Power Consumption Analysis of Bluetooth Low Energy, ZigBee and ANT Sensor Nodes in a Cyclic Sleep Scenario

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***Abstract* — This paper is intended to guide developers of wireless systems who are puzzled by the vast number of radio configuration parameters and options. We provide experimental data comparing power consumption of Bluetooth Low Energy (BLE), ZigBee and ANT protocols for a cyclic sleep scenario, in which a short-range and low-power wireless sensor node periodically sends a data packet to a remote 'hub' with intervening sleep intervals. Devices such as wearable health monitors often use this scenario when interfacing with a mobile phone-based hub. For all measured sleep intervals BLE achieved lower power consumption (10.1 uA, 3.3 V supply at 120 s interval), compared with ZigBee (15.7 uA), and ANT (28.2 uA). Most of the power consumption differences can be attributed to the time taken for a node to connect to the hub after waking up and the use of sleep between individual RF packets. For the three protocols we determined a sleep interval at which the trade-off between power consumption and data rate is optimized.**

***Index Terms* — Personal area network, Bluetooth Low Energy, BLE, ZigBee, body sensor network, ubiquitous computing.**

I. Introduction

As the ecosystem for consumer electronic devices continues to grow, a category of wirelessly-connected digital 'accessories' is becoming established. The wireless communications architecture of those accessories typically consists of a short-range, low data rate and low-power sensor node that is used to periodically transmit data to a remote hub (base station) such as a cell phone or application specific device. Examples include health and wellness monitoring devices like FitBit [1] WiThings [2] and the Nike+ [3]; mobile phone accessories and companion devices such as the Pebble Watch; and various monitoring and display products [4]. Also, such architecture is applied to sensor nodes that use ambient energy harvesting, such as RF from a cell tower. [5]

Developers of wireless devices such as those listed above, along with research practitioners who wish to explore new concepts in this space, have a plethora of radio communications protocols to choose between. Some applications warrant the development of a bespoke protocol that is optimised to minimise current consumption, latency, connection time, etc. However, over the past decade several standard low-power protocols that address many of these requirements have become established in the marketplace. Popular standards such as Bluetooth Low Energy (BLE), ZigBee and Ant also have the very real advantage that consumer devices such as cell phones increasingly support them, providing a ready supply of suitable 'hub' devices.

The nature of communications between a sensor node and a hub has a great impact on the power consumed. Unfortunately, much of the literature which compares the power consumption of different radios is theoretical and qualitative [6] or provides generalized experimental data [7] from which it is not possible to draw practical conclusions on power consumption in a given scenario. Furthermore, datasheets do not provide specific parameter or "rule of thumb" that will help a developer balance power consumption and data rate when selecting a radio for an application such as a cyclic sleep sensor node.

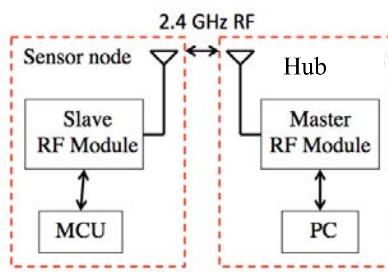

Fig. 1. Experimental setup of the slave sensor nodes. MCU stands for microcontroller.

In this paper we evaluate three low-power standards (BLE, ZigBee and ANT) with characteristics outlined in Table 1. As shown in Figure 1, evaluation is based on a cyclic sleep scenario, where a BLE, ZigBee, or ANT sensor node periodically transmits a data packet such a sensor reading to a hub. We present experimental results and suggest a measure of optimized sleep interval that balances power consumption and data rate, which we hope will be of use to practitioners who have to make choices about which radio communications components and parameters to use in a given system.

II. Experimental setup

A. Wireless Network Setup

The sensor nodes (slaves) were programmed for cyclic sleep such that they would wake up and transmit an 8 byte

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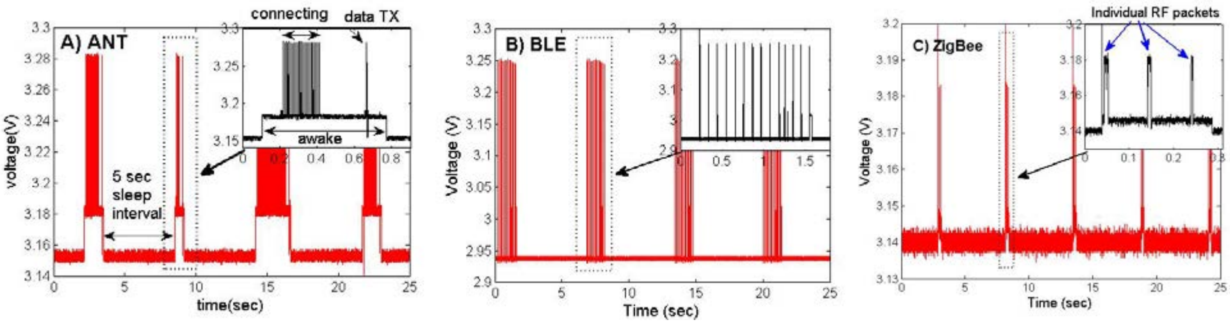

Fig. 2. Oscilloscope plots showing the voltage on a high-side shunt resistor as a proxy for sensor node current consumption. In each case one data packet is transmitted every 5 sec. The smaller boxed graphs at top-right show an expanded view of one transmission event. The spikes in voltage represent the node being awake and active and the plateau voltage between the spikes is when the node is asleep. The awake time was not explicitly controlled, and variations in this are seen in the ANT plot.

packet at the following intervals: 5 sec, 10 sec, 30 sec, 60 sec and 120 sec. The specific cyclic sleep activity at a 5 sec interval is clear from a plot of voltage drop across a shunt resistor and is shown in Figure 2 for each protocol. Note that the wake time was not directly specified but instead was naturally determined by the time each node took to connect to the hub and send a data packet. In each case, the nodes were configured to minimize power consumption by reducing the packet overhead and by maximizing the time the node spent in the lowest power sleep mode. Conversely, the hub (master) was optimized to establish a connection with a node as quickly as possible, by scanning frequently for new connections. To compare the protocols directly, all user accessible parameters on the nodes were made equal, in particular:

1) Each transmission had one 8-byte data packet of arbitrary values.
2) The transmit power was set to 0 dBm.
4) RF packet acknowledgement was required.
5) The distance between the slave and the master was fixed at 30 cm.
6) Encryption was disabled.
7) A 3.3 V power supply was used.

The experiments were conducted in an office environment but outside working hours to minimize sources of interfering RF traffic. An RF sniffer was used to verify that was no systematic interference was present.

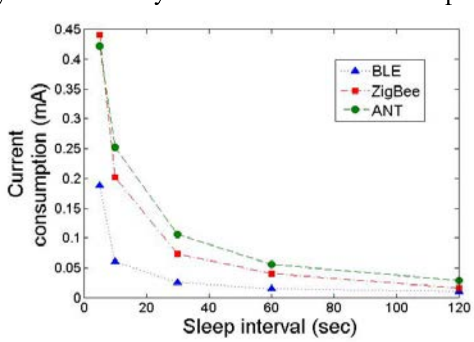

Fig. 3. Mean current consumption for three protocols at different sleep intervals.

TABLE I

CHARACTERISTICS OF RF MODULES USED IN THIS STUDY

	BLE	ZigBee	ANT
RX Sensitivity	-87 dBm	-102 dBm	-85 dBm
TX Power	0 dBm	0 dBm	0 dBm
Freq. hopping	Yes	No	No
Frequency	2.4 GHz	2.4 GHz	2.4 GHz
Radio chip	CC2450	XBee S2	AP2
Programmable	Yes	No	No
Advertising period	100 ms	100 ms	10 ms
Period between RF packets	100 ms	100 ms	250 ms

Two identical ZigBee (XBee S2, Digi International) modules were used, one configured as a coordinator (master) and the second as an end device (slave). An ARM Cortex M0+ microcontroller was used to monitor the data-ready pin (CTS) of the ZigBee module and to send the 8-byte data packet via an asynchronous serial interface at the maximum 119,200 baud rate once the ZigBee module had woken up from cyclic sleep.

The BLE slave node CC2450 chip (Texas Instruments) included a programmable 8051 microcontroller, which was used to control the radio. A Windows PC controlled the master USB dongle with a second CC2450 chip.

AP2 transceiver modules (Nordic Semiconductor) were used for ANT master and slave. The slave module was controlled with another ARM Cortex M0+ microcontroller via an asynchronous serial interface at 57,600 baud rate. The master AP2 module was mounted on a USB dongle and controlled by PC software. The transmission channel had to be closed when the ANT module went to sleep and reconfigured upon waking up.

B. Current Measurement

The sleep and active currents of the slave were measured separately to improve accuracy and include only

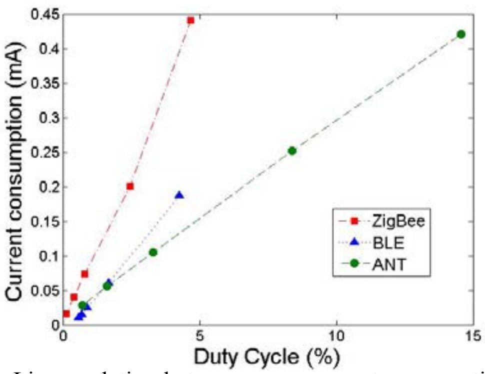

Fig. 4. Linear relation between mean current consumption and mean duty cycle. Duty cycle is defined as average awake time divided by total time for one complete cycle.

the relevant module in each case; any external components such as microcontrollers were not included. Sleep current was measured with a multimeter (Fluke 287, accuracy 0.15 %, resolution 0.01 uA) by using its 200 internal shunt resistor. Sleep current was sampled every 10 sec and a mean value over 5 min was computed. Active current was measured with a current measurement chip (INA226, Texas Instruments, accuracy 0.1 %, resolution 16-bit) with 1 or 10 shunt resistors. Current was sampled by the chip at 7000 Hz and then 64-sample averages were calculated inside the chip and sent to a PC via a serial link. At least 60 transmission events were measured. MATLAB was used to calculate the total current consumption and duty cycle by dividing time the slave was awake by total time.

TABLE 2
EXPERIMENTAL RESULTS USING 3.3 V SUPPLY

	BLE	ZigBee	ANT
Time of one connection ±SD*	1150 ms ±260 ms	250 ms ±9.1 ms	930 ms ±230 ms
Sleep current	0.78 uA	4.18 uA	3.1 uA
Awake current	4.5 mA	9.3 mA	2.9 mA
Min current (at 120 sec interval)	10.1 uA	15.7 uA	28.2 uA
Optimal sleep interval	10.0 s	14.3 s	15.3 s
*SD: standard deviation			

III. Results

The mean current consumption at sleep intervals of 5, 10, 30, 60 and 120 seconds is presented in Figure 3 and the results are summarized in Table 2. As seen in Figure 4 the duty cycle scaled linearly (R^2>0.99) with the power consumption, in line with our expectation. BLE showed lower current consumption than ANT and ZigBee for all sleep intervals. ZigBee showed slightly lower power consumption than ANT for all periods except at 5 sec. We were able to verify that less than 1% of RF packets were dropped during the experiments using the RF sniffer.

IV. Discussion

A. Power Consumption

Sleep current draw does not fully explain the power consumptions differences between protocols; sleep current was lower for ANT (3.1 uA) than ZigBee (4.18 uA), but the overall consumption of the ZigBee was lower. Similarly, awake current was lower for ANT (2.9 mA) than for ZigBee (9.3 mA). Much of the differences can be explained by the amount of time radio stays awake conceptually represented by plotting effective duty cycle as a function of the sleep interval, as shown in Figure 5.

Since the node disconnects after a transmission, a new connection has to be reestablished for each cycle, and awake time is largely governed by this. Upon waking the node starts advertising its presence, while the master listens, and data is only sent after master and slave are synchronized. ANT had a significantly higher duty cycle than ZigBee because it took longer to complete this process. As seen in Figure 2 the connection time had large variations and was significantly longer for ANT than ZigBee. The efficiency of the connection routine has one of the largest impacts on power consumption in this type of cyclic sleep application. Furthermore, BLE would appear to have an intrinsic disadvantage in a cyclic sleep scenario, since the frequency hopping scheme it uses inherently takes longer to connect compare to the fixed RF channel used in ZigBee and ANT.

ANT had a less good duty cycle than BLE, even

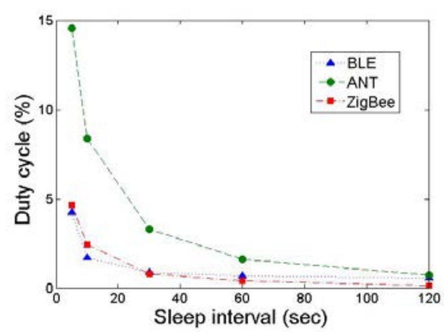

Fig. 5. Mean duty cycle at different sleep intervals.

through BLE took longer for one connection (1.15 s), than ANT (0.93 s) and ZigBee (0.25 s). This is because the BLE node was able to sleep for longer between individual RF packets, improving its duty cycle significantly.

B. Designer Friendliness

For practitioners building RF systems using the architecture under consideration here, an important factor is the complexity of setting up reliable cyclic sleep nodes. ZigBee did not require any programming since the manufacturer provided firmware included a cyclic sleep option. Since low-level radio functions were handled automatically by the ZigBee module, an external microcontroller was only needed to send data when the module woke up. The BLE module did not have cyclic sleep options and required its embedded 8051 microcontroller to be programmed to do this. However, this was simplified by the programming environment, which controlled many low-level radio functions. The ANT module did not have cyclic sleep option and required an external microcontroller to control many of the low-level radio functions. As a result it took more time to setup ANT than ZigBee or BLE.

C. Optimal Sleep Interval

A plot of current consumption vs. period (Figure 3) fits an exponential model ($R^2 > 0.99$). For a short interval (5 to 10 sec) a small change in period has a significant effect on power consumption. Furthermore, at intervals of 60 sec or more power consumption does not change significantly as the interval increases. We reasoned that there must be an interval that provides lowest power consumption and shortest interval between transmissions, and deviation from that interval will be costly in terms of power consumption or effective data rate. To quantify that interval we took the first derivative of the Figure 3 data, from which we picked a threshold of 0.01 at which derivative gets reasonably close to zero, as shown in Figure 6 The threshold yielded an optimal interval of 14.3 sec for ZigBee, 10.0 sec for BLE and 15.3 sec for ANT.

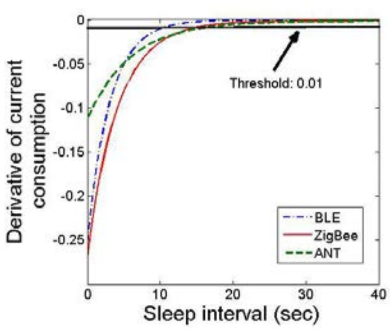

Fig. 6. First derivative of interval vs. current consumption data shown in Figure 3 after an exponential fit.

The optimal interval could be useful for applications where the designer does not need a specific transmission period for a sensor node but wants to transmit the maximum amount of data while minimizing energy expenditure. For example, in many temperature sensor applications with cyclic sleep, the exact period of transmission (e.g. 5, 10, 60, etc seconds) is not critical. The optimal interval could be standardized and provided by the radio manufacturers to help the designer choose the best interval for cyclic sleep radio scenarios like this.

V. CONCLUSION

In this paper we analyzed power consumption for the ANT, ZigBee, and BLE protocols in a cyclic sleep node scenario. We demonstrated that it is not straightforward to predict the exact power consumption in a cyclic sleep scenario from the data sheet alone. The actual power consumption is determined by combination of interacting factors, not just the average receive, transmit, and sleep currents and data rate typically given in the data sheet.

We found that BLE achieved the lowest power consumption, followed by ZigBee and ANT. The parameters that dominated power consumption were not the active or sleep currents but rather the time required to reconnect after a sleep cycle and to what extent the RF module slept between individual RF packets. In terms of time required for a designer to configure the cyclic sleep routine, in our evaluation ZigBee was the quickest, ANT took the longest, and BLE was in between the two. From the experimental data we propose a notion of optimal interval, a single parameter that can help the designers of wireless cyclic sleep nodes to pick an interval between transmissions quickly and choose an appropriate radio.

The results of this study should not be generalized to other scenarios. Furthermore, the power consumption of tested protocols might change depending on other factors such as packet size variations, transmitter and receiver distance, and hub parameters.

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