size and weight; bit rate in the order of few kilobits; license-free frequency band. Furthermore, the typical application scenarios of these devices are very diverse, ranging from smart home to automotive, cruise ships, and wearable devices [7].

Motivated by these considerations, in this paper we present a new, small size, low energy device for IoT applications, named micro.sp©, developed by STE Industries. More specifically, the device is explicitly tailored for the efficient, from the energy point of view, transmission of short messages, containing measures from sensors, in applications where the battery replacement is either impossible or not economical. To provide a performance benchmark, the energy efficiency of micro.sp© is then compared with that of two Bluetooth Low Energy (BLE) devices implemented by different manufacturers.

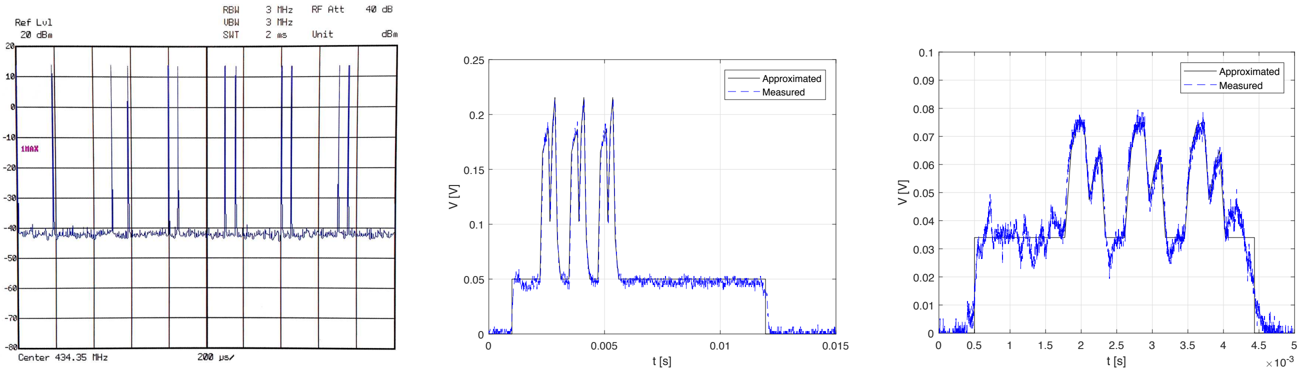
The contribution of the paper can be summarized as follows:

1) We describe the micro.sp© technology by addressing, in particular, the signal model and the synchronization technique.
2) We measure the energy consumption of the device for different message sizes and transmission duty cycles.
3) We compare the energy consumed by the micro.sp© device with that of two BLE transmitters, taken as performance benchmarks.
4) The measurement results are used to calculate average power consumption, the energy spent for the transmission of each bit, and the estimate battery lifetime as a function of the transmission parameters.

Results show that the proposed technology is more energy efficient of BLE when the application requires the transmission of small size messages.

II. Technical Characteristics of micro.sp©

The micro.sp© technology, patented by STE Industries, is a low consumption short-range device (according to ETSI definition) aimed to be implemented in IoT applications where the battery duration is a critical aspect. The device is explicitly designed for short range applications in which messages (whose carried information is generally collected via environmental sensors) are composed by a limited number of bits and need to be transmitted to a reader with refresh



(a) Signal waveform of micro.sp©. (b) Signal waveform of BLE Cypress. (c) Signal waveform of BLE Texas Instrument.

Fig. 1. Signal waveforms of the different devices.

frequency of some Hz or smaller. The device operates in the free band of 434 MHz or 315 MHz. The key-aspect of the device is the low consumption, which allows it to have a battery lifetime of several years. The low power consumption allows micro.sp© to replace the battery with a conventional energy harvesting device. To keep the power consumption limited, the transmission system is based on the generation of very short pulses, which carry synchronization and data information followed by an IDLE period.

During each transmission cycle, the first period is composed by the synchronization phase, followed by the data transmission phase, and finally by the IDLE state. The three phases are then periodically repeated. Typically, the duration of the IDLE state is much larger than that of the two previous phases, so that the electronics is specifically designed to reduce the power consumption in this phase. For synchronization and data transmission, a pulse position modulation (PPM) scheme is implemented, whose structure is shown in Fig.1(a).

At the beginning of each cycle, the transmitter sends two pulses separated by a fixed time interval TS. The two pulses have the purpose to synchronize the receiver with the transmitter. Then, after a time period TD0, the first data pulse is transmitted. As discussed above, a PPM scheme is used to transmit data messages. The information is then coded by exploiting the distance between the first and the second pulse of each couple. In particular, 16 different positions are considered; therefore, a nibble (4 bits) is conveyed for each couple of pulses. Since each bit is coded through the use of a time distance of 3 μs, and an initial offset of 53 μs is considered (to encode the binary sequence 0000), the maximum distance between the two pulses of the couple is 98 μs. In general, for N couples of pulses, the number of bits transmitted for each cycle is $4N$. To reduce the amount of energy spent during the transmission phase, the duration of the pulses is limited to the order of few μs. After the transmission of the N couple of pulses, the device enters in IDLE mode, till the next transmission cycle.

III. The Benchmark: Bluetooth Low Energy

As a benchmark for the performance of the micro.sp©, we consider the well known standard BLE, feature of Bluetooth 4.2. BLE is presently the most diffused standard for data transmissions from low power and low range communications (e.g., BLE is supported by a large number of smartphones models) and has been proved by various experiments (e.g., [8], [9]) to drain less energy than competitors ZigBee and ANT. Here we describe the main characteristics of the standard and discuss at what extent its performance can be compared to that of the micro.sp© technology. First of all, BLE signals are transmitted in the 2.4 GHz ISM band, with a frequency hopping mechanism over 40 channels of 1 MHz, each separated by 2 MHz. Compared to the frequency interval of 300-400 MHz used by micro.sp©, the 2.4 GHz band suffers of higher path loss and normally higher interference (it is used by other widespread technologies, such as Wi-Fi). Three of the 40 channels are devoted to signaling and are used when a connection is not available. When a device has a service to advertise, it normally sends a message over each of the three channels. A device searching for new services scans over the same three channels. While the receiver must scan all the three channels, the transmitter can advertise over one or two channels only; however, this is normally strongly discouraged because it implies that: i) some messages cannot be received just because the scanner is on a different channel at that time and ii) there could be a strong interference over the selected signaling channel or channels that prevents the communication (this event is far less probable if all the three channels are used). The nominal data rate of BLE is 1 Mb/s, with GFSK.

With the aim to periodically transmit a small amount of data from a sensor to a collector, there are three configurations:

1) *Unconnected, beaconing*: the transmitter and receiver are not connected and the sensor performs a beaconing with the sensed information; the transmitter wakes up periodically from the low power state, sends the message three times (one per each signaling channel) and returns to the low power state; in this case, no communication from the receiver to the transmitter is possible;
2) *Unconnected, advertising*: the transmitter and receiver are not connected and the sensor performs an advertising with the sensed information; the transmitter wakes up periodically from the low power state, sends the message

and listens for possible replies three times (one per each signaling channel), before returning to the low power state; in this case, the receiver can reply to the transmitter; if needed, with this configuration a connection can be initiated;

3) *Connected*: the transmitter and receiver are connected; the transmitter wakes up periodically from the low power state, sends the message, listens for a possible reply and returns to the low power state; also in this case, the receiver can reply to the transmitter; differently from the previous configurations, a connection needs to be activated before the sensor starts transmitting its data.

To compare the energy consumption, the BLE devices considered in this work were configured as unconnected, advertising (mode 2). Unconnected mode was preferred since the need for a connection could not be acceptable by some IoT applications. Furthermore, the advertising also allows the transmission of commands to the sensors, with a limited cost in terms of power consumption (as shown in the further). The transmitter was set to send a small packet (8 bytes of payload) every interval of either 1, 3.5, or 6 seconds, with a transmitted power of 0 dBm. Please note that the maximum advertising period (i.e., the maximum time interval between consecutive transmissions) is by standard 10.240 s; this value can be increased only by manually enable/disable the advertisement.

IV. Energy Consumption of micro.sp©

To measure the power consumption during transmissions and measurement sampling events, we have used an Agilent System DC Power Supply 6626, providing a fixed voltage of 3 V, and an Agilent DSO-X 3034A oscilloscope, with a resistor of 100 Ω introduced in series to measure the erogated current. During this measurement, the transmission duty cycle was set to 3 s (a packet transmission every 3 s) and a value of 0.5 s for the duty cycle of the sampling of the sensors. The measured values of the duty cycles were slightly longer, with one sampling event performed every 626 ms. The measured value of the transmission duty cycle was therefore 3.76 s. In other words, the micro-controller waked up from the IDLE state every 626 ms to sample the data from some sensors. The sensors available and polled were: 1) battery voltage; 2) temperature; 3) on/off state of two inputs; 4) on/off state of a reed switch; 5) voltage measurement at an input. The transmitted packet was 80 bits long, with 35 bits of header and 45 carrying data. Elaborating the output of the oscilloscope, we obtained that the device consumed 1.59 μJ to perform the sampling of the sensor measurements and 22.1 μJ to perform one transmission. Thus, the overall energy consumed for one transmission and six samplings of the sensing measurements was equal to 31.6μJ.

If we limit our attention to communication and considering that the energy to transmit a bit is independent to the bit position, it is derived an energy of $E_{\rm bit}^{\rm (M)} = 276$ nJ/bit including the header. Taking into account that $N_{\rm o}^{\rm (M)} = 35$ bits are used for the header, the consumption to transmit the $N_{\rm p}^{\rm (M)} = 45$ data bits increases to 490 nJ/bit.

In general, denoting as $E_{N_{\rm tot}^{\rm (M)}}^{\rm (M)} = 22.1$ μJ the energy consumed to transmit the full $N_{\rm tot}^{\rm (M)} = 80$ bits that include overhead and payload, we can thus infer an energy per data bit varying the payload size

$$E^{\rm (M)}(b) = \frac{E_{N_{\rm tot}^{\rm (M)}}^{\rm (M)} + E_{\rm bit}^{\rm (M)}(b - N_{\rm p}^{\rm (M)})}{b} = \frac{E_{\rm bit}^{\rm (M)}(N_{\rm o}^{\rm (M)} + b)}{b} \quad (1)$$

where b is the payload size in bits.

To measure the power consumption during the IDLE state, a HP Multimeter 3548A was used. The duty cycle was set to 10 s for the sensor measurements sampling and 180 s for the transmission. Based on measurements performed on the average current in several intervals of some seconds, we obtained that during the IDLE state the device absorbs around 540 nA. This corresponds to a power consumption of 1.62 μW.

Using the same HP Multimeter 3548A with transmission duty cycle equal to 3 s and sampling every 0.5 s, we also double checked the correctness of the measurement related to the overall energy consumed detailed previously. In that case, by averaging out the current absorption over periods of 1 minute, the average current was around 3.5 μA. Removing the current during the IDLE state, multiplying by 3 V and considering a repetition interval equal to the transmission period 3.76 s, we obtained a value of 33.3 μJ consumed per each transmission period. This is indeed quite close to the value obtained using the previous method (31.6 μJ).

V. Energy consumption of BLE

Given the peculiarities of the micro.sp© technology, its performance has been compared with that of BLE. To this aim, we performed coverage and energy consumption measurements under the same conditions as detailed in the previous section for two different BLE devices:

- Cypress CY8CKIT-042-BLE pioneer kit, which included a BLE Pioneer Baseboard with the CY8CKIT-142 PSoC 4 BLE Module as the transmitter, and a CY5670 CySmart USB Dongle (BLE Dongle) as the receiver.
- Texas Instrument (TI) CC2650EM-7ID as transmitter/receiver device with SmartRF06 Evaluation Board.

At the best of our knowledge, the TI device was among those offering the lowest BLE power consumption. In both cases, the energy usage was limited to the communication part, with no data polled by sensors. In particular, the firmware was optimized for power measurements as in [10].

A. Measurements with the Cypress BLE Device

During all measurements, the power supply was provided by an Agilent System DC Power Supply 6626 with fixed voltage of 3 V, and the consumption was measured through two steps.

Firstly, we measured the power consumption during the idle state. To this aim, we connected the board to an Agilent 34401A multimeter and we set the periodical transmission to the highest duty cycle (6 seconds). During idle periods, a current between 1 and slightly more than 2 μA was observed. Given the very small consumption and variability of measurements, a current of 1.3 μA will be used in the following, as declared by the manufacturer. The consumption outside the idle state was measured adding a resistor of 10 Ω in series to the power supply and connecting an Agilent DSO-X 3034A oscilloscope at the sides of the resistor. The current drawn during transmissions was directly obtained by dividing the voltage measured by the value of the resistance (10 Ω).

In Fig. 1(b), the measured voltage is shown for an advertisement event. It can be noted that an almost constant current is drawn during an interval of nearly 10 ms, with the exception of three intervals, when the absorption is significantly higher. Consumption due to wake-up and pre-processing is visible at the beginning. Then, three intervals, which are all almost identical, correspond to the transmission of a packet and a reception phase over one of the (three) signaling channels. A post-processing phase is then entered by the device before returning to deep sleep mode.

Elaborating a detailed file from the oscilloscope, the average drawn current has been calculated in about 7 mA with a payload of 8 bytes.

B. Measurements with the Texas Instrument BLE Device

Similar measurements were conducted for the TI CC2650EM. In that case, an Agilent E360A power supply and a LeCroy WavePro 7100 oscilloscope were used. Again, a 10 Ω resistor was inserted in series with the power supply and the oscilloscope connected to its extremities. The current was then derived from the voltage by a simple division. The result for an advertising with a payload of 10 bytes is shown in Fig. 1(c). As observable, the phases are the same as with the Cypress device. Due to a specific optimization carried out in the firmware, the duration is here reduced to about 4 ms, during which an average 4.5 mA was measured. Following the data sheet of the device, a current of 1 μA is assumed during deep sleep.

C. Inferred Consumption of BLE Devices

In both cases, the consumption in connected and beaconing modes, and with a variable duration of the payload were deducted from those shown. Several experiments, not shown here for brevity, were conducted to validate this approach.

In particular, when the connected mode is assumed, the consumption of only one transmission-reception is taken into account. When the beaconing mode is addressed, the reception phase is removed after all the three transmissions. Furthermore, the current consumption during transmission due to a different payload is obtained with the following equation

$$i^{(\mathrm{d})}(b) = \frac{i^{(\mathrm{d})}_{\mathrm{ref}} \cdot t^{(\mathrm{d})}_{\mathrm{ref}} + i^{(\mathrm{d})}_{\mathrm{TX}} \cdot (b - N^{(\mathrm{d})}) \cdot t_{1\mathrm{bit}}}{t^{(\mathrm{d})}_{\mathrm{ref}} + (b - N^{(\mathrm{d})}) \cdot t_{1\mathrm{bit}}} \tag{2}$$

where the superscript (d) denotes either the Cypress or the Texas Instrument device, $i^{(\mathrm{d})}_{\mathrm{ref}}$ is the average current with the reference payload, $t^{(\mathrm{d})}_{\mathrm{ref}}$ is the duration of the event with the reference payload, $i^{(\mathrm{d})}_{\mathrm{TX}}$ is the average current during transmission, $N^{(\mathrm{d})}$ is the length of the reference payload in bits, and $t_{1\mathrm{bit}}$ is the time to transmit one bit.

TABLE I
NOTATION AND VALUES USED IF NOT SPECIFIED.

Packet payload (B)	8 bytes
Transmission interval (ΔT)	10 s
Battery capacity	225 mAh
Battery voltage	3 V
BLE mode	Beaconing
Power consumption (P)	*output*
Energy per bit (E)	*output*
Battery duration in years (L)	*output*

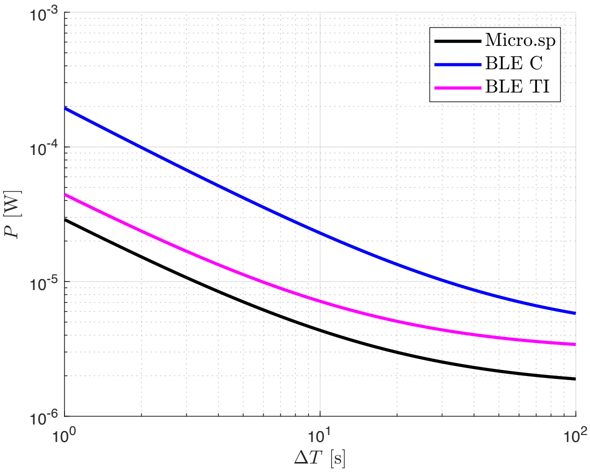


Fig. 2. Power consumption vs transmission interval. Comparison between micro.sp© and BLE.

In our measurements, for the Cypress device in advertising mode it was $i^{(\mathrm{d})}_{\mathrm{ref}} = 7.3$ mA, $t^{(\mathrm{d})}_{\mathrm{ref}} = 11$ ms, $i^{(\mathrm{d})}_{\mathrm{TX}} = 18$ mA, and $N^{(\mathrm{d})} = 64$. For the TI device in advertising mode it was $i^{(\mathrm{d})}_{\mathrm{ref}} = 4.5$ mA, $t^{(\mathrm{d})}_{\mathrm{ref}} = 3.9$ ms, $i^{(\mathrm{d})}_{\mathrm{TX}} = 7.5$ mA, and $N^{(\mathrm{d})} = 80$. In both cases, given the BLE bit rate it is $t_{1\mathrm{bit}} = 1$ μs.

The energy consumption is obtained by integrating the drawn current multiplied by the 3 V voltage.

VI. COMPARISON RESULTS

Comparison results are hereafter discussed, based on the measurements detailed in Sections IV and V. In the figures, we use *BLE C* to denote the Cypress device and *BLE TI* for that of Texas Instrument.

As input and output metrics, the following definitions are used results are here shown varying

- Transmission interval ΔT, defined as the time between two consecutive message transmissions;
- Payload size in bytes B;
- Average power consumption P; it is obtained as the wighted sum of the power consumed in idle and for a transmission during a transmission interval;
- Average duration in years of a reference coin battery L; the capacity of the reference is assumed equal to 225 mAh (which is the capacity of a typical CR2032 battery);
- Average energy per bit in Joule per meter E.

The main settings are summarized in Table. II.

In Fig. 2, the power consumption is shown varying the transmission interval, assuming a payload of 8 bytes and

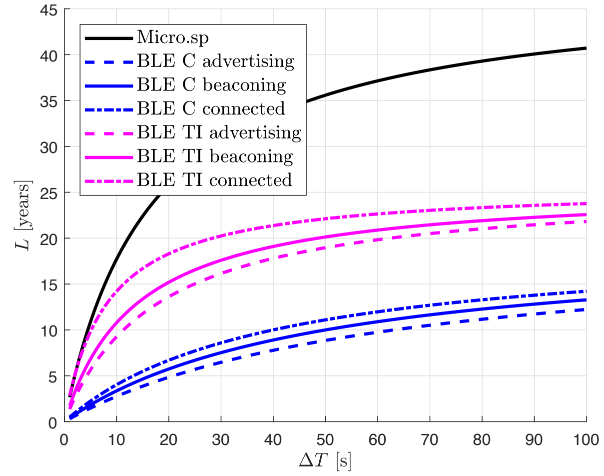


Fig. 3. Estimated battery duration vs transmission interval. Comparison between micro.sp© and BLE.

the beaconing mode for BLE. The shape of all curves are approximately linear with a small ΔT, where the consumption during the idle mode is almost negligible compared to that during transmission, and then slowly tend asymptotically to the value of the consumption in deep sleep. As observable, micro.sp© consumes 1.5/1.8 less power than the optimized BLE TI device and up to almost 7 times less than the other. As a specific example, if a transmission every 10 s is addressed, $P = 4.3\ \mu$W with micro.sp©, $P = 23\ \mu$W with the BLE C, and $P = 7.1\ \mu$W with BLE TI.

In Fig. 3, the duration of the reference coin battery is presented varying the transmission interval and considering all BLE transmission modes, assuming a payload of 8 bytes. Although, as obvious, BLE consumes less in connected mode (it transmits the message only once) and more in advertising mode, the difference is not remarkable. Also, this figure shows the higher efficiency of micro.sp©, which allows the battery to last more than 40 years with $\Delta T = 100$ s compared to less than 25 for the best BLE case.

Finally, the energy consumed per payload bit is shown in Fig. 4 as a function of the payload size, assuming a transmission interval of 10 s and the beaconing mode for BLE. Example values for the specific cases of 32 or 64 bits payload are also reported in Table II. As intuitive, in all cases the energy consumption reduces with an increase of the payload, since the impact of the overhead is distributed over a larger number of bits. Remarkably, with micro.sp© the energy consumption with a payload of 5-8 bytes is lower than 1 μJ/bit.

VII. Conclusion

The goal of the paper was the investigation of the technical characteristics of micro.sp© technology. More specifically, the energy consumption of the device was measured by considering different message sizes and transmission duty cycles. To compare the performance of the technology with existing stardards for low power transmission, the performance of BLE transmitters from two different manufacturers was also considered. The results showed that the energy per bit spent

TABLE II
Summary.

	Micro.sp	**BLE C**	**BLE TI**
Frequency band	434 MHz	2.4 GHz	
Modulation	PPM	GFSK	
Transmission power	14 dBm	0 dBm	
Peak data rate	6.7 kb/s	1 Mb/s	
Sleep current	540 nA	1.3 μA	1 μA
Average energy per bit, assuming B=32 bits and ΔT=10 s	1.1 μJ	7.1 μJ	2.2 μJ
Average energy per bit, assuming B=64 bits and ΔT=10 s	0.7 μJ	3.6 μJ	1.1 μJ

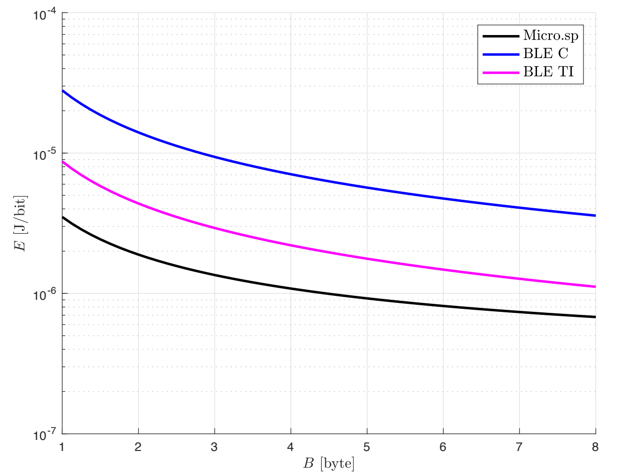


Fig. 4. Energy per payload bit vs payload size. Comparison between micro.sp© and BLE.

by micro.sp© to transmit packets with reduced size is smaller than convenstional BLE devices. In particular, the battery time-life of a micro.sp© device doubles that of the BLE devices used in the paper using the same kind of battery.

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