AN130501
Power Optimization Bluetooth Sensors

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1. Introduction

1.1 Scope

This application note describes the performance of three different Bluetooth Smart© sensor nodes, especially the low-power hardware/software platform design. The design of these sensor nodes contain a low power System-in-Package (SiP) module "ISP091201" which 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 host microprocessor LPC1114FHI33/302 from NXP.

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

The first sensor device is ISP120909A Bluetooth Low Energy (BLE) Wireless Temperature Detection Sensor, using TMP112 from Texas Instruments. The second one is ISP120911A Bluetooth Low Energy Wireless Light Detection Sensor, using APDS-9300 from Avago Technologies. The last one is ISP120901A Bluetooth Low Energy Wireless Orientation/Motion Detection Sensor, using MMA7660FC from Freescale Semiconductor.

The Bluetooth Smart© sensor nodes described herein are slave devices may be used in a wireless sensor network, to capture environmental information and send it back to a base station (Master).

1.2 Bluetooth Low Energy Wireless sensor nodes

The design of Bluetooth Smart© sensor nodes contain low power System-in-Package (SiP) module "ISP091201", the low power host microprocessor LPC1114FHI33/302 (NXP) and low power sensing device, as presented in Figure 1.

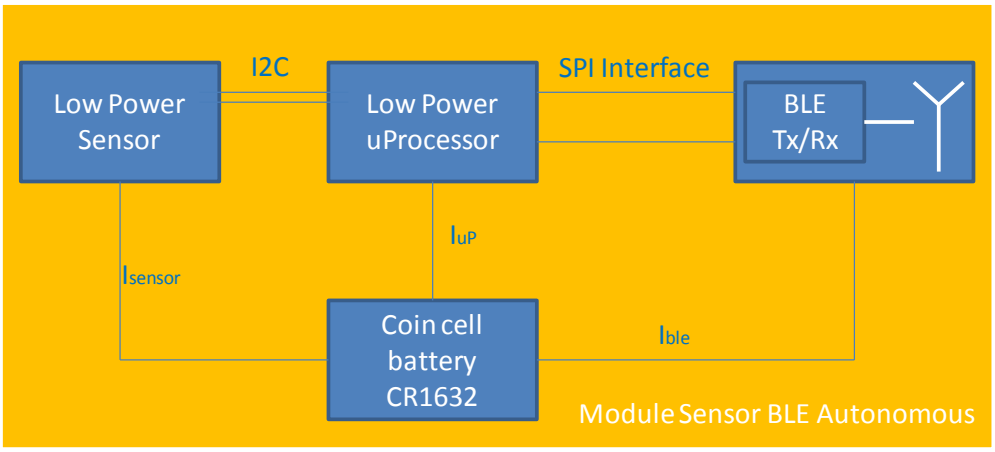


Figure 1: Schema Block of Bluetooth Smart© sensor modules

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

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
Temperature Detection	Accuracy	+/- 0.0625	°C
	Temperature range	-40 to +125	°C
	Resolution	12	bits
Light Detection	Light range	Dark to bright sun	Lux
	Resolution	16	bits
Orientation/Motion Detection	Number of axes	3	
	Acceleration range	+/- 1.5	g (9.81m/s²)

Table 1: specifications of the three Bluetooth Smart© sensor modules

2. Current Consumption Methods

2.1 Generalities

In this paragraph, we present the current drain over time for the three subsets of Bluetooth Smart© sensor node: module "ISP091201", microprocessor "LPC1114FHI33/302" and sensing device (temperature, light and orientation/motion).

The functioning 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 2 illustrates the two functioning phases of the Bluetooth Smart© temperature node. The measurements presented in Figure 2 are realized by the oscilloscope.

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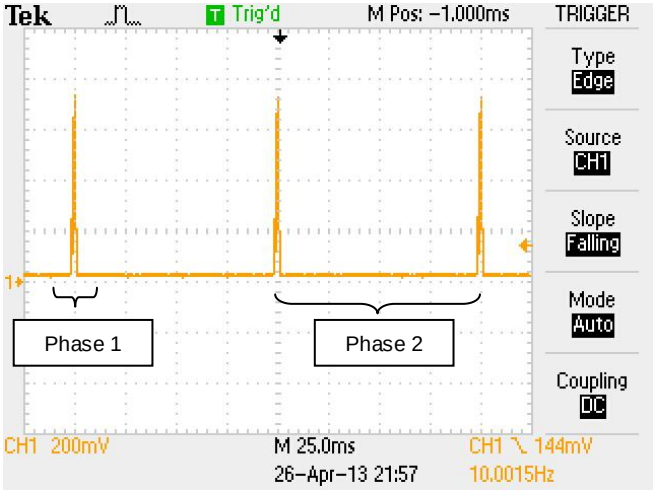


Figure 2: Functioning phases of the Bluetooth Smart© sensor nodes

We present next, the current consumption of the three subsets of Bluetooth Smart© sensor node: module BLE, microprocessor and sensing device (temperature, light and orientation/motion) according to their data sheets. Then, we present two measurement methods of current consumption to each subset and/or total current consumption.

2.1.1 BLE module, Microprocessor and Sensing device current consumption

Figure 3, illustrates the principle of current drain profile for a typical Bluetooth low energy (BLE) module "ISP091201" that is connected (Figure 3-a). It illustrates also the principle of current drain profile for the microprocessor LPC1114FHI33/302 (Figure 3-b) and for the sensing device (Figure 3-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 3-a. The current consumption profile is related to each state and operation. The numbers and related currents below correspond to that displayed in Figure 3:

- 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}).

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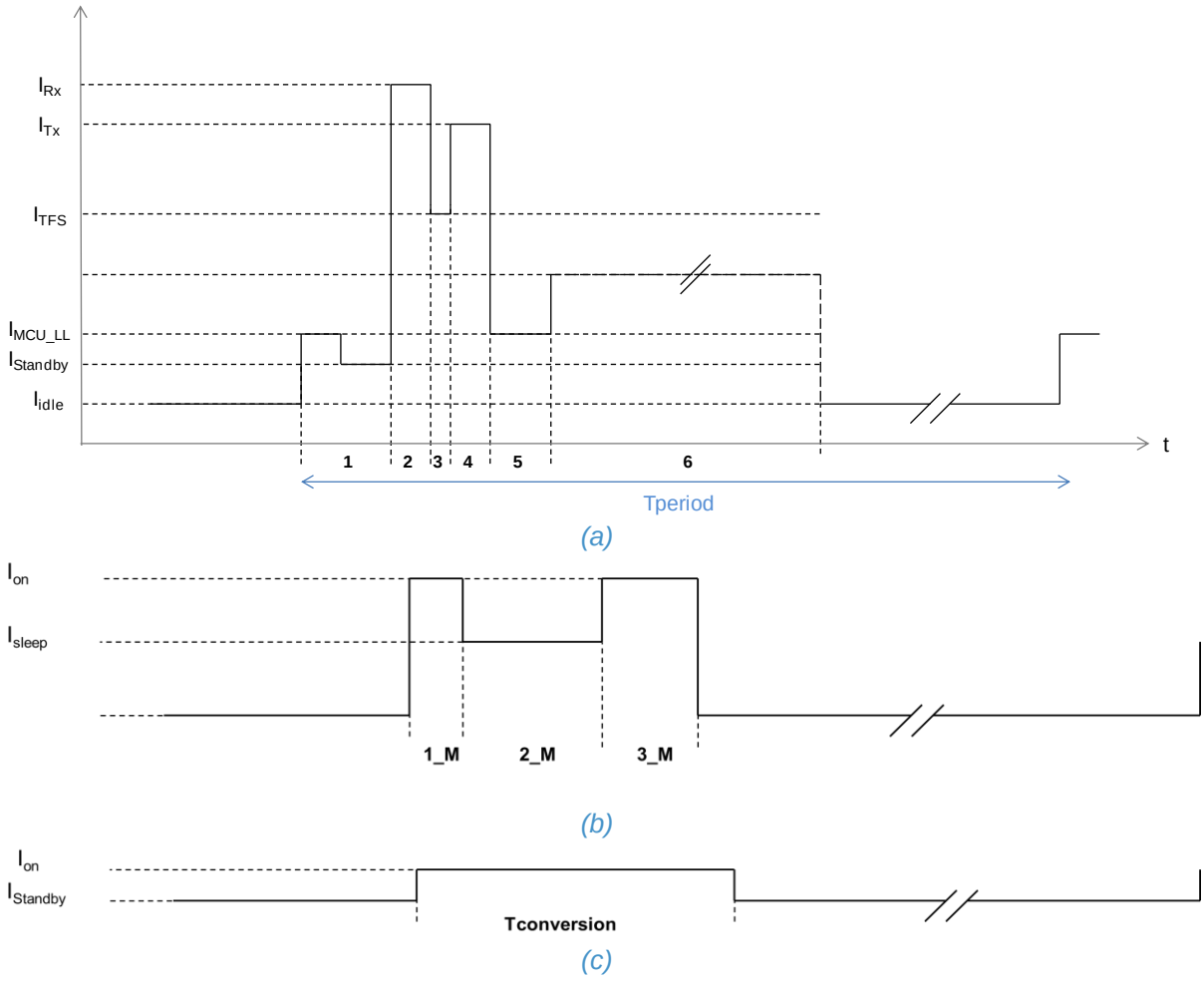


Figure 3: Current consumption over time for a typical module ISP091201(a), microprocessor "LPC1114FHI33/302" (b) and for sensing device (c)

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.

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

Table 2: Current consumption static values of BLE module

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For the microprocessor LPC1114FHI33/302, each connection event consists of three states and periods, as presented in Figure 3-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).

For certain sensing devices and depending to the application, the order of these three states can changed, or the 2_M state can be not used to reduce the microprocessor current consumption.

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

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
$I_{deep-sleep}$	Current of Deep-Sleep mode All the clocks are turned off	6	uA

Table 3: Current consumption values of microprocessor LPC1114FHI33/302

Finaly, for the sensing device, each connection event consists of two states and periods, as presented in Figure 3-c:

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

The used sensing devices are: temperature sensor “TMP112”, light sensor “APDS-9300” and orientation/motion sensor “MMA7660FC”. The values of current consumption of these three sensing devices in each connection event are defined in Table 4.

Temp sensor TMP112 – Symbol	Nom	Unit
I_{on}	40	uA
$I_{Standby}$	2.2	uA
Light sensor APDS – Symbol	**Nom**	**Unit**
I_{on}	0.24	mA
$I_{Standby}$	3.2	uA
Orientation/Motion sensor MMA7660FC – Symbol	**Nom**	**Unit**
I_{on}	0.047 to 0.294 Depending on Sampling Rate	mA
$I_{Standby}$	2	uA

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

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2.1.2 Power management and optimization of current consumption

The power management consists to minimize 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 proper functioning according to the intended application.

For the second phase, where the subsets are in Standby (Sleep) mode, it is to operate the BLE and the microprocessor in Sleep mode and deactivate the sensing device. The goal is to reduce the total current consumption during this long phase to near zero.

It is important to know that the total current consumption depend on the data size to be read by the sensing device and to be send by the microprocessor (after I2C communication) to BLE module using SPI interface, then the BLE module will send these data to Master using BLE wireless connection.

In fact, the total current consumption depends on the type and the number of used services defined in Bluetooth Low Energy protocol 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 TX 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 light node, we have defined just one service with data size of 4 bytes, which will lead to more current consumption. Clearly, larger the data size to be transmitted, greater Data Layer post-processing period and the Ion time of both microprocessor and sensing device, greater the level of current consumption by consequence.

In the next paragraph, we present two complementary methods for current consumption measurements. The first one using oscilloscope to measure the current consumption of BLE module and microprocessor during the connection phase (Phase 1), where the consumption is maximum. The sensing device consumption is very weak (of the order of a few uA), we will see that this measurement method using just the oscilloscope is not suitable for measuring low currents. Thus, we have developed another 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 can measure the total consumption during the Standby-sleep phase (Phase 2), where current consumption of each subset is very weak.

2.2 Oscilloscope measurement method

Oscilloscope measurement method is a simple one, based on fact to connect a low-value resistor (0.5 Ohm) to the power feed of each subset BLE, microprocessor and sensing device, as presented in Figure 4. These resistors have been integrated into the wireless miniature nodes. Voltages at each end of the resistance are returned to a measurement board by means of FPC cable for this purpose.

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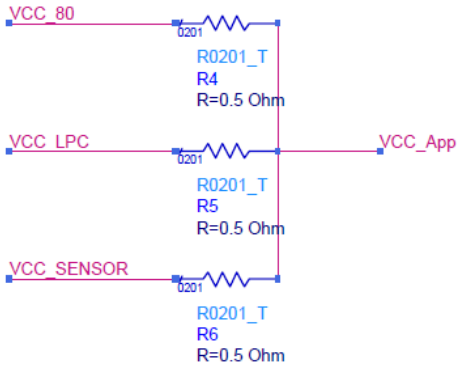


Figure 4: Electric Schema of current measurement for oscilloscope measurement method

On the measurement board, an INA195 amplifier (Texas Instruments) with gain 100 is used to amplify the differential voltage across the ends 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, then the total current consumption. The high gain of the INA195 allows us to measure relatively low currents.

2.2.1 Temperature sensor node

Figure 5 illustrates the two functioning phases of BLE module and microprocessor measured by oscilloscope method for temperature sensor node.

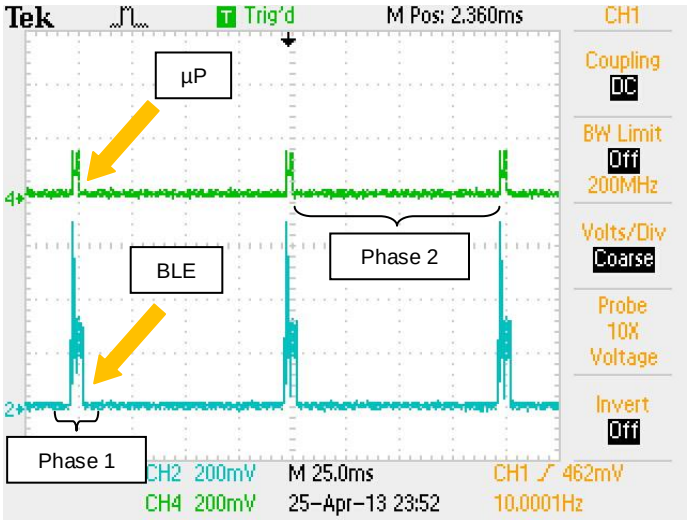


Figure 5: Temperature sensor node: two functioning phases of BLE module and microprocessor, as measured by oscilloscope method

To measure the current consumption of BLE module and microprocessor during phase 1, simply measure the voltage and duration of each segment of consumption displayed on the oscilloscope, as presented in Figure 6.

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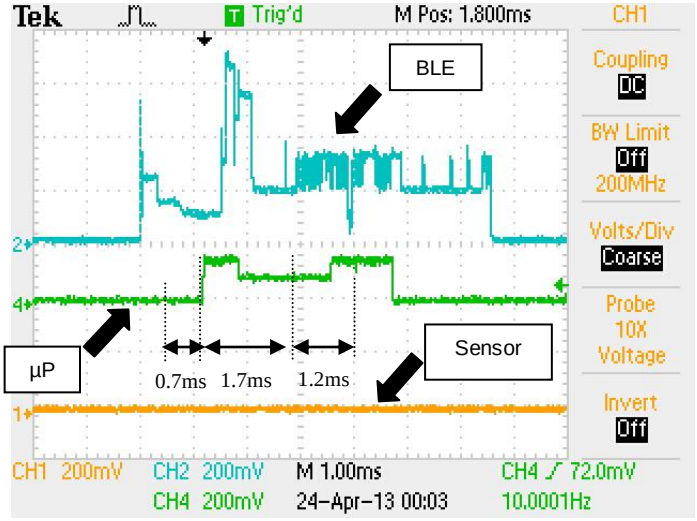


Figure 6: Temperature sensor node: current consumption measurements of BLE module, microprocessor and sensing device, as measured by oscilloscope method

For the microprocessor current consumption measurements in temperature sensor node, we have three consumption segments (0.7 ms, 1.7ms and 1.2 ms), as presented in Figure 6. The corresponding current and charge consumption values in these three segments is 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:

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

Temperature sensor node: Microprocessor 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	2.0	3.40
I_{on} (Data send)	1.2	170	3.4	4.08
Total	3.6			9.86

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

Similarly, to measure the BLE module current consumption in temperature sensor node, we have 6 consumption segments. These 6 segments 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 precedent equations. BLE module current consumption measurements are consistent with the values given by the software provided by Nordic Semiconductor (nRFgo Studio). In this software, depending on the type and the number of defined services and depending on the measurement time (Connection Interval), we can estimate the current consumption of BLE module.

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Temperature sensor node: BLE module Consumption				
Symbol	**Time (ms)**	**Voltage (mV)**	**Current (mA)**	**Charge (µC)**
I_{MCU_LL}	1.14	230	4.60	5.24
$I_{Standby}$	1.20	136	2.72	3.26
I_{Rx}	0.24	660	13.20	3.17
I_{TFS}	0.10	480	9.60	0.96
I_{Tx}	0.25	560	11.20	2.80
I_{MCU_HOST}	3.64	260	5.20	18.93
Total	6.57			34.36

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

For Temperature sensor node, for example, if we define just one service with data size of 2 bytes and for connection interval of one second, the estimated current consumption is about 35.04 µA, as presented in Figure 7. This is consistent with our measurements presented in Table 6, where the measured charge is 34.36 µC, thus:

$$I_{measured} = \frac{Q_{measured}}{\Delta t} = \frac{34.36\ \mu C}{T_{period}} = \frac{34.36\ \mu C}{1s} = 34.36\ \ \mu A$$

The measurement time (Connection Interval) of one second corresponds to parameter T_{period} in Figure 3, which is the sum of Phase 1 time and Phase 2 time. If we consider that the current consumption of BLE module in Phase 2 is negligible (2 µA, cf Table 2), so our measurements using oscilloscope method during Phase 2 are consistent with the data sheet and specifications given by the constructor.

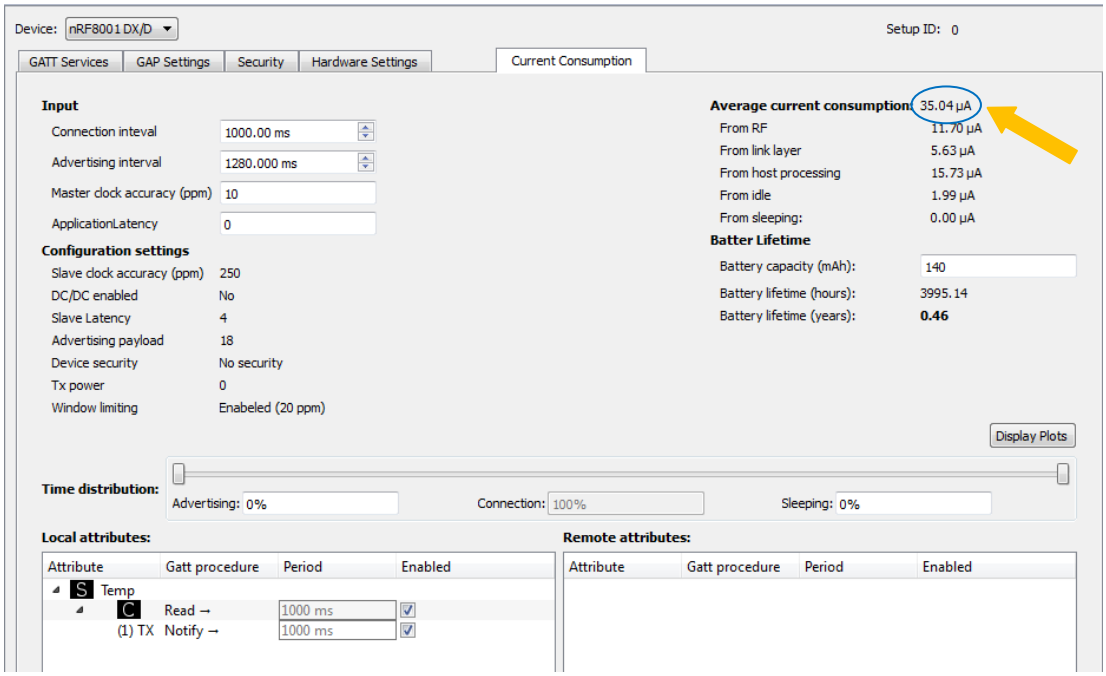


Figure 7: Temperature sensor node: BLE module current consumption, as estimated by nRFgo Studio software

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2.2.2 Light sensor node

Figure 8 illustrates the two functioning phases of BLE module and microprocessor measured by oscilloscope method for light sensor node.

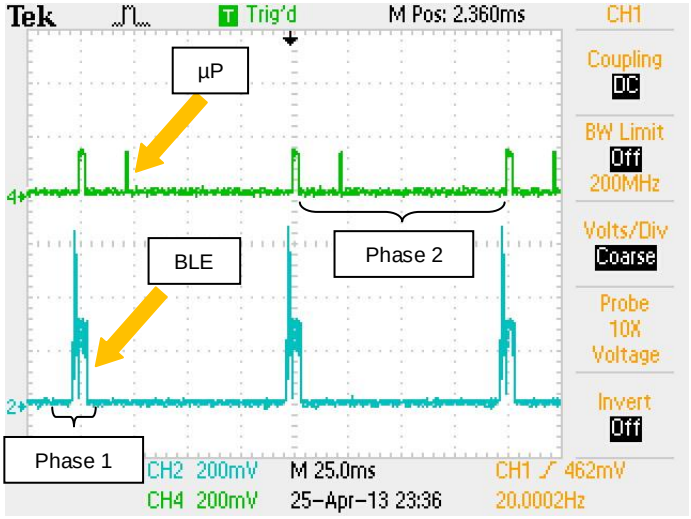


Figure 8: Light sensor node: 2 functioning phases of BLE module and microprocessor, as measured by oscilloscope method

To measure the current consumption of BLE module and microprocessor during phase 1, simply measure the voltage and duration of each segment of consumption displayed on the oscilloscope, as presented in Figure 9.

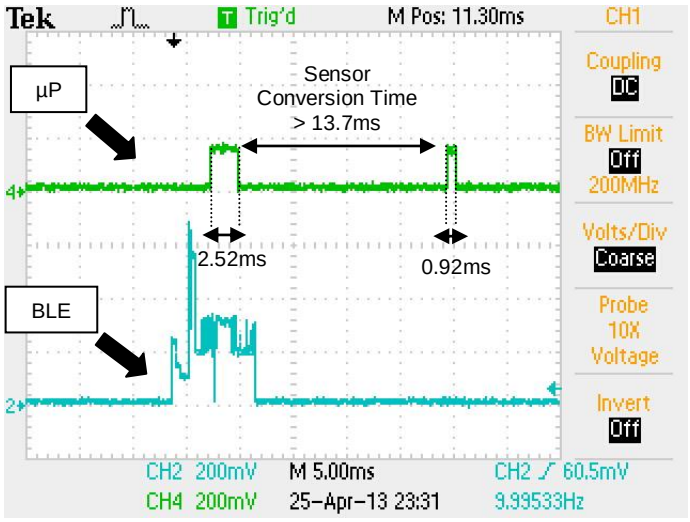


Figure 9: Light sensor node: current consumption measurements of BLE module and microprocessor, as measured by oscilloscope method

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For the microprocessor current consumption measurements in light sensor node, we have two consumption segments (2.52 ms and 0.92 ms), as presented in Figure 9. The corresponding current and charge consumption values in these two segments are presented in Table 7.

The third segment (I_{sleep}) is not used in light sensor node (I_{sleep}_time=0), because the Read operation (I2C communication between the sensing device and the microprocessor) is done after Radio activities to minimize the current consumption of the sensing device. In fact, the light sensing device has a relatively high current consumption when it is active (0.24 mA, cf Table 4), and it hasn't Shut_Down option after its conversion time as in temperature sensing device case. The power management, we have proposed, is to turn on the sensing device during the first microprocessor activity, waiting its conversion time (min_time > 13.7ms) using Deep Sleep mode, then read sensing device measurements and turn it off.

Light sensor node: Microprocessor LPC1114 Consumption				
Symbol	**Time (ms)**	**Voltage (mV)**	**Current (mA)**	**Charge (µC)**
I_{on} (Data send)	2.52	170	3.4	8.57
I_{sleep} (Wait)	0.00	100	2.0	0.00
I_{on} (Read)	0.92	170	3.4	3.13
Total	3.44			11.7

Table 7: Light sensor node: current and charge consumption measurements of microprocessor, as measured by oscilloscope method

Similarly, to measure the BLE module current consumption in light sensor node, we have 6 consumption segments. These 6 segments correspond to events presented in Table 2. Table 8 presents the corresponding current and charge consumption values of BLE module, as measured by oscilloscope method.

Light sensor node: BLE module Consumption				
Symbol	**Time (ms)**	**Voltage (mV)**	**Current (mA)**	**Charge (µC)**
I_{MCU_LL}	1.14	230	4.60	5.24
$I_{Standby}$	1.20	136	2.72	3.26
I_{Rx}	0.24	660	13.20	3.17
I_{TFS}	0.10	480	9.60	0.96
I_{Tx}	0.25	560	11.20	2.82
I_{MCU_HOST}	4.96	260	5.20	25.79
Total	7.89			41.25

Table 8: Light sensor node: current and charge consumption measurements of BLE module, as measured by oscilloscope method

2.2.3 Orientation/Motion sensor node

Figure 10 illustrates the two functioning phases of BLE module and microprocessor measured by oscilloscope method for orientation/motion sensor node.

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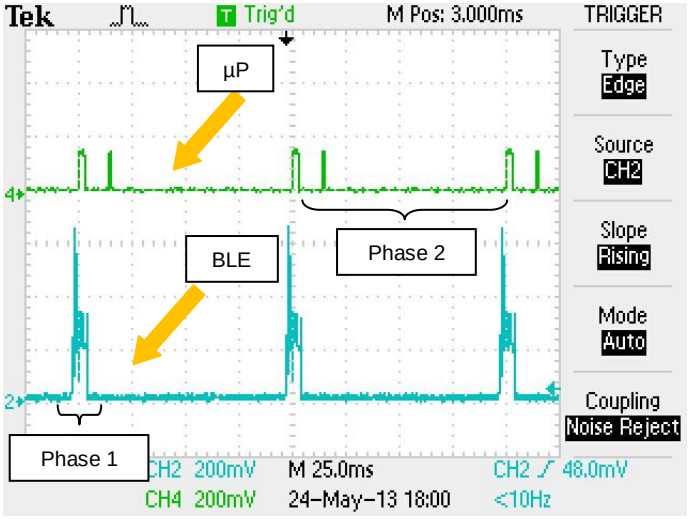


Figure 10: Orientation/Motion sensor node: 2 functioning phases of BLE module and microprocessor, as measured by oscilloscope method

To measure the current consumption of BLE module and microprocessor during phase 1, simply measure the voltage and duration of each segment of consumption displayed on the oscilloscope as presented in Figure 11.

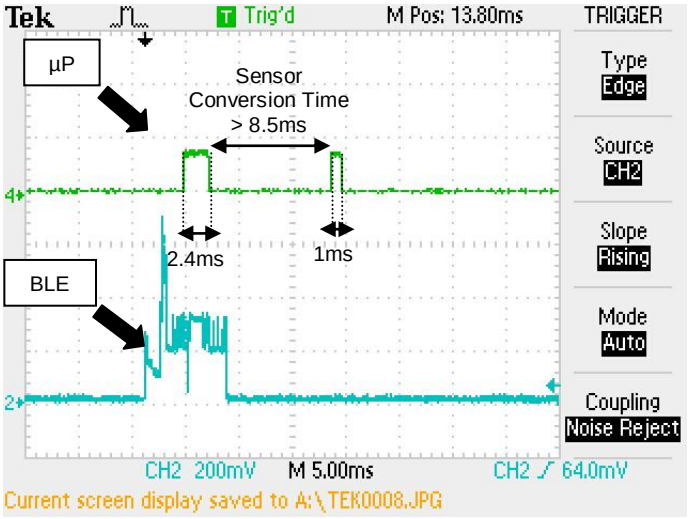


Figure 11: Orientation/Motion sensor node: current consumption measurements of BLE module and microprocessor, as measured by oscilloscope method

As for light sensor node, we have two consumption segments (2.4 ms and 1 ms), as presented in Figure 11 for the microprocessor current consumption measurements in orientation/motion sensor node. The corresponding current and charge consumption values in these two segments are presented in Table 9. The third segment (I_{sleep}) is not used in orientation/motion sensor node (I_{sleep}_time=0), as the case of light sensor node, to minimize the current consumption of the orientation/motion sensing device. The minimum conversion time for orientation/motion sensing device is 8.333 (120 Samples/second).

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Orientation/Motion sensor node: Microprocessor LPC1114 Consumption				
Symbol	**Time (ms)**	**Voltage (mV)**	**Current (mA)**	**Charge (µC)**
I_{on} (Data send)	2.4	170	3.4	8.16
I_{sleep} (Wait)	0.0	100	2	0.00
I_{on} (Read)	1.0	170	3.4	3.40
Total	3.4			11.56

Table 9: Orientation/Motion sensor node: current and charge consumption measurements of microprocessor, as measured by oscilloscope method

Similarly, to measure the BLE module current consumption in orientation/motion sensor node, we have 6 consumption segments. These 6 segments correspond to events presented in Table 2. Table 10 presents the corresponding current and charge consumption values of BLE module, as measured by oscilloscope method.

Orientation/Motion sensor node: BLE module Consumption				
Symbol	**Time (ms)**	**Voltage (mV)**	**Current (mA)**	**Charge (µC)**
I_{MCU_LL}	1.14	230	4.60	5.24
$I_{Standby}$	1.20	136	2.72	3.26
I_{Rx}	0.24	660	13.20	3.17
I_{TFS}	0.10	480	9.60	0.96
I_{Tx}	0.25	560	11.20	2.81
I_{MCU_HOST}	4.70	260	5.20	24.44
Total	7.63			39.88

Table10: Orientation/Motion sensor node: current and charge consumption measurements of BLE module, as measured by oscilloscope method

According to Table 7 and Table 8 for temperature sensor node, and comparing to Table 5 and Table 6 for light sensor node, or Table 9 and Table 10 for orientation/motion sensor node, we find that the current consumption of light or orientation/motion sensor nodes is more important than the current consumption of the temperature sensor node, especially the consumption of BLE module. In fact, this increase in current consumption of BLE module is mainly related to the consumption time of "I_{MCU_HOST}", which is longer in the case of light or orientation/motion sensor nodes, because of the greater data size (4 bytes for the light sensor node and 3 bytes for orientation/motion sensor node) relative to the 2 bytes in the case of temperature sensor node. The greater number of bytes (data size) also increases the consumption of the microprocessor, because it also requires a longer consumption time of "I_{on}" for reading measurements made by the sensing device and for sending them to BLE module.

Regarding the current consumption of the sensing device, it is very low (in the order of a few uA). Because of an intrinsic offset of INA195 component used in the oscilloscope measurement method, we cannot characterize this low current with this method. This is confirmed by Figure 6, where we cannot measure the consumption of the temperature sensing device.

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2.3 Capacitor measurement method

To overcome low currents limitation of oscilloscope measurement method and to obtain more accurate measurements, we developed another measurement method: the Capacitor Approach. This method is based on the principle of charging calibrated capacitor, then turns off the power supply and feed the sensor node by this charged capacitor. Total current consumption of sensor node will discharge this capacitor and decrease its voltage. By measuring the voltage drop across the capacitor 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:

$$I = \frac{Q}{\Delta t} \text{ où } Q = C \times \Delta V$$

This method allows the measurement of low currents (in the order of a few uA), 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 uF. To know the precise value of this capacitance, we have used an RC circuit to calibrate the capacitance value. For this, we have connected the capacitor to resistor with an accurate value of 1 KΩ, as shown in Figure 12.

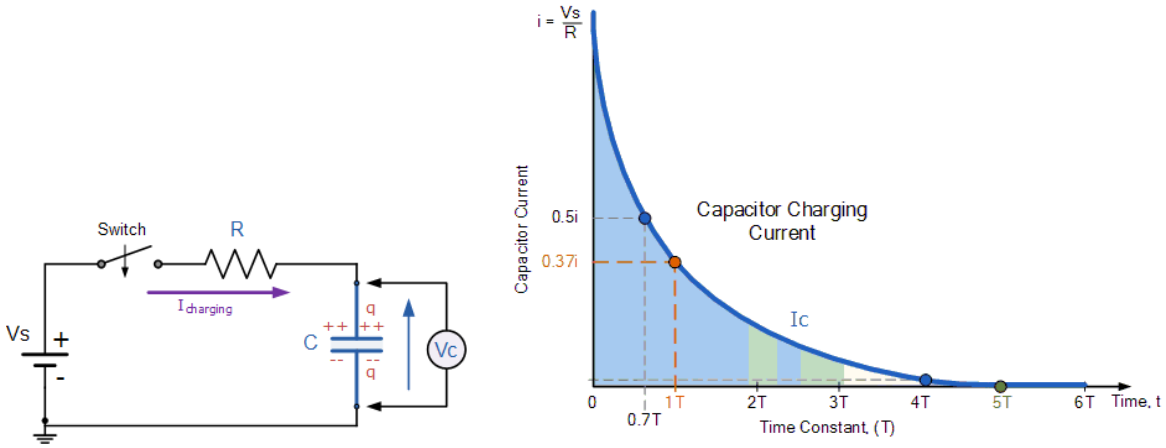


Figure 12: Electric Schema of RC circuit and its discharging curve, versus time

The time constant of this circuit is given as:

$$T = R \times C$$

So by measuring the time constant on the oscilloscope, we can calibrate the capacitance that we will use to accurately measure the current consumption. Figure 13 shows the discharge curve of the measured RC circuit.

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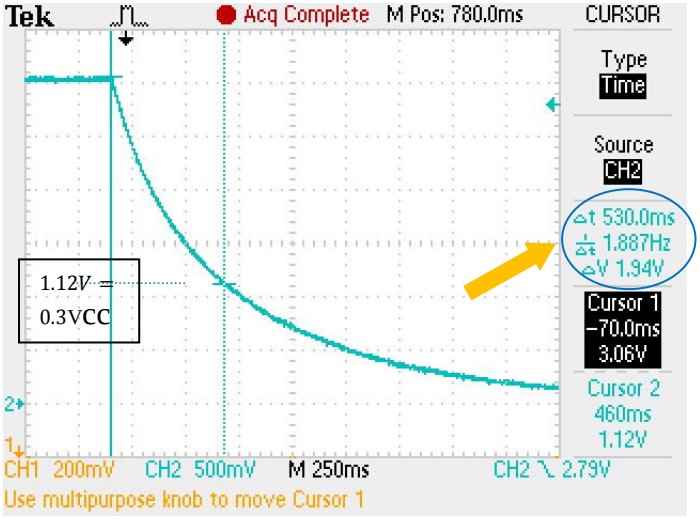


Figure 13: Discharging curve of RC circuit to calibrate the measurement capacitance, as measured

From Figure 13, the time constant is 530 ms, so the precise value of the capacitance is:

$$C = \frac{530\ ms}{1\ KOhm} = 530\ \mu F$$

Once the capacitance is calibrated, we applied the capacitor measurement method to measure total current consumption. Figure 14 shows the electric schema for measuring the total current consumption of sensor nodes using capacitor measurement method.

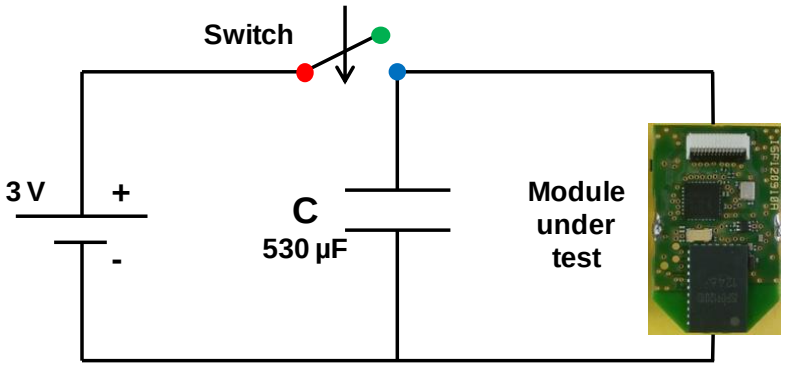


Figure 14: Electric schema to measure the total current consumption of sensor nodes using capacitor measurement method

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2.3.1 Temperature sensor node

Figure 15 shows the measurements of total current consumption of temperature sensor node for the two functioning phases (Phase 1+Phase 2), carried out by the capacitor method for measurement time (Connection Interval) of 1 second.

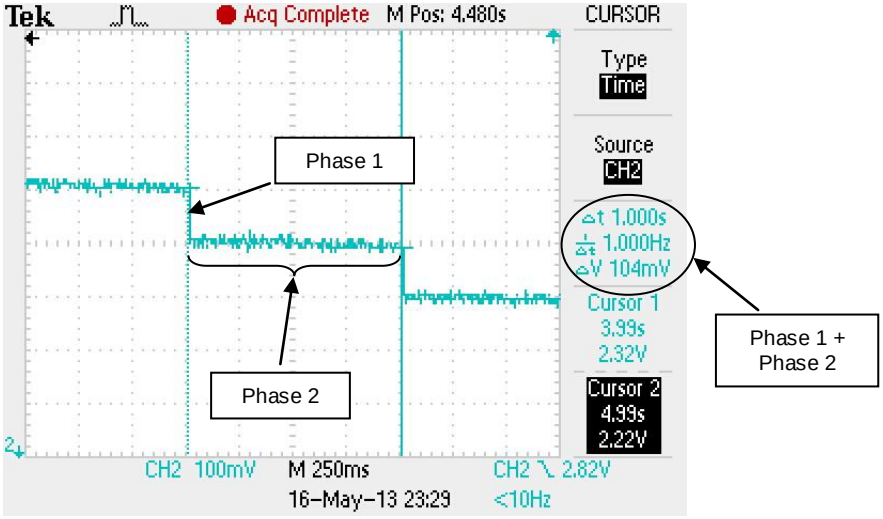


Figure 15: Temperature sensor node: total current consumption measurements, as measured by capacitor method

In these measurements that look like a staircase, the 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).

The total charge consumption of the temperature node sensor for (Connection Interval) ($T_{period} = 1s$), as presented in Figure 15, is of the order of:

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

Figure 16 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 of the order of:

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

This is consistent 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:
$Q_{sensor} = 46.64 - (34.36 + 9.86) = 2.42\ \mu C$.

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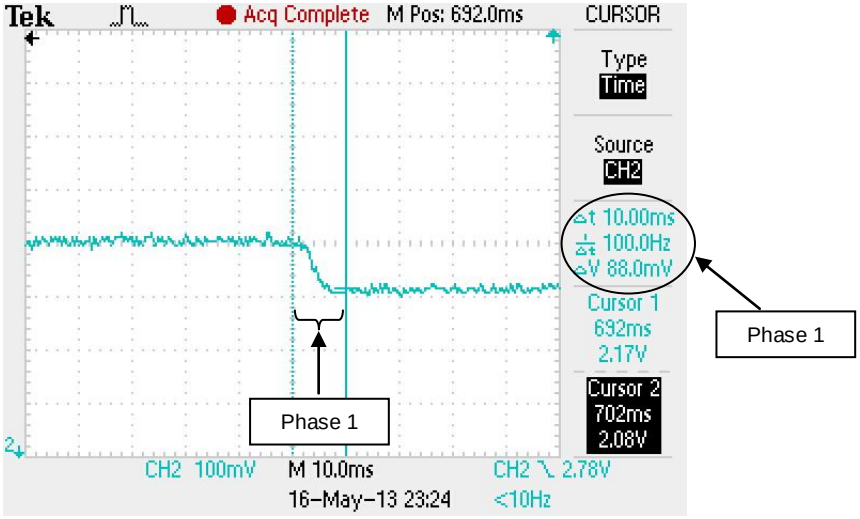


Figure 16: Temperature sensor node: total current consumption measurements during Phase 1, as measured by capacitor method

Figure 17 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 of the order of:

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

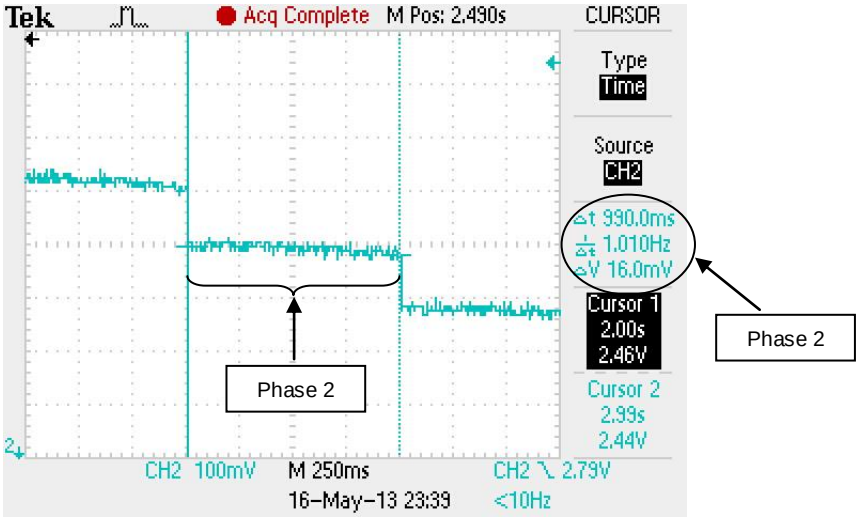


Figure17: Temperature sensor node: total current consumption measurements during Phase 2, as measured by capacitor method

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

$$I_{T_{period}=1s} = \frac{Q_{Phase\ 1} + Q_{Phase\ 2}}{1s} = (46.64 + 8.48)\mu A = 55.12\ \mu A$$

2.3.2 Light sensor node

Figure 18 shows the measurements of total current consumption of light sensor node for the two functioning phases (Phase 1+Phase 2), carried out by the capacitor method for measurement time (Connection Interval) of 1 second.

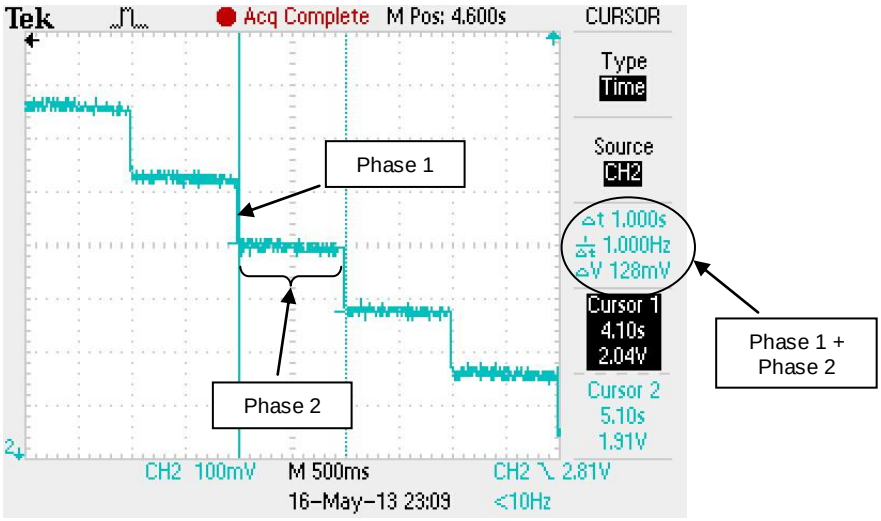


Figure18: Light sensor node: total current consumption measurements, as measured by capacitor method

The total charge consumption of the light sensor node for (Connection Interval) $(T_{period} = 1s)$, as presented in Figure 18, is of the order of:

$$Q_{Phase\ 1+Phase\ 2} = C \times \Delta V = 530\mu F \times 0.128V = 67.84\ \mu C$$

Figure 19 and Figure 20 show the total consumption in Phase 1 and Phase 2, respectively.

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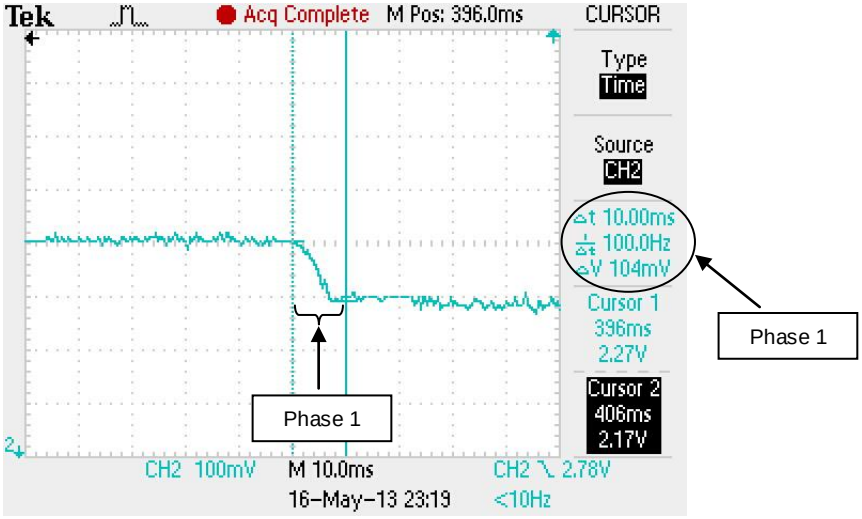


Figure19: Light sensor node: total current consumption measurements during Phase 1, as measured by capacitor method

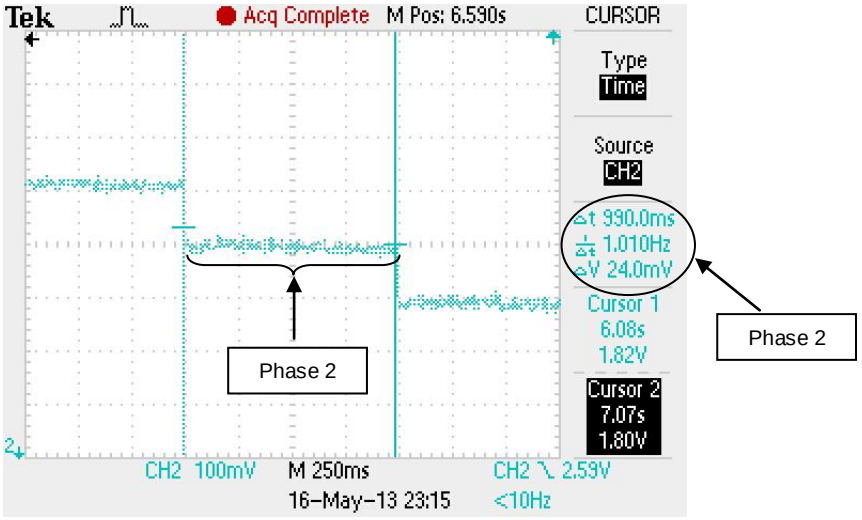


Figure 20: Light sensor node: total current consumption measurements during Phase 2, as measured by capacitor method

According to Figure 19, the total charge consumption of the light sensor node in the communication phase (Phase 1), is about:

$$Q_{Phase\ 1} = 530\mu F \times 0.104V = 55.12\ \mu C$$

This is also consistent with measurements made for the BLE module and the microprocessor by the oscilloscope method (Table 7 and Table 8), where: $Q_{BLE} = 41.25\ \mu C$ and$Q_{\mu P} = 11.7\ \mu C$. The difference between the two measurements is the consumption of the sensing device during the communication phase (Phase 1), so$Q_{sensor} = 55.12 - (41.25 + 11.7) = 2.17\ \mu C$.

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Similarly, according to Figure 20, the total charge consumption of the light sensor node in the Standby-sleep phase (Phase 2), is about:

$$Q_{Phase\ 2} = 530\mu F \times 0.024V = 12.72\mu C$$

So the total average current consumption of the of light sensor node for the period ($T_{period} = 1s$) is of the order of:

$$I_{T_{period}=1s} = \frac{Q_{Phase\ 1} + Q_{Phase\ 2}}{1s} = (55.12 + 12.72)\mu A = 67.84\ \mu A$$

As we have already seen, the current consumption of the light sensor node is higher than the temperature sensor node in the two phases of operation.

For the communication phase (Phase 1), this increase in current consumption of the light sensor node is related to the larger number of bytes to measure and to send. For the Standby-sleep (Phase 2), this increase is due to a higher current consumption of light sensing device compared to temperature sensing device (cf Table 4).

2.3.3 Orientation/Motion sensor node

Figure 21 shows the measurements of total current consumption of orientation/motion sensor node for the two functioning phases (Phase 1+Phase 2), carried out by the capacitor method for measurement time (Connection Interval) of 1 second.

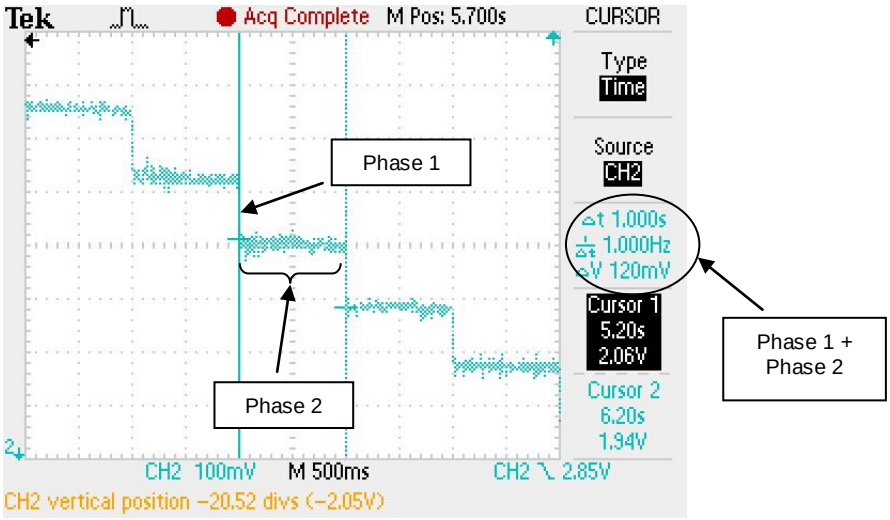


Figure 21: Orientation/Motion sensor node: total current consumption measurements, as measured by capacitor method

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The total charge consumption of the orientation/motion sensor node for (Connection Interval) ($T_{period} = 1s$), as presented in Figure 21, is of the order of:

$$Q_{Phase\ 1+Phase\ 2} = C \times \Delta V = 530\mu F \times 0.120V = 63.6\ \mu C$$

Figure 22 and Figure 23 show the total consumption in Phase 1 and Phase 2, respectively.

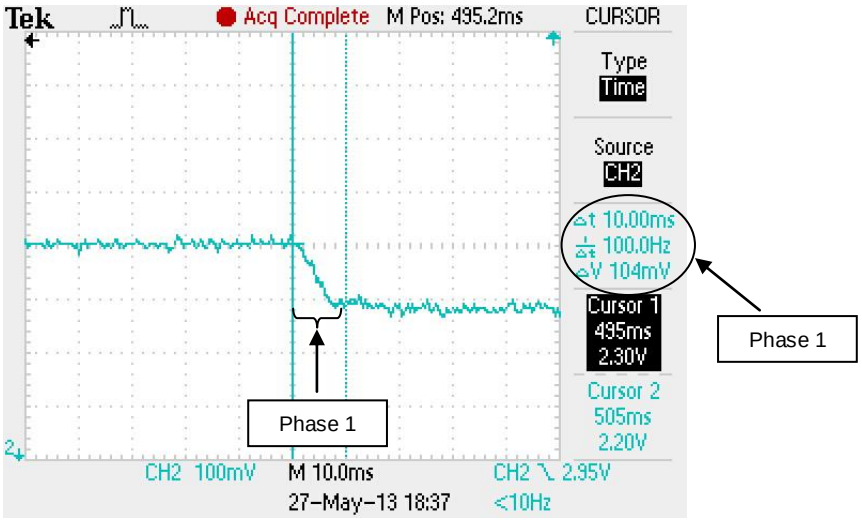


Figure 22: Orientation/Motion sensor node: total current consumption measurements during Phase 1, as measured by capacitor method

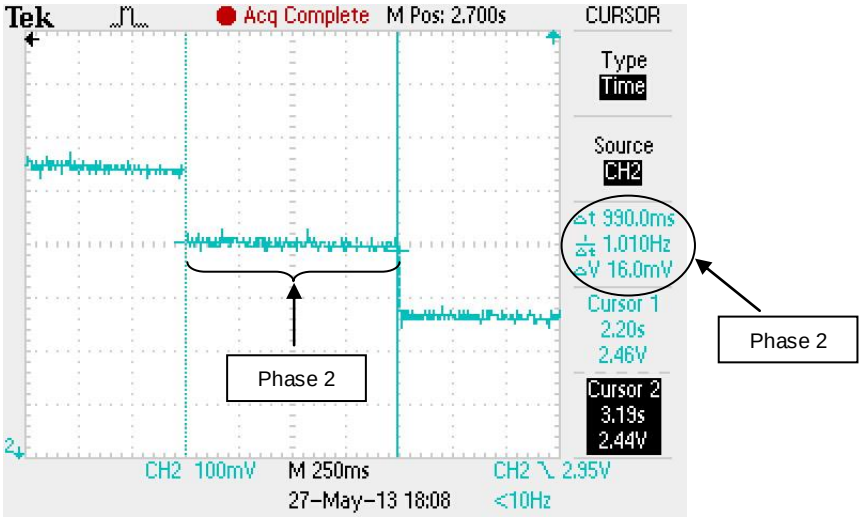


Figure 23: Orientation/Motion sensor node: total current consumption measurements during Phase 2, as measured by capacitor method

According to Figure 22, the total charge consumption of the orientation/motion sensor node in the communication phase (Phase 1), is about:

$$Q_{Phase\ 1} = 530\mu F \times 0.104V = 55.12\ \mu C$$

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This is also consistent with measurements made for the BLE module and the microprocessor by the oscilloscope method (Table 9 and Table 10), where: $Q_{BLE} = 39.88\,\mu C$ and $Q_{\mu P} = 11.56\,\mu C$. The difference between the two measurements is the consumption of the sensing device during the communication phase (Phase 1), so $Q_{sensor} = 55.12 - (39.88 + 11.56) = 3.68\,\mu C$. This difference is higher than that of the light sensor node, because during Phase 1, the current consumption of orientation/motion sensing device for maximum Sampling rate (120 Samples/second) is more than current consumption of light sensing device (cf Table 4).

Similarly, according to Figure 23, the total charge consumption of the orientation/motion sensor node in the Standby-sleep phase (Phase 2), is about:

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

However, during Phase 2, the current consumption of orientation/motion sensing device is lower than that of light sensing device and equal to that of temperature sensing device (cf Table 4).

The total average current consumption of the of light sensor node for the period ($T_{period} = 1s$) is of the order of:

$$I_{T_{period}=1s} = \frac{Q_{Phase\ 1} + Q_{Phase\ 2}}{1s} = (55.12 + 8.48)\mu A = 63.6\,\mu A$$

As we have already seen, the differences in total current consumption of the three sensor nodes are related to characteristics of the used sensing device. In the next paragraph, we present the total consumption measurements results of the three sensor nodes for different measurements times (Connection Intervals).

3. Measurement Results

3.1 Temperature sensor node

Table 11 presents total current consumption measurements of the temperature sensor node, which integrates BLE module designed by Insight SiP, LPC1114FHI33/302 microprocessor and temperature sensing device TMP112. The battery used in this sensor node is 3V coin cell battery CR1632 has a capacity of$140\ mAh$, so a charge capacity of $504\ C$. The autonomy of this sensor node is given by the following equation:

$$Autonomy = \frac{504\ (C)}{Total\ average\ charge\ consumption\ of\ sensor\ node\ (C)} \times Connection\ Interval$$

Measurement specifications for different measurement times (Connection Intervals) are described in Table 11:

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Temperature sensor node				
Connection Interval (ms)	Phase 1 (µC)	Phase 2 (µC)	Average Total Consumption (µC)	Autonomy (year)
1000	46.64	8.48	55.12	0.290
2000	46.64	2×8.48=16.96	63.60	0.503
3000	46.64	3×8.48=25.44	72.08	0.665
4000	46.64	4×8.48=33.92	80.56	0.794

Table11: Temperature sensor node: measurements results

3.2 Light sensor node

Table 12 presents total current consumption measurements of the light sensor node, which integrates BLE module designed by Insight SiP, LPC1114FHI33/302 microprocessor and light sensing device APDS-9300. The battery used in this sensor node is 3V coin cell battery CR1632. Measurement specifications for different measurement times (Connection Intervals) are described in Table 12:

Light sensor node				
Connection Interval (ms)	Phase 1 (µC)	Phase 2 (µC)	Average Total Consumption (µC)	Autonomy (year)
1000	55.12	12.72	67.84	0.236
2000	55.12	2×12.72=25.44	80.56	0.397
3000	55.12	3×12.72=38.16	93.28	0.514
4000	55.12	4×12.72=50.88	106.0	0.603

Table 12: Light sensor node: measurements results

3.3 Orientation / Motion sensor node

Table 13 presents total current consumption measurements of the orientation/motion sensor node, which integrates BLE module designed by Insight SiP, LPC1114FHI33/302 microprocessor and orientation/motion sensing device MMA7660FC. The battery used in this sensor node is 3V coin cell battery CR1632. Measurement specifications for different measurement times (Connection Interval) are described in Table 13:

Orientation/Motion sensor node				
Connection Interval (ms)	Phase 1 (µC)	Phase 2 (µC)	Average Total Consumption (µC)	Autonomy (year)
1000	55.12	8.48	63.6	0.251
2000	55.12	2×8.48=16.96	72.08	0.443
3000	55.12	3×8.48=25.44	80.56	0.595
4000	55.12	4×8.48=33.92	89.04	0.718

Table 13: Orientation/Motion sensor node: measurements results

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4. Model / Measurement Comparison

In this section, we present 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 can calculate the average consumption of each subset, the total consumption and the autonomy of sensor nodes for different Connection Intervals and for different types of batteries.

4.1 Consumption calculating model of temperature sensor node

Table 14 presents the calculating model of total current consumption of temperature sensor node. The specifications of each subset for one measurement per second are described below.

- BLE module (nRF8001) :
  - 1 connection per second,
  - 2 bytes data size,
  - Average consumption = 33.48 uA.

- Microprocessor LPC1114FHI33/302 :
  - 1 connection per second,
  - 2 bytes data size,
  - Average consumption = 15.84 uA.

- Temperature sensing device TMP112 :
  - Measurement time = 26 ms,
  - Average consumption = 2.99 uA.

The total average consumption is around 52.30 uA, which makes an autonomy of 0.31 year using a coin cell battery CR1632 that has a capacity of $140\ mAh$.

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nRF8001 BLE					
Current	(mA)	Time	(us)	Charge (nC	Notes
Imcu_II	3.5	Tstart	1140	3990	Needed for Xtal Startup+ Tpost-processing Radio
Istandby	1.6	Tpre-processing Radio	1200	1920	Tpre-processing Radio
Irx	14.6	TRx for 1 x 2 octets payload	240	3504	Assumes 1 packet with payload of 2 bytes =8 +2 bytes
Itfs	7	Tifs for 1 Rx and 1 Tx packets	100	700	100 us interframe space
Itx	12.7	TTx for 1 Tx packets	250	3175	Assumes 1 packet with payload of 2 bytes
Imcu_host	5	Tstop	3640	18200	Needed to transmit bits to Host processor = house keeping
Total Charge for 2*8 bits received				31489	
Iidle	0.002	Tperiod	993430	1986.86	1 Measurements /second
Total charge per cycle of 1 second				33475.86	
Estimated Average Current			33.48	uA	BLE
Sensor TEMP112					
Ion	0.04	Measurement	26000	1040	26 ms measurement time (conversion time)
Ion	0.04	I2C	60	2.4	Time to send to uP via I2C
Total Charge per measurement				1042.4	
Istandby	0.002	Shutdown	973940	1947.88	Time between measurements (1 Measurements /second)
Total charge per cycle of 1 second				2990.28	
Estimated Average Current			2.99	uA	Sensor
uP LPC1114FHI33/302					
Ion	3.4	I2C	700	2380	I2C Time to communicante to Sensor (read time)
Isleep	2	Waiting time besfore Host	1700	3400	Time before Host
Ion	3.4	uP Host time	1200	4080	Needed to transmit bits
Total Charge per Tx/Rx				9860	
Istandby (Deep-Sleep)	0.006	Tperiod	996400	5978.4	1 Measurements /second
Total charge per cycle of 1 second				15838.4	
Estimated Average Current			15.84	uA	µP
Total estimated current			52.30	uA	cf 52.30 uA due to standby alone
		mAh			Total
Lifetime for CR1632		140	2676.6	hour	
			111.5	day	
			0.31	year	Autonomy

Table 14: Temperature sensor node: Consumption calculating model

4.2 Consumption Calculating model of Light sensor node

Table 15 presents calculating model of total current consumption of light sensor node. The specifications of each subset for one measurement per second are described below.

- Module BLE (nRF8001) :
  - 1 connection per second,
  - 4 bytes data size,
  - Average consumption = 40.10 uA.
- Microprocessor LPC1114FHI33/302 :
  - 1 connection per second,
  - 4 bytes data size,
  - Average consumption = 17.68 uA.

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- Light sensing device APDS-9300 :
  - Measurement time (20 ms ≥ 13.7 ms),
  - Average consumption = 7.95 uA.

The total average consumption is around 65.72 uA, which makes an autonomy of 0.24 year using a coin cell battery CR1632 that has a capacity of $140\ mAh$.

nRF8001 BLE					
Current	(mA)	Time	(us)	Charge (nC	Notes
Imcu_II	3.5	Tstart	1140	3990	Needed for Xtal Startup+ Tpost-processing Radio
Istandby	1.6	Tpre-processing Radio	1200	1920	Tpre-processing Radio
Irx	14.6	TRx for 1 x 4 octets payload	240	3504	Assumes 1 packet with payload of 4 bytes =8 +4 bytes
Itfs	7	Tifs for 1 Rx and 1 Tx packets	100	700	100 us interframe space
Itx	12.7	TTx for 1 Tx packets	252	3200.4	Assumes 1 packet with payload of 4 bytes
Imcu_host	5	Tstop	4960	24800	Needed to transmit bits to Host processor = house keeping
Total Charge for 4*8 bits received				38114.4	
Iidle	0.002	Tperiod	992108	1984.216	1 Measurements /second
Total charge per cycle of 1 second				40098.616	
Estimated Average Current			40.10	uA	BLE
Sensor APDS-9300					
Ion	0.24	Measurement	20000	4800	26 ms measurement time (conversion time)
Ion	0.24	I2C	60	14.4	Time to send to uP via I2C
Total Charge per measurement				4814.4	
Istandby	0.0032	Shutdown	979940	3135.808	Time between measurements (1 Measurements /second)
Total charge per cycle of 1 second				7950.208	
Estimated Average Current			7.95	uA	Sensor
uP LPC1114FHI33/302					
Ion	3.4	I2C	2520	8568	I2C Time to communicante to Sensor (read time)
Isleep	2	Waiting time besfore Host	0	0	Time before Host
Ion	3.4	uP Host time	920	3128	Needed to transmit bits
Total Charge per Tx/Rx				11696	
Istandby (Deep-Sleep)	0.006	Tperiod	996560	5979.36	1 Measurements /second
Total charge per cycle of 1 second				17675.36	
Estimated Average Current			17.68	uA	µP
Total estimated current			65.72	uA	cf 65.72 uA due to standby alone
		mAh			Total
Lifetime for CR1632		140	2130.1	hour	
			88.8	day	Autonomy
			0.24	year	

Table 15: Light sensor node: Consumption calculating model

4.3 Consumption Calculating model of Orientation/Motion sensor node

Table 16 presents calculating model of total current consumption of orientation/motion sensor node. The specifications of each subset for one measurement per second are described below.

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- Module BLE (nRF8001) :
  - 1 connection per second,
  - 3 bytes data size,
  - Average consumption = 38.79 uA.
- Microprocessor LPC1114FHI33/302 :
  - 1 connection per second,
  - 3 bytes data size,
  - Average consumption = 17.54 uA.
- Orientation/motion sensing device MMA7660FC :
  - Measurement time (15 ms ≥ 8.5 ms),
  - Average consumption = 6.40 uA.

The total average consumption is around 62.72 uA, which makes an autonomy of 0.25 year using a coin cell battery CR1632 that has a capacity of 140 mAh.

nRF8001 BLE					
Current	(mA)	Time	(us)	Charge (nC	Notes
Imcu_II	3.5	Tstart	1140	3990	Needed for Xtal Startup+ Tpost-processing Radio
Istandby	1.6	Tpre-processing Radio	1200	1920	Tpre-processing Radio
Irx	14.6	TRx for 1 x 4 octets payload	240	3504	Assumes 1 packet with payload of 3 bytes =8 +3 bytes
Itfs	7	Tifs for 1 Rx and 1 Tx packets	100	700	100 us interframe space
Itx	12.7	TTx for 1 Tx packets	251	3187.7	Assumes 1 packet with payload of 3 bytes
Imcu_host	5	Tstop	4700	23500	Needed to transmit bits to Host processor = house keeping
Total Charge for 3*8 bits received				36801.7	
Iidle	0.002	Tperiod	992369	1984.738	1 Measurements /second
Total charge per cycle of 1 second				38786.438	
Estimated Average Current			38.79	uA	BLE
Sensor MMA7660FC					
Ion	0.294	Measurement	15000	4410	26 ms measurement time (conversion time)
Ion	0.294	I2C	60	17.64	Time to send to uP via I2C
Total Charge per measurement				4427.64	
Istandby	0.002	Shutdown	984940	1969.88	Time between measurements (1 Measurements /second)
Total charge per cycle of 1 second				6397.52	
Estimated Average Current			6.40	uA	Sensor
uP LPC1114FHI33/302					
Ion	3.4	I2C	2400	8160	I2C Time to communicante to Sensor (read time)
Isleep	2	Waiting time besfore Host	0	0	Time before Host
Ion	3.4	uP Host time	1000	3400	Needed to transmit bits
Total Charge per Tx/Rx				11560	
Istandby (Deep-Sleep)	0.006	Tperiod	996600	5979.6	1 Measurements /second
Total charge per cycle of 1 second				17539.6	
Estimated Average Current			17.54	uA	µP
Total estimated current			62.72	uA	cf 62.72 µA due to standby alone
		mAh			Total
Lifetime for CR1632		140	2232.0	hour	
			93.0	day	Autonomy
			0.25	year	

Table 16: Orientation/Motion sensor node: Consumption calculating model

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4.4 Model / Measurements comparison

Table 17, 18 and 19 respectively presents model / measurements comparison of the total current consumption and the autonomy of temperature, light and orientation / motion sensor nodes for different Connection intervals.

Temperature sensor node				
Connection Interval (ms)	Total Consumption "Model" (µC)	Total Consumption "Measurements" (µC)	Autonomy "Model" (year)	Autonomy "Measurements" (year)
1000	52.30	55.12	0.31	0.29
2000	62.30	63.60	0.51	0.50
3000	72.30	72.08	0.66	0.67
4000	82.30	80.56	0.78	0.79

Table 17: Temperature sensor node: Model/measurements comparison

Light sensor node				
Connection Interval (ms)	Total Consumption "Model" (µC)	Total Consumption "Measurements" (µC)	Autonomy "Model" (year)	Autonomy "Measurements" (year)
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	0.64	0.60

Table 18: Light sensor node: Model/measurements comparison

Orientation/motion sensor node				
Connection Interval (ms)	Total Consumption "Model" (µC)	Total Consumption "Measurements" (µC)	Autonomy "Model" (year)	Autonomy "Measurements" (year)
1000	62.72	63.60	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

Table 19: Orientation/Motion sensor node: Model/measurements comparison

From these three tables, we can find that the calculating 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) 7.5 ms to 4000 ms announced in the specifications of temperature, light and orientation/motion sensor nodes (cf Table 1).

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