Signal Characterization and Reorganization of Wireless Wake-up Sensors based on Magnetoelectric Magnetometer

by

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Abstract

Conventionally, Current Transformers (CTs) are used in current measurement application to check and maintain the transmission lines of the electrical grid. However, there is a major disadvantage of using CT which is the size and the weight of it is very large and heavy. Although some active current sensors have been used for the replacement of CT, they are not commonly used because the sensors draw a significant amount of power. Another problem of CT is that the results of current measurement cannot be determined and sent back to the power companies quickly since the measurement tool is not connected to the internet.

This project proposed a wireless approach to monitor power cables by using a passive current sensor called Magnetoelectric Current Sensor, which requires no external power supply. It will then connect to a self-powered wireless sensor node with wake-up feature based on Bluetooth which is a wireless communication technology, so that it can wake up an external device to send data back to the power company immediately and have less cable management.

Although the result of the was not done entirely, it still offers satisfactory wake-up system that can wake-up external devices and self-powered. This project can be applied in different areas of monitoring system. In summary, this project demonstrates that the proposed approach provides performance advantages over the conventional approach.
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Chapter 1

Introduction

1.1 Internet of Things (IoT) and Wireless Sensor Network (WSN)

The importance of Internet of Things (IoT) has increased rapidly in recent years. According to Internet Society [1], IoT means “A system in which objects in the physical world could be connected to the Internet by sensors”. Electronic devices, such as smartphone and smartwatch, are commonly used in many people’s life. Those devices record their habits and upload it to the internet for the use of big-data. Some trends, such as what do people like these days, can be found in these data and that is one of an example of the use of IoT. Aside from big-data, IoT is useful in numerous areas such as military, business and health. To achieve the concept of IoT, sensor is the essential element and it plays an important role in concept of IoT since it can be used for monitoring and target tracking. A survey conducted by J. Yick et al. [2] points out that sensor can be used in many applications in different areas, such as security detection in military area, patient monitoring in health area and bus tracking for public. The wide adaptation of sensors would improve quality of life.

However, there are different challenges and obstacles in installing large number of sensors in different places. Factors such as space and environment could affect the willingness of people to use sensor network in daily life. Large number of sensors and wires would bring inconvenience. Therefore, the concept of wireless sensor network (WSN) is important when achieving IoT. According to an article written by National Instrument [3], wireless sensor network (WSN) is “a wireless network consisting of spatially distributed autonomous devices using sensors to monitor physical or environmental conditions”. Wireless connectivity is necessary to WSN. With new technological advances, cost of WSN is getting lower and WSN could be commonly used in IoT. This neglects space occupied by wires. It gives great incentives for companies and personal purposes. Different wireless protocol such as Bluetooth, Wifi and Infrared communication can be used depends on different applications.
Another important factor of designing WSN is the power consumption since a large number of sensors would be used in IoT and each sensor node consumes energy. K. Sohraby et al. [4] comments that one of the key features of a WSN is that it should have lower power consumption. A significant amount of energy will be consumed for a network even small amount of power is used for each sensor node only. In addition, the WSN may need long time operation so that the power efficiency of a WSN should be as high as possible. Reduction of energy consumption will be pursued and expected.

1.2 Purpose of this project

As mentioned, IoT is useful and important in 21st century. To develop a smart city, a smart grid is an essential element. “Grid” is an electric grid which deliver electricity from the power plant to consumers. Regarding an article from SmartGrid.gov [5], the way to make the grid smart is by adding sensors along the transmission lines so that the grid is under monitoring. Data, such as what is the time of peak power demand and any error happened along the transmission lines can be detected, can be collected in a smart grid. The smart grid allows power companies to intergard the electricity transmission efficiency and develop renewable energy system. It also increases the stability of the grid by allowing power companies to discover faults quickly and restored the electricity within a short time.
In the past, the traditional way to check if any error appears along the transmission line is to use current transformer (CT) for current measurement as shown in Fig.1 [6]. CT usually has a large size, especially which those are used in the transmission line, so it is not easy to take around. A significant amount of wire is also used during measurement and need to be arranged. The low portability of CTs is inconvenience for workers during the measurement. Furthermore, the results of current measurement need to be checked manually and cannot be sent back to the companies immediately since they did not send the results by internet.

To tackle these problems, this project may be the solution. Instead of using CTs, a smart current sensor, called magnetolectric (ME) passive current sensor which is developed by Polytechnic University [7], is used in our project. It has a small size and higher portability when comparing to CT. More characteristics of the ME passive current sensor will be mentioned later in the methodologies part of this report.

The results of current measurement will be determined automatically by the wireless sensor node and wake up external device using Bluetooth, such as smartphone. Then the external device can send the information or signal back to the power company immediately through internet so that the power company can take reaction as soon as possible.
1.3 Objectives

This project aims to:

1. To develop a self-powered wireless sensor node for current measurement application with wake-up feature based on Bluetooth.
2. To evaluate the received voltage output signal from magnetoelectric magnetometer and to recognize the corresponding states from the received signal features.

1.4 Overview

In this report, details of this project will be discussed. In chapter 2, literature review, other existing approaches of wake-up system and other choices of circuit board will be discussed. In chapter 3, methodologies, every procedure will be explained thoroughly, including implementation of the project, development of both hardware and software and challenges encountered. Chapter 4 will present the results of the project. Chapter 5 will include future development and the conclusion of the project.
Chapter 2

Literature review

2.1 Signal for wake-up system

Minimizing power consumption is an important aspect of the design of a WSN since it maximizes the lifetime of both WSN and external devices. In this project, the wake-up techniques are used to fulfill this purpose. The wake-up system will be triggered only when there is sudden change in the transmission system in the application of this project. When the WSN is measuring current and operating normally, it stays in idle mode, consuming low amount of power. But when the system detects sudden changes, such as the sensor detect there is a fault current in the cable, the WSN will be triggered and becomes fully functional. In this “ON” state, the WSN consumes most amount of power. For most of the time, WSN should keep the power consumption only high enough for monitoring the cable. Even in its “ON” state, the power consumption should also be kept to the lowest level while maintaining its full functions. Although Bluetooth is used in this project, there are other practical ways to wake up the system. Different methods of implementing the wake-up system will be discussed in this chapter.

2.1.1 Magnetic Signal for Wireless Wake Up Sensor

According to a research conducted by Sifuentes at el. [8], magnetic sensors were used in vehicle detection application. Most vehicles contain a lot of ferrous metals. They produce magnetic anomaly due to their magnetic permeability, which is higher than the surroundings such as air. Hence, when the sensor gets close to other vehicles, the magnitude of the magnetic flux density (magnetic signals) inside and near the sensor is increased. When the change exceeds a given threshold, the sensor will send out signals to wake up the WSN. Therefore, the magnetic sensor can monitor the presence of the vehicle by detecting the change of the magnetic flux density based on the uniform Earth’s magnetic flux by receiving the Magnetic signals.
The advantages of using magnetic sensors is that they are relative sensitive, small and resistant to environmental factors such as rain and wind. However, the limitation of this method is that the accuracy decreases when the vehicles size differs too much. For example, the difference between the change of magnetic flux density of a nearby small vehicle approaching the sensor and that of a distant large vehicle may not be significant. Therefore, it cannot directly determine whether vehicles are too close to each other. In addition, adding one more optical sensor is needed to improve the detection. However, magnetic sensor cannot function properly when there is a permanent magnet or large current cable nearby.

2.1.2 Optical signal for wireless wake-up sensor

Optical sensors are able to sense the light and convert it from light signal to digital signal that can be read by the WSN. This characteristic of optical sensor was also used in vehicle detection application [8]. The optical sensor will be covered when a vehicle was parked in the detection zone. The sensor will detect a shadow since the vehicle is closed to it and the sensor cannot detect the light from the surrounding area. Then the WSN will be wake-up since the optical sensor detected a vehicle. A major advantage of using optical sensor is that the power consumption. The optical sensor in the application is a passive sensor so it only consumes low power when it is detecting vehicles. However, the wake-up system may be triggered due to error detection. The result of the detection may not accurate since it is possible that the optical sensor may detect a shadow which is cause by other objects instead of vehicles.

2.1.3 Radio Signal for Wireless Wake Up Sensor

Radio signals communication, including radio frequency (RF) transmitter and receiver, is used in Water Quality Measuring System [9]. A 2.4GHz RF is used. Signals from the sensors are
collected and transmitted wirelessly to the base monitoring station. When the reading which is transmitted by RF transmitter is over some specific values, it will wake up the WSN. The reading mainly includes value of pH, temperature, turbidity etc. which are detected by different sensors such as pH sensor. One of the advantage of using RF transmitter is that it can be small, low-cost, and transmit data such as sensor reading quickly. However, the disadvantage is that when the distance between the RF transceiver and WSN node increase, the power consumption will be increased. Furthermore, MATLAB in GUI platform is used to decode the signal.

In biomedical areas, Heartbeat monitoring [10] also use radio sensor to wake up the WSN. A 2.4GHz Zigbee as RF transceiver is used and wireless Heartbeat sensor to senses and transmits the variations of human Heartbeat in radio signal to central computing unit in WSN within the range, then store the variation as a graph. If the graph decoded is abnormal, the sensor will wake up WSN. The advantage of WSN is that it is more adaptable to the environment where wired system is inconvenient. Additionally, MATLAB (GUI) is used to decode the signal.

2.1.4 Acoustic Signal for Wireless Wake Up Sensor

Acoustic signals (i.e. sounds) is a mechanical wave that can transmit through the gases, liquids, and solid to an acoustic wake-up sensor. Acoustic sensor is used in Autonomous Underwater Vehicles (AUV) to monitor the water area [11] using underwater acoustic communications. When AUV is in shallow or deep water, other sensors such as water quality, pressure, temperature sensor will transmit acoustic signals to the acoustic sensor inside the AUV in order to collect different underwater environmental information. However, the disadvantage of using Acoustic signals is the long propagation delay compare to other different types of signal, narrow bandwidth, and low reliability since the speed of sound is much slower than the speed of light. To decode the corresponding states from received signal, Signal-to- Noise Ratio (SNR),
Bit Error Rate (BER) and Delivery Ratio are calculated by different channel models and the parameters come from sensors.

2.2 Circuit board for WSN

2.2.1 Arduino

An Arduino being an open-source platform, it has both user-friendly hardware and software which is easy to be learnt by beginners. Arduino circuit boards are programmed by using C language. In addition, by using only few function, pins on the Arduino circuit board can be used for reading or output signals. A circuit board called Arduino Uno as shown in Fig. 2 has been used by many projects since the price of an Arduino Uno is inexpensive. A journal written by S. Ferdoush and X. Li [26] points out that the design of Arduino is “low cost, easy to build, and easy to maintain”. They were using the design of Arduino with ZigBee module to build a wireless sensor network system in the project. Different Arduino circuit board can be used depends on different application so there are plenty options for developer to choose for their projects. However, the maximum clock speed for a microcontroller of an Arduino circuit board is only 20MHz. This clock speed may be slow for some application, considering some inefficient library may be written and used in the board, which consuming extra RAM and CPU cycles.
2.2.2 Raspberry Pi

To make the WSN suitable for a wide variety of applications for environmental monitoring, it needs to be relatively low-cost and have low power consumption. Raspberry Pi is one of the popular choice to work as a base station [13]. The raspberry pi is a single-board computer which is low cost and small-in-size. It has Broadcom system-on-chip (SoC) with an integrated ARM compatible central processing unit (CPU) and on-chip graphics processing unit (GPU). One of its model, Pi 3, has processor speed ranges from 700 MHz to 1.4 GHz and comes with a on-board memory ranges from 256 MB to 1 GB RAM. Raspberry Pi also supports numerous operating systems and programming languages, making it highly flexible [13] [14]. Raspberry Pi 3 Model B was released in February 2016 with a 64-bit quad core processor, and has on-board Wi-Fi, Bluetooth and USB boot capabilities [15]. Raspberry Pi can be connected to a local area network through Ethernet cable or USB Wi-Fi adapter, and then it can be accessed by more than one client from anywhere in the world through SSH remote login or by putty software by just putting raspberry pi IP address in it [13]. Due to it being highly accessible,
flexible, customizable, it is a very suitable to be used as a WSN nodes.

Fig. 3 Raspberry Pi
Chapter 3
Methodologies

3.1 Hardware development

3.1.1 Magnetic signal transmitter

A current-carrying wire or coil was used as a transmitter in this project. The current carrying wire produces a time-dependent magnetic field based on Ampere’s Law. The direction of this magnetic field depends on the current direction of the wire as shown in Fig.5 and Fig.6. This magnetic field can be recognized as a signal by WSN since it is time-dependent signal with encode feature. A current sensor can be used to receive signal of the changing magnetic field generated by a AC wire.

Fig. 4 System Diagram of the whole project
3.1.2 Magnetoelectric passive current sensor

The Magnetoelectric (ME) passive sensor, which is shown in Fig. 7, was provided by The Hong Kong Polytechnic University HJ803 Laboratory. According to Leung et al [7], the case with insulating epoxy enables a reliable detection of magnetic fields generated by current-carrying cables and minimizes vibration noise. The compact and lightweight design shown in Fig. 8 is more convenient for placement and installation and minimize weight loading of electric cables.
Fig. 7 ME sensor

Fig. 8 ME Sensor Element [17]
When an AC electric current is applied to an electric cable, an AC vortex magnetic field is induced along the electric cable according to Ampere’s law as mentioned in 3.1.1 [7]. The ME sensor’s composite sensing element, including magnetostrictive (Terfenol-D) on the top and the bottom, piezoelectric ceramic plate (PZT) in the middle, detects the magnetic field. This magnetic field causes magnetostrictive strains and stress the central PZT plate and producing the piezoelectric AC electric voltage which is sine wave as shown in Fig.9 due to piezoelectric effect.

![AC Voltage Output Waveform](image1)

*Fig. 9 AC Voltage Output Waveform*

A Current Injection Machine which is shown below in Fig.10 was used to find the characteristics of ME sensor which is the magnitude of current of the cable of Current Injection Machine against the corresponding ME sensor output voltage. The ME sensor was placed next to the Current Injection Machine’s Current-Carrying cable and the ME sensor’s output was connected to Oscilloscope. Different magnitude of current of Current Injection Machine produced different voltage output value of ME sensor. The data of RMS Voltage value of ME sensor was displaced in the Oscilloscope and recorded with corresponding current value of Current Injection Machine in Table1. Their relationship was plotted below in Fig.11.
Fig. 10 Current Injection Machine [15]

<table>
<thead>
<tr>
<th>Current (A) of Current Injection Machine</th>
<th>Voltage (mV) output of ME sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0-2</td>
</tr>
<tr>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>74</td>
</tr>
<tr>
<td>30.5</td>
<td>110</td>
</tr>
<tr>
<td>40.5</td>
<td>138</td>
</tr>
<tr>
<td>50</td>
<td>178</td>
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<tr>
<td>60</td>
<td>210</td>
</tr>
<tr>
<td>70</td>
<td>270</td>
</tr>
</tbody>
</table>

Table 1 characteristic of ME

Fig. 11 Voltage and Current relationship of ME sensor
3.1.3 Microcontroller

In this project, a SimpleLink multi-standard 2.4 GHz ultra-low power wireless Microcontroller Unit (MCU) CC2650 model from Texas Instruments (TI), which is a global semiconductor design and manufacturing company, was used in this project. TI focus on developing analog chips, embedded processors and education technology products including calculators, microcontrollers, and multi-core processors. And, the model used in this project which is shown in Fig. 12 was bought from IOT++, which is a Chinese electronic company that sells and processes microcontrollers and launchpads. The MCU, CC2650, is an ultra-low power wireless MCU and it can use Bluetooth technology to communicate with external device such a smartphone.

Fig. 12 CC2650 launchpad
3.1.4 Converting Analog signal to Digital

Since the voltage which is induced by magnetic field is an analog signal, it is necessary to convert the analog signal to digital signal for the microcontroller to decode. The microcontroller CC2650 that was mentioned in 3.1.2 has a 12 bit, 200 ksp, Analog-Digital-Converter (ADC) which is shown in Fig. 13. And, the ADC can convert input analog voltage to digital number. However, the magnetic field which is received by the magnetoelectric passive current sensor generates a AC sine wave voltage that was mentioned in 3.1.2. It means that the analog voltage value can be positive and negative. And, the ADC of CC2650 microcontroller can only receive voltage from 0 to 3V as shown in [19]. Thus, the microcontroller cannot read the negative part of received voltage resulting in the data not accurate. Therefore, the magnetoelectric passive current sensor cannot connect to ADC directly in order to get more accurate analog data. Moreover, a circuit is needed to ensure microcontroller can receive all the data by offsetting the voltage which is generated by the passive current sensor to a certain level which is between 0V and 3V.

First, a Low-Dropout-Regulator (LDO) was used in the prototypical circuit which is shown in Fig. 15 and Fig. 16. It was used because it can regulate the input voltage from 3.3V that is supplied by the launchpad to a fixed output voltage which is 1.7V. The voltage at ADC node which is shown in Fig. 14 and locates at the middle of two 20kΩ resistors is about 0.85V by using voltage divider. Then, the voltage of ME sensor with 0.85V offset voltage is about 0.75V to 0.95V when the voltage of ME sensor is about -0.1V to 0.1V and the current of the magnetic transmitter which was mentioned in 3.1.2 is about 20A according to Fig. 11. The voltage data which is received by ADC could be read by microcontroller.
Fig. 13 CC2650 MCU diagram

Fig. 14 Circuit diagram using LDO
The advantages of LDO is that the output of LDO can be stable and no switching noise signal. It can minimize the effect of the noise on noise-sensitive ME sensor. It was believed the LDO circuit design was ideal choice for the project.

However, the LDO circuit design was not adopted in this project because of technical problem. Although the prototype of the LDO circuit design which is shown in Fig. 15 and Fig. 16 had been made, the performance of the circuit was not satisfied because the LDO is too small that was not easy to solder it into the board and failed a lot of time. Therefore, the LDO circuit was not adopted to offset AC signal voltage by DC voltage in this project.

After that, a Zener diode was used instead of LDO to offset the AC signal voltage because it is easier to solder comparing to LDO. The circuit design and the finished product are shown in Fig. 17, Fig. 18 and Fig. 19 respectively.
Fig. 17 Circuit using Zener diode

Fig. 18 Back Side of Zener diode circuit

Fig. 19 Front Side of Zener diode circuit
From the circuit design, the 3.3V input voltage above is supplied by the launchpad. A Zener diode with 2.4V breakdown voltage was used and connected in parallel to R2 and R3 resistors to maintain the voltage across R2 and R3 to be 2.4V. The 10Ω resistor was used to adsorb the voltage which is (3.3-2.4) = 0.9V. Let the voltage at the ADC node be 0.8V. Then, R2: R3 is (2.4-0.8) / (0.8-0) = 2: 1 by using voltage divider. Therefore, R2 resistor was 20kΩ and R3 resistor was 10kΩ. After that, according to Fig.11, the voltage of ME sensor is about -0.1V to 0.1V when the current of the magnetic transmitter which was mentioned in 3.1.2 is about 20A. And, this AC voltage will pass through a 10μF capacitor and flow to the ADC node. The capacitor was used to prevent DC supplied voltage flow to ME sensor and allow the AC voltage of ME sensor flow to the ADC node. Eventually, the ADC will receive about 0.7V to 0.9V voltage which is the voltage of ME sensor and the offset voltage and is shown in Fig. 20. Then the ADC could also read all the data.

![Fig. 20 AC Voltage Output with Offset Voltage](image-url)
Although the AC signal voltage could be offset by 0.8V DC voltage, this design exists a problem which is the AC signal is weak that it is hard for decoding which will be mention in 3.2.1. Therefore, the AC signal was needed to be amplified.

Then, an Operational Amp (op-amp) which is shown in Fig. 21 was added to above circuit as shown in Fig. 24. A LM324 Low-Power, Quad-Operational Amplifiers which is shown in Fig. from Texas Instruments, which was mentioned in 3.1.5, was used. It can solve the weakling AC signal problem of the Zener diode circuit which is mentioned above.

![LM324 Op-amp](image1)

*Fig. 21 Circuit diagram of LM324 []*

The design of the circuit only uses one op-amp which is the pins 1,2,3 that are Output, Input+ and Input- respectively as shown in Fig.21. Pins 4 and 11 are used for DC bias. The op-amp for the circuit design is shown in Fig.22.

![Op-amp](image2)

*Fig. 22 Op-amp*
Fig. 23 Op-amp circuit without AC Signal source

Fig. 24 Op-amp circuit with AC Signal
The circuit design is shown in Fig. 24. Similarly, the DC voltage 3.3V is supplied by the launchpad, and the 2.4V breakdown voltage Zener diode is used to maintain the voltage across 20kΩ and 10kΩ resistors be 2.4V. Then, the voltage at input+ which is the pin 3 of the op-amp was connected to the Zener diode circuit without AC voltage source as shown in Fig. 23, and the DC voltage was 0.8V. The pin 2 of the op-amp was connected to the AC source and the AC signal is amplified about \((10k\Omega)/(1.3k\Omega) = 7.5\) times. The peak to peak voltage is amplified from -0.1V - 0.1V to -0.75V - 0.75V. Then, the voltage range at the output which is -0.75 – 0.75V added with 0.8V DC offset voltage, is about 0.05V to 1.55V that can also be read by ADC which was mentioned in above. Eventually, this circuit was adopted to offset and amplify the AC signal voltage. And, the prototype is shown in Fig. 25.

Since the output of the ME sensor is a Bayonet Neill–Concelman (BNC) connector which is shown in Fig. 26, and the input of circuit board which was mentioned above is a SubMiniature
Version A (SMA) connector which is shown in Fig.27, the connectors are not the same. Therefore, the BNC connector is converted to SMA by using SMA-BNC converter which is shown in Fig.28. Eventually, the ME sensor could connect to the circuit board.

![BNC connector](image1.png) ![SMA connector](image2.png) ![SMA-BNC converter](image3.png)

*Fig. 26 BNC connector [20]     Fig. 27 SMA connector [21]     Fig. 28 SMA-BNC converter [22]*

From the datasheet of the launchpad which is shown in Fig.28, the ADC node of above circuit can be connected to pin DIO30 which is the ADC of the launchpad. After connecting to this pin, the microcontroller can receive the digital data.

![Pins Diagram of CC2650](image4.png)

*Fig.29 Pins Diagram of CC2650*
### 3.1.5 Developing self-powered Microcontroller

A 3.7V 100mAh Li-ion battery which is rechargeable and a 03962A charger module were used in this project and provided in HJ803 Laboratory. They were connected as shown in Fig.30. Positive side of the battery which is the red wire was connected to B+ of the charger module, and the negative side of the battery which is the black wire was connected to B- of the charger module. After connecting the battery and the charging module, the battery can be charged by plugging micro-USB cable which is connected to a power source. Then the battery can power the microcontroller through the charging module.

XDS110, which is from the Texas Instrument, is used for flashing programs in to the launchpad in the project. According to the diagram of XDS110 interface which is shown in Fig. 30, the main power input of the launchpad is using pin VCC and GND. Therefore, the positive output of the charging module which is OUT+ was connected to VCC and the negative output which is OUT- was connected to GND. However, the maximum supply voltage for the launchpad is 3.8V regarding the datasheet of CC2650 [19]. The output of the battery, which is 3.7V, is close to the maximum value. It means that the output voltage of the battery might burn out the launchpad. Therefore, a Schottky diode was used to connect between the battery and the WSN as shown in Fig.30 in order to drop down the supply voltage. The model of the Schottky diode was used in the project is Pmeg1020EH, which is from a company called Nexperia. This schottky diode was claimed that it is suitable for low power consumption applications since it only drawn a small amount of power. Another major advantage of using the schottky diode is that it had ultra-low forward voltage drop. After using the schottky diode, the 3.7V battery was drop out down to 3.5V which can be used to supply power to the launchpad. Fig. shows the actual circuit connection between the battery and the WSN.
Fig. 30 Charger module and Li-ion battery

Fig. 31 Pins diagram of XDS110 interface

Fig. 32 Diagram of circuit connection between the battery output and the WSN
3.1.6 Wireless Communication

A wireless technology called Bluetooth Low Energy (BLE) using 2.4GHz Ultra High Radio Frequency was used for communication between microcontroller and external devices such as smartphone in this project. According to an article from LinkLabs [21], BLE was lower power consumption when compared to WIFI technology which is also Radio Frequency. They have the same function for communication. However, Bluetooth technology was adopted because it has better energy efficiency.

In addition, when using Bluetooth to technology to communicate, the external devices acts as Central role, and the MCU acts as peripheral role. Central respond in receiving data while peripheral respond in transmitting data as shown in Fig.34.
3.2 Software development

3.2.1 Software Tools

3.2.1.1 Code Composer Studio

In the develop cycle, couple of software were used for programming and testing. One of a software is called Code Composer Studio (CCS) shown in Fig.35, which is an Integrated Development Environment (IDE) that supports TI’s MCU, is a software used in this project to code and flash the program to the MCU. At the beginning stage of the project, CCS was used to write and flash the program into the CC2650 circuit board. However, some problems were encountered when flashing the program into the circuit board.

Fig. 34 Relationship between the central and the peripheral
3.2.1.2 Ingenjorsfirman Anders Rundgren Embedded Workbench

To address the problem of CCS, Ingenjorsfirman Anders Rundgren (IAR) Embedded Workbench shown in Fig. 36 has given a solution for the project. It is an alternative software that can build and download the program into the CC2650 circuit board. The software, IAR, is more convenient for developing program in the project when comparing to CCS, since there are more useful tutorials of how to use IAR can be found on the internet. Therefore, IAR is chosen as the developing software in the project.

3.2.1.3 Flash Programmer 2

An alternative program called Flash Programmer 2 shown in Fig. 37 is used to flash the program into the CC2650 circuit board using hex file that built by IAR software instead of using the IAR software itself.

3.2.1.4 LightBlue Explorer

A free apps for both IOS and Android system called LightBlue Explorer shown in Fig. 38 is used in the project. The app is used to use the Bluetooth function in smartphones for connection purpose. In this project, it is used to connect the smartphone and the CC2650 circuit board. The apps can be used to send or receive messages between the board and the smartphone or receive notification which is sent out from the CC2650 circuit board. The notification function will be used by the project since it is suitable for the wake-up system.
Fig. 35 Captured Image of CCS

Fig. 36 Captured Image of IAR Embedded Workbench
Fig. 37 Captured Image of Flash Programmer 2

Fig. 38 Captured Image of LightBlue Explorer
3.2.2 Programming

3.2.2.1 Program for current measurement

Since the output waveform of the ME sensors will be a sinusoidal waveform, calculation for an average value is necessary if the system needs to determine if there are any faults or not in the cable. To calculate the average value of a sinusoidal waveform, Root Mean Square (RMS) need to be found by using the definition of rms. According to an article from Electronics Tutorial [24], the meaning of RMS is “the square root of the mean value of the squared function of the instantaneous values”. The formula as shown in Fig. 40 is the RMS formula. Then the MCU can calculate the RMS value of the sinusoidal waveform, which is generated by the ME sensor, by a written program. The program code for this formula as shown below:

```
for(int i=0; i<50; i++){
    adcValue[i] = HwADCRead() - 760;
    square[i] = pow(adcValue[i], 2);
    sum = sum + square;
}

rms = sqrt(sum / 50);
```

In this program, 50 samples were collected for calculation. A function called

`HwADCRead` is used to collect the data of the ME sensor. Those data have to be minus by a number 760 since this number represented the offset voltage 0.8V which is caused by the Zener diode circuit as mentioned. Since 0.8/4.3*4096 ≈ 760 so the number 760 was applied in the program. The number 4.3 is the number of the maximum voltage that the ADC can read and the number 4096 is the number that the highest resolution the ADC can displayed (12-bits resolution for CC2650 as mentioned, so $2^{12} = 4096$). Then the data will be saved in an array called
The data in `adcValue` will be squared by using `pow` function and saved to another array called `square`. Data in `square` array will be sum up and save to a variable called `sum`. The sum of data will be divided by 50, which is the number of samples, and take square root by using `sqrt` function. The result after all the calculation is the rms value. The system block diagram of the program is shown in Fig. 39.

**Fig. 39 Block diagram for the rms value program**
3.2.2.2 Program for Bluetooth wake-up system

```c
int8_t y = 825;

if (SimpleProfile_GetParameter(HwADCRead(), &rms) > y) {
    int8_t x;
    x=1;
    SimpleProfile_SetParameter(SIMPLEPROFILE_CHAR4, sizeof(uint8_t), &x);
}
```

The above program code is the Bluetooth wake-up system. A variable SIMPLEPROFILE_CHAR4 is used for the notification for the smartphone or a client Bluetooth device. When the rms value larger than the value y, which is a certain level of rms value, the function SimpleProfile_SetParameter will be triggered and send a notification to the external device. The range of the value y can be set in the program depends on different situation. The system block diagram of the program is shown in Fig.41.
3.3 Energy harvesting by cooperation with others project

The time usage of the WSN is expected to be as long as possible so that it can run for a long time without giving external energy. To solve this problem, reduction of the power consumption is a solution. However, there is another approach for extending the time usage of the WSN. At the beginning of this project, energy harvesting was expected to include in the WSN. Unfortunately, the idea was given up due to time and technical problems until a project called “Magnetoelectric energy harvesting, storage, and management circuit” which is conducted by Chan Ngai Man was found. The project is an energy harvester which is to collect energy from cable by using CT. The energies which was collected will be save in a capacitor. When the capacitor saves a certain level of power, it will release the power to another device for charging purpose. The energy harvester is believed that can be the solution of energy harvesting of the WSN and both two projects can be used in current measurement application, so it is
suitable for cooperation. The project can be integrated by combining the WSN and the energy harvester together so that the time usage of the WSN can be extended. Fig. 42 shows that the energy harvester was collecting energy from a cable using CT and charging up the WSN. According to Chan, the output voltage of the energy harvester is around 3.5V which is the voltage that the WSN required. The output of the energy harvester can parallel with the output of the battery as shown in Fig. 43.

Fig. 42 Circuit diagram of the energy harvester

Fig. 43 Circuit connection for the energy harvester and the WSN
Fig. 44 System Diagram of the whole project after combing the energy harvester
Chapter 4

Results

4.1 Reading signal from ME sensor by WSN

The WSN can read signals from the ME sensor as shown in Fig. 45. The screen on the WSN displays the word “ADC”, then displays the reading of the voltage output. Unfortunately, we discovered that the value displayed on the screen is not the Root Mean Square (RMS) value, which is expected to display. The reason is that the finished program was unable to be flashed into the CC2650 circuit board of WSN. Even though the program is successful to be built without error, it cannot be run on the WSN. The program is checked many times and peer reviewed. The chance of having logic errors in the program is very low. However, the program was still unable to be run. The results shown in the Fig. 45 is an unstable reading from the ME sensor.

4.2 Self-powered WSN

The WSN is now self-powered as shown in Fig. 45. The battery is attached to the WSN successfully and no power cable is connected in order to use the WSN. It would increase the accessibility of the WSN, so that users could use the product without worrying about the power supply and the wires.

4.3 Receiving notification from WSN by external device

The wake-up system is one of the aims of this project. The external device, which is the smartphone, was able read notification from the WSN based on BLE technology. Fig. 46 shows that the smartphone was not receiving any notification, but it receives a notification by showing a
grey bar on the top of the user interface as shown in Fig. 47. It proves that the wake-up system is functioning as expected and can be used in the application.

4.4 The offset and amplified AC signal

The circuit that was mentioned in 3.1.3 was connected to the channel 1 of the oscilloscope. The waveform that shown in Fig. 48 is the output pin 1 of the op-amp. A DC voltage offset the AC sine wave voltage as shown in the figure. The DC offset voltage is about 0.8V and the peak to peak voltage is about 0.05V to 1.55V. It means that the finished circuit was successful. Then, the ADC of the WSN can receive data more accurate for measurement.

4.5 Integration of using energy harvester

Fig. shows that the energy harvester was charging up the WSN. When the battery of the WSN is run out of power and the WSN is off, the energy harvester can turn on the WSN in just couple seconds. However, we discovered that the energy harvester cannot give enough power to WSN in certain situations, such as when the WSN had been using the Bluetooth feature for a long period of time. Generally speaking, it is still successful for the WSN to use the energy harvester to extend the usage of time since the energy harvester is able to collect enough energy to supply power to the WSN for most of the time.
**Fig. 45 Result of the reading signal**

<table>
<thead>
<tr>
<th>Back</th>
<th>Peripheral</th>
<th>Clone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Software Revision String</td>
<td>&gt;</td>
<td>&gt;</td>
</tr>
<tr>
<td>Manufacturer Name String</td>
<td>&gt;</td>
<td>&gt;</td>
</tr>
<tr>
<td>Regulatory Certification Data List</td>
<td>&gt;</td>
<td>&gt;</td>
</tr>
<tr>
<td>PnP ID</td>
<td>&lt;57060000.010101&gt;</td>
<td>&gt;</td>
</tr>
</tbody>
</table>

- **UUID: FFF0**
  - **Characteristic 1** Properties: Read/Write UUID: FFF1
  - **Characteristic 2** Properties: Read UUID: FFF2
  - **Characteristic 3** Properties: Write UUID: FFF3
  - **Characteristic 4** Properties: Notify UUID: FFF4
  - **Characteristic 5** Properties: Read UUID: FFF5

**Fig. 46 Captured image of not receiving notification**

**Fig. 47 Captured image of receiving notification**
Fig. 48 The offset and amplified AC signal

Fig. 49 The connection of the energy harvester and the WSN
Chapter 5

Conclusions and Discussion

5.1 Discussion

5.1.1 Solution for reading signal from ME sensor

To tackle the problem of flashing program into CC2650 circuit board, a possible solution is to find a new replacement of the circuit board so that the program can be flashed into the board and run smoothly. The program has no any error or logic problem as mentioned. It should succeed if the program is transfer to another program using same logic and applied on the other circuit board. An advantage of using another circuit board is that a new development platform can be used which may be easier to develop program. Although the development software IAR has been used for coding and flashing program for the CC2650 circuit board in the project to solve the program of using another software CCS as mentioned, it is still quite difficult to use for beginners. There are few tutorials and resources can be found in the internet only, so it is not an easy task to learn how to use the software at a short time. However, the program was still finished but cannot be flash into the circuit board. A more user-friendly development software can be adopted if a new circuit board is used, such as Arduino and raspberry pi. The disadvantage is that the performance of the power consumption may be as well as the CC2650 circuit board since the low power consumption is the attraction of the CC2650 circuit board which is one of the important concern of this project.

5.2 Conclusions

In this project, a self-powered wireless Magnetoelectric Magnetometer is developed to receive magnetic signal from a magnetic transmitter and transmit radio signal to wake up the external device after recognizing the signal.
The traditional way in current measurement tool was large and tough and a lot amount of wires result in their installation was complicated and the maintenance was expensive. In addition, some active sensors are connected with power cables result in complex cables management and arrangements. And, some active sensors that use limited battery life which is non-rechargeable are also troublesome to renew a new battery.

In contrast, wireless passive sensor integrated with wireless communication units prevent the complex cables management, and rechargeable Li-ion batteries with the energy harvested from surrounding also prevent using external power supplies cables to power the sensor. The batteries will be recharged by energy harvesting for energy storage to supply stable power to the Magnetoelectric Magnetometer to prevent suddenly shut down due to not enough energy. Also, as mentioned in Chapter 3, the size of passive sensor combines with some circuits and the launchpad is compact and small compare with traditional way. Thus, the self-powered wireless Magnetoelectric Magnetometer does not have these traditional current measurement tool’s disadvantages as mentioned above.

5.2.1 Suggestions for Future Development

5.2.1.1 Reduction of the cost

The overall cost of this project is around $900. However, by redesigning the WSN circuit with cheaper materials, smaller circuit size and more suitable for mass production, the cost is estimated to be reduced to around $400.

5.2.1.2 Software interface development

The app LightBlue Explorer is used for the whole development process in this project. However, it does not have a user-friendly interface. Therefore, an user-friendly application could be designed specifically for our WSN circuit. This avoid getting potential customers frustrated and lose their interest before they understand the true usage of the product.
Beside a new user interface, the app can also be designed to send data back to the central management system automatically for data analysis of WSN, which might opens up opportunities to create more functions in the future development, such as graph plotting and analyzing data collected to detect sudden change.

### 5.2.1.3 Wireless communication improvement

The data from the WSN can wake up external devices using WiFi technology which has a wider communication range when compared to BLE technology. Unfortunately, the power consumption of WiFi is higher than that of BLE. The power supplied from the WSN may not be enough. According to a research conducted by Putra et al. [25], Bluetooth has lower power consumption than WiFi in data transmission application. Therefore, Bluetooth would possibly be the best way of wireless connection for the WSN. However, in situation where one external device manages numerous WSN, wider communication range, higher transmission frequency and larger data capacity per transmissions would be required. Wifi may be a better choice in this scenario. It is similar to the concept of smart home that many devices are under control by a smartphone or a tablet in a house, whereas many WSN would send data to the external device at the same time. Although it would increase the power consumption for the whole system, it has better management and wider communication range. Therefore, we would adapt built-in WiFi in the WSN in the future development.

### 5.2.1.4 Development for other application

This project is aimed to achieve current measurement application from the beginning. But in the development process, we have discovered that the ME sensor may be capable in different areas due to its high sensitivity and small-in-size characteristic. The future development of this project would be exploring different applications that is suitable for the ME sensor and make good use of it in the age of IoT.
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