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<p>The project aimed to design a system that consumed power as optimized as possible. The main components of the system included two Xbees, an Arduino Micro; otherwise, there were also an LED and a resistor that supported the current measurement.</p> <p>In the built electronic circuit, two Xbee devices transmitted and sent data by wireless communication under the same radiofrequency. Additionally, those two Xbee modules used serial communication to connect with a PC and an Arduino Micro.</p> <p>To fulfill the goal of the project, an Xbee module that was connected with an Arduino Micro was set up in the sleep mode. When no data transmission, it went to sleep, then woke up periodically and by a pin controlling as well. This helped to save power consumption for the device. Moreover, current measurement methods were studied and applied in this project.</p>	
Keywords	Embedded System, Microcontroller, ZigBee Technology, Arduino, Power Consumption, Sleep Modes

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1 Introduction

Electric energy consumption is the actual energy demand which is made on the existing electricity supply. There are many statistical reports about the amount of electricity consumption around the world, it has continued to go up rapidly years by years. Therefore, power consumption optimization is a crucial issue because it is a part of the environment protection battle.

In the electronic field, power consumption is also an important issue. Power consumption always should be used optimally to generate several effects. It helps the battery life of hardware to last longer and to maintain the data transmission stable as well.

In this project, a system was designed consisting of wireless modules (Xbees) and an Arduino Micro. A programming environment was utilized in the project to support the programming of system functions. The main purpose of this project was to design a small embedded system so that the power consumption is used as optimized as possible.

2 Theoretical Study

An embedded system is an electronics system that includes software and hardware integrated to perform a particular function of the system. An embedded system uses a Microcontroller or Microprocessor which are designed to perform a specific task. However, embedded systems can work as independent systems, or they can be a part of any large system. Typical examples of the embedded systems are for example fire alarms, smart homes, IoT systems, etc.

Nowadays, embedded systems have become more popular because of their characteristics and advantages. In the system, it is quite often set up with a device that consumes a small amount of energy. This is a bonus point to improve the green environment. Moreover, the system is also considered as a low-cost and easy-to-customize system. That is the reason why it is applied in several fields of our life.

2.1 Power Consumption and Sleep Modes

2.1.1 Power Consumption

Power consumption is defined as the amount of used energy from electrical equipment per unit time, which is usually measured in watts (W) or kilowatts (kW). There is no equipment working with 100% efficiency, and the energy needed is always less than the energy used by equipment, since power is wasted as vibrations, heat, or electromagnetic radiation. Theoretically, power consumption is just the operating current multiplied by the voltage. This becomes a difficult calculation because of the voltage changing and loading conditions when batteries are used to discharge. [1.]

In that case, energy consumption is calculated to measure how much energy is consumed from the battery to complete a specific task. Energy consumption is the power consumption multiplied by the number of usage hours per day [2].

$$E_{(kWh/day)} = P_{(W)} \times t_{(h/day)} / 1000_{(W/kW)} \quad (1)$$

Nowadays, suppliers often give product datasheets that have information about power consumption for different modules and operating conditions for the Microcontroller Unit (MCU).

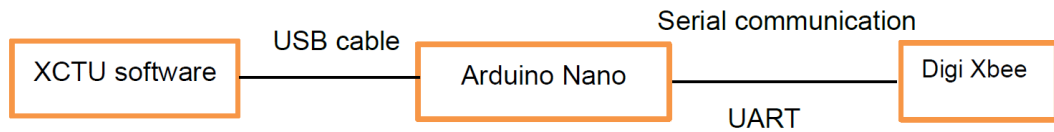


Figure 2: End Device circuit (Receiver part)

In this situation from the receiver part (end device), sleep mode is applied for Xbee to optimize the amount of power consumption. When it is activated, one Xbee goes to sleep in a period of time that is set up in XCTU software. Then it will be awake again when the data transmission is detected. This can make sure that the power in the device is always maintained, the data transmission is not interrupted.

2.3 Current Measurement

The intensity or rate of flow of an electric charge is defined as an electrical current. Several methods are used to measure electric current, current sensing is a kind of popular solution in electrical engineering. Current sensing measurement is essential because of two main reasons. It shows how much current flows in a circuit, and also determines if it is a fault condition for the circuit. A signal is provided to shut down the application when the current is over the safe limits. Magnitude, bandwidth, accuracy, or isolation are requirements of choosing a current sensing method. It is divided into two major groups: direct and indirect methods. In the direct method, it is connected directly to the measured circuit and measurement components are exposed to the line voltage.

For example, there is a parallel circuit as in figure 3 below. The current is 5A, there are three resistors, value 5Ω, 6Ω and 10Ω respectively. The voltage drop across a resistor is similar to the voltage drop across all resistors.

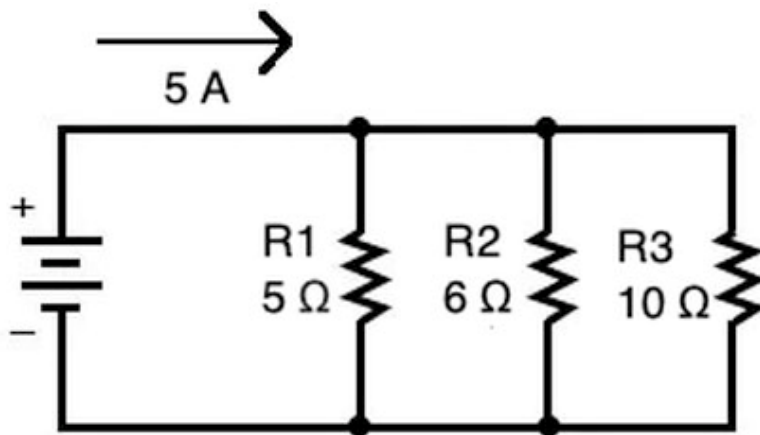


Figure 3: A parallel circuit [4]

The combined resistor is calculated by the formula:

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \quad (2)$$

$$\frac{1}{R_{total}} = \frac{1}{5\Omega} + \frac{1}{6\Omega} + \frac{1}{10\Omega}$$

$$\rightarrow R_{total} = 2.14\Omega$$

$$\text{The voltage drop is calculated by Ohm's Law: } V = I * R \quad (3)$$

$$\rightarrow V = 5A * 2.14\Omega = 10.7V$$

In a serial circuit, the voltage drop across a resistor is different from the voltage drop of a serial circuit. Figure 4 is an example of a serial circuit with a 3A current, three resistors, value 3Ω, 10Ω, and 15Ω respectively.

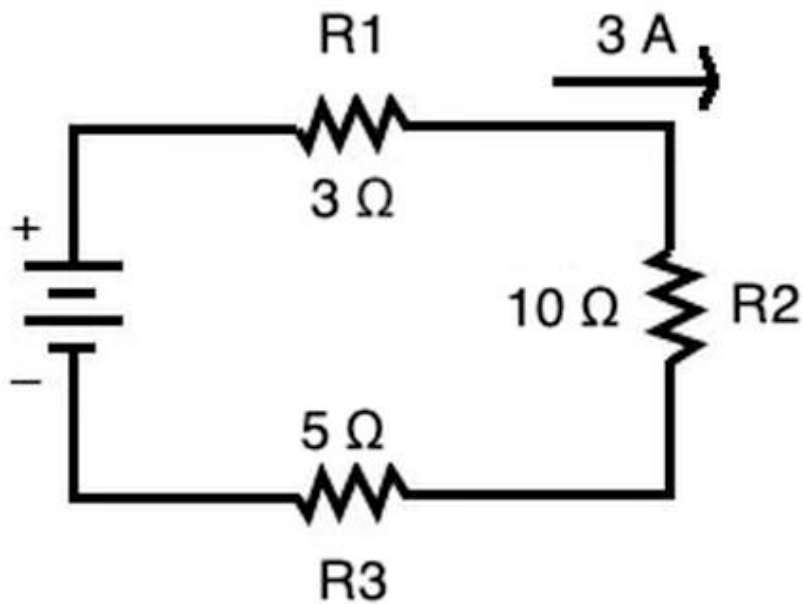


Figure 4: A serial circuit [4]

The voltage drop across each resistor by Ohm's Law:

$$V_1 = R_1 * I = 3\Omega * 3A = 9V$$

$$V_2 = R_2 * I = 10\Omega * 3A = 30V$$

$$V_3 = R_3 * I = 5\Omega * 3V = 15V$$

The voltage drop circuit is the sum of the voltage drop across each resistor.

$$V = V_1 + V_2 + V_3 \quad (4)$$

$$\rightarrow V = 9V + 30V + 15V = 54V$$

Therefore, the voltage drop is calculated by different methods in different situations.

2.3.1 Current Sense Resistors

Current sense resistors are components detecting and converting current to a measured output voltage. These low-value and high-power resistors are utilized for minimizing power consumption. In a circuit, they are placed on the conduction path between the power source and the load (figure 5). A typical resistance value of a current sense resistor is in the range of ohms. Basically, current sense resistors have similar working principles as standard electrical resistors, however, they aim for monitoring purposes.

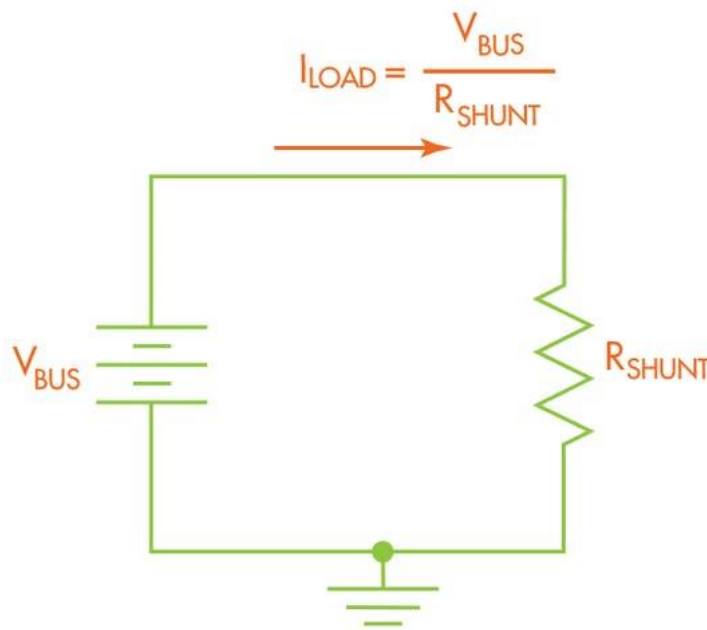


Figure 5: A shunt resistor in the circuit [5]

When choosing a current sense resistor, a voltage drop is a concerning issue. Because of the resistor's place in the circuit, it affects current flow causing a small amount of power dissipation. This much of power is converted into heat.

Besides, there are advantages and disadvantages of current sense resistors. Low cost and accurate wideband measurement are plus points to select them for designing circuits. However, as mentioned above, power dissipation is an important problem that must be controlled. That is why choosing the best ohmic value is a useful solution. The value should be balanced, not too low, not too high. If it is too low, noise issues and resolution will influence accurate measurement. If it is too high, there is wasted power converted into heat, and voltage regulation lost.

2.3.2 Inductor DC Resistance

The DC resistance (DCR) of an inductor represents the amount of resistance of an inductor for DC signals with frequencies of 0Hz [6]. DC signals are allowed by inductors to pass through without any impediment of the passing of high-frequency signals. The DC current is used to measure the DC resistance of an inductor. DC current flows through the inductor, therefore, the resistance is calculated from the current and the voltage in the circuit by the formula $R = V / I$.

The value of resistance of the coil is related to the wire's length, and this also depends on the inductance value of the inductor. Therefore, low-value inductors offer low resistance. The DCR of an inductor often has a small value, typically ranging from less than 1/100 of 1Ω to about 3 – 4Ω [7]. In a datasheet, the DCR number is just a maximum rating. That means that it is basically a maximum resistance that is contained.

When applying this method, zero cost is one advantage. On the other hand, low accuracy factor and very poor TCR create drawbacks for this current measurement. The temperature coefficient of resistivity (TCR) of copper is approximately 3900 ppm, it is considered as a high value. In this case, the resistance value increases by 39% for a 100°C above room temperature. [8.] Therefore, it has to be adjusted to become an acceptable current measurement. Compared to a sense resistor method, this method has the benefit to increase the power supply efficiency and eliminate the sensing resistor power loss.

2.3.3 Current Transformer

A current transformer is a machine working based on the transformation principle, from a high value to a proportional lower value. A current transformer includes an iron core with a primary and a secondary winding which are wound around. The primary winding is connected with a load in series, and the actual current is carried to the load through it. The secondary winding is connected to a measuring device with many turns, they are proportional to the current flowing through a primary winding. [9.] Figure 6 shows detail about the structure of a current transformer.

When in the primary winding there is an alternating current flowing through, at the same time alternative magnetic flux is produced, then brings the alternating current in the secondary winding. Hence, the current in the primary winding is dependent on the current flowing in the primary winding. The current transformer is applied in short circuit conditions because of a small load impedance.

This indirect current measurement method is lossless as there are pretty little resistive losses while the current passes through the windings, but a small amount of power is still lost. This is a benefit of this method compared to others.

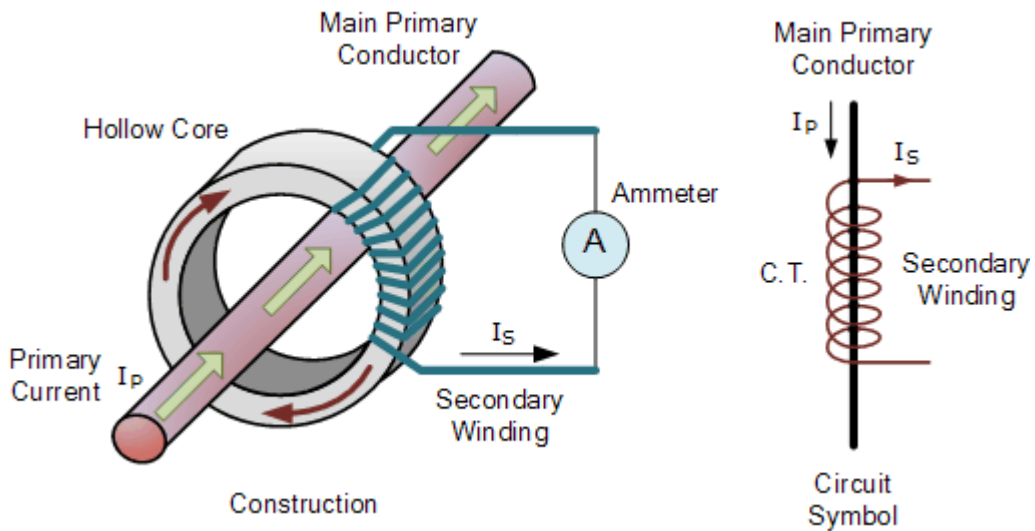


Figure 6: Current Transformer [10]

3 Hardware

3.1 Arduino

3.1.1 Arduino IDE

Arduino is known as an open-source platform that is utilized to build electronics projects. It includes both a physical circuit board and software, that is Arduino IDE. IDE stands for Integrated Development Environment. [11.]

Arduino IDE software is mainly used for programming in computers, then the code is compiled and uploaded in Arduino boards. Nowadays Arduino IDE becomes more and more popular because it is simple and easy-to-use software. It is also because of the availability of many operating systems such as Linux, Windows, and macOS as well.

There are three parts of this IDE environment. They are Editor used for writing the required code, Compiler used to compile, and Uploader used to upload the code into Arduino Modules. C and C++ programming languages are supported in Arduino IDE. Arduino IDE software is downloaded from its main website.

Arduino understands Hex Decimal files, therefore, it creates those files for the code when written and compiled. After that, by using a USB cable, it is sent to physical boards. In

all official Arduino boards are integrated with microcontrollers, they receive hex files and run the programmed codes.

3.1.2 Arduino Micro

The Arduino Micro is introduced as a microcontroller board that is based on the ATmega32U4, developed in conjunction with Adafruit. An Arduino Micro board is designed with 20 digital input/ output pins, a 16 MHz crystal oscillator, a reset button, a micro-USB connection, and an ICSP header. With a similar design as other popular Arduino boards, the Arduino Micro package includes a micro-USB cable to connect it to a computer, and it can be easily placed on a breadboard. [12.]

As similar to other different types of Arduinos, Micro board also can be programmed with Arduino IDE (Arduino software). With the new design, the Micro uses a resettable poly-fuse to protect the computer's USB ports from shorts and overcurrent, and the USB connection is utilized as a power supply. There are also power pins on the Micro board, they are V_I pin (input pin), 5V pin, 3.3 V pin, and GND (ground pins). The Micro board has 20 digital i/o pins that operate at 5 volts. Figure 7 is a pinout diagram of an Arduino Micro board.

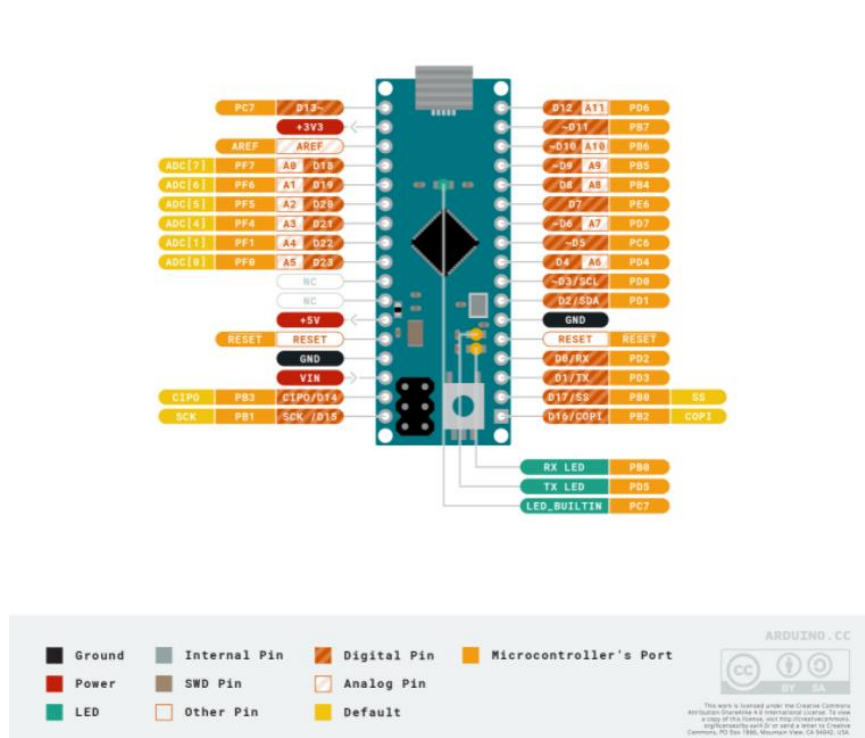


Figure 7: Arduino Micro pinout diagram [13]

A Micro PCB has 4.8 cm length and 1.77 cm width. There are LEDs on the board to show when data is transmitted. The layout is easy for users to place on a solderless breadboard. One special characteristic of the Micro is a reset button. There is no physical reset button on a Micro board, instead of that, it will be reset by software running on a connected computer.

3.1.3 Arduino NANO 33 – BLE SENSE

Arduino NANO 33 – BLE SENSE (figure 8), which is known as a product of Arduino, is designed for embedded system projects. This is a developed version of the traditional Arduino Nano, and there are more powerful processors in the unit. As introduced by Arduino supplier, Arduino NANO 33 – BLE SENSE includes a 32 – bit ARM Cortex – M4 CPU running at 64 MHz, a nRF52840 from Nordic Semiconductors, a micro-USB connector, as well as a set of embedded sensors. This Arduino is programmed with the support of Arduino Software (IDE).

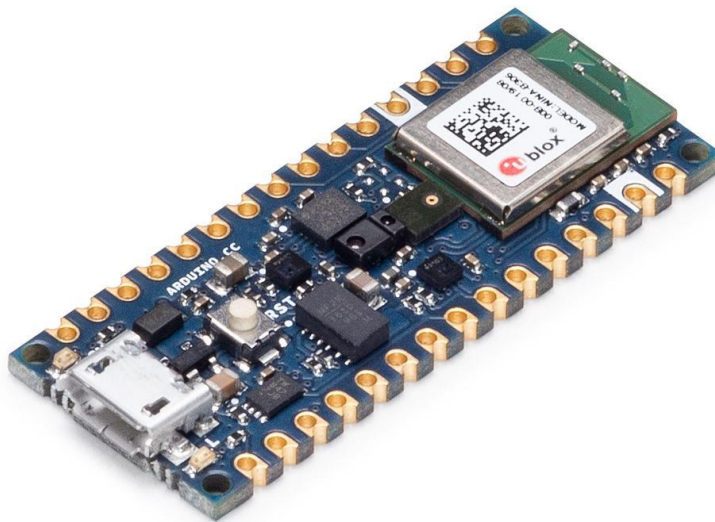


Figure 8: Arduino NANO 33 – BLE Sense [14]

Arduino NANO 33 – BLE SENSE is designed to work at 3.3V in Digital and Analog pins. It is required that there is no voltage exceeding 3.3V because it damages the Arduino NANO 33 - BLE SENSE if connected with higher volume signals.

The 5V pin is not connected by default since previous Arduino boards use 5V I/O signals. In this way, it is avoided to damage accidentally the board by powering circuits with 5V. However, there is also a solution to avoid this risk. Like the design, a 5V pin is on the

header between RST and A7 pins, they are not connected because of the default factory setting. The 5V pin works effectively only when a solder bridge is made on two pads marked as V_{USB} , and Nano 33 BLE AENSE is powered through the USB port. In the case of connecting the board from the Vin pin, there is not any regulated 5V voltage, and no power comes out of the 5V pin even if there is a solder bridge. Anyway, 3.3V is still a standard voltage for electronics ICs. [15.]

The new design of Arduino NANO 33 – BLE SENSE contains a lot of features that support users effectively while building the circuit. For example, ADC and PWM resolution is a plus point of this Arduino (similar to Arduino Micro). It helps to change its analog read resolution from 10 bits up to 12 bits ADC. MP34DT05, a digital microphone is attached to the Arduino to produce an output coded in PDM (Pulse–density modulation).

3.1.4 Sensors (of Arduino NANO 33 – BLE SENSE)

There are several sensors designed with NANO 33 – BLE SENSE. APDS9960 is a gesture sensor in this Arduino, it works to recognize colors, gestures, proximity, and ambient illumination. It is utilized to estimate the room's brightness and detect motions in the area as well. LPS22HB is a barometer sensor working as a digital output barometer, it is used to make a weather station.

HTS221 is a humidity and temperature sensor, which is also an ultra-compact sensor. This kind of sensor is produced with a new technology to get highly accurate measurements of the environmental conditions. It is recommended to avoid thermal sources in the surroundings to improve the effectiveness of the sensor's working. By using the lowest possible power modes and reducing to a minimum the processor activities, the board self-heating is minimized, this support effectively the utilization of the humidity and temperature sensor.

3.1.5 Arduino Shields

Arduino shields are add-on pieces that provide additional functionalities to an Arduino board. Shields can come with a board as preassembled or as kits, they also can be complex or simple. Shield kits are assembled freely on Arduino boards, that is why they are utilized as multifunctional electronic hardware, depending on the user's purposes. Shields are designed to implement a specific function and have the same pin position on Arduino. Users need Arduino shields because it helps to reduce the wiring complexity on the circuits, also decreases the building time and construction process.

Depending on different categories, shields can be alone or stacked on top of each other. In the case of dissimilar physical sizes of shields, it causes short circuits and damages the boards. There is a limitation about the amount of current flowing through the input/output (I/O) pins. If the limit is over, the board will be damaged and other attached shields. It is critical to connect exactly certain pins to avoid sending the wrong voltage to places.

Prototype shield (figure 9) is one of the simplest Arduino shields. Users can decide how to build a prototype in the circuits by soldering the components or not. Another type of Arduino shield is IO expansion shield, it is allowed to connect Analog and Digital IO devices to Arduino without soldering and breadboard. 3.3V and 5V supplying voltage are selected for sensors.

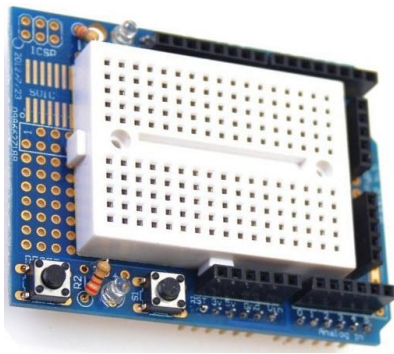


Figure 9: Prototype shield [16]

Xbee shield (figure 10) is known as one of the best ways to simplify for adding Xbee Modules in Arduino projects. Xbee shields support different wireless networks, for example, Zigbee and Bluetooth Low Energy. In the market of electronics components nowadays, several shields have specific functions depending on users' purposes, such as GPS shield, USB Host shield, microSD shield, or Wifi shield.



Figure 10: Xbee shield [16]

3.2 ZigBee Technology

Zigbee is a global standard wireless technology to enable low-cost, low-power wireless IoT networks. The standard operation of Zigbee is on the IEEE 802.15.4 physical radio specification which is also a standard for wireless personal area networks (WPANs). The frequencies allowed are at 868 MHz, 900 MHz, and 2.4 GHz. [17.] Zigbee is applied for low-data rate, low-power applications. Because of that, Zigbee has a short range of 10 – 100 meters indoors. This makes the battery life of Zigbee last several years. Moreover, there is another upgraded version – Xbee 3 PRO, that can give a longer range, but it consumes more power than the previous revision. Unlike Wifi, Zigbee supports much lower data rates, uses a mesh networking protocol.

ZigBee works with digital radios by allowing separated devices to converse through another device. They are a coordinator, a router, and end devices. Those Zigbee devices can send and receive messages or data between Zigbee devices. There is one coordinator in each network, it is considered as the most important device in this network due to the original place of the system. However, it depends on the purpose of the network, that coordinator performs different tasks. A coordinator is the most essential equipment in the Zigbee network, it is a place where users can set up permissions as well as the accessing allowance. It coordinates both the Personal Area Network (PAN) and the Internet with a gateway.

On the other hand, routers are responsible for message routing among the various nodes. They receive messages from a coordinator and store them till the end devices are ready to pick them up. Routers have the right to allow other routers and end devices to connect to the network. Unlike routers or coordinators, end devices have responsibilities to communicate with routers and coordinators to control small information. They are utilized to request messages waiting from nodes where all traffic can be routed forward. In these nodes, data is held until end devices are in a ready situation to get them through.

In general, there are three different devices in the Zigbee network, coordinator, router, and end device. A coordinator is the most important device that must be in every network because data is handled and stored there. A router is an intermediary device as it permits data to pass to other devices. An end device is in limited function to talk with the nodes. Depending on the type of network, for example, mesh network, tree network, or star

network, there is a suitable amount of each device. Figure 11 is an example for a typical Zigbee Mesh Network.

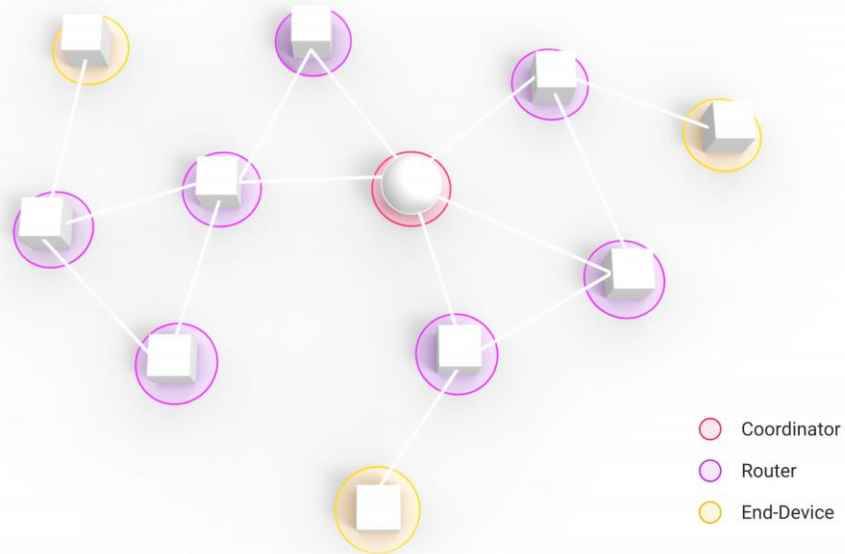


Figure 11: A Zigbee Mesh Network [18]

Nowadays, Zigbee is quite popular in use even though it is not a perfect solution for embedded systems. In the Zigbee system, when one device is kicked out because of a Wi-Fi signal or any reason, Zigbee devices will reroute automatically. Otherwise, Zigbee is also a power-efficient system, its devices do not use so much energy in the sleep mode. This perfectly saves battery life and reduces electric usage. Zigbee network is also cost-effective because of its cheap system. On the other hand, Zigbee uses 128-bit AES encryption keys, this makes Zigbee become a secure system.

4 Results

4.1 Electronic circuits

Transmitter part

In figure 12 below, an Xbee 3 is placed on a Grove Xbee carrier, it has one chip that converts between a USB and a UART chip. The Xbee 3 and the carrier board are connected by UART. A serial communication (USB port) is used to connect between the board and a computer (XCTU software).

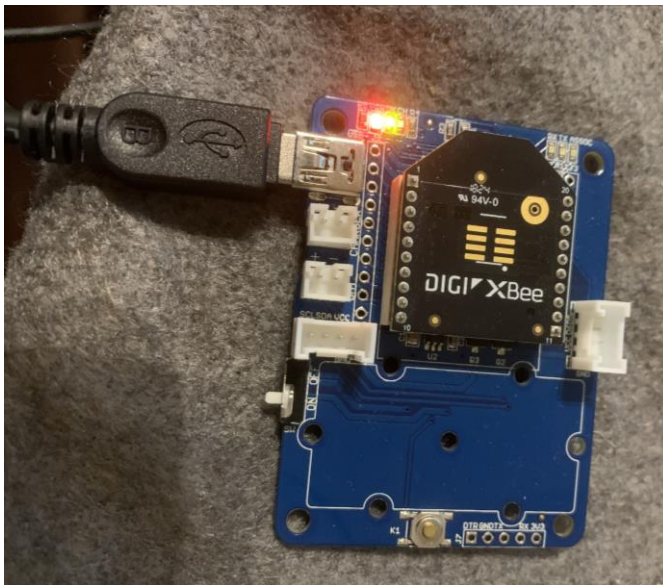


Figure 12: Transmitter board

Receiver part

This part includes one XBee board that is connected to the Arduino Micro by i/o pins, then the Micro also uses a USB port to get a power supply from a computer. A LED is utilized for visual indication when the Xbee is in sleep mode. When the LED is bright, it means that the Xbee is now awake. After three seconds without any data transmission, the XBee goes to sleep mode, a blinking LED appears then. The 1 Ohm resistor supports current measurement (figure 15). Figure 13 shows that the Xbee is connected successfully to the Arduino Micro, and it is in the awake status (the bright LED).

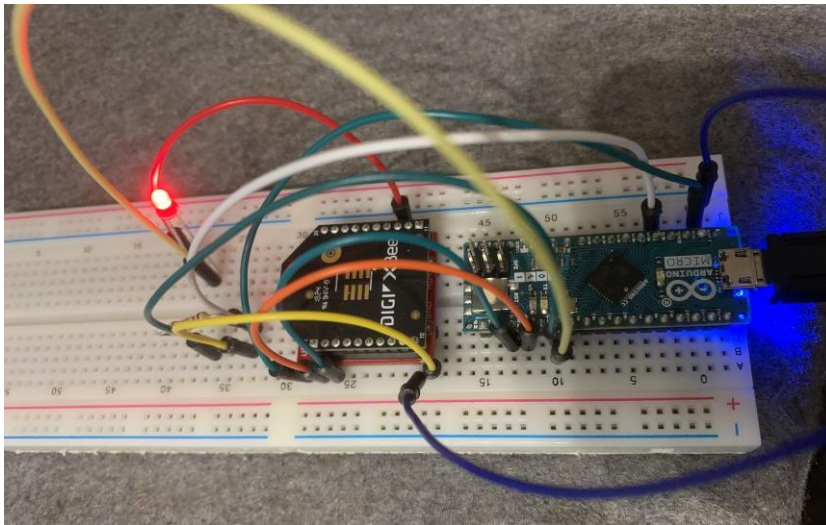


Figure 13: Receiver circuit on the breadboard

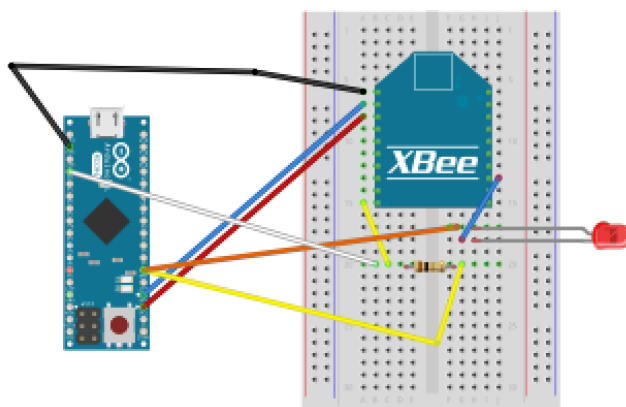


Figure 14: Receiver circuit – A circuit diagram

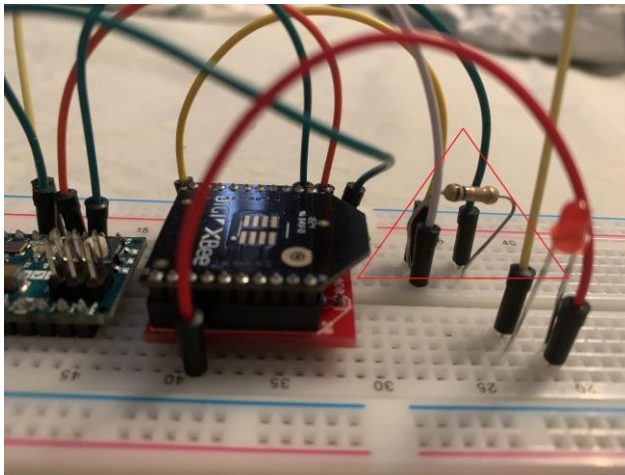


Figure 15: The 1-Ohm shunt resistor in the receiver circuit

4.2 Arduino IDE

As mentioned before, Arduino IDE software is used for programming Arduino Micro. In this study, a serial-pass-through code is applied for that Arduino Micro as in listing 1 below. The baud rate is 9600. After compiling and uploading successfully, the Micro is connected with the Xbee.

```
void setup() {
  Serial.begin(9600);
  Serial1.begin(9600);
}

void loop() {
  if (Serial.available()) { // If anything comes in Serial (USB),
    Serial1.write(Serial.read()); // read it and send it out Serial1
    (pins 0 & 1)
  }

  if (Serial1.available()) { // If anything comes in Serial1 (pins
    0 & 1)
    Serial.write(Serial1.read()); // read it and send it out Serial
    (USB)
  }
}
```

Listing 1. Serial-Pass-Through code for Arduino Micro

4.3 XCTU Software

Specification setting in XCTU for Xbee devices

XCTU is designed as a free multi-platform application to support users to interact with Digi RF modules. XCTU becomes nowadays more and more popular because of its friendly user interface and functions to help users easily to work with RF modules.

After compiling and uploading successfully with Serial-Pass-Through code in Arduino IDE, basically, at that time Xbee is connected to Arduino Micro. After that, XCTU can discover the Xbee depending on the baud rate setting.

Because of the wireless connection, those two Xbees need to have a similar Network PAN ID so that they can communicate with each other. Moreover, the specification of Destination Address Low and 16-bit Source Address needs to be set up similarly as well.

In figure 16, the left picture shows the setting for the independent Xbee device. The right picture shows the same setting for the Xbee connected with the Arduino Micro, it is called Arduino in the XCTU setting. Both of them are in channel C and the Network PAN IDs are 2244.

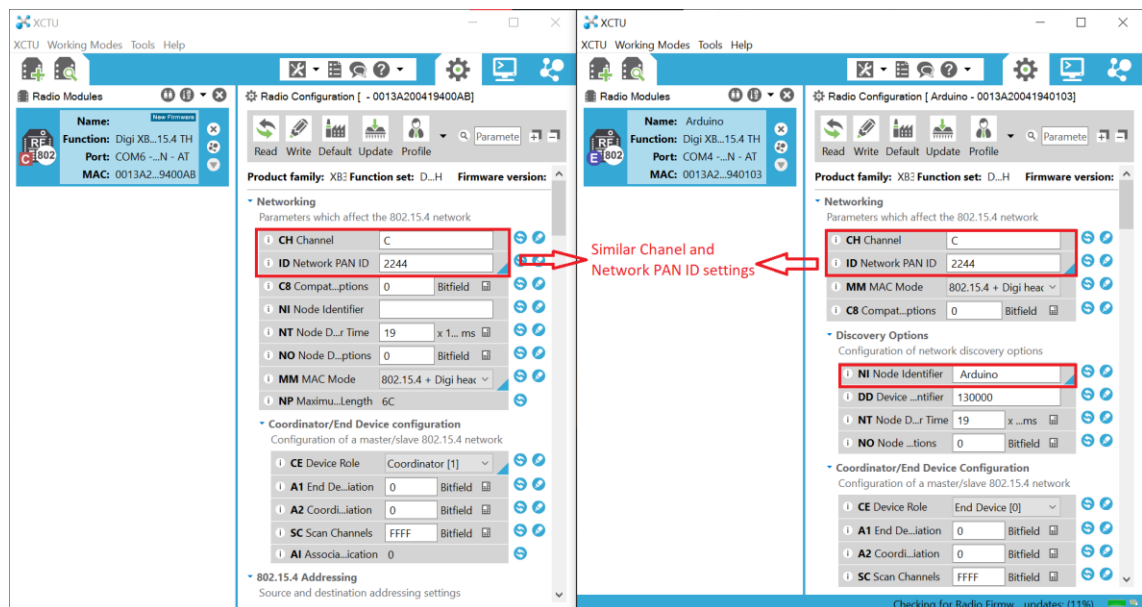


Figure 16: Network PAN IDs are similar between 2 Xbee modules

To make those Xbee devices talk with each other, the Destination Address Low must be the same as the 16-bit Source Address of another Xbee. In this situation, for example, the 16-bit Source Address of the first Xbee is 5678, therefore, the Destination Address Low of the second Xbee must be 5678 as well. Figure 17 below shows more details about these settings.

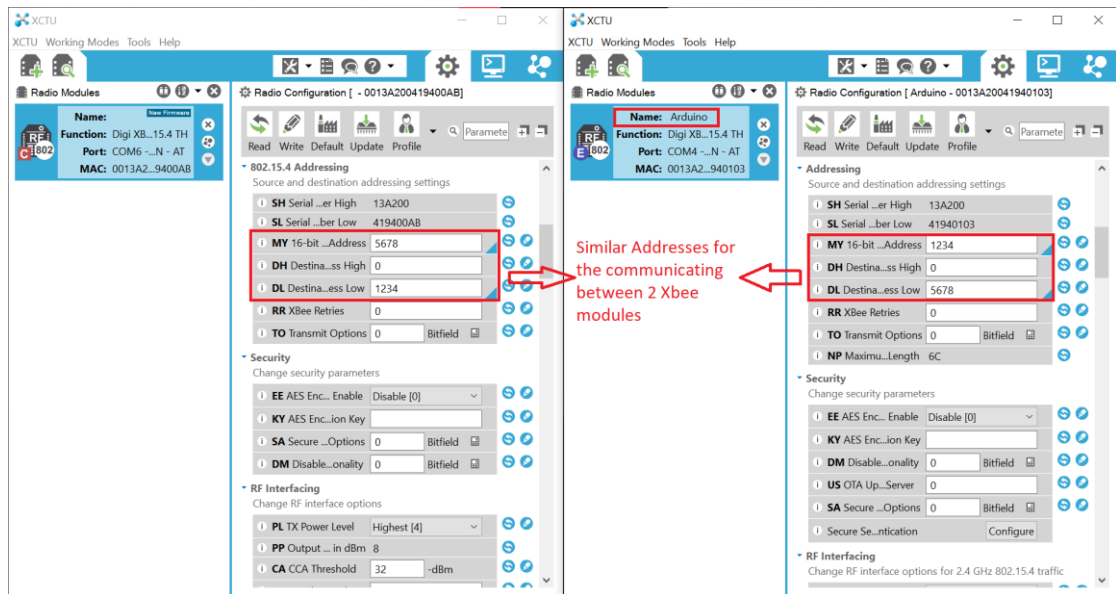


Figure 17: Specification settings in XCTU for two XBees

Figure 18 shows the sleeping mode settings in the XCTU software of Xbee modules. No-sleep mode means that the Xbee device never goes to the rest, it is just awake all the time although there is no data traffic. A sleeping mode 5 is set up for the Arduino Xbee meaning that it goes to sleep when no data transmission. It wakes up periodically and by controlling pin 9 on the Xbee board as well. After all specification settings are suitable, two XBees can communicate with each other as in figure 19.

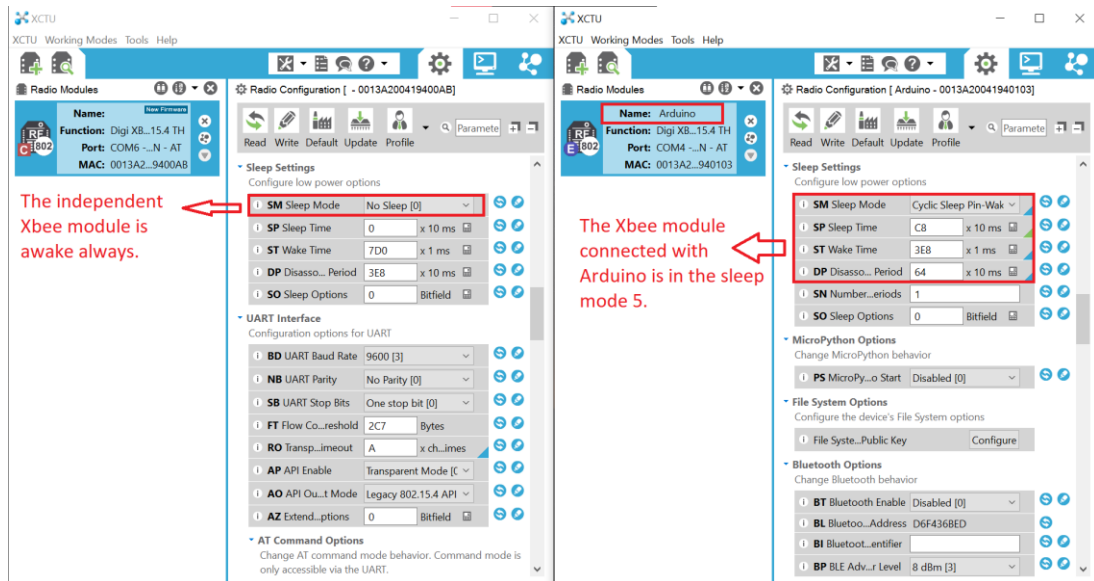


Figure 18: Sleeping modes settings for two XBees

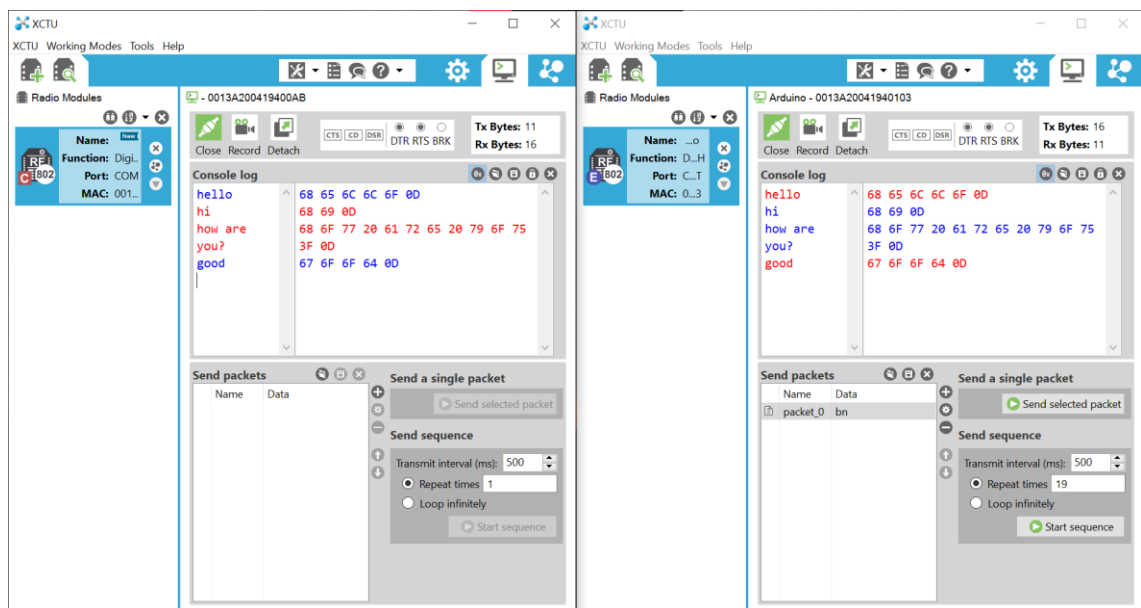


Figure 19: Two XBees communicate with each other

Sleep Mode

As mentioned before, to optimize the power consumption, Xbee is set up a sleep mode with a pin wake up. In this case, Xbee is put in sleep mode 5 (figure 20), it will go to rest in 3 seconds when no data is transmitted and sleeps in a period of time that is set up in XCTU software. The Xbee will wake up by pulling pin 9 (of the Xbee) low. There is also a LED in the circuit that is connected to pin 13 of the Xbee. The LED is bright all the time

when the Xbee is awake, and it blinks when the XBee is sleeping. Figure 21 proves that there is no communication when it is in sleep mode.

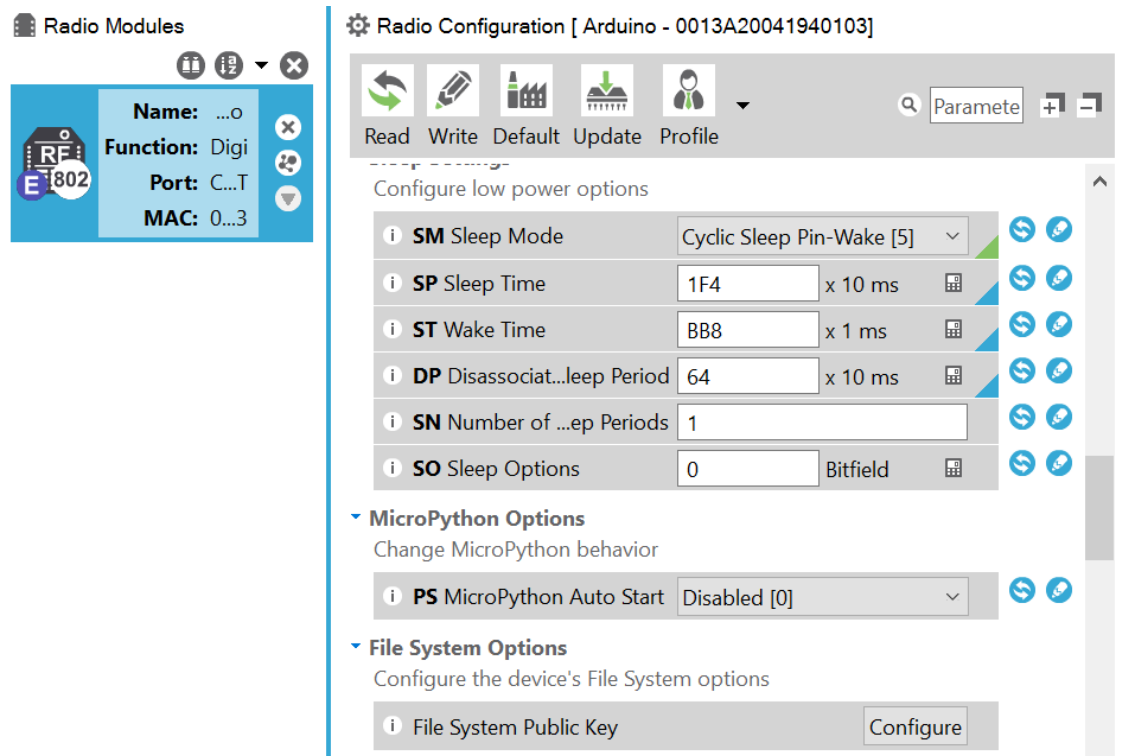


Figure 20: Sleep mode setting for receiver part's XBee

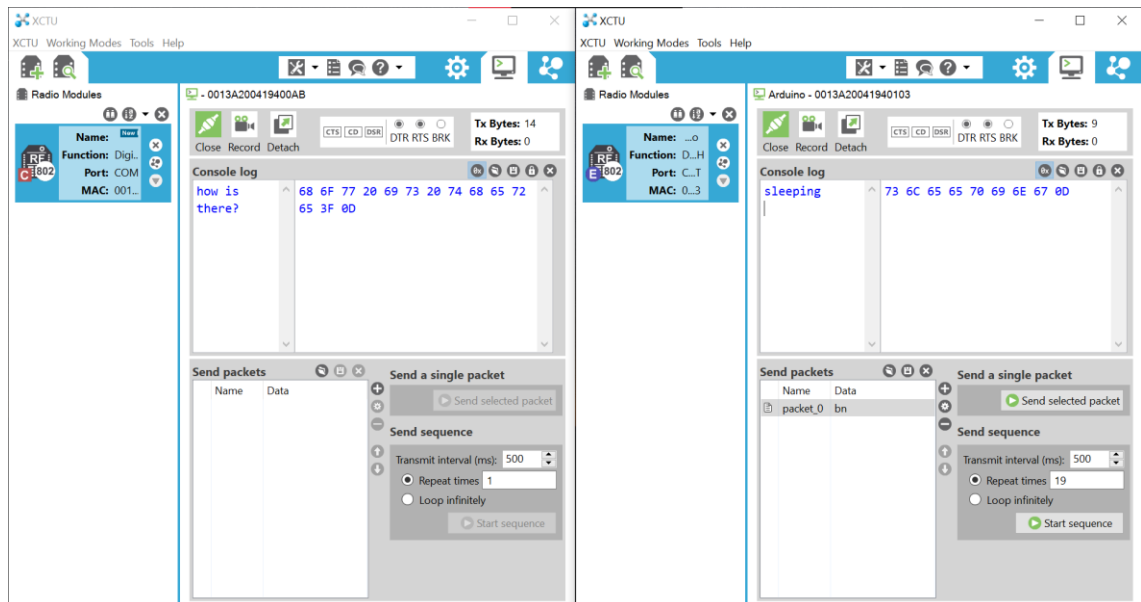


Figure 21: No traffic between to Xbees when receiver part's Xbee is sleeping

5 Power Consumption Measurement

In the circuit, there is one 1 Ohm resistor ($R_1 = 1\Omega$) connected serially with the Xbee. By using a multimeter, the measured voltage is 0.01V ($V = 0.01V$).

Because of the serial circuit, the current of the whole circuit is the current that goes through the Xbee. Therefore $I = I_{Xbee} = V / R_1 = 0.01V / 1\Omega = 0.01A$

The resistance of the circuit: $R_{total} = V_{Xbee} / I = 3.3V / 0.01A = 330\Omega$

The resistance of the Xbee: $R_{Xbee} = R_{total} - R_1 = 330\Omega - 1\Omega = 329\Omega$

The power consumption of Xbee: $P_{Xbee} = I^2 \times R_{Xbee} = (0.01A)^2 \times 329\Omega = 0.0329W$

According to a datasheet from the vendor [19], the amount of power consumption of an Xbee 3 module is 40 mA at 3.3V. Based on that, the calculated power consumption is 0.1304W. This number represents the amount of power that an Xbee 3 module consumes typically during the data transmission.

Therefore, it is assumed that the actual power which an Xbee device uses is less than the typical power. It could save about 0.0975W.

6 Conclusion

In conclusion, power consumption optimization is important in both real life and technology life. It plays a role to save our living environment. When energy is used optimally, the equipment saves the lifetime itself and saves the planet as well.

Nowadays embedded system technology has been developed more and more to catch up with the development of the whole wide world. The most significant goal for every project is to design as low-cost system as possible, but still maintain the effect of the system. Therefore, the main goal of this project is also based on that factor.

As the result, the Xbee is set up in sleep mode when no data transmission. This supports optimizing the power consumption of the Xbee. It was intended that the power consumption would be measured by an oscilloscope, but because of the time shortage and a few other personal reasons, it is measured by a multimeter. On the other hand, the application of a shunt resistor to measure the current also helps to understand more about the current measurement.

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