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Sleep Modes and Power Consumption of a XBee

Metropolia University of Applied Sciences

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Abstract

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The goal of the project was to build an embedded system and to measure difference in energy consumption between normal mode and sleep mode to prove the efficient reduction in consumption. The system was built with Xbee wireless modules and programmed with mbed.

After measuring the current during sleep mode phase, the study concludes there is great conservation of power consumption in comparison to normal phase. It is suggested appliances should use sleep mode to optimize power consumption.

Keywords: power consumption, sleep mode, Xbee technology, wireless module, embedded system.

Contents

1 Introduction

In today's world, power consumption is one of the main concerns in electrical fields. With the amounts of electrical devices being used, it is important to keep energy consumption as low as possible. The easiest way is shut down all the unnecessary appliances when they are not in use, but a lot of time there are devices that must stay awake and cannot be shut down. To solve this problem, many companies nowadays have been manufacturing sleep modes for their devices to reduce the power used.

The paper aim to implement an embedded system with XBee and measure the system's power consumption in normal state and sleeping state. A detailed study about the subject is provided in below sections. Thesis also describes the materials and methods used to configure the system. In the practical study, sleep mode was active but XBee woke up occasionally. After measuring with and without activating sleep modes, power consumption is calculated and compared to show the efficiency.

The discussion resolves around the result numbers to confirm the differences, addresses problems occurred during the experiment and gives out suggestions for future research in this area.

2 Theoretical Study

2.1 Power Management

2.1.1 Power Consumption

Power consumption refer to the amount of electricity consumed per unit of time. To calculate power consumption, the most common used formula is multiplying its wattage by the number of operational hours.

$$E_{(kWh/day)} = P_W \times t_{\left(\frac{h}{day}\right)} / 1000_{\left(\frac{W}{kW}\right)} \qquad (1)$$

To calculate the electric power in watt (P), the formula is:

$$P = V \times I \qquad (2)$$

For an appliance to function properly, it needs power supply to all the components. The exact power consumption of a module in practice usually varies based on numerous reasons. Energy used always exceeds energy needed since there is some amount of power losing through many factors. Due to this knowledge, designing a power efficient system is very complex and difficult.

2.1.2 Sleep Modes

In previous section, it has been illustrated the importance of power management in designing system. Not all parts of the system need to maintain power supply all the time. There are several occasions where an appliance is not active and cannot be shut down at the same time. To solve this problem, most devices are programmed with different sleep modes to conserve the power as much as possible.

Sleep mode is a low power operation for modules when not in use. During this phase, power is cut to unneeded system while other components can still stay active. Thus, the system can optimize and reduce the amount of power consumption. Another use of sleep mode is when the main power source is not available; therefore, to increase battery life, the device stops operating and can only be woken up by instructions or after a certain period.

2.2 Current Measurement

Current is the flow which carries electrons in a complete electrical circuit. The measurement of the rate of current past a point in a circuit is called current measurement, and the unit of measurement is Ampere (A). Current sensing is defined as techniques used to measure electric current. Its role is to monitor "how much" current is flowing in the circuit for power management, or to alert when the current is "too much" (Yarborough 1, 2015). As a result, it is important to choose suitable methods with appropriate design to carry out the measurement process.

There are three types of measurement methods:

- Resistive (direct)
- Magnetic (indirect)
- Transistor (direct)

These methods can also be classified into two main categories: direct and indirect. Each methods have their own advantages and disadvantages based on different conditions that are critical to the reliability of the application. In this research, current sense resistor method is being used for the practical study.

2.2.1 Current Sense Resistor

This is the current measurement method which uses current sense resistors also known as shunt resistors. It belongs to the resistive methods. Shunt resistors are devices to gauge the current flow for measuring output voltage. Since the method is direct, the current sense resistor introduced into the current conducting path needs to be measured, which generates a substantial amount of power loss (Ziegler et al. 2, 2009). This power conversion provides voltage signal to be measured and therefore, the current can easily be determined by calculating via Ohm's Law.

$$I = V/R \quad (3)$$

The current sense resistors can be inserted into either the forward (high-side sensing) or return path (low-side sensing). If it is used in return path, the resistor is placed between the load and the ground in figure 1, which simplifies the interface to the voltage-reading analog. However, this topology results in problems with load integrity and control since the circuit connected after current sense resistor are not related to ground anymore. In practice, many installations require a neutral wire to carry the load current back to the source due to this design. Placing resistance between the load and the ground also negatively impacts the dynamics and control. For these reasons, low-side sensing approach is barely used in real world problem. (Schweber, 2018)

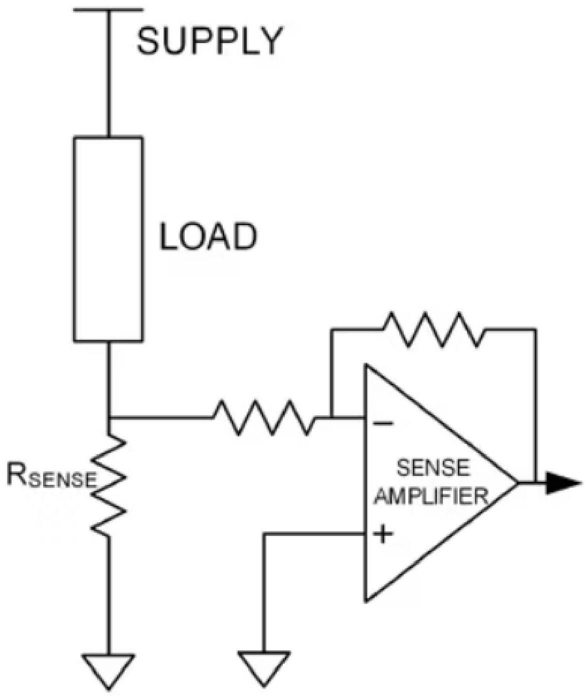


Figure 1. Low-side sensing topology (Schweber, 2018)

High-side sensing on the other hand is more commonly acceptable. In this design, current sense resistor is placed between the power rail and the load in figure 2; thus, it has a potential above ground. While this solves problems created by ungrounding the load, it complicates the amplification stage since the circuitry that senses voltage across the resistor could not be ground, which leads to employing a differential or instrumentation amplifier. (Schweber, 2018)

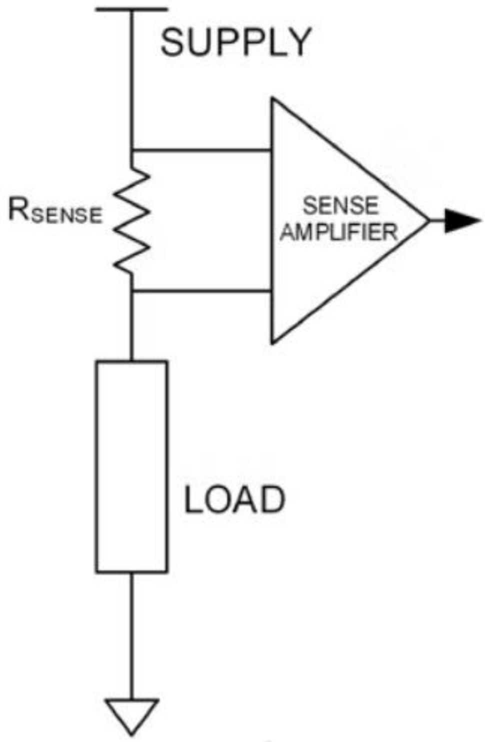


Figure 2. High-side sensing topology (Schweber, 2018)

Not only having benefits of simplicity and linearity, but this method is also cost-effective with stable temperature coefficient of resistance (TCR) and accurate wideband measurement. Nevertheless, there are some limitations as well. When the power loss is too high, it would be difficult to measure high currents. Overcurrent can permanently damage the resistor, and power dissipation must be controlled carefully. (Ziegler et al., 2009)

2.2.2 Hall Effect Device

Hall effect method was found out in 1879, and named after its discoverer, Edwin Hall. It is a magnetic method to measure current. A magnetic field includes two crucial factor, flux density (B) and polarity. The hall effect device is a rectangular current-carrying conductor that allows current passing continuously passing through itself. When it presents in a magnetic field, a force caused by the magnetic flux lines affecting on the conductor which changes the flow of charge carriers. Hall found out if the conductor is placed perpendicular to the magnetic field, electrons flowing within conductor were pulled to one side (Jost, 2019). This is shown in figure 3 below. As both magnetic field and current flow exists, the interaction between the magnetic field and the charge causes the distribution of current to change, and therefore, creates the Hall voltage (Yarborough 3, 2015).

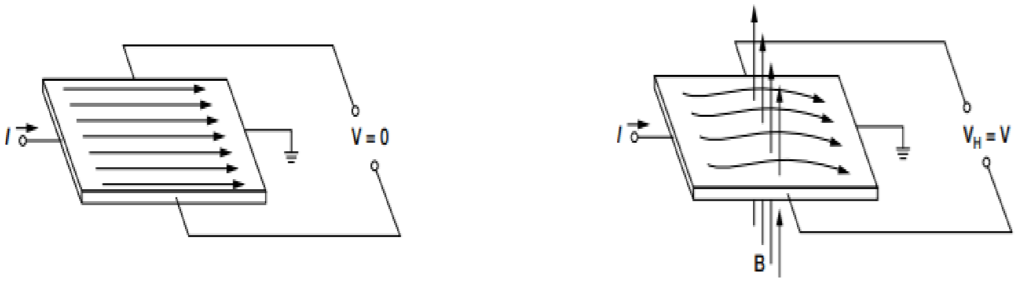


Figure 3. Hall effect principle without and with magnetic field (Yarborough 3, 2015)

This current sensing method has two main topologies: open-loop and closed-loop. In an open-loop, the device employs a magnetic transducer to create a voltage proportional to the sensed current (Milano, 2018). This is shown in figure 4. The current flows through the conductor inside a magnetic core and creates a magnetic field inside the core. This field can be measured by Hall effect device placed in the core air gap (Arar, 2021). When the IC is over temperature due to non-linearity or drift in sensitivity, it produces error.

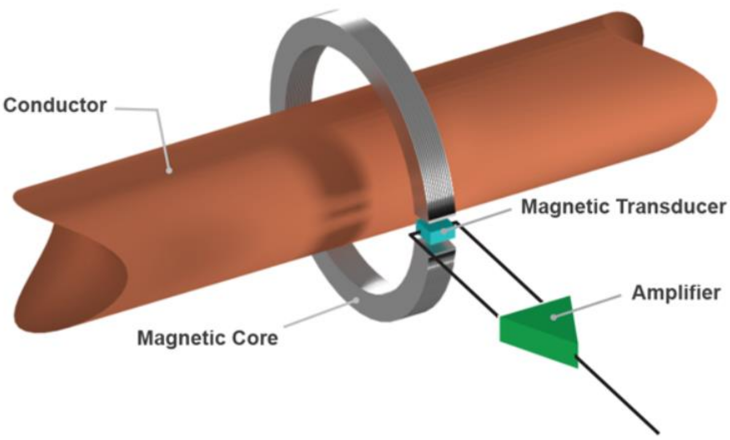


Figure 4. Open-loop topology (Milano, 2018)

Closed-loop configuration on the other hand is more complex, but it can eliminate these errors associated with Hall effect device IC. In this approach, the sensor uses a coil actively driven by the current sensor IC to produce a magnetic field that opposes the field produced by the current in the conductor (Milano, 2018). This is shown in figure 5. Since the secondary coil is driven by high-power amplifier, the closed-loop architecture requires larger area, higher power consumption and as well higher price (Arar, 2021).

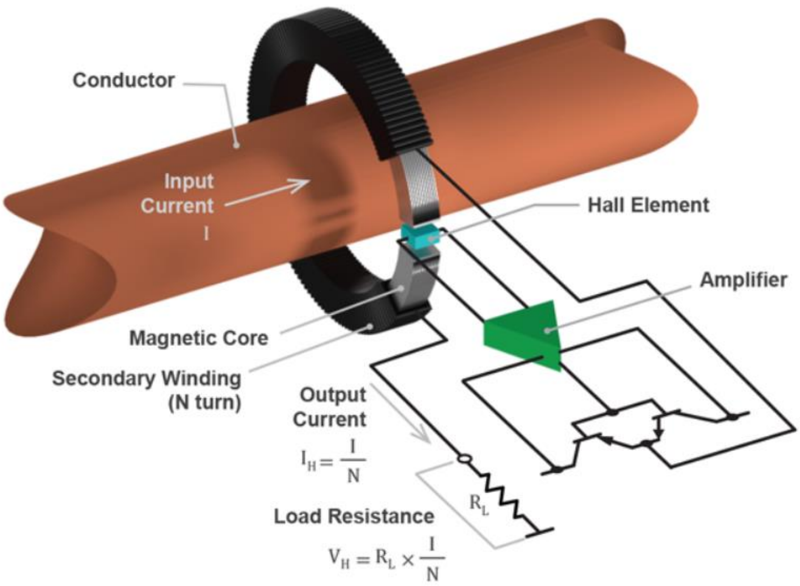


Figure 5. Closed-loop topology (Milano, 2018)

Hall effect sensor is one of the most popular magnetic field sensors. It has many advantages, including capability of measuring large currents with low power dissipation (Yarborough 3, 2015). Since this an indirect method, the approach provides higher safety due to galvanic isolation between sensor and the measured current. However, this approach faces numerous problems as well. When AC currents is in high frequency, the core material may be overheated. Distinct thermal drift must be compensated, and overcurrent introduces magnetic offset had to be eliminated with a degaussing cycle (Ziegler et al. 20, 2009). Limited bandwidth and high cost are also main limitations to their use.

2.2.3 Ratio Metric

Ratio metric belongs to transistor group of current measurement methods. It is also known as current sense MOSFETs. The MOSFET consists lots of parallel transistor cells, and small portion of them are used to connect to the common gate and drains which is illustrated in figure 6. This action creates another isolated transistor. When the transistor is on, the current passing it will be ratio comparable to the main current through other cells (Yarborough 4, 2015). Typically, a ratio metric device would be a strain gauge output pressure sensor, and the output sensitivity is the ratio between output and input supply voltage.

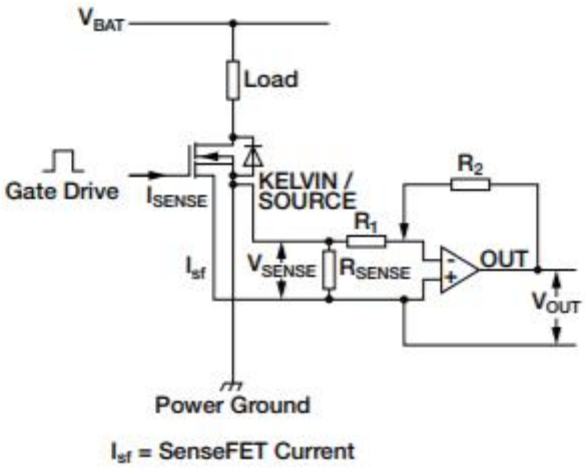


Figure 6. Ratio metric design (Yarborough 4, 2015)

The accuracy of this method is moderate; depends on the transistor products, the range can vary from 5% to 20%. Thus, it is not applicable for current control application that requires high accuracy measurement. Overcurrent and short circuit, however, is suitable with this method. Ratio metric is also preferable by design engineers when they need to utilize the same power supply without having to introduce another precision reference to support a regulated transducer. Some other advantages of this approach are small size and reasonable cost.

2.3 Sensors

Sensors are devices, modules and subsystems that measure physical input from surrounding environment. These inputs could be heat, motion, pressure, light or any environmental phenomena. The information on the device then be sent to other electronics such as computer processor to convert into data that human or machine can understand. Some frequent uses of sensors in daily life are temperature measurement, touch-sensitive function, and sound detection. A microphone, for example, is a sensor for converting sound energy to electrical signal.

There are multiple types of sensors for different purposes, but in general the signals of electronic sensors can be put into two categories: analog and digital. Analog signals are continuous and be represented in form of line waves, while digital signals are discrete and be represented in form of square waves. Both signals are compared in figure 7. The range of analog signals are not set while digital signals are limited from 0 to 1. During the record process, analog signals keep the information as received, but digital signals convert it to binary data. Human voice is an example of analog signals, and data transmission in a computer is digital signals.

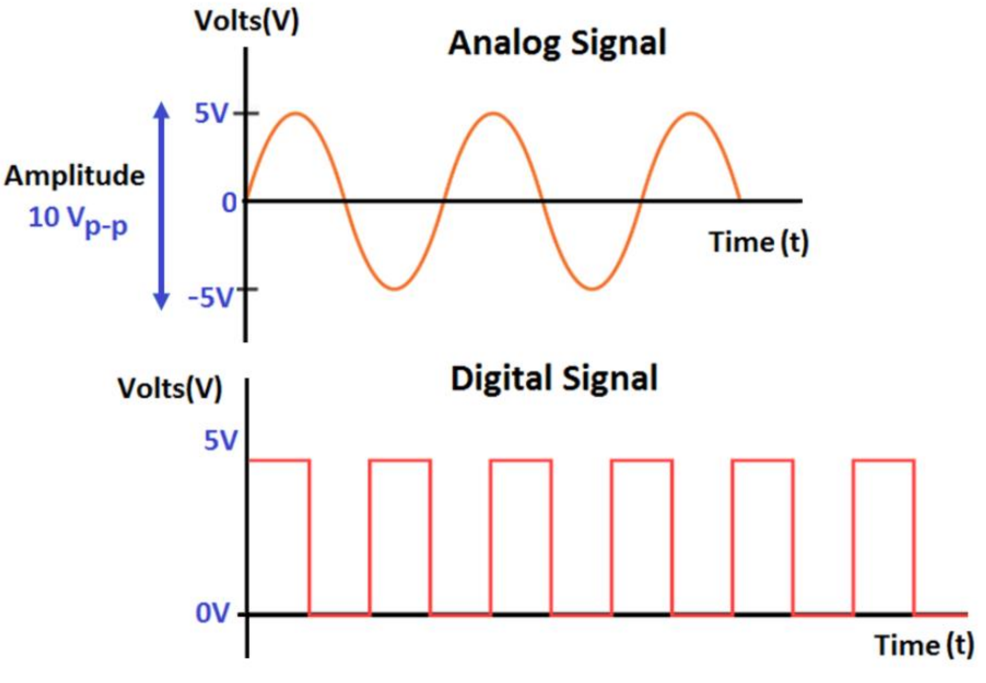


Figure 7. Comparison between Analog Signal and Digital Signal (Rao, n.d.)

Due to their natural characteristics, both types of signals have advantages and disadvantages. Theoretically, analog signals are more precise than digital signals and they are easier to process. However, the accuracy of analog signals might be affected by noise or during data transmission stage. It is best suited for any representation that requires refined information. Digital signals on the other hand are stable and do not be affected while transmit data even over long distance. The information is more secure since it can be encrypted and compressed. Therefore, the cost and amount of bandwidth for digital communication is generally higher than analog communication (Analog Signals vs. Digital Signals, n.d.).

Sensor works with analog signal, but it can be converted to digital format in the sensor or later in the microcontroller. The output of the sensor can be analog or digital. Some of the following rules should be kept in mind when choosing suitable sensors for the project:

- Stability: Different circumstances can lead to different problems during the recording and transmitting progress. Therefore, the sensors have to be able to complete the jobs under given environment.
- Sensitivity: To have accurate data, the sensors must be sensitive as much as possible. However, they should be insensitive to other properties that might encounter during the record process.
- Simplicity: Sometimes an application does not need complex built system, even if it results in more precise data. Complexity often comes with higher cost, so it should be considered during the architecture design phase.

3 Hardware

3.1 System and Materials

The system consists of two components: receiver part and transmitter part. The receiver contains a wireless module while the transmitter carries a wireless module, a microcontroller and a sensor. This is illustrated in figure 8 below.

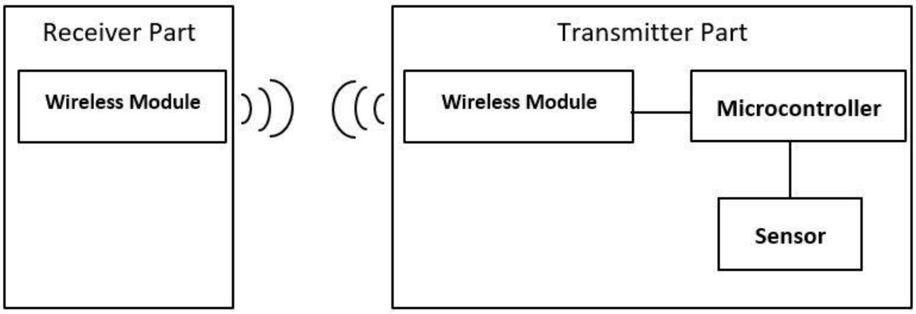
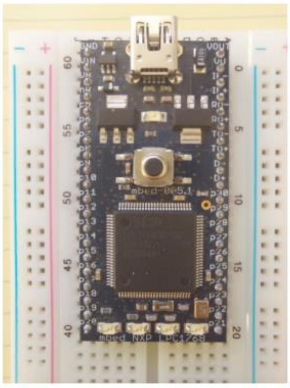


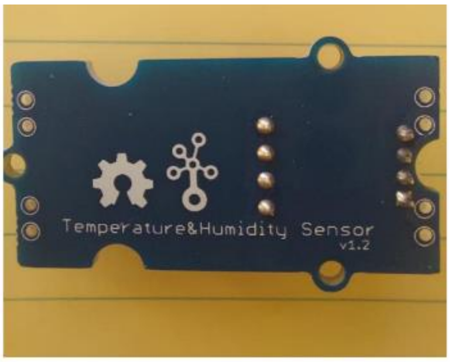
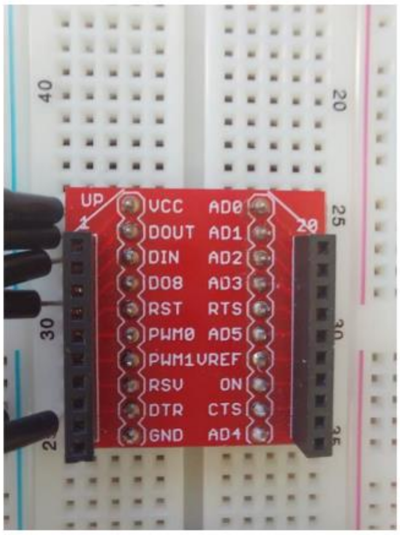
Figure 8. Diagram of the system

XCTU is used to configure Xbee. The microcontroller is programmed with Mbed Online Compiler in C++ language.

The full list of materials used for the system is given in table 1 below.

Table 1. Hardware materials used

Name	**Image**	**Amount**
Xbee 3 RF Module – PCB Antenna		2
Grove Xbee Carrier		1
mbed NXP LPC 1768		1

Temperature and Humidity Sensor		1
2.54mm to 2mm adapter		1

3.2 Xbee Technology

Xbee is a group of RF modules by Digi International that are common for cellular modems and RF modules. They provide simple and reliable tools for wireless connections in an IoT system. The environment of Xbee also bring about different network management tools and IoT gateways. Their modules are configurable, supporting multiple protocols, sharing common pin layout and are available in compatible footprint. Due to these reasons, Xbee technology is commonly used by engineers worldwide.

According to Digi Xbee reference manual, the table below shows the general power requirements for Xbee 3 RF Module.

Table 2. Power requirements for Xbee 3 RF Module (Digi Xbee 3 RF Module Hardware Reference Manual 29, 2022)

Specification	**Xbee 3**	**Xbee 3 - PRO**
Adjustable power	Yes	
Supply voltage	2.1 – 3.6 V	
Operating current (transmit, typical)	40mA @ +3.3V, +8dBm	135mA @ +3.3V, +19dBM
Operating current (receive, typical)	17mA	
Power-down current, typical	2µA @ 25° C	

For Xbee 3 RF Module, there are four basic sleep behaviours as below:

- Pin sleep
- Cyclic sleep
- Cyclic sleep with pin wake-up
- MicroPython sleep (with optional pin wake-up)

Based on the above manual, the sleep mode can be operated in two ways which are recognized via their names: pin-controlled sleep modes and cyclic sleep modes. Also following the manual, this mode is always disabled by default.

In pin-controlled sleep modes, quiescent power is minimized. Because of the voltage level activation of the mode, Xbee module enters sleeping whenever the 3.3 voltage is connected to Xbee's Sleep_RQ pin (Sleep_RQ is asserted or pulled high). During pin sleep, the device does not react to any serial or RF activities. To wake up from pin sleep mode, Sleep_RQ is woken up from the pin sleep mode by via de-asserting after CTS goes low.

Cyclic sleep modes on the other hand give devices the ability to occasionally check the RF data. After being configured to go to sleep, the module wakes up once per cycle to check data from a coordinator, then sends a poll request to the coordinator at a specific interval. If there is no UART activity detected and the coordinator does not respond with queued data, device will immediately enter sleeping. Otherwise, the device will wake up. Cyclic sleep modes could also work with an addition of pin-controlled wake up at the remote device for event-driven communication.

3.3 Microcontroller

Microcontroller is an integrated circuit designed to control specific tasks of embedded system. It is a small simple microcomputer which is able to perform operations of small features belonged to larger components. For this study, we are using mbed NXP LPC1768 microcontroller, which is ARM Cortex-M3 based microcontroller possessing a great degree of integration while consuming little energy. Its limiting values is represented in table 3.

The 3.3 V ($V_{DD(3V3)}$) pins of the LPC17xx power the I/O pads, while the $V_{DD(REG)(3V3)}$ pins power the on-chip voltage regulator, which in turn powers the CPU and most peripherals. Depending on the application, there are two options to manage power consumption in mbed NXP LPC1768 microcontroller

The first approach regards power consumption as unimportant and connects the $V_{DD(3V3)}$ and $V_{DD(REG)(3V3)}$ pins. As a result, it can be operated with a single 3.3 V for the pads, CPU, and peripherals. This technique is straightforward yet a drawback can be realized: it cannot power down the I/O pad ring while maintaining the CPU and peripherals.

The second approach requires two 3.3 V power supplies: one for the I/O pads $V_{DD(3V3)}$ and another for the CPU $V_{DD(REG)(3V3)}$.. The I/O pad power supply can be turned off while the CPU and peripherals remain operational because the on-chip voltage regulator is powered independently of the I/O pad ring.

Table 3. Limiting values of LPC17xx (LPC1769/68/67/66/65/64/63 Product data sheet 45, 2020)

Symbol	**Parameter**	**Conditions**	**Min**	**Max**	**Unit**
$V_{DD(3V3)}$	supply voltage (3.3 V)	external rail	-0.5	+4.6	V
$V_{DD(REG)(3V3)}$	regulator supply voltage (3.3 V)		-0.5	+4.6	V
V_{DDA}	analog 3.3 V pad supply voltage		-0.5	+4.6	V
$V_{i(VBAT)}$	input voltage on pin VBAT	for the RTC	-0.5	+4.6	V
$V_{i(VREFP)}$	input voltage on pin VREFP		-0.5	+4.6	V
V_{IA}	analog input voltage	on ADC related pins	-0.5	+5.1	V
V_I	input voltage	5 V tolerant digital I/O pins; $V_{DD} \geq 2.4$ V	-0.5	+5.5	V_I
		$V_{DD} = 0$ V	-0.5	+3.6	

		5 V tolerant open-drain pins PIO0_27 and PIO0_28	-0.5	+5.5	
I_{DD}	supply current	per supply pin	-	100	mA
I_{SS}	ground current	Per ground pin	-	100	mA
I_{latch}	I/O latch-up current	$-(0.5V_{DD(3V3)}) < V_I < (1.5V_{DD(3V3)})$; $T_j < 125$ °C	-	100	mA

LPC17xx has four operating modes to cut down power: sleep mode, deep-sleep mode, power-down mode, and deep-power down mode. In order to control the clock rate of the CPU, it is necessary to modify clock sources, adjust PLL parameter, and/or change the CPU clock divider parameter. On the other hand, Peripheral Power Control provides for the stoppage of each on-chip peripheral clocks and the adjustment of energy usage by removing all unnecessary dynamic power for the operation in the peripheral. During these modes, integrated PMU (Power Management Unit) can change internal regulators by itself to reduce power usage.

In sleep mode, the clock to the core is paused. The processor only needs to reenable the clock to the Arm core to resume from sleep mode. During this process, unless there is an interrupt or a reset, all executions of instructions are suspended. Peripheral functions can continue operating and may create interruption to let the execution of the processor continue.

Deep-sleep mode of LPC17xx is activated by turning off the oscillator and stopping receiving internal clocks of the chip. To terminate or resume normal operation, the device can either reset or interrupt certain parts that can operate without clocks. If the internal RC (IRC) was operated before the LPC17XX activates deep-sleep mode, it could be resumed after going through 4 cycles. If the main external oscillator was run, the code execution would continue after going through 4096 cycles. Since all unnecessary operation of the chip is interrupted, power consumption in deep-sleep mode has a shallow value.

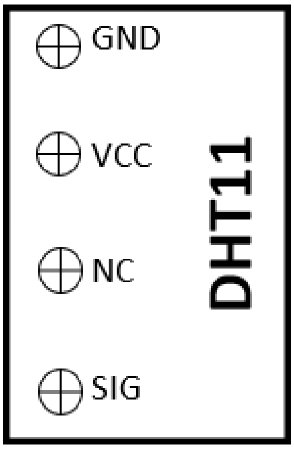
Power-down mode is almost the same as deep-sleep mode. However, the difference between these two modes is in the power-down mode, LPC17xx also cut down the energy to IRC oscillator and the flash memory. If the IRC was operated before the LPC17XX activates power-down mode, it needs 60 us to restart IRC. After going through 4 IRC cycles, the code execution can be continued if this code comes from SRAM. The Flash wake-up timer has to count 4 MHz IRC clock cycles to create the 100 □s flash activated time. When it runs out of time, the device will access the flash. While this action reduces more energy usage, it must wait for reactivation of flash operation before running execution in the flash memory.

The deep power-mode can only be done from the RTC block. Power in the entire chip is shut off except RTC module and the RESET pin. To reactivate from deep power-down mode, LPC17xx can be used RESET pin or an alarm match event of the RTC.

4 Methods and Configuration

4.1 Sensor Interface

Figure 9 shows the design of the sensor used in this project.



Figur. Grove temperature and humidity sensor DHT11

The sensor has 4 pins:

- 1 pin (VCC) is connected to the 3.3 V power supply or Pin 40 (V_{out}) of mbed.
- 1 pin (GND) is connected to ground or Pin 1 (GND) of mbed.
- 1 pin is connected to Pin 18 of mbed to receive data from the sensor.
- 1 pin is not connected to anything else.

To check whether the sensor is working properly, figure 10 shows a short code that is used to print the values to the terminal.

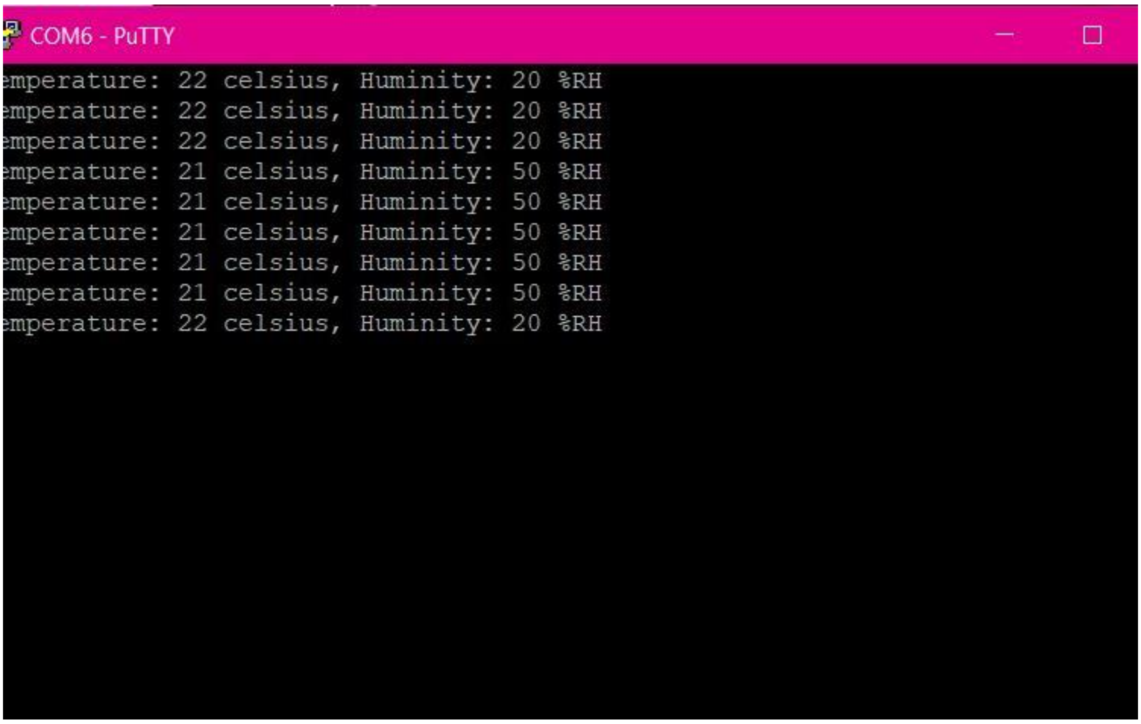


Figure 9. Sensor testing execution

4.2 Xbee Interface

Figure 11 shows the design of XBee module used in this project.

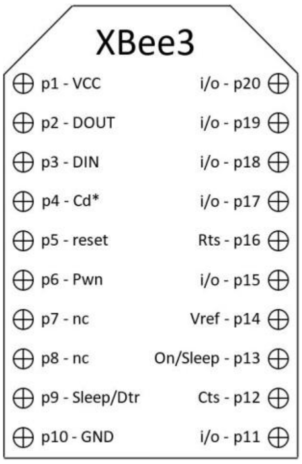


Figure 10. XBee 3 wireless module

Pin 1 and Pin 10 (VCC and GND) of Xbee are connected to Pin 40 and Pin 1 (V_{out} and GND) of Mbed or connected directly to the power supply. Pin 2

(DOUT) of XBee is connected to Pin 10 (Rx) of mbed. Pin 3 (DIN) of Xbee is connected to Pin 9 (Tx) of mbed. Pin 5 (RST) is connected to Pin 11 of mbed.

For sleep mode, Pin 9 (DTR/Sleep_RQ) is connected to Pin 8 of mbed. Pin 12 (CTS) is connected to Pin 20. Additionally, Pin 13 (ON_Sleep) of Xbee can be connected to a LED light to specify awake and sleep status of Xbee. If Pin 13 equals 1 and light turns on, Xbee is awake. If Pin 13 equals 0 and light goes off, Xbee has entered sleep mode.

There are two modes for Xbee to communicate to each other: transparent mode and API mode. Here, we are using transparent mode for configuration. The settings of this mode include:

- CH: Channel (same on both side)
- ID: Network PAN ID (same on both side)
- CE: Device Role (the Xbee in transmitter part is “End Device” while the Xbee in receiver part is “Coordinator”)
- MY and DL

The networking on transmitter part and receiver part are given in figure 12 and figure 13.

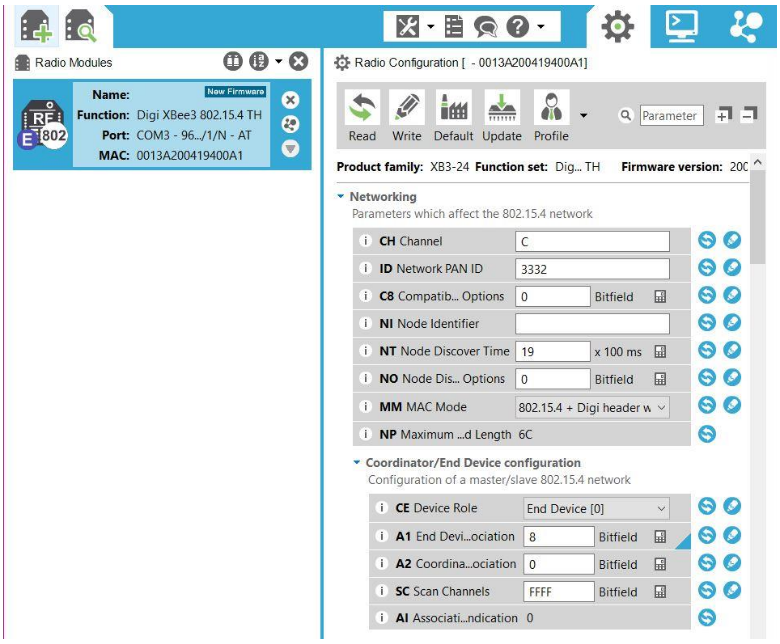


Figure 11. Networking on transmitter part

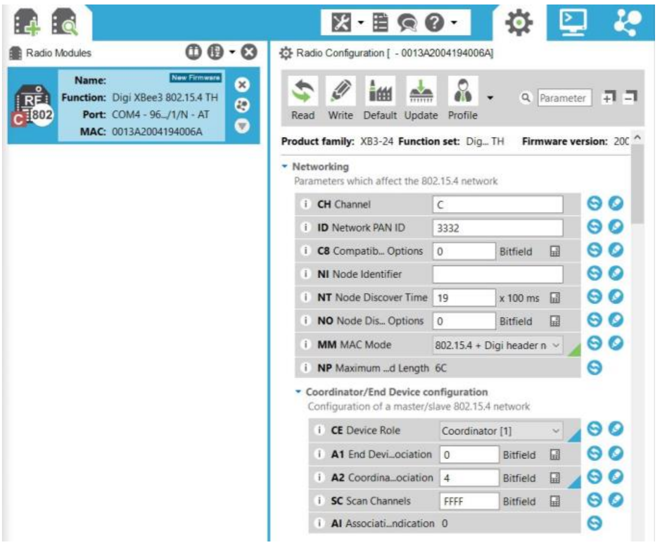


Figure 12. Networking on receiver part

For the two Xbee's to communicate, the MY of "End Device" is the DL of "Coordinator" and vice versa.

Sleep mode settings for "End Device":

- SM = 5 (Cyclic Sleep with Pin Wake-up)
- SP: 3E8 (equals to 10s)
- ST: BB8 (equals to 3s)
- D7: CTS flow control
- D8: DTR/Sleep_Rq
- D9: Awake/nSleep indicator

The sleep settings and UART pin configuration on end device is shown in figure 14 and figure 15.

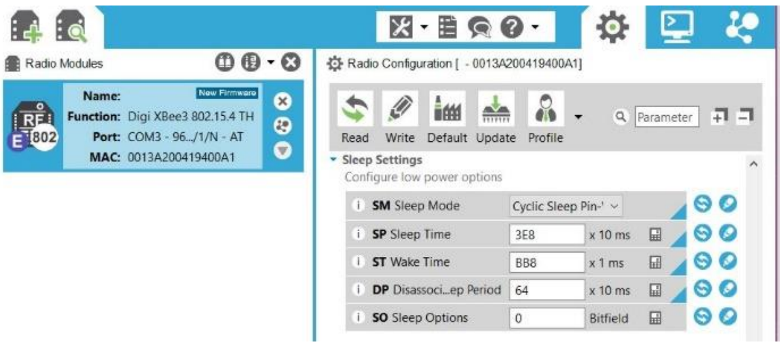


Figure 13. Sleep settings for end device

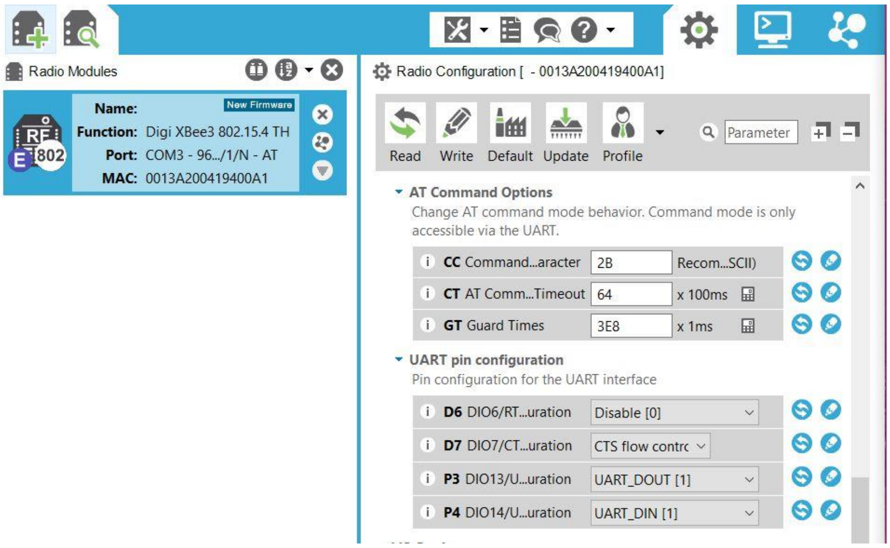


Figure 14. UART pin configuration on end device

Figure 16 represents the I/O settings of the device.

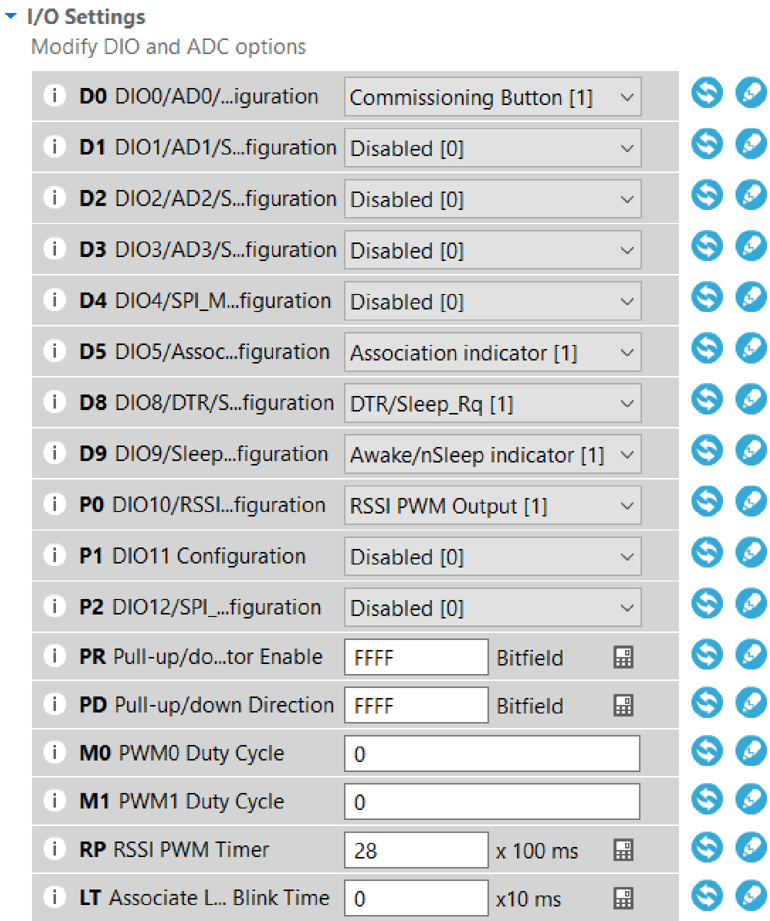


Figure 15. I/O settings

In the setting of the “Coordinator”, sleep mode is changed to No Sleep as seen in figure 15.

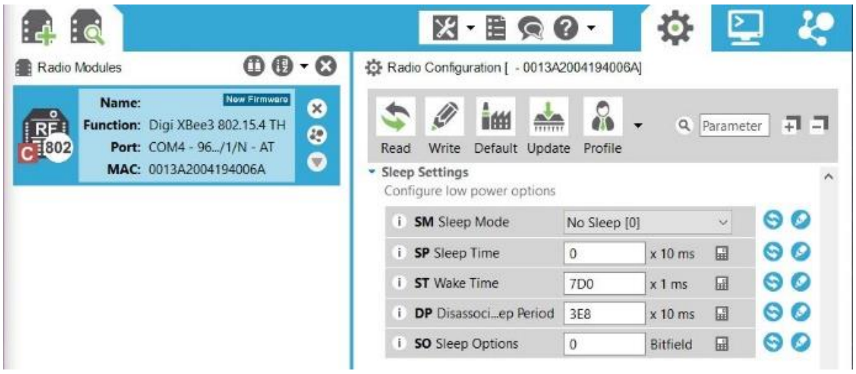


Figure 16. Coordinator sleep settings

4.3 Current Measurement with Current Sense Resistor

A 1 Ohm resistor R_{shunt} is connected between Pin 1 (VCC) of Xbee and Pin 21 (VOUT, 3.3 V) of microcontroller, then use a multimeter to measure the amperage of R_{shunt}. The design of the circuit is shown in figure 16. Since the current in a series circuit is the same through any component, it is also the current of Xbee.

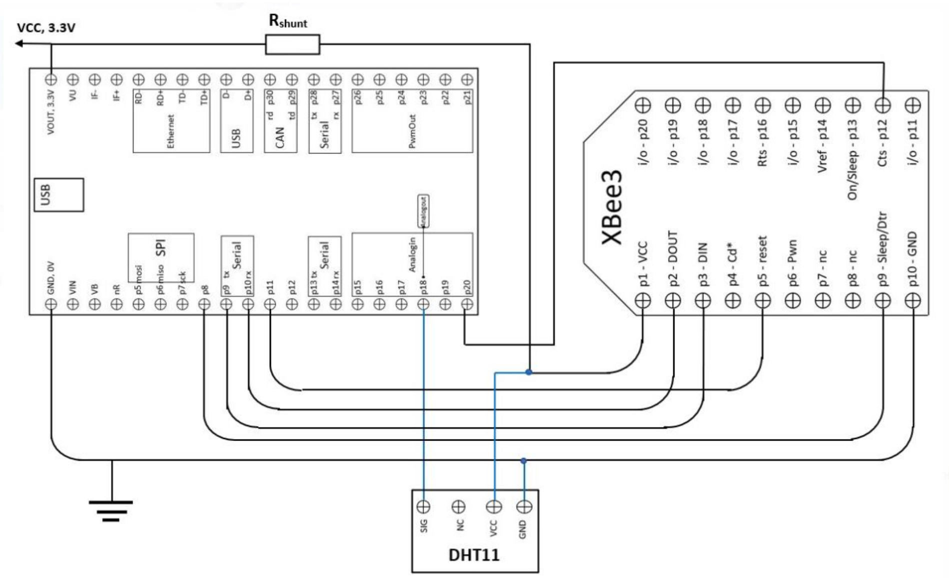


Figure 17. Diagram of the circuit

5 Results and Discussion

A LED is connected to pin ON/Sleep (pin 13) of Xbee to determine whether the system is active or in sleep modes. When the light turns on, the system is awake. When the light turns off, the system enters sleep mode.

Multiple attempts to measure voltage waveform have been made by using different equipment, but unfortunately the measurement returned with negative value. This is shown in figure 19.

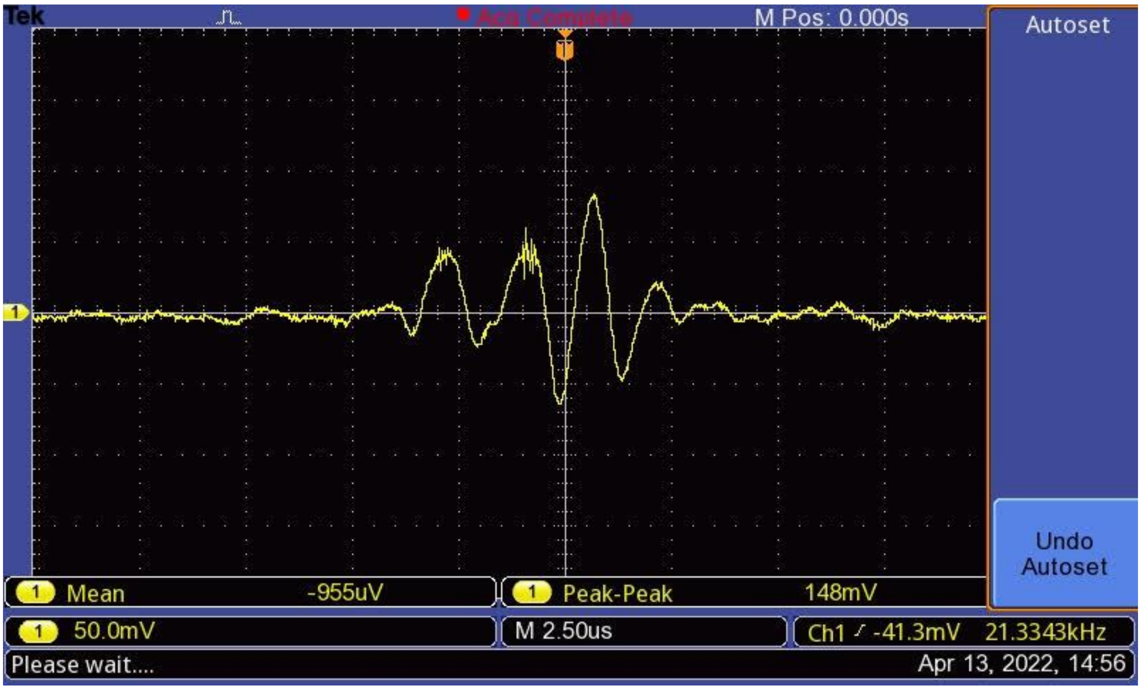


Figure 19. Failed measurement

However, thanks to supervisor Janne Mäntykoski who has done his measurement independantly with similar system, the project is proved to work properly as intended. Based on figure 18 the circuit should have a sensor current going through the shunt resistor, but for simplicity he only set up a simulation for sensor instead of using a real sensor. The records should not affect the final result. Below is his recorded graph of transmission start, sleep and noise.

Figure 20 shows the transmission start and figure 21 shows sleep and noise measurement.

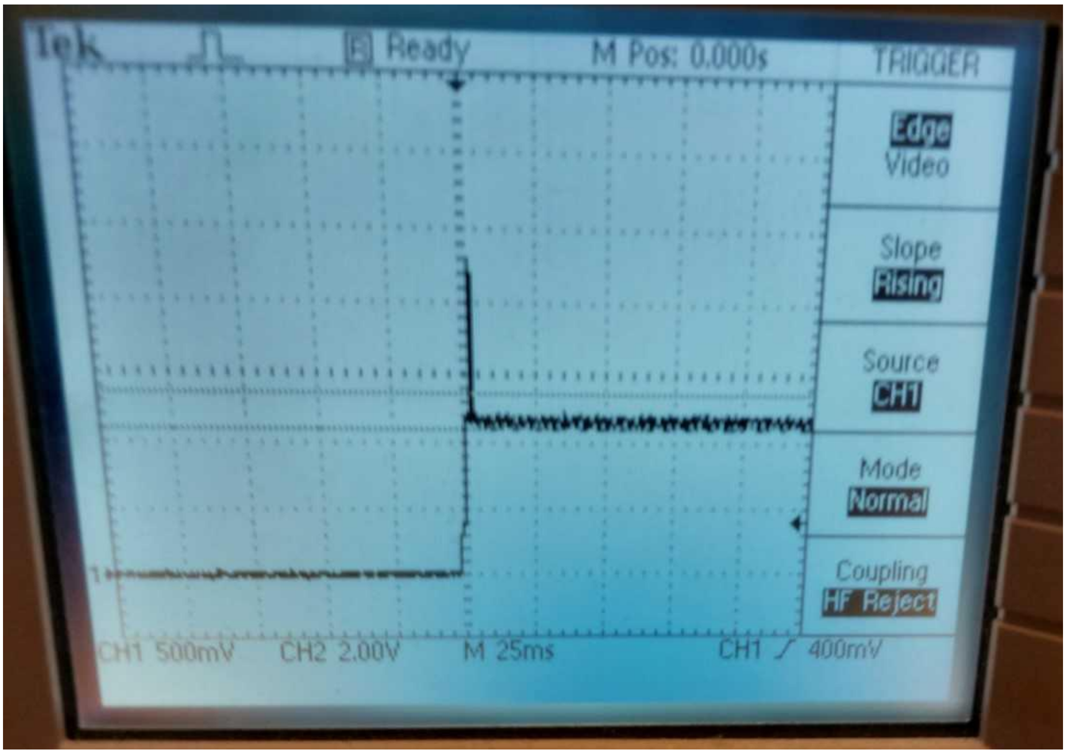


Figure 20. Transmission start (Janne Mäntykoski)

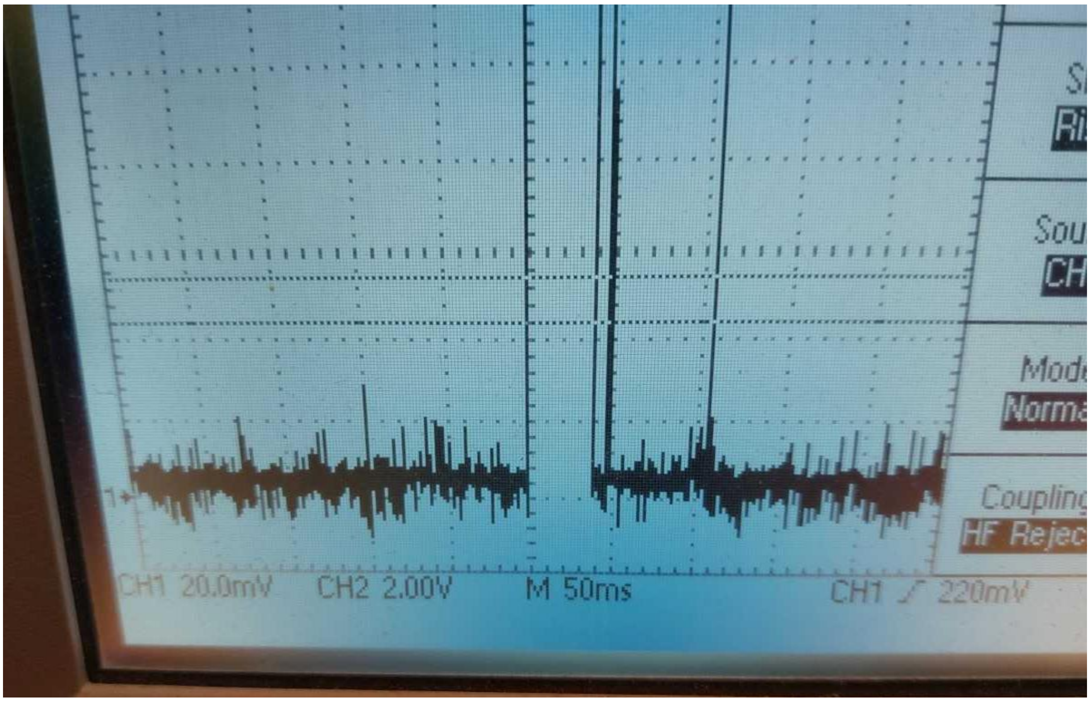


Figure 21. Sleep and noise (Janne Mäntykoski)

Table 4. Voltage of each stage

State	**Voltage**	**Voltage of R_{shunt}**
Sleep	20 mV	0.4 mV
Transmit	1.96 V	39.2 mV
Receiver	1.12 V	22.4 mV

Table 4 shows the voltage measured from Xbee during different stages. The result voltage values need to be divided by 50 to get the voltage of R_{shunt}, as the instrumentation amplifier INA121 with gain 50 is used to connect with R_{shunt} to amplify the measured value.

$V_{total} = 3.3V$

Sleep mode: $V_{shunt} = 0.4\ mV$

- ⇨ $V_{Xbee} = V_{total} - V_{shunt} = 3.3\ V - 0.4mV = 3.29996\ V \quad (4)$
- ⇨ $I = I_{shunt} = I_{Xbee} = \frac{V_{shunt}}{R_{shunt}} = \frac{0.4\ mV}{1.1\Omega} = 0.363\ mA \quad (5)$
- ⇨ $P_{Xbee} = V_{Xbee} \times I = 3.29996\ V \times 0.363\ mA = 0.0012\ W \quad (6)$

Therefore, when Xbee in in sleep mode, power consumption is $0.0012\ W$.

Applying formula from (4), (5) and (6) the power consumption of each stage is listed in table 5.

Table 5. Power consumption of each stage

State	Voltage of R_{shunt}	Current of Xbee	Power consumption
Sleep	0.4 mV	0.363 mA	1.2 mW
Transmit	39.2 mV	35.636 mA	116.2 mW
Receiver	22.4 mV	20.364 mA	66.7 mW

Except for the current measured during the sleep state, the measurements of current from table 5 are almost the same as those from table 2. The reason for such difference is due to the noise during measuring.

From the results, it can be established that Xbee used a very small amount of energy when entering sleep mode in comparison to its normal state. By calculation, the system could save up to $115\ mW$.

As mentioned earlier my circuit cannot be measured by oscilloscope; therefore, I decided to directly measure the current of R_{shunt} via a multimeter. Figures 22 the measurement results of the current of R_{shunt} at sleep state.

Figure 22. The measured current of R_{shunt} at sleep state

By Multimeter measuarement, the current runs through Xbee in my circuit during sleep mode is 0.5 uA.

$V_{total} = 3.3V$

Sleep mode: $I_{shunt} = 0.5\ uA$

- ⇨ $I = I_{shunt} = I_{Xbee} = 0.5\ uA$ (5)
- ⇨ $V_{Xbee} = V_{total} - V_{shunt} = 3.3\ V - 0.5\ uA\ x\ 1.1\ \Omega = 3.2999995\ V$ (4)
- ⇨ $P_{Xbee} = V_{Xbee} \times I = 3.2999995\ V \times 0.5\ uA = 0.00165\ mW$ (6)

My thesis still has a limitation which is a unexpected result of the measurement of my circuit. I and my supervisor cannot find out the reason for this problem, even though we tried many ways such as changing the component to check if there are any broken components. I still need further research to come up with a reasonable explanation.

6 Conclusion

Power consumption has already become a major concern to the world. Governments and organizations are investing in finding methods of decreasing total energy used without affecting the general use of appliances. This study has proved that the implementation of Xbee wireless module' sleep mode could reduce a large amount of power consumption. It would greatly affect the total energy used of the device.

The only drawback is due to error in measuring voltage waveform, which remains unsolvable. However, the supervisor of this project was able to output correct measurement with similar system, thus it could be used to prove the credibility of the practical study.

Since this project only tested pin sleep mode and cyclic sleep mode of Xbee wireless module, a suggestion for future research is to measure differences between different sleep modes for optimization and practical use. Future research could also go into details about the conditions and circumstances that should be take into consideration when implement different sleep modes.

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