WIRELESS POWER AND INFORMATION TRANSFER

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STATEMENT OF CANDIDATE

I, (Tianhang FU), declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Electronic Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment an any academic institution.

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ABSTRACT

Wireless power transfer technology emerges transmitting power from a sender to a receiver through an air gap. The most common way of wirelessly transferring power to a mobile device is by an inductively coupled pair of coils. However, data transfer is often required, as the wired, power and data interface as USB. In this case, it requires a wireless communication system to accomplish replacing of USB. However,adding an information system to existing wireless power systems leads to a series of challenges, especially at high data rate. In this project, first, we completed the literature review to determine its feasibility and how to do it. Next, three different possible proposals are discussed and designed. Based on their advantages and disadvantages, make a take-off and select the best proposal. After that, the detail design and simulation is shown. In the end, it summarizes the whole project and describes the potential improvements in the future.

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Chapter 1

Introduction

Nowadays, there are thousands of people use cell phones and other mobile devices in their daily life. Meanwhile, users need to periodically charge their device due to the limitation of batteries. To overcome this inconvenient behavior, engineers and scientists started to focus on wireless power. Now, users just place suitable devices front side up on a mat or a charging station. Once the two inductive surfaces are close enough, the charging process starts. But it could not entirely replace functions of USB cables due to lack of communication. This project aims to design a USB-interface wireless power and information system that not only charge devices wirelessly but also communicates with the host device using the same coils. Additionally, increasing data rate is studied and become a significant point of this project.Moreover,the convenience of wireless power and information transfer can highly increase customers experience.

In particular, device connectivity enabled by wireless communication technologies such as Bluetooth, NFC(near field communication) and Wi-Fi can give customers well a good experience regardless of place or environment in fields of health, communication quality, and recreation. For instance, there is audio-visual connectivity for playing media files stored on a desktop on a wireless speaker. Also, there is in-vehicle connectivity for hands-free calling and audio playing from an in-vehicle speaker, and there is health monitoring connectivity for collecting data from health measurement devices, updating data on network servers and sending health history to the medical center, etc.

The main task of mobile devices is to connect a pre-defined communication point whenever it is placed a specific location. With the evolution of the smart homes, short-range communications gradually went into mobile devices, such as the laptop. In the process of evolution, there are plenty of communication technologies were used. The first solution is based on IrDA(Infrared Data Association) and Bluetooth. They are designed to perform as a cable replacement, usually for effectuating simple jobs such as exchanging data or connecting wirelessly peripheral equipment(chiefly for Bluetooth).The next evolutionary technologies are cellular air interfaces which support higher data throughputs, multiple device connections.However, in many cases, short-range system are designed to be just a communication channel. In addition to mentioned short-range wireless power technologies, such as inductive coupling, magnetic resonance coupling ,capacitive coupling and so on, have been introduced.

Another important point of this project is that the total cost of WIPT should be as low as possible. If the total cost of WIPT devices is too high, then none is willing to purchase them. Even though WIPT devices have many advantages and provide conveniences to users, a high price stops people to accept and purchase them. Thus, during the hardware selection, the cost always is the most significant factor.

1.1 Motivation and Background

Now, the wireless power is becoming a new category of customer products and infrastructure. Thus, improving the performance of wireless device is the core research project of the Wireless Power Consortium (WPC) and The Alliance for Wireless power, which includes hundreds of companies and organizations, such as Microsoft, Panasonic and Samsung . [40] [41] Depending on the market research of the Technavio, it predicts that the global wireless market to develop rapidly at a CAGR (compound annual growth rate) of more than 33% in the next 5 years. [33] In this document, the author pointed out that the adoption of wireless electric devices such as mobile phones will necessitate the need for wireless power devices and the customer no longer need to worry about the lack of cables as wireless power solutions help in charging devices whenever and wherever. Also from an Australian Government report, innovative micro firms are more interested in the use of wireless technology and are leading the development of it in Australia [17].

However, in the existing wireless power solutions, there are no devices could transfer the information to the receiver. Thus, none of them could totally supplant cable in the communication manner. Although there are plenty of laptops have built-in Bluetooth, many desktops do not have Bluetooth inside. In the other hand, with the development of Bluetooth, now the Bluetooth 3.0 + HS provides theoretical information speeds of up to 24Mbit/s. [13] Meanwhile, the USB 2.0 standard announced the theoretical maximum transfer data are 480Mbit/s and the latest USB 3.1 could reach 10Gbit/s theoretically. In data transfer speeds, the difference between USB2.0 and Bluetooth can be extreme. However, the inconvenient manner of USB is that the customer always must plug in the USB cable to their device. The project aims to design a wireless power and information transfer system by using Qi standard devices. It could eliminate the disadvantage of USB cables and preserve the data transfer rate at a receivable level. [35]

The significant of this project is to develop a new idea in the current wireless power field and the wireless communication field by simply using a couple of coil component, and hopefully, it will be applied in the real world. Thus, the aim of this thesis project is to provide a reliable solution to the customer in order to satisfy the wireless-communication need in the wireless power system. This project also focuses on the trade-off between power efficiency and data singling rate. To achieve it, during the hardware selection, it must put the power efficiency and data rate in top priority. In addition, this project also aims to provide some suggestions for the future work.

1.2 Aims

- To design a wireless power and information transfer system, understand wireless power technologies and trade-off, then select a suitable wireless power technology for this project.
- The input and output should be compatible with USB interface, thus, information and power should be outputted via a single USB port.
- In the circuit design, the receiver should be designed as small as possible, therefore, customers would not feel any different in daily life.
- To protect charging devices and users' health, the WPIT output voltage should be stable and current should be limited to a safety range.
- The WPT system should be compatible with most of other wireless power devices. Thus, other wireless power devices could be powered in this WPIT system.
- The WPT system could be suitable for lower-power sources. Thus, in some emergency situations that could not find any appropriate power source, the WPT system still works with the limited maximum power transfer.

1.3 Project Specifications

Table 1.1 shows the specifications of the proposed WPIT device.

Input Voltage	5V
Input Current	2 A
Output Voltage	5.3V
Output Current	1A
Maximum Distance between Receiver and Sender	Less than 5mm
Data rate	1 Mb/s
Power Efficiency	~50%
USB standard	USB 2.0

Table 1.1: Device specification

1.4 Functional Objective

- Ability to support the inductive coupling devices.

- Ability to determine whether the receiver is suitable for data transfer. If not, only transfer power to the receiver. If it was possible, it could communicate with multiple devices at a time.
- Once the receiver is placed on the sender, the system operates automatically.
- Ability to be compatible with USB devices, and transfer enough power via the WPT system.

1.5 Usability Objective

- Sender and receiver are enclosed in separate parts.
- The receiver will have a button and a light. The button is used to switch on/off the sender and the light indicates whether the receiver is placed properly on the sender.
- Once the receiver is properly connected to the sender, the data transfer will automatically start as the user operates.
- When the coupling coils start to wirelessly charge, wire, inside of coils, may become warm.

1.6 Thesis Overview

A short sum-up of this project will be point out in this section. The project is supervised by Profession Graham Town, Senior Member of the IEEE and co-supervised by Dr. Nazmul Huda, lecturer in Mechanical Engineering. Weekly meeting with academic supervisor ensured that the project is on the right track to the set aims. Consultation Meeting Attendance Form is added in Appendix B of this document.

This thesis report is organized as follows. Chapter 2 describes the existing power transfer technologies and discuss advantages and disadvantages of each information communication technologies. The power transfer technologies include capacitive coupling, directive RF power beamforming, RF radiation, inductive coupling, and resonance coupling. And it also explains the standards and features of short-distance communication technologies including Bluetooth, near field communication, ZigBee, Wi-Fi, wireless USB and Infrared radiation. In the end, it compares each short-range communication technologies and selects the one that best fit. It also describes possible proposals that transfer information and power via a pair of inductive coils.

Chapter 3 will discuss three different proposals that could be realized in this project, and compare each of them, select a proposal that best fit. It starts with the three proposals: USB-interface WIT with a Bluetooth chip, USB-interface WIT with a development kit for Bluetooth, and USB-Interface via a pair of inductive coils. Then, it compares the first proposal with another two proposals and explains why the first proposal is better than another two proposals. It also describes the hardware selection for each proposal.

Chapter 4 discuss the main design issues in this project. Detail design split two ways: WPT system and WIT system. In the WPT system, it describes the wireless power modules that are used in this project. In the WIT system, it primarily consists of simulation results obtained from Matlab.

Finally, Chapter 6 sums up the thesis and describes its contributions. Then, the future work and future research are followed.

Chapter 2

Literature Review and Theory

2.1 Wireless Power Requirement

The keys for selecting wireless power systems depends on the requirement of the project. The chosen systems should satisfy the following requirements:

- It should have high reliability, easy operations and excellent compatibility. Thus, users do not have to learn any complicated operations, and it is simultaneously compatible with most of the existing produces.
- In order to let more customer to accept this product placing USB cable, the cost should be as cheap as possible, because of the low cost of USB cable.
- To control charging time into an acceptable range, the power efficiency should be as larger as possible. And the output voltage should be limited at 5 V.

2.2 Wireless Power Technologies

There are many short-range wireless power technologies, in this project, we need to select an appropriate technology to meet wireless power requirement.

As the Figure 2.1, wireless charging technologies can be classified into two parts: non-radiative Coupling-based charging and radiative RF-based charging. The former includes three main techniques: Inductive coupling, magnetic resonance coupling, and capacitive coupling, meanwhile it also is sorted into Directive RF power beamforming and non-directive RF Power transfer [22].

2.2.1 Capacitive Coupling

The available area of the device decides the achievable amount of coupling capacitance in capacitive coupling. But it is difficult to generate enough power density for charging for a normal-size mobile electronic device, such as mobile phones. Thus, it is a huge challenge to design a capacitive coupling system.

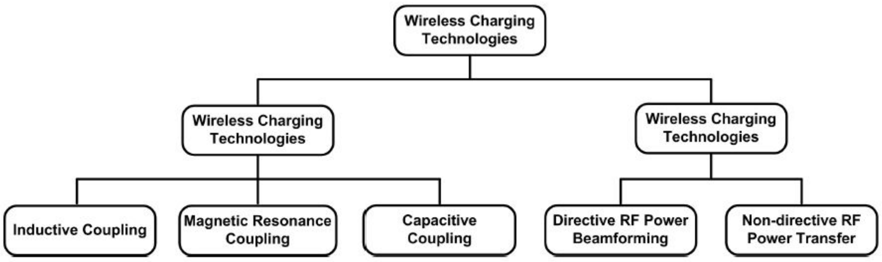


Figure 2.1: Classification of wireless charging technologies [22].

2.2.2 Directive RF Power Beamforming

The limitation of the directive RF power beamforming is that the power sender needs to know the exact location of the power receiver. Due to the limitation of above two techniques, the existing wireless power solution usually is based on other three techniques:

- Inductive Coupling
- Resonance Coupling
- Non-Directive RF Radiation

2.2.3 Inductive Coupling

Figure 2.2 shows the typically model for inductive coupling. The inductive coupling is generally defined as the near field wireless transmission between two coils where the resonant frequency is same. When the alternating current crosses the primary coil, it produces a varying magnetic field across the secondary coil at the receiver. The voltage, at receiver coil, can be used for supporting power to the portable device. The inductive couplings operating frequency is typically in kilo Hertz. Since the transferred power attenuates with increasing distance, the effective charging distance usually is in 20cm [42].It works best when receiver node and sender node are close in contact typically less than a coil diameter [24].

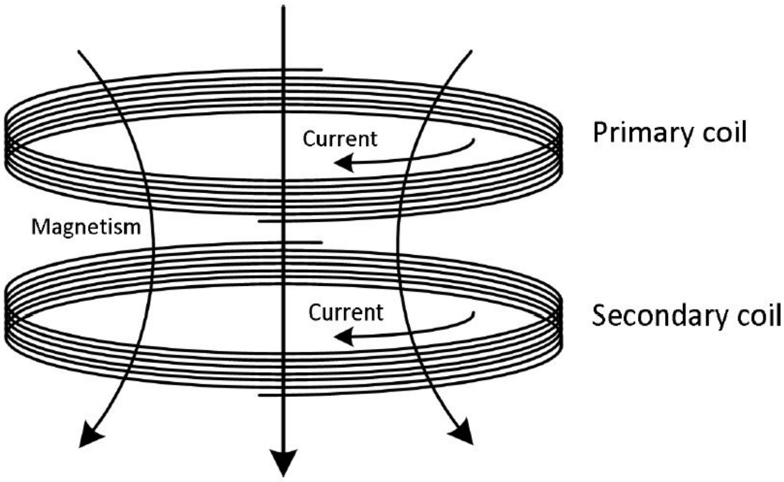


Figure 2.2: Model of wireless charging systems for inductive coupling [22]

The advantages of inductive coupling consist of easy operation, high power efficiency and low risk in a short distance. Thus, plenty of electronic devices has been already made based on this technology.

2.2.4 Resonance Coupling

The Fig2.3 shows the schematic diagram of the Magnetic Resonance Coupling, which generates and transfers electrical energy between two different objects because of the combination of inductive coupling and resonance. Also, when two resonant coils operate at the same resonant frequency, energy will be shifting back and forth between magnetic field around the capacitor. Because of the property of resonance, the magnetic resonance coupling only affects each other, which has the advantage of immunity to environment noise and line-of-sight transfer requirement. Some articles demonstrated that Magnetic Resonance Coupling is enabled to transfer power over a longer distance than inductive coupling, with higher power efficiency than non-directive RF radiation. Another advantage of magnetic resonance coupling is that can be used between one transmitting resonator and many power receivers. Thus, it could perform as a power hub which could charge multiple devices simultaneously.

The magnetic resonance coupling usually operates in MHZ range, which means the quality factors are quite high. The high quality factor helps coupling coefficient prevent from rapidly decreasing with the increase of changing distance. In 2007, The MIT research team announced that they were able to transfer 60W power over a distance more than 2 Meters based on strongly coupled magnetic resonance. And the efficiency increased up

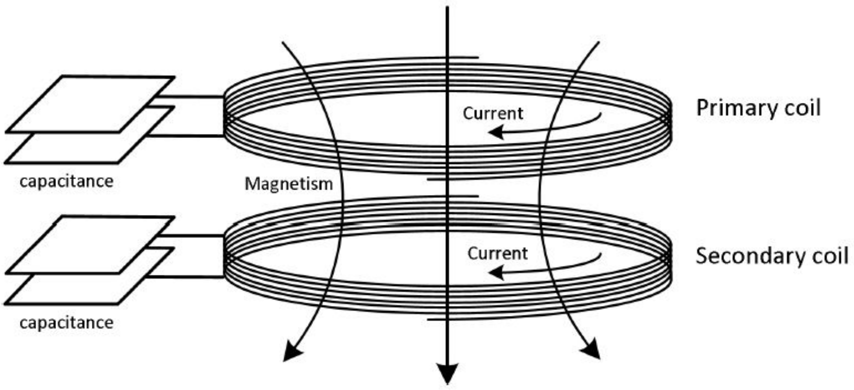


Figure 2.3: Model of wireless charging systems for Resonance Coupling [22].

to 90% when the distance is down to one meter. But, it is hard to reduce the size of the receiver due to the scale of a distributed capacitive in receiver [10].

2.2.5 RF Radiation

The diffused RF/microwave could be used as a medium to carry radiant energy, which is called an RF power transfer. In the spectrum of electromagnetic radiation, the frequency of RF ranges from 300MHz to 300GHz. The Fig2.4 shows the structure of RF/microwave power system. First, the power starts with the AC-to-DC converter; then the DC power crosses the magnetron converting DC to RF at the transmitter side. The receiver antenna would catch the RF/microwave; then RF-to-DC converter would rectify the RF/microwave into electricity.The captured power density depends on the RF-to-DC conversion efficiency at the receiver antenna [22]. After catching RF power, the impedance matching is used before the Voltage Multiplier which would convert the RF signal to DC power.

The RF energy could be radiated isotropically or toward the assigned direction by using beamforming. For point-to-point transmission, beamforming transition converts electromagnetic to energy beamforming, which can improve the power transmission efficiency. In order to improve the power transmission efficiency, increased number of transmit antennas could change the sharpness of energy beamforming via massive antenna arrays. For example, the Powercaster transmitter and receiver could isotropic transfer 1W or 3W power [15].

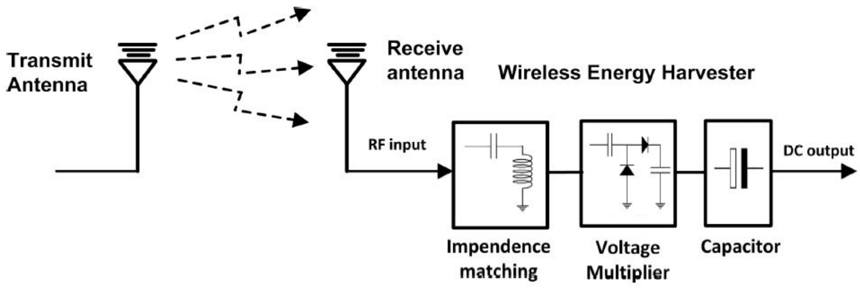


Figure 2.4: Model of wireless charging systems for RF/Microwave [22].

2.2.6 Summary of Wireless Charging Technique

The Table 2.1 [22] summarize the advantages and disadvantages of each wireless charging technique.

2.3 Selection of Wireless Power System

To select a suitable wireless power system, it is necessary to review what is the requirement of this project on Subsection 2.1.

The decision is made by following reasons:

- The safety factor is prior to all other parameters, and since the RF/Microwave radiation is not safe when the RF density exposure is high, thus, the RF/Microwave radiation has ruled out from the candidate. Then the wireless power system will be selected from the inductive coupling and resonance coupling. And the PWC represents the standard of inductive coupling while A4WP represents the standard of resonance coupling.

- In this project, this is a tightly coupled system between the Tx and Rx coils, since tightly coupled systems tend to produce less heat than loosely coupled systems, because tightly coupled systems have higher efficiency than loosely coupled systems have. This is an advantage to products with a tight thermal budget, specifically, smart phones.

Table 2.1: Overview of different wireless power techniques

Wireless Charging technique	Pros	Cons	Charging Distance	Application
Inductive Coupling	High charging efficiency, Safety for body, Suitable for portable device, high market share	Short Charging Distance, need tight alignment between sender and receiver	For a few millimetres to a few centimetres	Mobile Devices, Toothbrushes
Magnetic Resonance Coupling	Non-line-of-sight transfer, Multiple-device-charging	Middle charging Distance, low market share	For a few centimetres to a few meters	Mobile Devices
Microwave radiation	long charging distance	Low charging efficiency, line-of-sight transfer, not safe when the RF density exposure is increased	For several tens of meters, up to serval kilometres	RFID card, wireless sensor

- To receive high energy from Resonance transmitter, it causes increased electromagnetic interference with lower efficiency comparing with inductive coupling.

First, it is a short-range distance project. The microwave radiation has long charging distance with low power efficiency which is highly unsuitable with this project. Thus, the microwave radiation is excluded from the list. The rest is inductive coupling and resonance coupling. The significant feature of Resonance Coupling is multiple device charging which is not required in this project. Moreover, the Inductive Coupling has higher power efficiency than resonance coupling has. In addition, the standard of the Inductive Coupling while the standard behind the Resonance Coupling is A4WP. The market share of Qi standard is higher than A4WP. For example, The Qi devices have high market share. 80% of car manufacturers claimed that they will release cars with support for Qi standard. Also now 15 cars have built-in Qi changers or available as a factory option, such as the new 2016 Toyota Camry [25]. Qi devices are widely applied in many applications. Overview, the advantage of Inductive coupling's advantage is not obvious in this application, but since the market share of the Inductive-coupling-based devices is much higher than those of Resonance Coupling. Therefore, Inductive Coupling is selected.

2.4 Short-Range Wireless Information Transfer requirement

The rest of this chapter decreased how to add a wireless information transfer system into the wireless power system. Also, the data rate should be as larger as possible to be compatible with USB 2.0. To increase the bandwidth of a coupled-inductor circuit, the circuit design, and the gap distance will be considered in this chapter.

2.5 Currently Short-range Wireless Technologies

Plenty of wireless technologies are available and standardized such as Bluetooth, NFC, ZigBee, and Wi-Fi. Most are produced in small, low-cost IC chips or in complete modules. It is a challenge to select a suitable technology for a given application.

2.5.1 Bluetooth

Figure 2.5: Bluetooth Smart [14]

The Bluetooth wireless communication as a wireless alternative to communicatin cable by using the ISM band from 2.4 to 2.485GHZ [13]. Now, there are two main versions of Bluetooth devices: Version 3.0 + HS (high speed) and Version 4.0.

The Version 3.0 + HS has two signification features: high speed and enhanced power control.The data-substitution method is applied in Bluetooth devices which provide faster throughout via briefly use a subsidiary radio. By using a secondary radio, Bluetooth devices could have a high-speed communication while reduces costs. Another advantage of Bluetooth is 'enhanced power control' that reduces consumption by using high-speed radio only when needed. To achieve power control, the open loop power control is removed via design a new closed looping power control [14].

BLE (Bluetooth Low energy) is a subset of Bluetooth Version 4.0 with extra power efficiency. It is perfect for low-battery devices that run for long periods on batteries. The

Bluetooth 4.0 chip is designed to be used in the novel applications such as health monitoring, fitness, beacons and home entertainment. Comparing with the Bluetooth Version 3.0, BLE provides fairly reduced power consumption and cost while retaining a considerable communication range.An Australian Company called Daelibs, develop Bluetooth beacons as a location attendance device which is being used in a mine in Australia. It helps companies keep track of location and safety of staff [28].Because of the BLE technology, Daelibs' produce, called Ambient intelligence, is able to keep monitoring on power sources for a long period.

2.5.2 Near Field Communication

Figure 2.6: NFC [27]

The NFC wireless communication uses the 13.56MHz band. Two devices can activate communication by bringing them within 4cm of each other.The NFC specifications have been combined in contactless cards and mobile phones for reading data and exchanging information such as Australian Commonwealth Credit cards and Samsung galaxy S6. As an ultra-short-range technology, NFC was designed for secure payment transactions and so on. The maximum distance between a sender and a receiver is about 20 cm, and the typical link distance is 4 to 5 cm.

The NFC are powered up by the interrogation of an NFC communication signal while reading NFC tags. The low-power tags could convert communication signal into DC that supports processor inside of a passive NFC tag. Thus, NFC tags do not require batteries. They get power from being near a power NFC device without power sources. Also, the NFC is compatible with existing RFID infrastructures. But the NFC power consumption is larger than that of Bluetooth V4.0 BLE because activating the passive tag require extra power [27]. There are numerous NFC transceiver ICs are available to design new applications, and many standards exist:

- ISO/IEC
- GSMA
- ECMA 340
- ECMA 352

2.5.3 ZigBee

Figure 2.7: ZigBee [43]

The ZigBee is a wireless global standard to structure low-cost, low-power networks. Based on the IEEE 802.15.4 physical radio specification, the ZigBee standard operates at unlicensed bands consisting with 2.4GHz, 915MHz and 868MHz. For the 2.4GHz band, there are sixteen channels, the maximum data rate reaches 250kbps. At the 915MHz band, there exists ten channels and the maximum data rate is 40kbps, when at the 868MHz band, only one channel exists with 20kbps maximum data rate.

The distance that can be realized transmitting from a ZigBee device to the next station up to 70 meters. Also, the distance could be achieved a much greater distance by relaying data from one node to the next node in a network. At the same time,the maximum packets size of data is 128 bytes, which allows for 104 bytes maximum payload [43]. Therefore, the ZigBee should be used to the applications that are not required high data rates such as lighting controls, tank monitoring, and building automation systems. But ZigBee enables deployment of a wireless network with low-cost and low-power features.It could support few monitoring and control applications to run for years on low-cost batteries [23].

2.5.4 Wi-Fi

Wi-Fi is one of the most of the common wireless technologies in the daily life, allowing fixed or mobile devices to connect to a WLAN network. It mainly operates in 2.4GHz and 5GHz radio band [39]. It is widely used and available in residential areas and public place - consisting of coffee bars, hospitals, and universities. It structures one of the most popular wireless communication technologies available today.

There are four major different types of Wi-Fi including 802.11a, 802.11b, 802.11g and 802.11n. Each of standards can communicate with each other,nevertheless newer visions can provide better performance. 802.11b and 802.11g are the two most common Wi-Fi

Figure 2.8: Wi-Fi [39]

types, which operate at 2.4GHz radio band. The following table 2.2 shows the main characteristics of Wi-Fi stands:

Wi-Fi	Modulation	Enhanced Data Speed Up to	Indoor Distance
802.11a	OFDM	54 Mbps	35
802.11b	DSSS	11 Mbps	35
802.11g	OFDM	54Mbps	38
802.11n	MIMO-OFDM	350MHz	70

Table 2.2: Wi-Fi standards [39]

There are plenty of Wi-Fi chips and modules available to implement numerous applications such as smartphones, laptops, and tablets. This is a great choice where long-distance and higher data speeds are required for applications.

2.5.5 Wireless USB

The Wireless USB is a short-distance wireless communication protocol with high bandwidth, which created by Wireless Promoter Group. Wireless USB was designed based on the UWB(Wimedia Alliance's Ultra-WideBand) common platform that is enabled to send 480Mbit/s at the maximum distance up to 3 metres [38].

The Wireless USB is a high-speed personal technology, aiming to the satisfied need of PC peripherals, mobile devices, and multimedia devices.There is a signification advantage

Figure 2.9: Wi-Fi [38]

of the Wireless USB that will preserve the functionally of the wired cable USB and unwriting the cable connection. This provides supports for streaming multimedia devices and PC peripherals. Also, since there is no wires or ports required, there is no longer required for hubs, and Wireless USB architecture allowed to connect a host with up to 127 devices.The data rate of Wireless USB reaches up to 480Mbps [38] which matches the capabilities and transfer rates of USB closely and enables to design a natural wireless application for USB.

To be compatible with the existing USB device from wired to wireless, Deice Wire Adapter (DWA) is introduced, also called 'Wireless USB hub', which allows existing USB 2.0 device to be connected with a wireless USB host. Wireless USB host could be connected to existing PCs by the use of a Host Wire Adapter(HWA), which is a USB 2.0 device that connects to a desktop or laptop's USB port.

2.5.6 Infrared radiation

Figure 2.10: Infrared Data Association

Infrared wireless technology use low-frequency, invisible light instead of radio, which can serve as a +carrier of high-speed data. The IR data transmission is used in the short-distance communication among peripheral and control systems. IrDa (Infrared Data Association) established standards of the infrared wireless communication. The Remote controls and IrDA devices use LEDs to emit infrared signals that are modulated to prevent disturbance from another light source such as sunlight and lamplight. The receiver converts the infrared radiation to the digital signal, which only responds to the rapidly pulsing signal from the transmitter and ignores slowly infrared changing from another light source. Nevertheless, modulation and receiver could decrease interference from other sources of infrared , it cannot completely isolate interference. Thus, Infrared communication technology tends to be used for indoor use. However, Infrared radiation could not penetrate walls and do not generate an electromagnetic field. So it does not interfere with any electronic devices.

2.5.7 Summary of Short-range Wireless Technologies

Table 2.3 shows the main characteristics of short-distance wireless technologies.

	Standard	Bandwidth	Distance	Modulation
Bluetooth 4.0	802.15.1	24 Mbit/s	60.96 m (200 feet)	MB-OFDM
NFC	NFC Protocol	424 kbit/s	Max. 20 cm	ASK
ZigBee	802.15.4	250 kbit/s	70 m	BPSK, OQPSK
Wi-Fi	802.11n	Max. 600 Mbit/s	100 m	DBPSK, DQPSK, etc
Wireless USB	802.15.3a	53480 Mbit/s	3-10 m	MB-OFDM
Infrared	IrDA	16Mbps	Depend on the wavelength	38kHz Modulation

Table 2.3: Specifications of each short-range technologies [14] [27] [43] [39] [38]

2.6 Selection of Short-range Wireless technology

To select a suitable short-range wireless technology, it is necessary to understand what is the features of each technology.

2.6.1 Bluetooth V3.0 VS Bluetooth 4.0

- The Bluetooth V3.0 provides the highest data rate of up to 24 Mbit/s and enhanced power control.
- The features of Bluetooth V4.0 is ultra-low power. The single-mode chips of Bluetooth V4.0, feature a ultra-low power idle mode, reliable point-to-multipoint data transfer with low-power and secure connections. Also, Bluetooth V4.0 includes the main features of Bluetooth 3.0.

Thus, Bluetooth V4.0 has better power efficiency with low-cost better than Bluetooth V3.0 has.

2.6.2 Near Field Communication VS Bluetooth 4.0

- The cost of NFC tags are much lower than that of Bluetooth 4.0. But the bit rate of NFC tag is up to 424 kbit/s meanwhile the highest data rate is up to 24 Mbit/s.

- NFC standard is based on the existing RFID standards, and it just a platform for establishing communication between two devices. But hacker could eavesdrop the NFC transaction and steal the data when NFC communication was established. But Cryptography is used in the Bluetooth communication.

- The NFC only supports point-to-point communication, but Bluetooth V4.0 could provide a WPAN network.

For a wireless communication, guaranteeing the security of information transfer is a significant point, but the NFC communication transfer is not encrypted. Although the cost of NFC tags is much lower than Bluetooth chips Bluetooth V4.0 chips are not costly. Bluetooth V4.0 has longer communication distance than NFC has, and Bluetooth V4.0 support point-to-multipoint communication, but NFC only performs point-to-point communication. Although USB communication does not require point-to-point communication and long distance communication, Bluetooth V4.0 has a better performance than NFC has.

2.6.3 ZigBee VS Bluetooth 4.0

- The power consumption of any wireless communication system depends on the type of data being transferred, the distance between the sender and receiver, required power to be retained by signals. Bluetooth is a protocol that exchanges almost all types of data such as multimedia, message; meanwhile, ZigBee is protocol known for operational instruction, thus, not much plenty of data is to be exchanged by ZigBee. Summary up, ZigBee consumes remarkable less power than Bluetooth. For most of applications, ZigBee instrumentations are 2.5-3 times more power efficiency than Bluetooth devices.

- The maximum data rate of Bluetooth V4.0 is up to 3 Mbps while ZigBee-based networks have the maximum data up to 240 Kbps.

Based on the features of ZigBee, ZigBee-based communication aims to structure a wireless networking among sensors and small size, low-power devices, for example, Smart Home Control system, medical instruments. BlueTooth-based system is used in PCs peripherals such as wireless keyboard, Surface pens, wireless head speakers and so on. Since this thesis aims to design a WPIT to replace USB cable, it should be able to transfer most of the data with high data rate. But ZigBee is not able to reach high-speed data transfer, and not much types of data could be exchanged based on a ZigBee system. Thus, ZigBee is ruled out.

2.6.4 Wi-Fi VS Bluetooth 4.0

- Bluetooth technology is designed to transfer data between two or more than two devices.Bluetooth adaptors could directly connect with each other. Wi-Fi is suited for structuring networks due to faster connections and better range. But wireless adaptors are required to access wireless router or wireless access points.

- The cost of Wi-Fi modules or packages is expensive than Bluetooth's price, which is an advantage of Bluetooth. Also, Bluetooth is fairly simple to operate, and can be used to connect multiple devices at a time. It is easy to discover new devices or switch between devices.

Wi-Fi has much higher information transfer rate than Bluetooth has, and larger distance as well. But consider the aim of this thesis, distance is not a significant point. The bit rate of Wi-Fi is more suitable to USB 2.0 speed, which can send and receive more data than Bluetooth in a certain period of time. However, the power supply of USB is limited and the Wi-Fi has much higher power consumption. On the other side, Bluetooth is more customer-friendly, which only requires a simple operation to connect each other. But Wi-Fi is more complex and configuration of hardware and software. Therefore, in this special application, Bluetooth is more suitable than Wi-Fi.

2.6.5 Wireless USB VS Bluetooth 4.0

- Wireless USB is developed by USB Promoter Group, and it is compatible with USB2.0. It could structure true USB systems, formed by host and device support. It also allows common wired USB devices to be connected and has a fully compliant USB interface. Wireless USB could be considered as a multiple wired USB. Because it supports one or more communication pipes to host.

- Wireless USB could easily adapter with USB interface since it is a general USB-based technology. On the other side, Bluetooth may have a connection issue with USB interface.

Although Wireless USB provides greater transfer speeds, Bluetooth V4.0 data rate can satisfy most of the transfer needs. And wireless USB is more compatible with USB 2.0, it is a general USB-based technology. On the other side, after years developments, there are plenty of Bluetooth devices have USB interface, thus, the interface issue is not a huge design problem.

But it is very hard to find wireless USB modules or chips. On the Australian local electronic components storage, such as Element 14 or RS Online, there are barely wireless USB components while plenty of Bluetooth modules or chips are selling online. On the other side, Fig 2.5 shows the Bluetooth has a much higher market share than Wireless USB has. Now, it is a trade-off between data rate and development-friendly. Due to the time limit of the thesis, Bluetooth is the winner.

2.6.6 Infrared Radiation VS Bluetooth V4.0

- The line of light. The infrared transmitters and receiver must be almost directly aligned; otherwise, the communication may disconnect. Also, the communication may be blocked by materials, such as paper. Once transmitters or receivers are covered by materials, communication shut down.

- The infrared radiation is sensitive. Direct sunlights, rain, fog, dust could affect transmission, even disconnect communication.

The Bluetooth V4.0 has no line of light, common materials would not block communications, and it can connect each other penetrating most solids or walls. Also, Bluetooth is not as sensitive to environmental conditions. Thus, Bluetooth is much suitable for this thesis.

2.6.7 Summary of Information Technology Selection

The previous sections 2.6.1 to 2.6.6 show the advantages and disadvantages of Bluetooth V4.0 and other technologies. In the end, based on the previous comparisons, the Bluetooth is selected to be the information system in this thesis.

2.7 Combine Wireless Power and Wireless Information Transfer

In the history, Claude Shannon and Nikola Tesla designed a similar coupled-inductor circuit in the Fig 2.11. The Tesla designed it to transfer power, while Shannon used it to deliver information [21]. Based on that, it is possible to design a wireless information and power transfer system across an inductive coupling circuit.

In this proposal, we need to consider the bandwidth efficiency and energy efficiency of wireless network which are the primary resource constraints.

Trade-off between capacity and received power

The available power is defined as [21]:

$$\int_f \left(\frac{log_2(e)}{\lambda_{water}} - \frac{N_0}{\eta(f)}\right)^+ df = P^{avail} \tag{2.1}$$

Assuming the $P^{del}_{water} = P^{avail}$, then $P^{del} \geqslant P^{del}_{water}$

From the David and Pramod's book [34], when the maximum rate is reached, the optimal power allocation is given by $P^*(f) = (\frac{log_2(e)}{\lambda_* - \eta(f)\mu^*} - \frac{N}{\eta(f)})^+$ then

$$\int_f \left(\frac{log_2(e)}{\lambda^* - \eta(f)\mu^*} - \frac{N}{\eta(f)}\right)^+ df = P^{avail} \tag{2.2}$$

and

$$\int_f \eta(f)\left(\frac{log_2(e)}{\lambda^* - \eta(f)\mu^*} - \frac{N}{\eta(f)}\right)^+ df = P^{del} \tag{2.3}$$

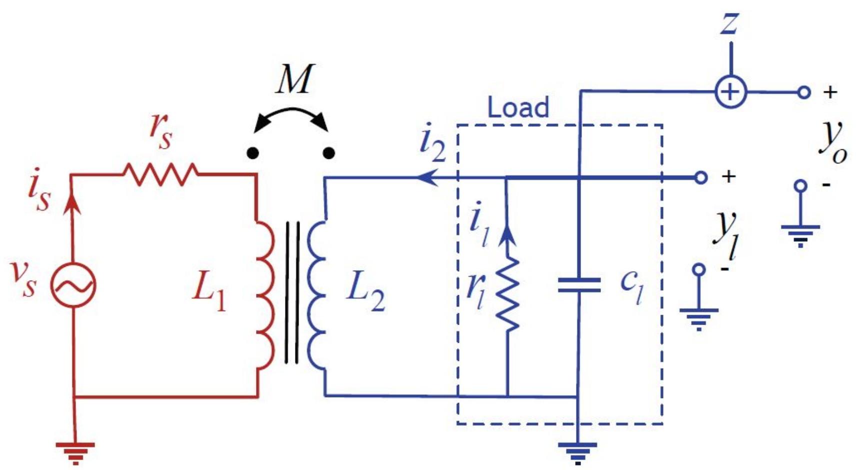


Figure 2.11: Claude and Nikola's Combined Circuit [21]

The optimal power allocation reaches the following maximum $C(P^{avail}, P^{del})$ is given by [21]:

$$C(P^{avail}, P^{del}) = \int_f log_2(1 + \frac{\eta(f)P^*(f)}{N_0})df \tag{2.4}$$

In the Grover and Sahai's report [21], it describes a model of wireless and information transfer system. The circuit is showed in Fig 2.11. Fig 2.12 represents the trade-off between capacity and receive power when $L_1 = L_2 = 0.1mH, M = 0.03mH, r_s = 10\Omega, r_l = 10k\Omega$ and $c_l = 10\mu F$.

In the equation 2.3, it shows that the optimal power allocation depends on the value of $\eta(f)$ and P^{del}. However, the value of P^{del} is affected by $\eta(f)$ [21]. Increased $\eta(f)$ would decrease P^{del}; while to increase P^{del} $\eta(f)$ will decrease. Then since the log in the equation 2.2, the relationship between $\eta(f)$ and P^{del} is not linear.

To achieve the best performance of wireless power system, it is necessary to guarantee the both of capacity and P^{del} at a suitable level. Therefore, in this case, when the capacity could be selected between 70 to 60 bit/sec, the P^{del} would be around 95 Watts. Then in this conditions, the power efficiency and data rate are traded-off with good performance.

Power Efficiency Function

The efficiency function $\eta(f)$ for the right-side circuit, is shown below [32]:

$$L_2\frac{di_2(t)}{dt} + M\frac{di_s(t)}{dt} + i_l(t)r_l = 0 \tag{2.5}$$

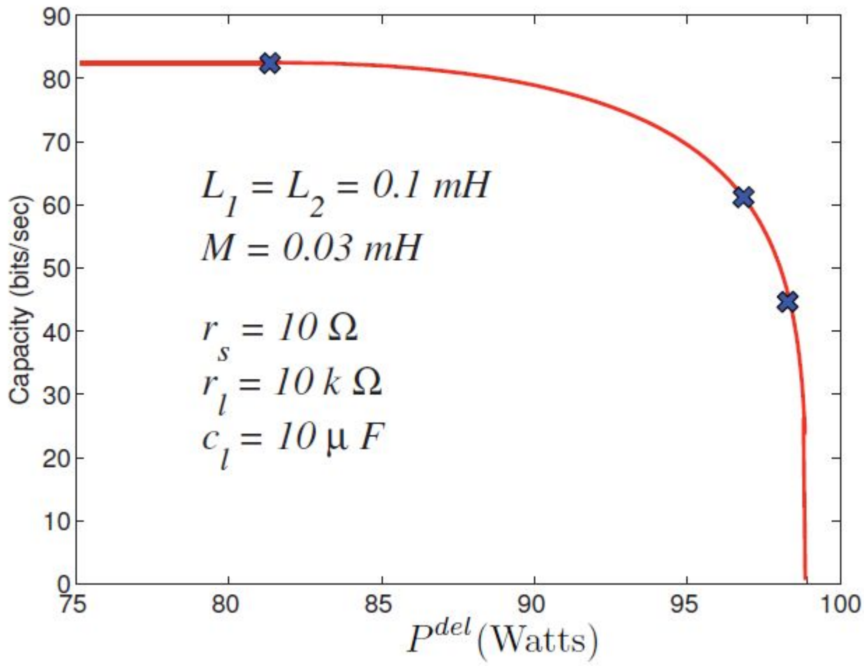


Figure 2.12: Tradeoff between capacity and received power [21]

Then Fourier Transform is used in the above equation:

$$j\omega L_2 I_2(j\omega) + j\omega M I_s(j\omega) + I_l(j\omega) r_l = 0 \tag{2.6}$$

Then

$$I_l(j\omega) = \frac{j\omega M}{j\omega L_2(1 + j\omega r_l c_l) + r_l} \tag{2.7}$$

Assuming that the power consumed at the source resistance r_s is

$$P_s = \int_\omega |I_l(j\omega)|^2 r_l d\omega \tag{2.8}$$

Further, algebraic manipulation of (4.3) and (4.4) [18]

$$\eta(\omega) = \frac{|I_l(jw)|^2 r_l}{|I_l j\omega|^2 r_l + |I_l(j\omega)|^2 r_l + |I_s(j\omega)|^2 r_s} \tag{2.9}$$

Finally,the efficiency function is represented as $\eta(f) = \eta(\frac{\omega}{2\pi})$.

Bandwidth and Message Signal

To achieve a high bandwidth and bandwidth efficiency, it requires having a spectral-efficiency modulation and a high-frequency carrier signal.

In the Gokhale's book [20], it introduces the Carson's bandwidth Rule:

$$BW = 2(\Delta f + f_m) \tag{2.10}$$

The Δf is peak frequency deviation and f_m is the highest frequency of message signal

In the USB 2.0 POwer Delivery specification [36], it defined the USB nom frequency deviation is 500 KHz.

Assuming the bandwidth of WPIT is 4MHz

$$4MHz = 2(500KHz) +_m \tag{2.11}$$

then

$$f_m = 1.5Mbits/s \tag{2.12}$$

Thus, the largest data rate of this proposal is 1.5 Mbits/s.

Modulation Selection

In the book [19] Table 3.1 compares the Carrier-to-noise ratio(CNR) and energy per bit to noise power spectral density ratio(E_b/N_o) required for a selection of MPSK and QAM to yield a probability of bit error of 10^{-6}.

Modulation	C/N ratio(dB)	E_b/N_o
BPSK	10.6	10.6
QPSK	13.6	10.6
4-QAM	13.6	10.6
8-PSK	18.8	14.0
16-PSK	24.3	18.3
16-QAM	20.5	14.5
32-QAM	24.4	17.4
64-QAM	26.6	18.8

Table 2.4: Comparison of various digital modulation schemes when $P_b = 10^-6$ and $B_T = 1.0$ [19]

Comparing QPSK with QAM, the C/N ratio is exactly same, but QPSK has a higher Eb/N0(the energy per bit to noise power spectral density ratio)than QAM has, which means QPSK could transfer more signal instead of noise for each bit. Although 8-PSK or 16-PSK has higher spectral efficiency, it is hard to design a modulator or demodulator circuits with higher cost. Thus, QPSK is selected as the information system modulation.

Chapter 3

WIT Proposals

In the development period, there are three different proposals:

- USB-interface WIT with a Bluetooth Module
- USB-interface WIT with a development kit for Bluetooth
- WPIT Via A Pair Of Inductive Coils

and in the rest of chapter, we describe advantages and disadvantages of both of design, then based on the requirements of this project, trade-off between two proposals, in the end, select a suitable proposal in this application.

3.1 USB-interface WIT with a Bluetooth Chip

This proposal is based on Bluetooth chip. The requirement of a Bluetooth chip should satisfy the following requirements:

- The Bluetooth chip is based on Bluetooth V4.0.
- The Bluetooth must have BLE feature.
- The full-duplex mode (provides communication in both direct at a time) is not necessary. The half-duplex(allow communication in both direction,but only one direction at a time) is more cost-efficiency and power efficient.
- To be compatible with USB interface, the Bluetooth chip must have USB or UART interface.

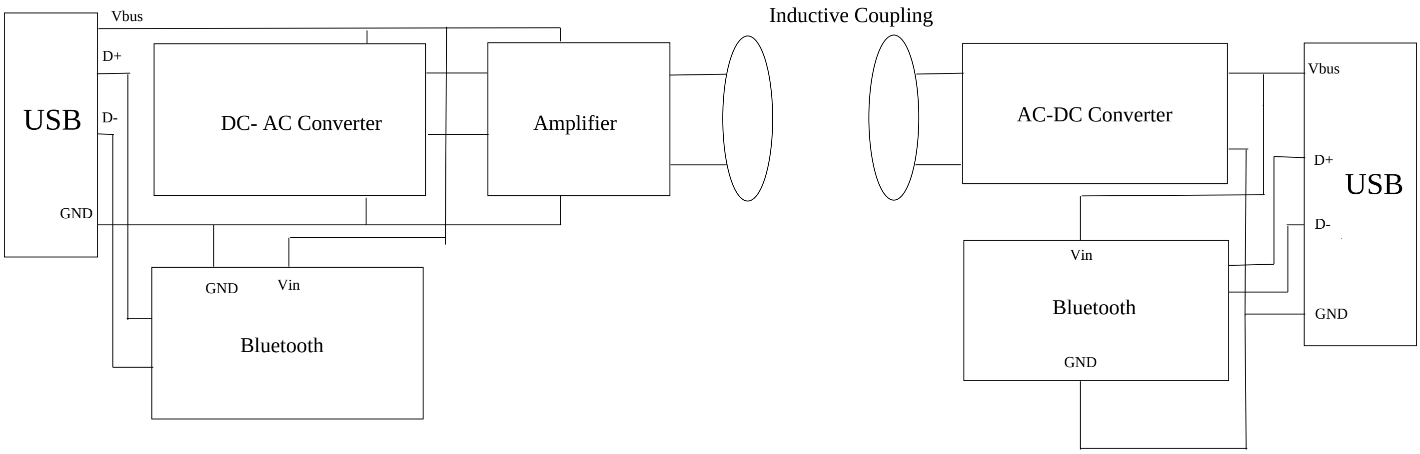


Figure 3.1: The simple schematic of second proposal

3.1.1 Hardware Selection

The general circuit schematic is given in Fig 3.1.

The Bluetooth chip, whether it is in a sleep mode or communication mode, must consume as little power as possible. Because, in this project, the power efficiency and is of major concern since it is unreasonable making a WIT system that consumes more power without achieving the low power requirement. The higher power the information system consumes, the lower power efficiency the WPIT system achieves. From system design point of view, this is important. In the selection process, different Bluetooth chips are analyzed in order to select the one that best fit.

All the possible chips offer the Bluetooth low energy features. For example, the PAN1720 has a very low power consumption of less than 5 mA with 2.35 to 3.3 V in the Tx mode that allows it to operate on coin batteries for few years.

BlE112-A-v1

BlE112-A-v1 is a Bluetooth low energy single mode chip that offers all Bluetooth all energy features: read, stack, profiles and application space. Since BLE112 only cost 400 nA [1] and will wake up in few hundred ms in the sleep mode, it provides an excellent performance as a low-power information system.The highest data of BLE112-A-v1could reach 1 Mb/s. According to the data sheet of BLE112 [1],the USB D+ and USB D- are on Pin 11 and 12, and the Pin 9 and Pin 10 are on the V_{DD} and GND.

BlE113-A-v1

BlE113-A-v1 is an ideal Bluetooth Module for small and low power sensors and applications. Comparing with BLE112, BLE113 reduces 30% size and only uses 30% less power than BLE112 with 3 V DC power supply [2]. Also, its highest data rate could reach 2 Mb/s that is 1 Mb/s faster than data speed of BLE112.

PAN1720

PAN1720 satisfies the requirements of WIT system as well. The PAN1720 is another ideal choice for application where very low power consumption is required. The PAN1720 uses only 500 nA in the sleep mode and will wake up in 3 us from the sleep mode [6]. Its highest data could achieve 1 Mbps.

PAN1740

The Panasonic PAN1740 module is the upgraded version of PAN1720 module with lower size and power consumption. The PAN1740 is only 9.0*9.5*1.8mm, is the one of the small BLE components available with full shield case. It only consumes 5 mA power in Tx or Rx mode [7].

Summary of Bluetooth Modules

Table 3.1 compares the specifications of different popular Bluetooth chips on the market.

	PAN1740	BLE113-A-v1	BLE112-A-v1	PAN1720
Price	$28.14	$18.46	$19.02	$27.36
Data rate	1 Mb/s	2 Mb/s	1 Mb/s	1 Mb/s
Supply Voltage	2.35 V to 3.3 V	2 V to 3.6 V	2 V to 3.6 V	2 V to 3.6 V
Interface Type	I2C, SPI, UART	UART	SPI, UART, USB	SPI, UART, USB
Mfr.	Panasonic	SiliconLabs / Bluegiga	Silicon Labs / Bluegiga	Panasonic

Table 3.1: Specification of Bluetooth chips

3.1.2 Trade-off Between Bluetooth Modules

In all the possible choices, although the BLE113 has the best performance (smaller size and lower power consumption) and lowest cost, it only supports UART interface. So BLE113 requires a UART-to-USB Converter to communicate with PCs and other USB-interface devices. Similarly, PAN1740 only supports UART interface as well.

The rest of options are BLE112-A-v1 and PAN1720. Both of them is powered from 2 V to 3.6 V DC supply, also supports SPI, UART, and USB interface. But the BLE112-A-V1 is only $19.02 per module, and PAN1720 is $ 8.34 higher cost then BLE112-A-v1 price.In the end, the BLE-112-A-v1 only not has the cost the second least amount but also supports USB interface. Although its data rate is lower than another option, it is the best option that fit project requirements.

3.1.3 DC-DC Converter

According to the datasheet of the Bluetooth chip BLE112-A-v1, the input voltage is 2.35 to 3.3 V while the DC input voltage of USB power supply is 5 V. The system input voltage is not suitable to the Bluetooth chip. To match input voltage to the Bluetooth chip, it requires a DC-DC converter to reduce the input voltage to around 3.3 V. The maximum power consumption is in the Active Mode Tx 2 dBm that requires maximum 36 mA current with 5 V input voltage.

Then the maximum power consumption of the BLE112-A-v1 is:

$$P = 36 * 10^{-3} * 5 = 0.18W \tag{3.1}$$

The we decide to use RM-053.3S DC-DC converter to match the input voltage for Bluetooth chips.

Input Voltage Nominal	5 V DC
Input Voltage Range	4.5-5.5 V DC
Output Voltage	3.3 V DC
Output Current	0.076A
Efficiency (Max.)	72%

Table 3.2: Specification of DC-DC converter [8]

The RM-053.3S is a 0.25W SIP Single Output Unregulated Isolated DC-DC Converter, which could provide enough power to the Bluetooth chip with an appropriate output voltage. Although the power efficiency is 65-72% [8], which is not a high-efficiency converter. But consider the nominal output power is 0.25 W, the power loss would be controlled less than 0.1 W. Comparing with the power loss in the inductive coupling, this power loss could be ignored. Also, this DC-DC converter has the short circuit protection. If the wireless power system was short-circuited, it would not affect and damage the Bluetooth chips, isolate wireless power system from the whole system, and avoid further losses.

3.2 USB-interface WIT with a development kit for Bluetooth

This proposal uses microprocessor development board to communicate with Bluetooth chips instead of directly connecting to Bluetooth chips. The advantage of this proposal is that it simply the circuit. Because the microprocessor development board has the USB interface and low voltage supply, we do not have to design or consider the voltage matching and USB interface connection. It could significantly shorten the design period by simplifying the circuit design. Obviously, the disadvantage is the increasing cost.

3.2.1 Controlling Unit

Before selecting a Bluetooth development kit, we need to decide what controlling unit or microprocessor development board that is used in the proposal. For this project, power efficiency is the major concern since there is no point making the information transfer system that consumes much power. The higher power the controlling unit consume the less power efficiency. From the engineering system design of view, this is undesirable. In the end, different microprocessor development boards are considered in order to select the one that best fit.

Table 3.2 compares the common microprocessor development boards on the market.

	Arduino Uno RV3	Arduino Mega 2560	Raspberry Pi 2B
Clock Speed	16 MHz	16 MHz	9000 MHz
Flash	32 Kb	256 Kb	Max. MicroSD 32Gb
RAM	2 Kb	8 Kb	1 Gb
USB Port	1	1	4
Power	0.3 W	2.75 W	4 W
Cost	$ 44.32	$ 79.19	$ 59

Table 3.3: Specifications of microprocessor development boards [11] [12] [30]

Among the all possible choice, the Arduino not only has the lowest cost but also has the least amount of power consumption. And consider about the power efficiency, and the Arduino Uno has the best power control with only 0.3 W. Moreover, there are plenty of Arduino Bluetooth modules on the market. In the end, Arduino Uno is not just a cost-effective choice in terms of finance and power, but also is compatible with Bluetooth modules.

3.2.2 Bluetooth Module

Figure 3.2: The HM-10 Bluetooth module

The HM-10 requires 3.3 V DC power supply and the Arduino Uno could provide 3.3 V power supply instead of a DC-DC converter. In this case, the information could be transmitted to Arduino Uno, and Arduino UNO could send information to the HM-10 Bluetooth module via UART interface.

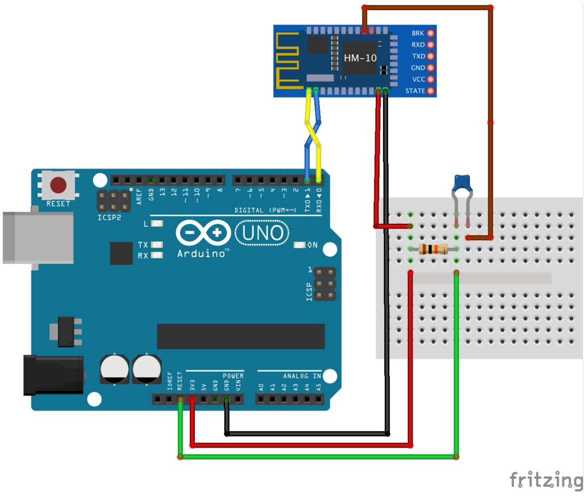


Figure 3.3: HM-10 Bluetooth connection

The HM-10 Bluetooth Module is given in Fig 3.2. The connection between the HM-10 Bluetooth Module and Arduino Uno is shown in Fig 3.3.

3.3 USB-interface WPIT Via A Pair Of Inductive Coils

This proposal is discussed in section 2.7. It combines wireless power system and wireless information system together. Comparing with previous proposals, this proposal is more complex and harder to implement. Unlike the previous proposal, in this proposal, the WIT system is integrated into the WPT system, thus, we could not use the existing WIT modules such as Bluetooth. It greatly increases the complexity of circuit design and extends design period.

Circuit Design

Fig 3.3 shows a simple circuit of this proposal. For the USB 2.0 type A, there are four pins: two for power transfer (Vbus and GND and two for differential data signal (D+ and D-). D+ and D- constitutes a differential pair, providing half-duplex transfer to USB 2.0. Fig 3.4 shows the pin configuration of USB 2.0 type A.

Design Proposal

This proposal requires a modulator and a demodulator to operate information transfer.According to the section 2.7.2, the QPSK is selected as the modulation in this project.

The NRZI (Non-Return-to-Zero Inverted)encoding is used to transfer data in pin D+ and D-, also it can synchronize the host and receiver clocks. Unlike the traditional signal transfer, the differential signaling uses two complementary signals to transmit information.

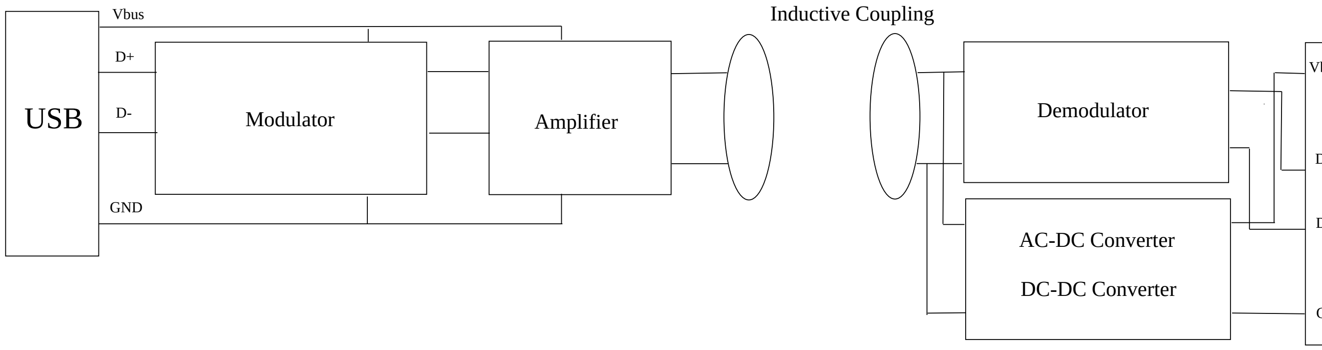


Figure 3.4: The simple schematic of first proposal

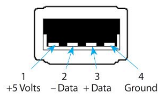


Figure 3.5: Pin configuration of USB 2.0

Since the receiver only needs to detect the difference between two differential signals, it resists electromagnetic noise compared to single-ended signaling. But in this application, we only have a pair of coils to transmit information. Thus, we have to restore differential signal to single-ended signal. After that, to transmit signals via inductive coils, it requires modulation to reduce the effect of noise. But no matter what modulation it uses, single-ended inputs always has the noise problem, especially, EMI or RFI is present. Also, the small signals are very susceptible to noise. Thus, in this proposal, the noise figure of each component should be as small as possible. Otherwise, the receiver would have many wrong bits that lead to loss packets.

Moreover, to match with USB interface and the modulator and the demodulator, it requires multiplexers(MUX) and demultiplexers(DEMUX). The multiplexer is used to convert USB differential signals to a single-ended signal. Then the single-ended signal is modulated to be transmitted to the receiver. Meanwhile, the receiver would use the demultiplexer to restore the single-end signal to USB differential signals.

To match with USB interface, the output of the AC-DC converter should reach 5V, also the demodulator needs to restore modulated signals to differential signals. Thus, the receiver device could be enabled to recognize input signals.

3.4 Selection of Proposals

3.4.1 First Proposal VS Second Proposal

USB-interface WIT with a Bluetooth Chip does not need any microprocessor development boards that consume extra power. It is no reasons to add an extra power-consuming component into the circuit. Although microprocessor development boards have a potential for peripheral development, could give users or developer infinite possible to add other modules into the system, there is no concern about peripherals for this project. Moreover, Bluetooth chips could directly connect with laptops or desktop without any extra components. From the engineering design point of view, any extra power consumption is undesirable, and we should avoid wasting any power. On the other side, adding a microprocessor development board into circuit would significant increase the size of the receiver and the sender without meeting the requirement of the project. Moreover, the largest differences between two proposals are the power supply. In the first proposal, there is a DC-DC converter to convert 5 V USB DC to 3.3 V DC that power the Bluetooth chip; meanwhile, the second proposal could easy power from Arduino Uno. Also, the Arduino Uno need to be programmed to run the Bluetooth Module.

Thus, the first proposal is much suitable for this project than the second proposal.

3.4.2 First Proposal VS Third Proposal

In the third proposal, it combines wireless power and wireless information transfer into a system. The information and power could be transfer via a pair of coils. But it requires Mux, DEMUX, modulator, and demodulator to support it, which significant increase complexity of the system and improve the instability. On the other hand, those components would increase the power consumption of the whole system that is contrary to the design concept. And it is hard to control the power consumption of that consumption in the third design. Although there are modulator boards on the market that integrate those components together, modulator boards are not cheap that significantly increases the whole cost of the project to an unacceptable level. However, with the development of the Bluetooth technology, components are highly integrated into Bluetooth chips and modules with deign-friendly interfaces. The power consumption of the Bluetooth V 4.0 is reduced to a ultra-low level, for example, the PAN1740 only consumes 25 mW in the sleep mode. Also, the Bluetooth communication is encrypted due to a security issue, but there is no existing encryption system from the third proposal. So it requires to design an encryption system, leave it at the eavesdropping risk. But this project aims to design a WIPT system to replace the USB cable, and the information security is an important feature of the USB cable. It does not point to sacrifice the security of information as a replacement for the USB cable. As a result, the third proposal is knocked out.

3.4.3 The Potential Disadvantages of The Third Proposal

Compared with another two proposals, WPIT Via A Pair Of Inductive Coils has few significant cons.

- The first concern is the security issue. The communication is undoubtedly under risk without any encryption technologies. If it was used in a public place, the attacker could easily gain unauthorized access to the user's any personal data and saved therein. There are no existing standards for this design. NFC standard may be used, but the maximum data rate of NFC standard is up to 424 kbit/s [26]. The potential maximum data rate is up to 1.5 Mb/s. Also, NFC has its security issue as well.

- Secondly, the power control issue. The third proposal requires plenty of components to perform modulations, such as waveform filter, MUX, DEMUX. But the power is limited, if the modulator and the demodulator consume too much power, there is not enough energy to output. Meanwhile, components are highly integrated into Bluetooth chips and modules with deign-friendly interfaces, it highly reduces Bluetooth devices power consumption. The Bluetooth V 4.0 modules have the Bluetooth Low Energy Technology that highly increase the power efficiency.

- Third, point-to-point communication. The form and structure design of the third proposal determines that it is a point-to-point communication. However, the Bluetooth technology supports point-to-multipoint communication. It can send and receive information to multi devices at a time.

- Fourth, USB interface issue. Bluetooth chips or modules have USB or UART interface. But for the third proposal, it has to design a USB interface to achieve the project requirement.

3.4.4 Summary of WIPT Proposal Selection

The previous section 3.1 to 3.3 describe three proposals in this project. And the section 3.4.1 to 3.4.2 compare the first proposal with another proposal, which describes advantages and disadvantages of each proposal. In the end, based on the previous comparisons, the USB-interface WIT with a Bluetooth Module is selected to be the WIT system design.

Chapter 4

Detailed Design

In this section, we split this project into two part and describe the detail about WPT system and WIT system. It also provides the circuit schematic for each system and simulates the WIT system in the different environments.

4.1 WPT

To complete a WPIT system, the first thing is to structure a wireless power system. It should satisfy the following requires:

- WPT system should follow Qi standard. Other Qi-standard devices could charge from the transmitter.
- The output power should be about 5 W.
- The WPT system should contain over-temperature, over-Voltage, and over-current protection to prevent users from any risks.

4.1.1 Extra Power Supply

Although laptops and desktops provide power to peripherals, the maximum power is limited. According to the USB power specification [36], the high-power USB ports only support maximum 2.5 W with 5 V and 500 mA. Assuming the power transfer efficiency is 70%, and Bluetooth Low Energy only cost 0.3 W during the communication

$$(2.5W - 0.3W) * 70\% - 0.3 = 1.24W \tag{4.1}$$

Without considering the power loss during AC-DC conversion and DC-AC conversion, in the best case, the maximum output power from the receiver is 1.24 W. Since the total power is limited by the USB power supply, we decide to use an extra power instead of USB power supply, and the USB interface could directly connect with Bluetooth chips for information transfer.

4.1.2 WPT Hardware Description

P9038-R-EVK Wireless Power Transmitter

The P9038-R-EVK from IDT is a 5 Watt, Qi-compliant wireless power transmitter kit. It consists of an easy-to-use board designed for fast prototyping and design integration. The board powered by a ubiquitous Micro-USB connect to 5 V, 2 Amp Micro-USB charger [5]. Although the lower-power source could be used, the maximum power transfer is limited. Once the Qi-standard receiver is placed on the top of the coil spacer, the green LED of the transmitter begins to blink that represents the coupling has been established and power transfer is working.

Figure 4.1: P9038-R-EVK wireless power transmitter

P9025AC Wireless Power Receiver

The P9025AC is a 5 Watt, Qi-compliant Wireless power receiver kit. As an integrated single-chip, it receives AC power signal from the transmitter and converts AC power signal into a typical 5.3 V DC output voltage [4]. It consists a high efficiency Synchronous Full Bridge Rectifier to increase the power conversion efficiency, and it automatically optimal efficiency via detecting the transmitter types. The purpose of the above features is to guarantee 5 W output power. The voltage is set 0.3 V higher than USB power standard 5V rail to provide extra headroom for voltage drop due to heavy loads. Although there is no output interface for the receiver, the 5.3 V output pad could be wired to desired loads.

Figure 4.2: P9038-R-EVK wireless power transmitter

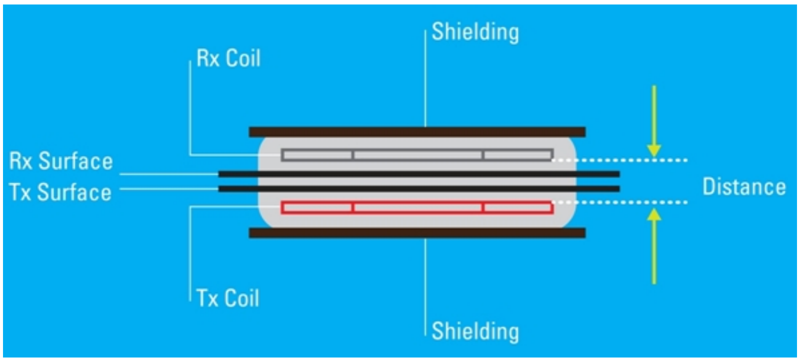


Figure 4.3: The magnetic field with ferrite shielding material [16]

4.1.3 Ferrite Shields

The ferrite shields have two main important features to structure a WPIT system:

- First, the ferrite shield modifies the circular flow of the magnetic flux lines, and it keeps magnetic field closer to coils.
- Second, the ferrite shield concentrates electromagnetic field in a particular area and reduce the amount of electromagnetic radiation. The electromagnetic radiation is generated by the WPT transmitter, it could be transferred to power by the WPT receiver.

Although the ferrite shield would lose energy due to hysteresis and eddy currents internal into the ferrite material. Also, this loss energy would be transfer to heat, increasing material's temperature. It increases the potential risk of self-heating [16].

A particular magnetic field using ferrite shield material is shown in Fig 4.3.

4.2 WIT

In this project, the WPT and WIT are combined into a device, and the WPT is structured by inductive coils that could generate a strong electromagnetic field . The electromagnetic field is the reason that power could transfer via a pair of inductive coils, but it also could affect the performance of all charged objects in the field, in this case, Bluetooth chips. The electromagnetic interference (EMI) affects a circuit by electromagnetic coupling from the WPT system. And it disturbs the performance of the circuit or even damages the components in the Bluetooth circuit. The electromagnetic field not only could degrade components' performance, but also increases the error rate and a total loss of data [31]. To solve it, the ferrite shields are added into the WPIT system.

The ferrite shield materials not only increase the power efficiency but also reduces effects of the electromagnetic field on the WIT system.

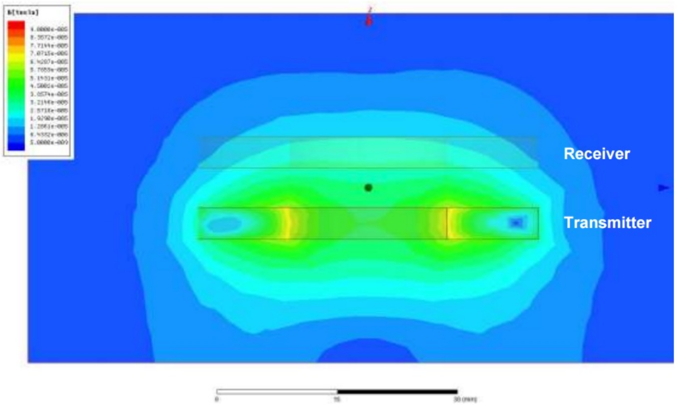


Figure 4.4: Magnetic flux density withoutout ferrite shielding materials [9]

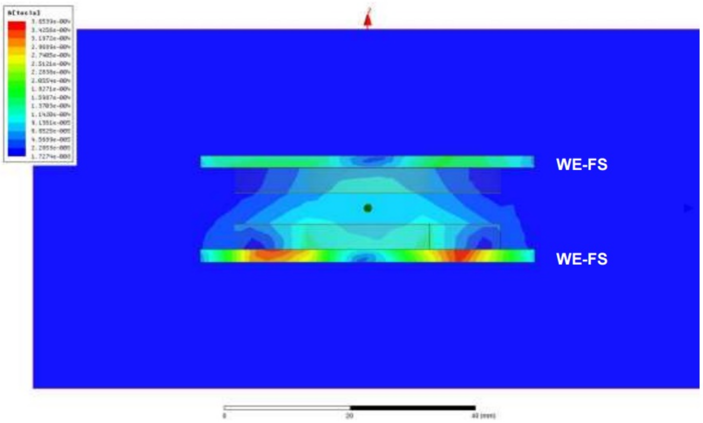


Figure 4.5: Magnetic flux density with ferrite shielding materials [9]

The Fig 4.4 and Fig 4.5 shows the result of the magnetic flux density distribution with/without ferrite shielding materials from Wurth Electronic Inc [9]. Without ferrite shielding, the flux is not only concentrated in the transmitter and interaction with the receiver, but also passed beyond the coils into the back of the transmitter. Once the ferrite sheet is placed behind the transmitter and receiver, the magnetic flux is concentrated between the receiver and the transmitter. Thus, the outside circuit is protected.

4.2.1 WIT Simulation

Path Loss

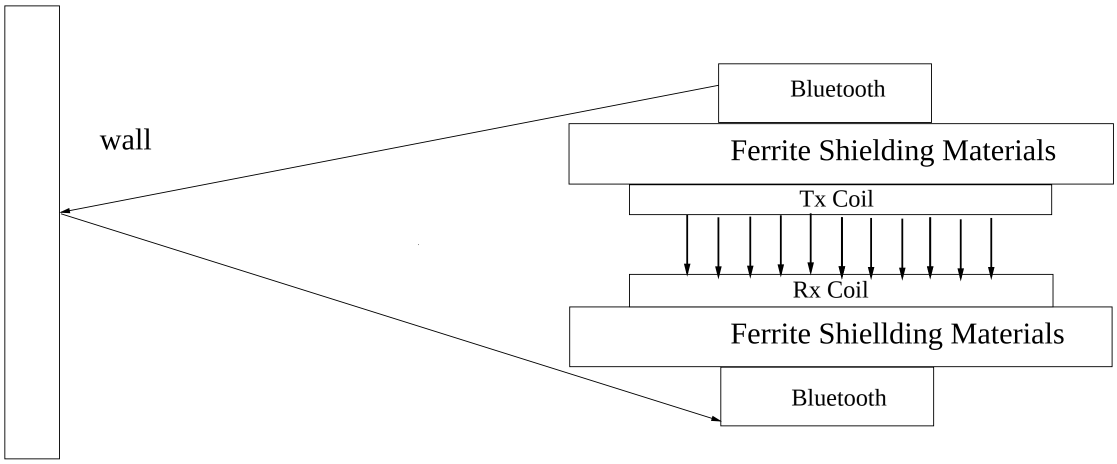


Figure 4.6: The communication path of Bluetooth chips

The communication path schematic is shown in Fig 4.6. Because of the features of the ferrite shielding material, the Bluetooth chips could not penetrate the ferrite shielding material, and the Bluetooth chips only can receive the signal that is reflected by the wall or another material. Although ferrite shielding material could block the electromagnetic radiation from the inductive coils, the some electromagnetic radiation could reduce communication quality. The communication distance between the transmitter and the receiver leads to the path loss or path attenuation that is the lessening in the power density of an electromagnetic wave. It helps designer analysis a point-to-point telecommunication system. Many effects lead to path loss, such as propagation medium, terrain contours, the distance between the transmitter and the receiver, and the location of antennas. In this case, we ignore propagation medium, terrain contours, and the location of antennas. We focus on how does the distance between the transmitter and the receiver affect the path loss.

To measure the path loss between two isotropic antennas in free space, the simplified path loss formula in dB is represented as [29]:

$$L = 20log_{10}(\frac{4\pi d}{\lambda}) \tag{4.2}$$

where L represents the path loss in dB; d represents the distance between the transmitter to the receiver and λ represents the wavelength.

To measure the path loss, we need to know the wavelength of the Bluetooth communication frequency. The Bluetooth uses the 2.4 GHz short-range radio frequency band, and assuming the speed of light is $3 * 10^8 m/s$. Then, the wavelength is measured by the following equation:

$$\lambda = \frac{3 * 10^8}{2.4 * 10^9} = 0.125m \tag{4.3}$$

Combine the equation 4.2 and 4.3,

$$L = 20log_{10}(\frac{4\pi d}{0.125}) \tag{4.4}$$

The path loss in the different distance is shown in Appendix A, and the related diagram is shown in Fig 4.7 that points out the path loss reduces with the increasing distance.It is clear to see that the reduction of path loss is not linear. The path loss is reduced rapidly at beginning, and the decreasing becomes slower and slower with increasing distance.

And the received power not only depends on the transmitted power and path loss but also depends on the transmit antenna gain and receive antenna gain. However, the BLE113-A-v1(selected Bluetooth Chip) does not have any antenna gain. Thus, the received power could be represented as following equation:

$$P_{Received} = P_{Transmitted} - P_{PathLoss} \tag{4.5}$$

The typical Tx power of the BLE113-A-v1 is -10 dBm and the typical Rx sensitivity is -88 dBm. Thus, the maximum path loss could be -78 dBm which is equal to 48 dB. Then

$$48 = 20log_{10}(\frac{4\pi d}{0.125}) \tag{4.6}$$

solve the above equation

$$d = 2.4986m \tag{4.7}$$

Therefore, the maximum communication distance of BLE113-A-v1 is 2.4986 meter. Thus, this Bluetooth chip should not be used in a long-distance telecommunication system that is greater than 2.5 meter. In other words, the communication system would lose its functions in a free space or public places.

Generally, the bit error rate (BER) only depends on the SNR. However, the path loss could reduce the received power, meanwhile, the noise power would not be changed and remain constant. Thus, the SNR would be reduced due to the following equation:

$$SNR = \frac{P_{received}}{P_{Noise}} \tag{4.8}$$

To prove the above conclusion, it is necessary to simulate Bluetooth communication. In this case, we simulate Bluetooth transmission in the Simulink Matlab. We use the Matlab R2015b, and ignore the Additive white Gaussian noise(AWGN), set path loss from 26.07 dB to 48 dB. It could simulate Bluetooth transmission performance in a different distance.

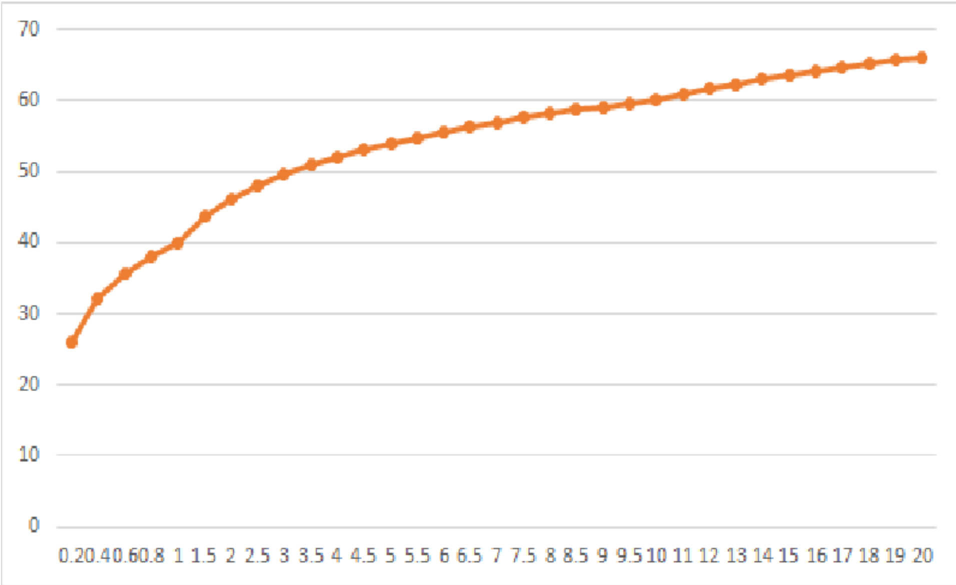


Figure 4.7: Magnetic flux density withoutout ferrite shielding materials

Path Loss(dB)	Distance(m)	Raw_BER	FER
26.07	0.2	0.004398	0.025
35.61	0.6	0.004399	0.026
40.05	1	0.00439	0.026
43.57	1.5	0.00439	0.026
48	2.499	0.00439	0.026

Table 4.1: Bluetooth BER and FER in different path loss

The schematic circuit is shown in Fig 4.8, and the simulation result is shown in the table 4.1.

According to the simulation result, the path loss has no significant influence on the bit error rate and frame error bit. It may because the transmission distance is limited in 2.5 meter, and the path loss is up to 48 dB. Path loss may become a significant factor in a long-distance communication transmission. But in this project, path loss would not have an obvious influence on the Bluetooth communication.

To sum up, the path loss may reduce the signal power in a long-distance communication, and leads to an increasing SNR. But in this case, due to the limitation of communication range of Bluetooth, it barely affects the communication quality.

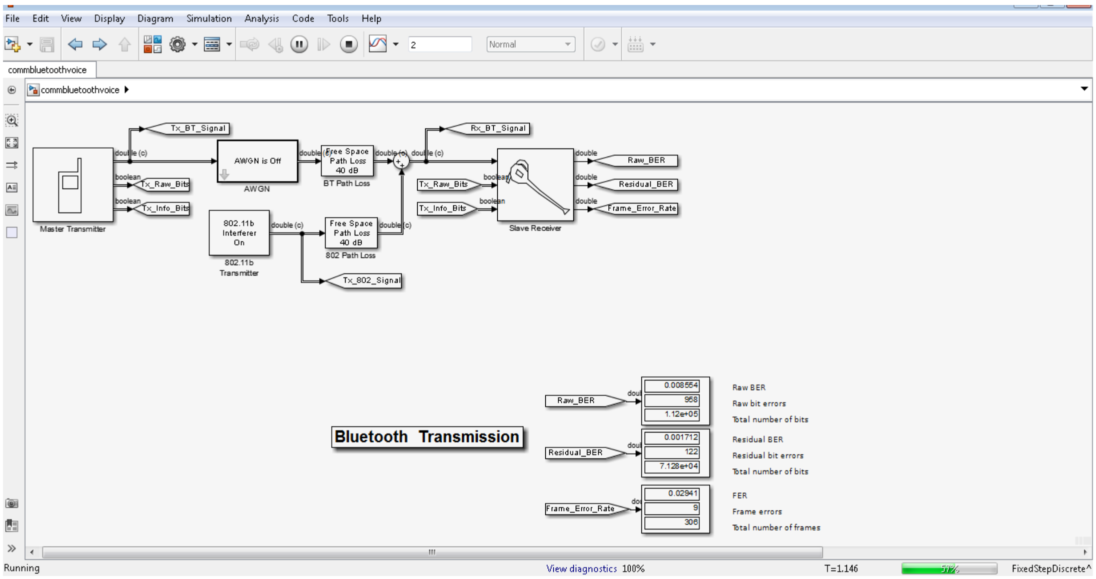


Figure 4.8: Schematic Circuit

Chapter 5

Conclusions and Future Work

5.1 Conclusion

In this chapter, accomplishments of this project are listed as follow:

- A critical literature review of the wireless power technologies and wireless communication technologies.
- Investigation of three different proposals. Also, this report describes schematic and selected hardware for each proposal.
- Simulation for path loss.

The device constructed in this project achieve the following specification:

- The transmitter weight is about 70 gram, and the receiver weight is around 20 gram. The total weight of WIPT system is about 200 gram.
- Physical specification of the transmitter is 53.5*84.4*0.8 mm, and the size of the receiver is 33.8*67.8*1.6 mm. Both of them is ultra small, could be easily carried by users.
- The maximum data rate of Bluetooth chips in the WPIT system is up to 1 Mb/s.
- Due to the feature of ferrite shielding materials, the WIT system should not run in free space or outdoor places. Otherwise, the Bluetooth chips in the WIT system may not find each other.
- Due to the communication feature of Bluetooth chips, this WPIT system not only communicates with each other, but also could communicate with another Bluetooth devices. Although the WPT system only supports point-to-point power transmission.

- The input power of the transmitter is 4.5 to 6.9 V, and the input power should not exceed 12 V DC. The typical input power is 5 V, 2 Amp. The output provides nominal 5.3 V with 1 A. The extra 0.3 V is used to provide extra headroom for voltage drops due to heavy loads.
- The transmitter and receiver are compliant to the WPC 1.1.2 Qi standard [5] [4]. Thus, the WPT system could transfer power with other Qi standard devices.
- The wireless communication transmission and power transmission runs automatically when switched on.
- The input communication interface and output interface is USB 2.0.

The main limitation of the WIPT system is that it could only transfer power in several millimeter. The WPT system should keep a small gap between the transmitter coil and receiver coil. According to the Qi specification [3], the separation gap is about 1.75 to 2.5 mm on the receiver side to achieve optimal wireless power efficiency. Also, the winding of the transmitter should be facing up and the coil of the receiver should be placed on the transmitter. The coil of the receiver should be aligned with the coil of the transmitter to start power transmission.

5.2 Future Work

This section points out possible enhancements that can be made to the current design. The suggestions are listed as follow:

Replacing Inductive Coupling with Resonance Coupling

As discussed in the section 4.12, the main limitation of the WPT system is that it cannot transfer power over a long distance, which limits location of the receiver. The resonance coupling could transfer power in a longer distance, thus, the resonance coupling receiver does not have to be close to the power transmitter as the inductive power transmitter does. The resonance coupling is a loosely coupled system, although, it has higher electromagnetic emissions than inductive coupling or called tightly coupled system. Thus, the resonance coupling need to trade-off between larger distance and higher electromagnetic emissions.

Replacing Bluetooth with Wireless USB

Wireless USB was designed based on the UWB(WiMedia Alliance's Ultra-WideBand) common platform that is enabled to send 480Mbit/s at the maximum distance up to 3 metres [38]. The Wireless USB is a high-speed personal technology, aiming to the satisfied need of PC peripherals, mobile devices, and multimedia devices. Wireless USB architecture allowed connecting a host with up to 127 devices.

Although the Bluetooth is using wider than Wireless USB, the data rate of Wireless USB reaches up to 480Mbps [38] which matches the capabilities and transfer rates of USB closely and enables to design a natural wireless application for USB port which is more suitable to the USB-interface requirement.

Using USB 3.0 for Output and Input Interface

The USB 3.0 not only supports higher data transmission rate and provides higher power supply. USB 3.0 provides the new SuperSpeed transfer mode that provides a data rate of 5.0 Gbit/s that is 15 times faster than USB 2.0 data rate. On the other hand, the maximum current of USB 3.0 is increased to 900 mA and the maximum current of USB 2.0 only remains 500 mA [35]. And there is a Battery Charging Specification [37] that increases the current up to 1.5 A, but it does not allow information transfer when the high current is passing through the USB 3.0 cable.

Chapter 6

Abbreviations

AWGN	Additive White Gaussian Noise
WPC	Wireless Power Consortium.
WPIT	Wireless Power and Information Transfer
A4WP	Alliance for Wireless Power
USB	Universal Serial Bus
GAGR	Compound Annel Growth Rate
RF	Radio frequency
dB	Decibels
Hz	hertz: unit of frequency
SNR	Signal to Noise Ratio
CNR	Carrier-to-noise ratio

Appendix A

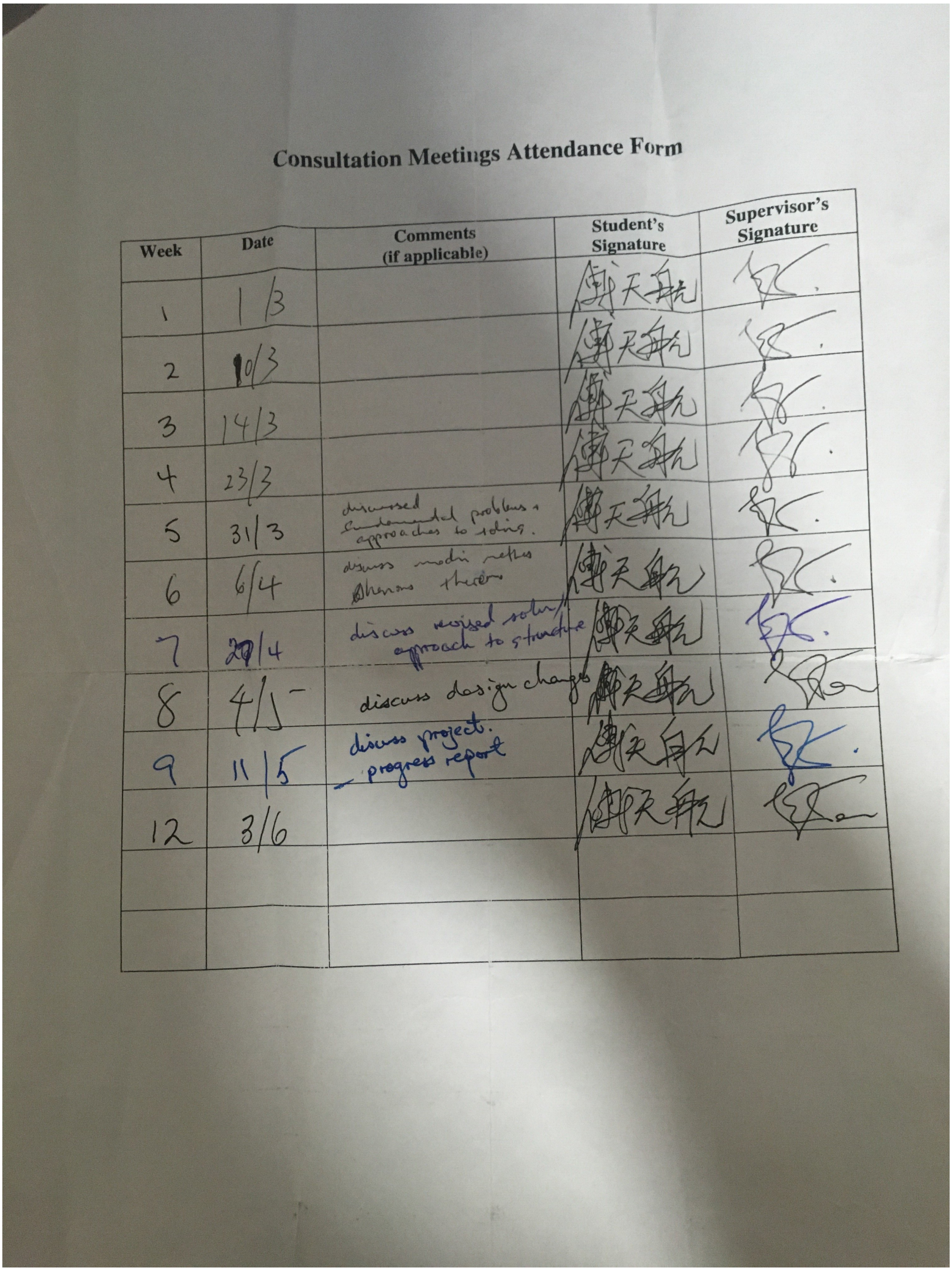
The path loss in different transmitter-receiver distance

Distance(Meter)	Path loss(dB)
0.2	26.07
0.4	32.09
0.6	35.61
0.8	38.11
1	40.05
1.5	43.57
2	46.07
2.5	48.00
3	49.59
3.5	50.93
4	52.09
4.5	53.11
5	54.03
5.5	54.85
6	55.61
6.5	56.30
7	56.95
7.5	57.
8	58.11
8.5	58.63
9	59.13
9.5	59.30
10	60.05
11	60.87
12	61.63
13	62.32
14	62.97
15	63.56
16	64.13
17	64.6
18	65.15
19	65.62
20	66.07

Table A.1: The path loss in different transmitter-receiver distance

Appendix B

Consultation Meetings Attendance Form



Consultation Meetings Attendance Form

Week	Date	Comments (if applicable)	Student's Signature	Supervisor's Signature
1	1/3		[illegible]	[illegible]
2	10/3		[illegible]	[illegible]
3	14/3		[illegible]	[illegible]
4	23/3		[illegible]	[illegible]
5	31/3	discussed fundamental problems + approaches to solving.	[illegible]	[illegible]
6	6/4	discuss [illegible] [illegible] [illegible] theorem	[illegible]	[illegible]
7	20/4	discuss revised soln/ approach to structure	[illegible]	[illegible]
8	4/5	discuss design changes	[illegible]	[illegible]
9	11/5	discuss project. progress report	[illegible]	[illegible]
12	3/6		[illegible]	[illegible]

Figure B.1: Consultation meeting attendance form

Appendix C

Time and Financial Plan

C.0.1 Time Budget

Table C.0.1 summarizes the time plan. The most of time is used to research and design the proposals. The rest of time is used to realize the proposal.In order to complete the project, the middle-semester break is used to research.

Research and Design Time	75 days
Realize Time	35 days

Table C.1: Time Budget

C.0.2 Financial budget

The project has $300 financial budget to be completed. The some hardware can be found in the university lab, such as inductors and capacitors. Also, we need two Bluetooth chips are $ 19.02 for each. The wireless power transmitter is $35 and the wireless power receiver is $ 30. Thus, the total amount of the WIPT system is $ 103.04

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