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BLUETOOTH SMART© LOW POWER SENSORS

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Abstract

Low power wireless sensing applications pose great challenges for hardware/software platform design, cost, performance, and flexibility.

Depending on the sensor type, the technology, the sampling time and power supply characteristics, the platform may need to incorporate different features in order to operate in a low-power, energy-efficient manner.

The Bluetooth Low Energy (BLE) standard, now called Bluetooth Smart©, is an ideal candidate for low-power wireless sensing applications. This is due to drastically reduced maximum peak current consumption and low duty cycles with synchronized connection periods.

In this paper, we present the design and performance of three different Bluetooth Smart© low-power sensor devices, optimized for current consumption. The resulting sensor devices with 3V coin cell battery CR1632 have overall PCB dimensions of 18 x 29 x 6 mm^3. A complete demonstrator system will be presented using software developed in house, allowing remote sensing of three different physical parameters.

Introduction

Ultra Low Power (ULP) wireless devices based on the Bluetooth Low Energy standard have received much attention recently due to their low power consumption and low duty cycles. BLE devices can use standard coin cell batteries and have life-times from several months to several years.

A sensing system contains much more than digital circuits. It also contains a variety of sensing devices and wireless interfaces. This poses a number of challenges for low-power hardware/software platform design, including size, cost, power consumption, connectivity, performance, and flexibility.

The Bluetooth Smart© sensor nodes described herein may be used in a wireless sensor network, to capture environmental information and send it back to a base station. These nodes are cheap, small and run for a year without the need to replace the battery.

In this context, Insight SiP has designed several Bluetooth Smart© sensor nodes, based on a System-in-Package (SiP) module (ISP091201) [1]. These sensor nodes contain a low power SiP module that integrates both a miniature Antenna-in-Package (AiP), and all the electronic components (transceiver, quartz, SMT components) to ensure RF communication at 2.4 GHz. The node also contains a low power sensing device and the low power microprocessor LPC1114 from NXP.

The resulting sensor node with 3V coin cell battery CR1632 has overall PCB dimensions of 18 x 29 x 6 mm^3 that make it ideally suited to highly space constrained applications, as presented in Figure 1. Different sensor nodes can be implemented using the same PCB with minor modifications related to the sensor.

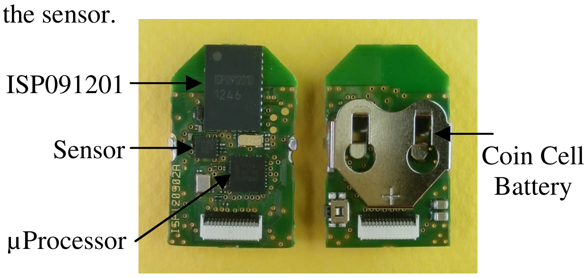

Figure 1: Bluetooth Smart© sensor module: top and bottom views

In this paper, the design of these Bluetooth Smart© sensor nodes is explained in detail. In particular the optimization of the current consumption is clearly demonstrated. The design and performance of three different Bluetooth Smart© sensor nodes will be presented, especially the low-power hardware/software platform design. The first sensor node is an accelerometer device using MMA7660FC from Freescale Semiconductor, the second one is a temperature sensor using TMP112 from Texas Instruments and the last one is an ambient light sensor using APDS-9300 from Avago Technologies.

Two complementary methods for current consumption measurements will be presented, in addition to a life time calculation model. Conclusions and perspectives based on the results and comparisons between the model and measurements will be presented.

The prototypes have been manufactured using high volume subcontractors. Current consumption characterization shows performance equivalent to the reference data sheets of the SiP module, the microprocessor and the sensors.

Finally, a demonstrator system will be presented. A short visual presentation of potential applications of these wireless sensor nodes will be made using software developed in house.

Design of smart BLE sensor nodes

Bluetooth Smart© sensor nodes contain low power System-in-Package module ISP091201 (Insight SiP), low power host microprocessor LPC1114FHI33/302 (NXP) and low power sensing device, as presented in Figure 2.

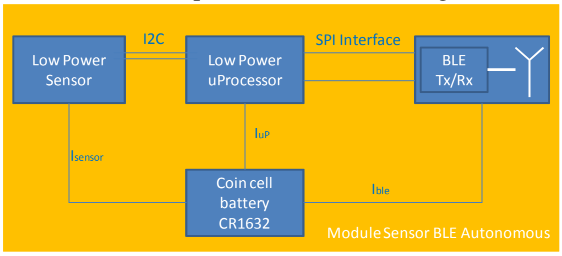

Figure 2: Schema block of Bluetooth Smart© sensor modules

The microprocessor uses a SPI interface to communicate with the BLE and an I2C interface to communicate with the sensing device. The specifications of these nodes depend on the sensing device used, as presented in Table 1.

Table 1: Specifications of Bluetooth Smart© sensor nodes

Module	Parameter	Value	Unit
	Power supply	3	V
	Coin cell Battery	CR1632	
	Connection Interval	7.5 to 4000	ms
	PCB dimensions	18 x 29 x 6	mm^3
Temperature	Accuracy	+/- 0.5 (0 – 65)	°C
	Temperature range	-40 to +125	°C
	Resolution	12	bits
Light	Light range	Dark to bright sun	Lux
	Resolution	16	bits
Orientation/ Motion	Number of axes	3	
	Acceleration range	+/- 1.5	g 9.8m/s²

Current consumption/optimization

The behavior of these Bluetooth Smart© sensor nodes can be separated in two phases:

Phase 1: phase of slave-master communication or connection phase. In this phase, the BLE module communicates with the master to send the measurements read by the sensing devices and sent to BLE module by the microprocessor. Thus, the BLE module, the microprocessor and sensing device are active and consume the maximum of current.

Phase 2: Standby (Sleep) phase. In this phase, there is no communication between the BLE module and the master. Thus, the BLE module and the microprocessor are in Standby mode.

Figure 3 illustrates the two operational phases of the Bluetooth Smart© temperature node. The measurements presented in Figure 3 are made using an oscilloscope.

Figure 3: Operational phases of the Bluetooth Smart© sensor nodes

According to the component data sheet, Figure 4 illustrates the principle of current drain profile for a typical BLE module ISP091201 which is in a connection event (Figure 4-a). It illustrates also the principle of current drain profile for the microprocessor LPC1114FHI33/302 (Figure 4-b) and for the sensing device (Figure 4-c).

For the BLE module, each connection event consists of the following states and operations (different periods related to each connection event), as presented in Figure 4-a. The current consumption profile is related to each state and operation. The numbers and related currents below correspond to that displayed in Figure 4:

1: Radio pre-processing period (I_{MCU_LL} and $I_{Standby}$),
2: Active radio receive time (I_{Rx}),
3: Radio Inter frame Space (I_{TFS}),
4: Active transmit time (I_{Tx}),
5: Link layer post processing period (I_{MCU_LL}),
6: Data post processing period, enabled only if data has been received (I_{MCU_HOST}).

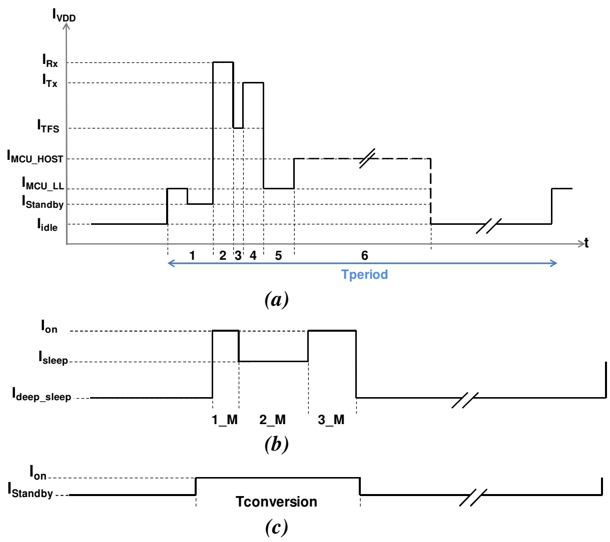

Figure 4: Current consumption over time for the module ISP091201 (a), for the microprocessor LPC1114FHI33/302 (b) and for the sensing device (c)

The values of static current consumption of BLE module ISP091201 for its different states and operations in each connection event are defined in Table 2.

Table 2: Current consumption static values of BLE module

Symbol	Parameter (condition)	Nom	Unit
I_{Rx}	Peak current, receiver active	14.6	mA
I_{Tx}	Peak current, transmitter active	12.7	mA
I_{TFS}	Peak current when switching between receive and transmit	7	mA
I_{MCU_HOST}	Peak current for host processing	5	mA
I_{MCU_LL}	Peak current for LL processing	3.5	mA
$I_{Standby}$	Standby current	1.6	mA
I_{Idle}	Current drain between connection/advertising events ACI=active mode, 32kHz Osc active	2	uA

For the microprocessor LPC1114FHI33/302, each connection event consists of three states and periods, as presented in Figur4-b:

1_M : Read period (I2C communication with sensing device to read measurements),

2_M : Waiting time (related to post-processing period),

3_M : Send period (SPI communication with the BLE to send the measurements).

The values of current consumption of microprocessor LPC1114FHI33/302 for its different states and operations in each connection event are defined in Table 3.

Table 3: Current consumption values of microprocessor LPC1114FHI33/302

Symbol	Parameter (condition)	Nom	Unit
I_{on}	Current of active mode	3 to 4	mA
I_{sleep}	Current of Sleep mode All the clocks are active	2	mA
$I_{deep\text{-}sleep}$	Current of Deep-Sleep mode All the clocks are turned off	6	uA

Finally, for the sensing device, each connection event consists of two states and periods, as presented in Figure 4-c:

$I_{Standby}$: Standby period current,

I_{on} : Active period current (I2C communication with microprocessor + conversion time).

The values of current consumption of the three sensing devices in each connection event are defined in Table 4.

Table 4: Current consumption values of temperature, light and orientation/motion sensors

Sensor	Symbol	Nom	Unit
Temp TMP112	I_{on}	40	uA
	$I_{Standby}$	2.2	uA
Light APDS-9300	I_{on}	0.24	mA
	$I_{Standby}$	3.2	uA
Orientation/Motion MMA7660FC	I_{on}	0.047 to 0.294	mA
	$I_{Standby}$	2	uA

The power management consists of minimizing the current consumption of the three subsets BLE, microprocessor and sensor in the two phases of operation. For the first phase, where the BLE, microprocessor and sensing device are active, we must choose the operation parameters of the three subsets that reduce the current consumption to the minimum. We must therefore manage the time and the level of current consumption while maintaining the correct operation according to the intended application. For the second phase, where the subsets are in Standby (Sleep) mode, we must put the BLE and microprocessor in Sleep mode and also deactivate the sensing device. The goal is to reduce the total current consumption near to zero during this long phase.

It is important to know that the total current consumption depends also on the data size to be read by the sensing device and to be sent by the microprocessor (after I2C communication) to BLE module using SPI interface, and then from the BLE module to the Master using a BLE wireless connection. In fact, the total current consumption depends on the type and the number of used services defined in the Bluetooth Low Energy protocol [2], for a given application. The transmitted data between the microprocessor and the BLE module are managed by these services. Thus, the number of defined services and the data size of each service will define Data Layer post-processing period, together with the T_X time and, consequently, the level of current consumption.

For example, for the temperature node, we have defined just one service with data size of 2 bytes which are the temperature measurements. While for the orientation/motion and light nodes, we have also defined one service but with data size of 3 and 4 bytes respectively, which lead to more current consumption. Clearly the larger the amount of data to be sent, the greater is the Data Layer Post-processing period. This leads to longer I_{on} times for both the microprocessor and the sending device, which in turn increases overall current consumption.

Current measurement methods

In this paragraph, we present two complementary methods for current consumption measurements. The first one uses an oscilloscope to measure the current consumption of the BLE module and microprocessor during the connection phase (Phase 1), where the consumption is maximum. As the sensing device consumption is very weak (a few µA), we will see that this measurement method with oscilloscope is not suitable for measuring very low currents during standby phase. Thus, we have developed a second method, based on the principle of charging and discharging a capacitor to measure the total current consumption, including low-consumption sensing device. In addition, this method allows the measurement of the total current consumption during the Standby-sleep phase (Phase 2), where current consumption of each subset is very low.

In the following, these two methods are described and illustrated by showing the results for the temperature sensor nodes. The measurement results of the three Bluetooth Smart© sensor nodes will be summarized at the end of this article (cf Table 7).

Oscilloscope method

Oscilloscope measurement method is a basic method, which consists of connecting a low-value resistor (0.5 Ohm) to the power feed of each subset BLE, microprocessor and sensing device, as presented in Figure 5. These resistors have been integrated into the wireless miniature nodes. Voltages at each terminal of the resistances are sent to a measurement board thanks to a FPC cable.

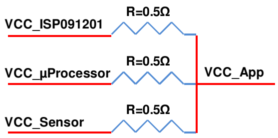

Figure 5: Electrical Schematic of current measurement for oscilloscope measurement method

On the measurement board, an INA195 amplifier (Texas Instruments) with gain of 100 is used to amplify the differential voltage across the terminals of each resistor. So, by measuring the voltage at the output of each INA195, we measure the current consumption ($I = V/_{0.5}$) of each subset, and then the total current consumption. The high gain of the INA195 allows us to measure relatively low currents.

Figure 6 illustrates the two functioning phases of BLE module and microprocessor measured by oscilloscope method for temperature sensor node. To measure the current consumption of BLE module and microprocessor during Phase 1, it consists in measuring the voltage and duration of each segment of consumption displayed on the oscilloscope, as presented in Figure 7.

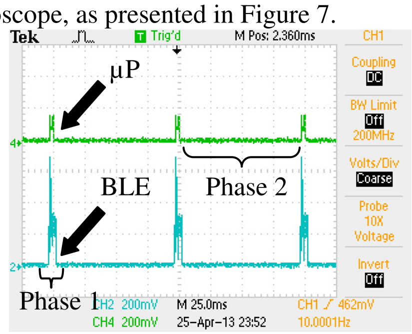

Figure 6: Two functioning phases, as measured by oscilloscope method

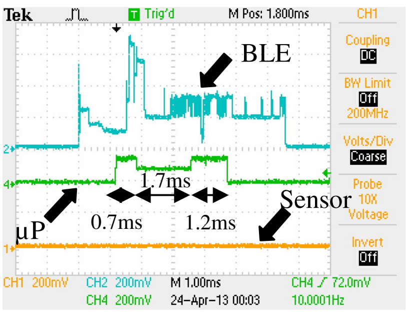

Figure 7: Temperature sensor node: current consumption measurements of BLE module, microprocessor and sensing device, as measured by oscilloscope method

For the microprocessor current consumption measurements, we have three segments (0.7 ms, 1.7 ms and 1.2 ms), as presented in Figure 7. The corresponding current and charge consumption values in these three segments are presented in Table 5. These three segments correspond to events presented in Table 3. The current and charge consumption calculations associated with each segment are based on the following two equations:

$$I = \frac{V_{osc}/_{100}}{R} = \frac{V_{osc}/_{100}}{0.5} = \frac{V_{osc}}{50} \text{ and } Q = I \times T$$

Table 5: Temperature sensor node: current and charge consumption measurements of microprocessor, as measured by oscilloscope method

	Temperature node: µprocessor LPC1114 Consumption				
	Symbol	Time (ms)	Voltage (mV)	Current (mA)	Charge (µC)
	I_{on} (Read)	0.7	170	3.4	2.38
	I_{sleep} (Wait)	1.7	100	2	3.4
	I_{on} (Data Send)	1.2	170	3.4	4.08
Total		3.6			9.86

Similarly, to measure the BLE module current consumption, we have 6 consumption segments which correspond to events presented in Table 2. Table 6 presents the corresponding current and charge consumption values of BLE module, as measured by oscilloscope method using the two previous equations.

Table 6: Temperature sensor node: current and charge consumption measurements of BLE module, as measured by oscilloscope method

	Temperature node: BLE module Consumption				
	Symbol	Time (ms)	Voltage (mV)	Current (mA)	Charge (µC)
	I_{MCU_LL}	1.14	230	4.6	5.24
	$I_{Standby}$	1.2	136	2.72	3.26
	I_{Rx}	0.24	660	13.2	3.17
	I_{TFS}	0.1	480	9.6	0.96
	I_{Tx}	0.25	560	11.2	2.80
	I_{MCU_Host}	3.64	260	5.2	18.93
Total		6.57			34.36

Concerning the current consumption of the temperature sensing device, it is very low (a few µA). Because of an intrinsic offset of INA195 component used in the oscilloscope measurement method, we can't characterize this low current with this method. This is confirmed by Figure 7, where we can't measure the consumption of the temperature sensing device.

Capacitor method

To overcome low current limitations of the oscilloscope method and to obtain more accurate measurements, we have developed another measurement method: the capacitor method. This method is based on the principle of charging a calibrated capacitor, then turning off the power supply and finally feeding the sensor node via this charged capacitor. Total current consumption of the sensor node will discharge this capacitor and decrease its voltage. By measuring the voltage drop across the capacitor terminals as a function of time, we can determine the total current consumption and/or the total charge consumption, as presented in the two following equations:

$$I = \frac{Q}{\Delta t} \; with \; Q = C \times \Delta V$$

This method allows the measurement of low currents (a few µA), particularly to characterize the current consumption of sensing device during the connection phase (Phase 1), but also to characterize the total current consumption during the Standby-sleep (Phase 2), where the current consumption of BLE module, microprocessor and sensing device is very low.

The capacitor used in this method is a ceramic capacitor of about 600 µF. To determine the precise value of this capacitance, we have used an RC circuit to calibrate the capacitance value. In this way, we have connected the capacitor to a resistor of 1 KΩ (tolerance 1%). The time constant of this circuit is given by $T = R \times C$. Thus, by measuring the time constant on the oscilloscope, we can calibrate the capacitance that will be used to accurately measure the current consumption. The precise value of the capacitance is 530 µF.

Figure 8 presents the electrical schematic for total current consumption measurement by the capacitor method.

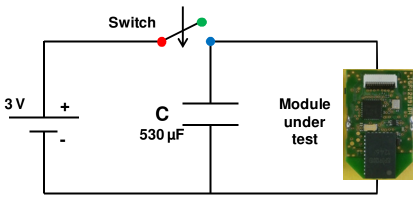

Figure 8: Electrical schematic for current consumption measurements, using capacitor measurement method

Figure 9 shows the measurements of total current consumption of the temperature sensor node for the two functioning phases (Phase 1+Phase 2), carried out by the capacitor method for a measurement time (Connection Interval) of 1 second.

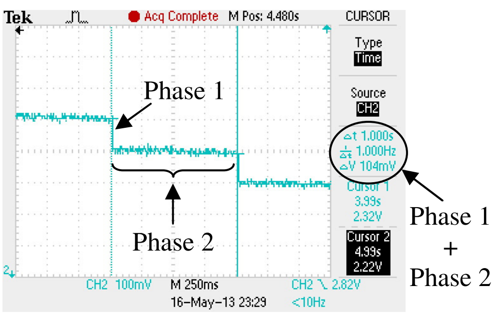

Figure 9: Temperature sensor node: total current consumption measurements, as measured by capacitor method

In these measurements, the high voltage drop is related to the total current consumption of the sensor node during the communication phase (Phase 1) where there is a high consumption for a short time (6-10 ms). However the low slope of consumption is related to the total consumption of the sensor node for the Standby-sleep phase (Phase 2). Thus, the total charge consumption of the temperature node sensor for the period ($T_{period} = 1s$), as presented in Figure 9, is:

$$Q_{Phase\,1+Phase\,2} = C \times \Delta V = 530\mu F \times 0.104V = 55.12\;\mu C$$

Figure 10 presents the measurements of total consumption of temperature sensor node during the communication phase (Phase 1). We observe a voltage drop of 88 mV during this phase, so the total charge consumption in the communication phase is:

$$Q_{Phase\,1} = C \times \Delta V = 530\mu F \times 0.088V = 46.64\;\mu C$$

These results are in accordance with measurements made for the BLE module and the microprocessor by the oscilloscope method presented in the previous paragraph (Table 5 and Table 6), where: $Q_{BLE} = 34.36\;\mu C$ and $Q_{\mu P} = 9.86\;\mu C$. The difference between the two measurements is the consumption of the sensing device during the communication phase (Phase 1), so: $Q_{sensor} = 46.64 - (34.36 + 9.86) = 2.42\;\mu C$.

Figure 11 presents the measurements of total consumption of temperature sensor node during the Standby-sleep (Phase 2). We observe a voltage drop of 16 mV during this phase, so the total charge consumption in the Standby-sleep phase, is:

$$Q_{Phase\,2} = C \times \Delta V = 530\mu F \times 0.016V = 8.48\;\mu C$$

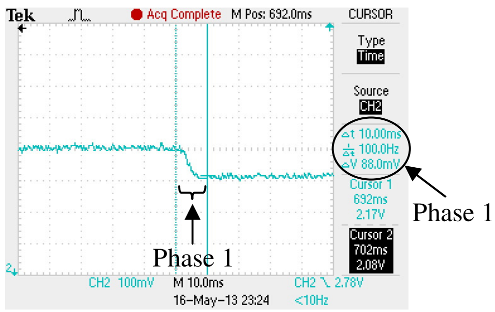

Figure 10: Temperature sensor node: total current consumption measurements during Phase 1, as measured by capacitor method

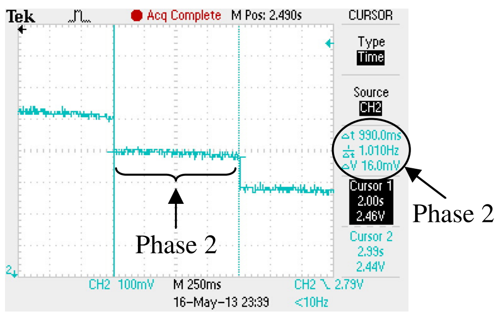

Figure 11: Temperature sensor node: total current consumption measurements during Phase 2, as measured by capacitor method

Thus, the total average current consumption of the temperature sensor node for the period ($T_{period} = 1s$) is:

$$I_{T_{period}=1s} = \frac{Q_{Phase\,1} + Q_{Phase\,2}}{1s} = 55.12\ \mu A$$

Life time model/measurements

In addition, we have developed a model for calculating current consumption of temperature, light and orientation/motion sensor nodes. This model is based on the data sheets of the components, that is to say, the current consumption values of each subset BLE module, microprocessor and sensing device, as they are given in their data sheets. This model allows the calculation of the average consumption of each subset, the total consumption and the autonomy of sensor nodes for different Connection Intervals and for different types of battery.

Table 7 presents model/measurement comparison of the total current consumption and the autonomy of temperature, light and orientation/motion sensor nodes, respectively, for different Connection intervals.

Table 7: Model/Measurements comparison for Temperature, Light and Orientation/Motion sensor nodes

Sensor node	Connec Interval (ms)	Cons Model (µC)	Cons Meas (µC)	Auton Model (year)	Auton Meas (year)
Temp	1000	52.30	55.12	0.31	0.29
	2000	62.30	63.6	0.51	0.50
	3000	72.30	72.08	0.66	0.67
	4000	82.30	80.56	0.78	0.79
Light	1000	65.72	67.84	0.24	0.24
	2000	76.92	80.56	0.42	0.40
	3000	88.12	93.28	0.54	0.51
	4000	99.32	106	0.64	0.60
Orientation Motion	1000	62.72	63.6	0.25	0.25
	2000	72.72	72.08	0.44	0.44
	3000	82.72	80.56	0.58	0.60
	4000	92.72	89.04	0.69	0.72

Regarding this table, we note that the calculation model of current consumption is quite reliable and provides good estimations of consumption and autonomy close enough to the real operation case in the range of measurement time (Connection Interval) 1000 to 4000 ms.

Demonstrator

Finally, a demonstrator system will be presented during the session of the conference. A short visual presentation of potential applications of these wireless sensor nodes will be made using software developed in house.

Conclusions

This paper has described the design and the performance of low power Bluetooth Smart© sensor nodes. In particular, the optimization of the current consumption is clearly demonstrated. Two complementary methods for current consumption measurements have been presented, in addition to a life time calculation model/measurements. The resulting sensor node has overall PCB dimensions of 18 x 29 x 6 mm^3 with a life time between 0.29 year and 0.79 year using 3V coin cell battery CR1632.

Acknowledgements

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References

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