Researching the BLE based intelligent lighting control system

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Abstract

Several leading lighting companies for example NXP and Philips work in a project to explore the next generation intelligent lighting system. One innovation of the project is using a distributed architecture to replace current centralized system to increase robustness and extensibility.

As a core component of wireless lighting control system, there are many wireless communication protocols can be applied in distributed system. We choose BLE protocol which is a new wireless communication protocol as the communication protocol of distributed system to do research because BLE has a huge potential in low power consumption. However, there exist some problems in BLE based distributed lighting control system. One of these problems is a commissioning problem.

The commissioning problem we come up with is that a constrained device (no screen) router, cannot display a scanning list of BLE based lamps. This prevents specific BLE based lamps which user want to remotely control, from securely joining in the existing access point (router).

The main purpose of this thesis is to solve the commissioning problem in a BLE based intelligent lighting control system to make BLE become an appropriate candidate in this field. An innovative solution, developed on standardized BLE protocol, which is used for overcoming the commissioning problem through utilizing modified BLE protocol in a smartphone. The modified BLE protocol is a application protocol. With the modified BLE protocol stack, a third device which is a Commissioning Tool(smartphone) can securely instruct specific BLE based lamps to router.

As part of this thesis, a demo was set up and the solution to the commissioning problem has been tested on this system. Results proved that the solution was valid to solve the commissioning problem of BLE based intelligent lighting control system.

Keywords: BLE, intelligent lighting control system, commissioning

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Preface

Thesis project is the last task in my master career. During this time, I have suffered many problems which make me think I cannot finish this thesis. Sometimes, I wanted to give up. However, my committee members, Prof. dr. ir. G.J.T. Leus, Dr.G.J.M.Janssen and Dr.Cheng Guo gave me a lot of help. With their support, I have conquered these problems and finished my thesis. I would like to show my thanks and respect to all of my committee members. Without your help, I cannot achieve my master degree. Thank you!

Cong Nie

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Acronym

WLAN: Wireless Local Area Network

GATT: Generic Attribute Profile

ATT: Attribute Profile

GAP: Generic Access Profile

LL: Link Layer

CT: Commissioning Tool

BLE: Bluetooth Low Energy

PLC: Power Line Communication

DALI: Digital analog

Chapter 1 Introduction

1.1 Background

Lighting is an essential part of people's daily life; due to lighting we can study, work and do many other things with clear visibility, even at night [20]. Therefore, it would be hard to imagine how we would live without lighting.

In the area of lighting, LED draws the attention due to its excellent performances in efficiency, color, size and lifespan. The use of LED has led to an interest in the development of a intelligent lighting control system [40]. The objective of this intelligent control system is not only to bring about a potential cost saving, but also to utilize its potential for improved convenience.

The development of the intelligent lighting control system has led to a great success, but did bring with it a number of challenges/problems. Because of these challenges, a group of European companies and academic institutions, for instance NXP and Philips, have been collaborating in a program with the aim of developing the next generation of intelligent lighting control system [31]. One of the aims of this program is to exploit the potential of solid-state lighting via innovations in the intelligent lighting control system. This would make the centralized architecture of current day lighting control systems move towards a more distributed architecture, thereby improving the robustness and extensibility of the lighting system.

A central component of a wireless lighting control system is the wireless communication protocol, which is the regulating part of the message exchange between objects or devices [21]. Though many wireless communication protocols (such as Wi-Fi, Zigbee and Bluetooth [6, 5, 9]) can be applied in the next generation intelligent lighting control system, the preference is to focus on a BLE based intelligent lighting control system. The focus on BLE as the wireless communication protocol to use is due to some distinct advantages of this protocol, such as low energy costs and a small time delay. The motivation for this decision is further clarified in section 2.2.

However, there are still some problems remaining with a BLE based intelligent lighting control system. These problems prevent further development of the BLE in this field. One of these problems is a commissioning problem which will be discussed in the next section.

1.2 purpose and problem

Starting with this thesis project, the author participated in a project on the topic of an intelligent lighting control system. Working on this project, an innovative architecture of intelligent lighting control system had been investigated.

Over the course of the project the focus had been on a core component of the intelligent lighting control system, which is the communication protocol. Each communication protocol has its advantages and disadvantages and they can all be applied in the distributed intelligent lighting control system; however it became apparent that a new wireless communication protocol, BLE, had some distinct advantages compared to other wireless communication protocols. For this reason the focus of the thesis project is on a BLE based intelligent lighting control system.

In the BLE based intelligent lighting control system, however, there is a commissioning problem to be found. Nowadays, users are not satisfied with only being able to control a single or a number of lamps. They would like to achieve remote control via the internet. To give an example, in a single lamp control mode there can be a number of BLE based lamps and smartphones. Each smartphone can retrieve a list of detected devices through scanning and the user can select those devices he or she wants to connect to. However, this will not work properly in a remote control mode. In a remote control mode, each lamp needs to be connected to an existing AP (otherwise known as a router). Though, for a constrained device (router), there is no display for any scanned results due to not having screen. This brings forth the question that will be focused on, namely how to make specific BLE based lamps which user want to remotely control securely join in the existing access point(router).

To solve this commissioning problem for a BLE based intelligent lighting control system, the idea is to introduce a third device (referred to as CT) to instruct the lamps to migrate to the internet (this will be clarified in the next section). To summarize the main objective briefly: the aim of this thesis project is to use a modified BLE protocol and utilize it in a CT, which can be used for instructing specific BLE based lamps through securely connect to a Wi-Fi router, supporting a Bluetooth low energy protocol.

1.3 Contributions

This thesis report is limited to discussing wireless lighting control systems, mainly focused on home networks and networks used by small businesses. To provide a framework for this thesis a number of assumptions have been made.

1. Lamps fitted with chips and the router will be taken as constrained devices, meaning that there is no physical interface present.
2. The router supports both Wi-Fi and BLE as the wireless communication protocols.

In the following part the set-up of this thesis (or the structured approach towards solving the commissioning problem) has been listed.

1.Solving the commissioning problem from the viewpoint of the BLE protocol. The approach to this problem is to use a CT with a modified BLE protocol stack. With this, a link can be set up between the BLE based lamps and the user who wants to remote-control them. Furthermore, the CT securely instructs the lamps to migrate to an existing AP.

Figure 1 shows the architecture of this modified Bluetooth low energy protocol. It can be seen that this modified Bluetooth low energy protocol focuses on the application layer and that the lower layer remains the same. The lower layer functions of Bluetooth low energy protocol can be supported by a general BLE based set of chip. With this modified BLE protocol stack, the CT (or in this case the smartphone) can retrieve the addresses of BLE based lamps and send them to the router. This will let the router know which lamps the user wants to remote-control. After this instruction, the router can connect to those specific lamps. The exact workings of this procedure will be discussed in chapter 3.

2.Build a demo for evaluation. After having designed a modified BLE protocol stack, a demo is provided in order to verify whether this solution will solve the commissioning problem. The demo has been made with the help of CC2540 developing kit (provided by Texas Instruments). The program for this model has been developed in IAR 8.20. Texas Instruments also provided the Bluetooth low energy stack, containing the open source of the Bluetooth low energy protocol.

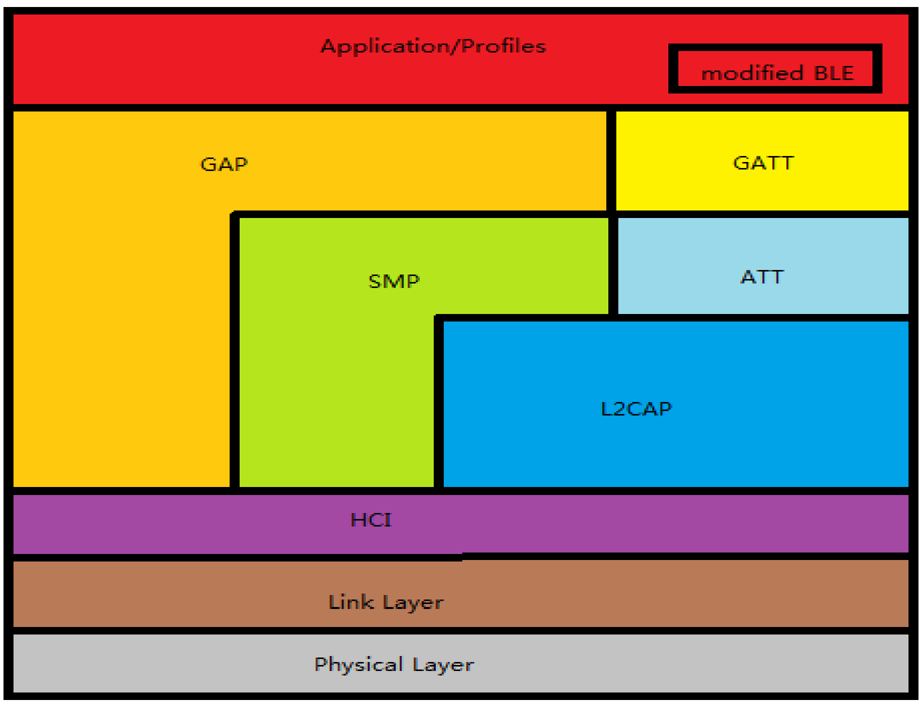

Figure 1: Architecture of modified BLE protocol

3. Validation of results through experiments. For the BLE network three parameters are tested: roundtrip, throughput and scalability. The outcomes have been used to evaluate the performance of a BLE network and determine whether the results meet the requirements of intelligent lighting control system.

1.4 outline

This thesis report consists of 7 chapters. Chapter 1 provides an introduction to the problem, the approach and the objectives of this thesis. Chapter 2 gives a literature overview of the next generation intelligent lighting control system and the different wireless communication technologies that can be used in intelligent lighting control system. Also, a comparison is made between the different wireless communication technologies in order to come to a suitable architecture and communication protocol for the wireless lighting control system. Chapter 3 provides the solution to the commissioning problem from the viewpoint of the BLE protocol. Chapter 4, the demo is discussed and a validation of the solution discussed in chapter 3 is provided. Chapter 5 lists the measurements done with the demo, based on which a number of conclusions will be drawn, summarized in chapter 6.

Chapter 2 Literature review

Lighting system is one of the most commonly used facilities in our daily life. In this system, we cannot figure out how many times we do operations on a large number of lamps and switches. As a significant component, LED lighting [40] takes over 60% of total margin of lighting market. Due to LED lighting's excellent energy saving and greater product lifetime, it has bright market prospects. By the end of 2020, it is predicted that LED will reach 112.5 million dollars. The rapid development of LED lighting offers a lot of opportunities for wireless intelligent lighting control systems since intelligent lighting control system have huge potential in power saving and convenience. Thus, the intelligent lighting control system draws significant attention.

In this chapter, we focus on literature review of intelligent lighting control system. In section 2.1, we show development trend of intelligent lighting control system and focus on an new architecture of intelligent lighting control system. In section 2.2, we explain why we do research on BLE based intelligent lighting control system by comparing between different wireless communication protocols. In section 2.3, we introduce a commissioning problem in BLE based intelligent lighting control system.

2.1 An innovative architecture of intelligent lighting control system

Nowadays, several leading lighting companies like NXP, Philips have set up new projects [11] to overcome challenges in current intelligent lighting control system. One aim of this project is to plan the new architecture of the next generation intelligent lighting system. This can be used for solving a challenge that is faced by the current system which is lack of robustness and extensibility. In this section, we will introduce difference between this new architecture which is distributed and architecture of current intelligent lighting control system which is centralized.

2.1.1 Introduction of intelligent lighting control system

Before introducing the difference between distributed intelligent lighting control system and centralized intelligent lighting control system, we briefly introduce components of a simple intelligent lighting control system.

In this system, there are three main components. They are controller, light and sensor.

A lighting controller is a device which can be used for controlling the operation of light. The main function of lighting controller is control dimmers, switch on/off light. Some controllers have more functions for example, they can control lighting according to specific scenarios.

A sensor is a device which can be used for detecting a real-world condition and converting this information into an analog or digital representation.

A light is an actor of lighting system. This device can be used for executing commands which comes from controller.

2.1.2 Centralized lighting system

In this section, we introduce centralized intelligent lighting control system. The following figure shows a simple centralized intelligent lighting system.

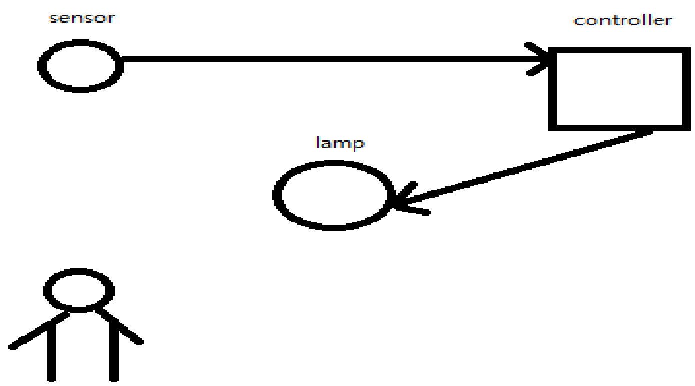

Figure 2：A simple intelligent centralized lighting control system

Work process:

1.The sensor detects that a man is walking. It sends this event to the controller.

2.Controller receives events and analyzes these events.

3.Controller sends commands to the lamp.

4.The lamps receives the command and turns on.

Disadvantage of this system:

From the architecture, we can see the controller is the "brain" of the whole lighting system, it can analyze events and send commands. It is convenient for controller to control the whole lighting system. However, it brings some disadvantages. As the "brain" of the lighting system, the controller needs to deal with every event. Because the resource, for example hardware resource of the controller is limited, the amount of devices it can handle at the same time is limited. What is worse is that, when the controller is broken, the whole system will be paralyzed. This influences robustness of an intelligent lighting system.

From the discussion of last section, we can see the architecture of original lighting system is limited by robustness.

2.1.3 Distributed intelligent lighting control system

The next generation architecture of intelligent lighting control system is distributed(decentralized). The following figure shows a simple structure of this new architecture.

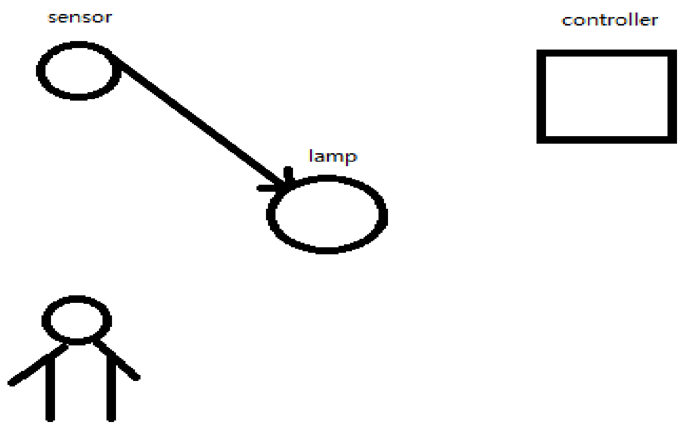

Figure 3: A simple distributed lighting system

Work process:

1.The sensor detects a man is walking.

2.The sensor sends these events to the lamp.

3.The lamp analyzes this event and turns on.

In this process, the sensor does not need to send event to the controller. It just sends that event to the lamp instead. This can reduce the burden of the controller and reduce the delay of the system. As a result, no single point of failure but graceful degradation when node fails in this system. This successfully increases robustness of intelligent lighting control system. On the other hand, nodes can be easily added, changed and (re-)configured which increases extensibility of the whole system. As a conclusion, distributed architecture has better performance than centralized and would be the architecture of next generation intelligent lighting control system.

2.2 Communication protocols

In this distributed system, devices need to exchange data between each other. As a core component, communication protocol is digital rule for data exchanging within devices and it is the "language" of intelligent lighting control system. So how to choose a suitable communication protocol is significant for distributed intelligent lighting control system.

In a distributed system, each device needs to communicate with one another. If we choose wired communication protocols for example, DALI, KNX, they need to add many lines between each device. This brings a lot of inconvenience. Therefore, wireless communication protocols have more advantages in this new architecture of intelligent lighting control system. So we focus on several wireless communication protocols.

In this section, we would like to review some wireless communication protocols. Since, different communication protocols have different characteristics it is hard to compare which is better. Hence, we compare some significant characteristics of each communication protocols which are related to lighting control field. In the following part we will introduce these characteristics of each communication protocol. These characteristics can provide a basis for us to choose suitable communication protocol.

The first characteristic is RF frequency. This parameter determines two things. One is that, some RF frequencies are free license but some are not. Second is that, protocols which use the same RF frequency may have problem of coexistence.

The second is power consumption. One advantage of wireless communication protocol is that it is easy to install because it does not use a power line. Without power line, device needs to be powered by battery. However, users do not want to change battery frequently. So this characteristic is significant for a communication protocol applied in lighting control field. The requirement of this parameter in lighting filed is more than several months.

The third thing is range. Lamps in lighting system are dispersed over the whole house. So communication protocol we choose should have enough cover range for communication. However, the same reason as the second characteristic, network topology, this thesis focuses on a small business network and this characteristic is relatively relaxed. The requirement of this parameter in lighting filed is more than 30m.

The last is about latency. The latency of a wireless system can be defined by a user action sent to a receiving device. It is a parameter that contribute to network speed. So this is also a significant characteristic. The requirement of this parameter in lighting filed is less than 200ms.

2.2.1 Zigbee

2.2.1.1Introduction

Zigbee protocol [25] is managed by ZigBee Alliance. This protocol is a suite of applications which require low power usage, low data rate and secure networking. Zigbee protocol based device can build up a mesh network which means they can transmit data through intermediate node. This can lead to a longer cover range. In addition, Zigbee has a much simpler and less expensive specification than Wi-Fi and Bluetooth [4].

2.2.1.2 Characteristics [27]

-Latency is around 20ms.

-Automatic network establishment by the coordinator.

-Power management to ensure low power consumption. Batter life can last months to years.

-16 channels in the 2.4GHz ISM band, 10 channels in the 915MHz and one channel in the 868MHz band.

-range coverage is 100m.

2.2.1.3Stack of Zigbee protocol

Zigbee is a protocol which is based on 802.15.4 protocol [4][27] and completed through adding the upper networking layers. The figure 4 shows the protocol stack of Zigbee [5][39].

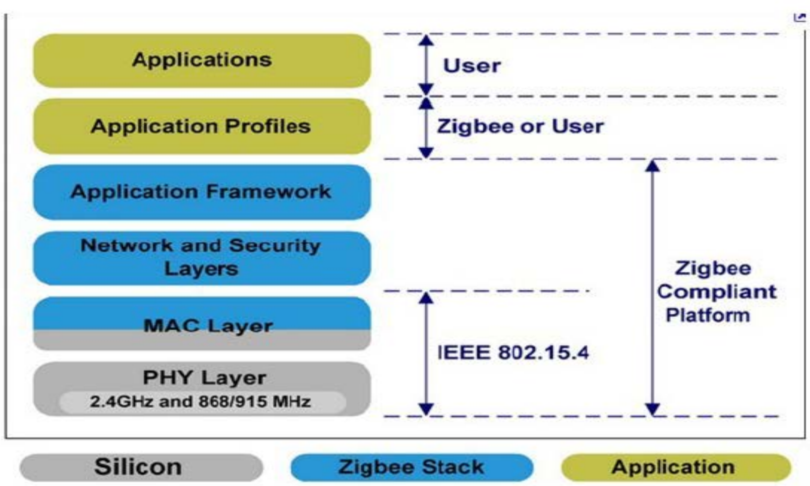

Figure 4: Stack of Zigbee protocol

ZigBee provides excellent performance power usage. It has relatively large range coverage and small latency. However, due to low bandwidth [15], the physical layer of Zigbee specifies 3 different frequency bands: 868-868.6 MHz (1 channel, 20 kb/s),902-928 MHz (10 channels, 40 kb/s) and 2.40-2.48 GHz (16 channels, 250 kb/s). As a result, ZigBee is not available on general purpose devices, like mobile phones, PDAs or personal computers. In addition, Zigbee has another disadvantage which is it cannot co-exist well with other WLAN protocols [23][24].

2.2.2 Wi-Fi

Wi-Fi is defined by Wi-Fi Alliance [6] and based on IEEE 802.11 standard [7]. Usually, the 802.11b referred as to Wi-Fi which is an amendment to 802.11 specification and can increase throughput up to 11Mbit/s. On one hand, this protocol aims at long coverage, high data rate applications. Wi-Fi can be widely applied in a lot of applications, for example, personal computers, smartphones, digital cameras. On the other hand, these Wi-Fi based devices can connect to Internet via wireless network access point. The following figure shows a simple Wi-Fi network.

2.2.2.2 Characteristics

-2.4GHz ISM band

-Latency is around 1.5ms

-Range coverage is around 150m

-Battery life is about several hours

2.3.2.3 Wi-Fi protocol stack

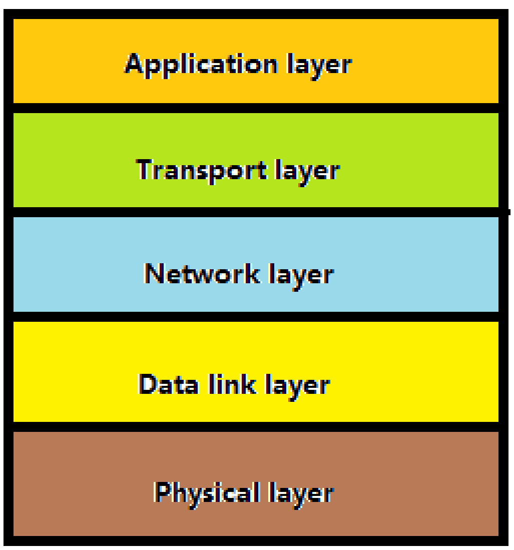

Figure 5: Wi-Fi protocol stack

Wi-Fi has an excellent performance in latency and range coverage. However, Wi-Fi based network is sensitive to the signal strength. To guarantee quality of connection, it takes higher power consumption than other wireless communication protocols. Its battery life can just last several hours and this brings a lot of inconvenience for users.

2.2.3 Z-wave

2.2.3.1 Description

Z-wave is a wireless communication protocol which is designed by Z-Wave Alliance. This protocol is a low power wireless technology. A Z-wave network is made up of up to 232 devices and uses source-routed mesh topology. Z-wave is a reasonable choice for reliable, low latency applications. This protocol aims at home automation, especially can be used in residential and light commercial environments [8].

2.2.3.2 Performance Characteristics

-Operates in the ISM band, around 868 MHz

-Latency: 20ms

-Battery life: months to years

-Range: 30 meters assuming "open air" conditions, with reduced range indoors depending on building material.

2.2.3.4 Z-Wave stack architecture

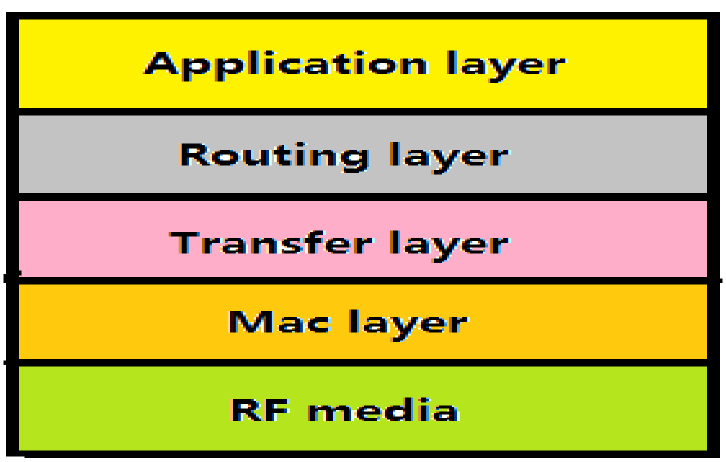

Figure 6: Z-Wave stack architecture

Z-Wave works at 868MHz and this can be coexistent with other wireless communication protocols. In addition, its power consumption is excellent. It has a relatively low performance at range coverage. However, the RF channel is not free license is relatively low.

2.2.4 Bluetooth

Bluetooth [1] is a wireless technology for transmitting data over short range. This technology is designed by Bluetooth Special Interest Group [2].

2.2.4.1 Characteristic:

The “classic” Bluetooth radio:

-2.4 GHz ISM band and with adaptive Frequency Hopping

-Batter life can last days to weeks.

-Communication is within piconet. Piconet is set up by the first device who initiates the conversation. Number of active members in one piconet is limited to 8, slaves cannot talk directly, nodes cannot connect to multiple piconets simultaneously, therefore broadcast is not efficiently supported

-Communication coverage is from 10-300m which depends on different profiles.

- Latency is over 100ms.

2.2.4.2 Bluetooth (BT) Stack Architecture

The stack architecture of BT is shown in Fig 7 [3]:

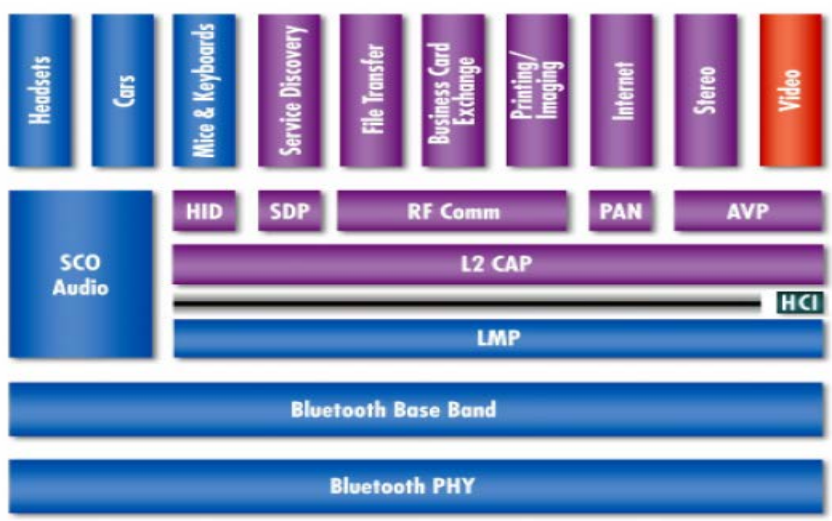

Figure 7: The stack architecture of BT

BT works at 2.4 GHz ISM band and its adaptive frequency hopping can make it co-existent with Wi-Fi. Its range coverage are enough for an intelligent network. However, its performance in power consumption is not so good. Its battery life can just last only several weeks. In addition, its latency is too large by comparing with other wireless communication protocol.

2.2.5 Bluetooth low energy

2.2.5.1 Introduction

Bluetooth technology is a short-range communications technology whose robustness, low power, and low cost make it ideal for a wide range of devices ranging from mobile phones and computers to medical devices and home entertainment products [30]. The base technology is defined and maintained by the Bluetooth Special Interest Group (SIG) in the "Core Specification," which serves a uniform structure for devices to inter-operate. BLE technology has a good future, for example, in [37] the authors predicted that BLE-based devices would dominate the Wireless Sensor Network (WSN) application market by 2015.

Compared to classic Bluetooth protocol, Bluetooth low energy [9][31] is characterized by an entirely new protocol stack, for rapid build-up of very simple links. The figure11 shows the new protocol stack of Bluetooth low energy.

2.3.5.2 Performance Characteristics

-Operates in the ISM band, 2.4 GHz

-Latency: 2.5ms

-Battery life: months to years

-Range: over 100 meters(outdoor)

2.3.5.3 Architecture of Bluetooth low energy

We can see the Bluetooth low energy is an extended version of Classic Bluetooth but it simplifies the stack from classic Bluetooth stack. Due to this new stack, Bluetooth low energy protocol has a huge potential in power consumption. Compared to Zigbee protocol, Bluetooth low energy protocol also has good performance at other directions. So we think Bluetooth low energy protocol can replace Zigbee protocol and become the better choice for intelligent lighting control system.

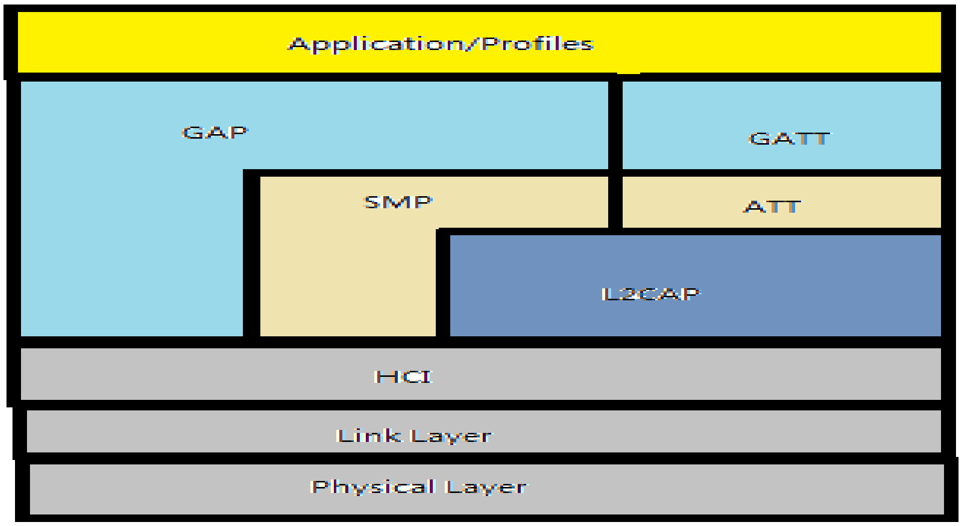

Figure 8: Bluetooth low energy stack

BLE works at 2.4GHz which is free license. Its adaptive frequency hopping makes it well coexistent with Wi-Fi. It has huge potential in power consumption and latency. Its range coverage is enough for requirement.

2.3.6 Comparison between different communication protocols

Standard	Zigbee	Bluetooth	Wi-Fi	Bluetooth low energy	Z-Wave	Requirement
Industry organizations	Zigbee Alliance	Bluetooth SIG	Wi-Fi Alliance	Bluetooth SIG		
Topology	Mesh, star, tree	Star	Star	Star	Mesh network with source routing	
RF frequency	868/915 MHz, 2.4GHz	2.4GHz	2.4GHz 5.8GHz	2.4GHz	868MHz	
Latency	20ms	100ms	1.5ms	2.5ms	20ms	200ms

Range	100m	100m	150m	>100m	30m	30m
Power	Very low	Low	High	Very low	Low	
Battery operation (life)	Months to years	Days to weeks	Hours	years	Months to years	Months

Table 1: Comparison between different communication protocols

There are some related works which have been done in this field. In [11], author compares Wi-Fi and Bluetooth protocol. In [12], Zigbee, Wi-Fi, Bluetooth and UWB are compared. In [13], author analyzes the difference between Zigbee and Bluetooth. And in [14], author estimates the performance of IEEE.802.15.4 for low-rate personal area network. From the above summary of the works stated in literature and table 1 we conclude on the system development in section 2.4.

For a intelligent lighting control system, latency and range coverage are relatively relaxed in a small lighting network. All these 5 wireless communication protocols are enough for basic requirements. However, Bluetooth is too weak in latency even it can satisfy the requirement of intelligent lighting control system.

Power consumption and RF frequency are two significant parameters. As far as power consumption is concerned, people do not want to change battery frequently. Among these protocols, BLE, Zigbee and Z-wave are excellent candidates with respect to power consumption, Bluetooth are good but Wi-Fi is very weak. From this stand point, BLE, Zigbee and Z-wave are the best candidates for distributed lighting control system.

For RF frequency, BLE, Zigbee, Bluetooth and Wi-Fi uses 2.4 GHz which is free license and Z-Wave uses 868MHz which increases the cost. On the other hand, due to adaptive frequency hopping, BLE and BT can well coexist with Wi-Fi. However, Zigbee cannot avoid this problem. In addition, ZigBee is not available on general purpose devices, like mobile phones, PDAs or personal computers [15]. This makes Zigbee not very appealing from an infrastructural view point. Z-wave also suffer this problem. For BLE, it is compatible with Internet device for example, smartphone and will not suffer the same problem.

From the above discussion, we can conclude that, BLE is the most suitable wireless communication protocol for next generation intelligent lighting control system.

2.3 Limitations in BLE based intelligent lighting control system

From last section, we know there are many good performance characteristics of BLE. However, there also exist many limitations when applying this technology in lighting control field.

A commissioning problem in BLE based intelligent lighting control system

With development of lighting control system, control mode needs to change from single lamp control to remotely control via Internet which is important.

For single lamp control, we can use a CT to connect to a BLE based lamp. To show this procedure clearly, a connection step between a CT and a lamp are described:

1.A lamp broadcasts its advertisement which can be detected by other BLE devices at its communication range.

2.A CT, for example, smartphone can get a list of detected devices through scanning.

3.The user can choose the device he wants to connect to and click on “connect”. And a connection between a lamp and a CT is established.

For single lamp control, this procedure works well. However, for remotely control, there exists a commissioning problem. A router is usually a constrained device which does not have a screen to display a list of detected devices after scanning. Thus, a router cannot securely connect to specific lamps which a user wants to remotely control. This is the main question we focus on and we will show the solution to this problem in chapter 3.

Chapter 3 Main components

As we have discussed in chapter 2, there is a commissioning problem in BLE based intelligent lighting control system. In this chapter, we first describe the problem in detail in section 3.1, which is followed by the challenges of commissioning problem in section 3.2. An analysis of the commissioning problem is presented in section 3.3 which finally leads to the solution in section 3.4 .

3.1 Problem description

In a room, there are several BLE based lamps. The user can use a smartphone to turn on or off these lamps through the BLE technology. However, when he is outside of his room, the lamps will not be in control anymore. If the user wants to connect to these lamps remotely, he may need a machine which not only can access to the Internet, but also supports BLE technology to control the lamps in his room. A router is just what he wants. If he could make the lamps connect to the router, he can remotely control the lamps via Internet. However, as we know that the lamp and the router are both constrained device, so how to connect specific lamps to the existing Internet is a commissioning question in this scenario. Therefore, it is also the main challenge in this project.

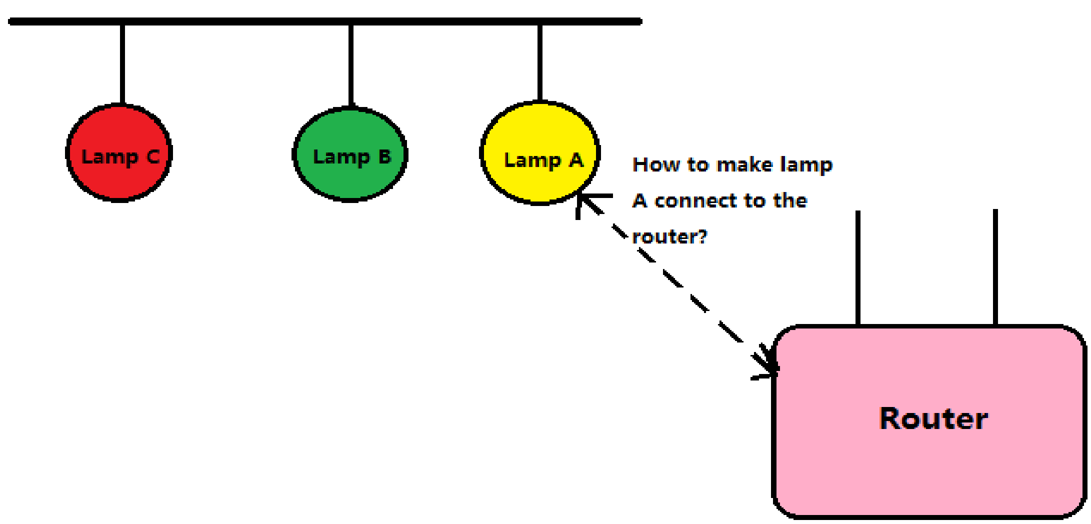

Figure 9: Problem description

3.2 Challenge of this topic

There may remain another question: why we need to remotely control lamps? In traditional life, when we come to the room, we can turn on lamps. When we leave, it is easy to turn off lamps. It seems that this "remotely controlling" design is not necessary. However, in some cases, this design is very useful as illustrated below:

Case 1: A user goes to another place on a business trip. When he is on the plane, he remembers that he forgot to turn off the living room lamps. It is impossible for him to go back to his house and it would lead to much power consumption. If he can remotely control these lamps, it would be very convenient for him and eventually will save power.

Case 2: Alice lives with her mother who is very old and not able to move freely. Alice works at the day time and is usually back home very late. In order to reduce difficulties for her old age mother while she was not around, she wants to remotely control the house lamps. With this remote controlled lighting she can change different colors and brightness of the house lighting without the need for her mother to move a lot. Thus, we see that remote control will bring much convenience for users.

In addition, this design is not only used in the lighting system. We can migrate this design to other applications. For instance, a humidifier which is based on Bluetooth low energy where we can increase the air humidity of the house from outside. As a conclusion, this topic is reasonable for research.

3.3 Problem analysis

As we have discussed in chapter 2, Bluetooth low energy protocol has good potential when it is applied in lighting system. However, its communication range is limited. If we want to achieve remotely controlling lamps which is Bluetooth low energy based, we need to make these connect to the existing Internet. We assume there is a router which supports Bluetooth low energy protocol.

But there is still a commission problem remaining as of how to make specific constrained device(lamps) connect to the router. Here, we come up with several solutions and look for the best solution for this commissioning problem.

It is learned from the Bluetooth low energy protocol [32] that there are several procedures which are used to build a connection. There are two device A (lamp) and B (router).

Connection procedure:

i)A broadcasts advertisement periodically.

ii)B scans these broadcast channels, and waits for the advertisement from A.

After the advertisement has been received, B will send scan request to A.

iii)When B has received scan response from A, it sends connection request to A.

iv)After B has received the connection response from A, connection between A and B is established successfully.

Base on this procedure, we find three solution to achieve remote control and they are listed in the following part.

3.3.1 Solution 1

The solution 1 is that we add a button on the constrained device (lamps) side and two buttons the router side. On the lamps side, the button controls the on/off of advertisement. The function of two buttons on the router side is controlling on/off of scanning and connecting. However, there are two obvious disadvantages in this solution.

i)Complexity

One disadvantage is that this will increase the complexity of original structure of lamp and router due to addition of buttons. This results in a higher cost which is not good for the Lighting company.

ii)User experience

If we add a button on lamps which are located on the roof of the house, it is inconvenient for user to access that button. Thus, this design structure of lamps is not accepted by users and this may influence the economic benefit of Lighting company directly.

3.3.2 Solution 2

Based on solution 1, adding a button on lamps side is not good idea. So we come up with solution 2. In this solution, we do not add anything new at the lamp side, instead we just add buttons on the router side. By this, we can use buttons on the router side to control on/off of scanning and connecting. For the lamps side, when they are powered up, the lamps will send advertisement all the time. As a result, when we press the button on the router, the router starts scanning and by pressing another button it connects to lamps. We can see that this solution has overcome the user experience problem which is remaining in the solution 1. However, there is still an unsolved problem.

The problem is that the router does not know which lamp user wants to connect to and which he/she does not want. For example, there are three Bluetooth low energy based lamps A, B and C in user's house. Lamps A and B are in the dining room and the lamp C is in living room. When he wants to leave, he prefers to make lamp C connect to the router and be remote controlled. However, the router just does the scanning and the connecting, and it does not guarantee whether the preferred lamp will be connected to the router.

If we want to achieve this function, we need to add a screen on this router to display each address of lamps and connect to user preferred lamp to be remotely controlled. But this will lead to increased cost of the router. Thus this is also not an ideal solution for the lighting company.

3.3.3 Solution 3

Since solutions 1 and 2 are not very appealing for the user and the lighting company we come up with a new solution to improve upon the previous solutions. Here we do not add any buttons on either lamps side or router side instead we instruct a commissioning tool to make the lamps migrate to the existing Internet. For example, the commissioning tool can be a smartphone. The following paragraph will introduce on how we can use a third device(commissioning tool) to finish this function.

Since Bluetooth low energy is more and more popular, the Bluetooth low energy based application has been used in most of smartphone. One of these is lighting application. We can use smartphones to control lamps by pressing virtual buttons on a smartphone. For example, we can control on/off, color and some other commissioning commands for lamps.

The core of solution 3 is to introduce a third device(smartphone) to communicate with both the lamps and the router. In section 3.4 we will show how we use a commissioning tool (smartphone) to make lamps migrate to the router in detail. Here we can see the advantage of this solution.

Applying this solution, we do not need to add any button on either lamps side or router side. As a result, we have not increased complexity of original system. On commissioning tool (smartphone) side, only software update is needed. Utilizing a modified application protocol in a third device) is more feasible than adding some physical interfaces on either two sides. In comparison with former two solutions, the solution 3 has advantage over others and will be discussed in the following part.

3.4 Solution to the commissioning problem

As we have discussed in section 3.3, we need to introduce a "third" device to achieve this function. The device is a commissioning tool. In this thesis, this commissioning tool is a smart phone. The solution to this problem is divided into three tasks. The following section describes them in detail.

3.4.1 Task 1 Using CT to control the lamp

A. Communication between two devices

In task1, the CT chooses the lamp, for example, the lamp A which we want to migrate to the existing Internet. When they are powered up, the lamps broadcast their advertisements.

The CT scans the advertising channel and can get scanning response from lamps. This process is shown in Figure 10.

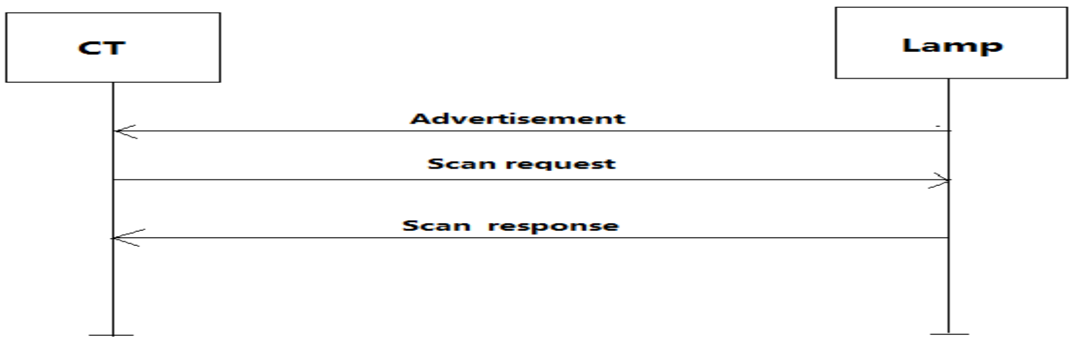

Figure 10: Process of scanning

Steps:

1. Lamps broadcast their advertisements at the advertising channels. A brief introduction of the BLE channels is presented below:

One important difference between BLE and Classic Bluetooth is that, to obtain simpler and cheaper radio chipsets, BLE uses only 40 channels, 2 MHz wide, while Classic Bluetooth uses 79 channels, 1 MHz wide.

The 40 BLE channels are shown in the figure 11. Three channels, which are located exactly between the Wireless LAN channels, are used for device discovery and connection setup. These channels (also known as "advertising" channels) are used by the technology to search for other devices or promote its own presence to devices that might be looking to make a connection. In comparison, Classic Bluetooth technology uses 32 channels for the same task. This change makes BLE reduce scanning time. Because BLE just needs 0.6-1.2ms to scan all of these channels. However, for Classic Bluetooth, this scanning time is about 22.5ms. As a result, BLE consumes much less power than Classic Bluetooth [32].

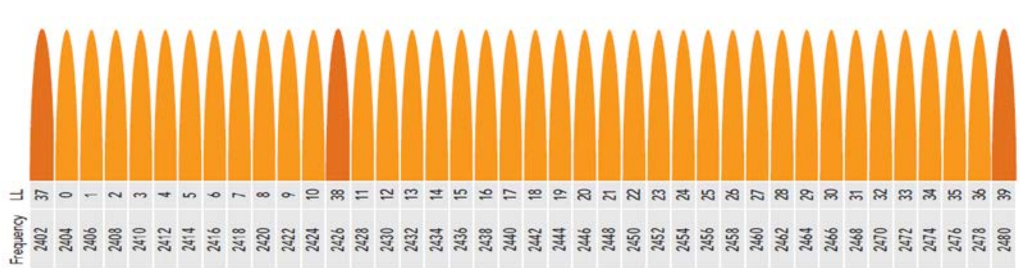

Figure 11: BLE communication channels

2. The CT starts scanning at advertisement channel(37,38,39).

3. The CT receives the scanning response from lamps and gets a list of scanning result.

If the CT prefers to connect to one of lamps, it can send connecting request to that lamp. After receiving the connecting response from the lamp, the connection procedure is finished. This process is shown in Figure 12.

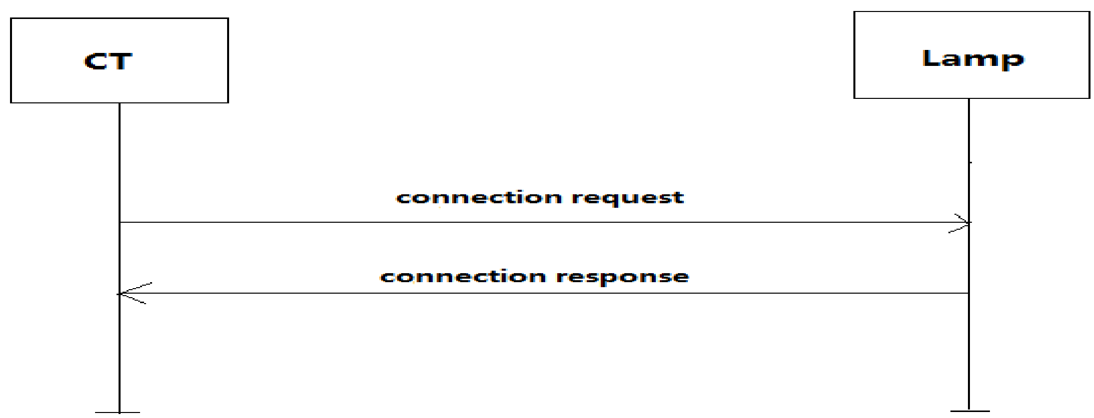

Figure 12: Process of making connection

B. Data transmission

To control the lamp, the CT need to send commissioning commands to the lamp. That means there are data from the CT to the lamp. So now we first introduce the process of sending data from the CT to the lamp, which is drawn in Figure 13.

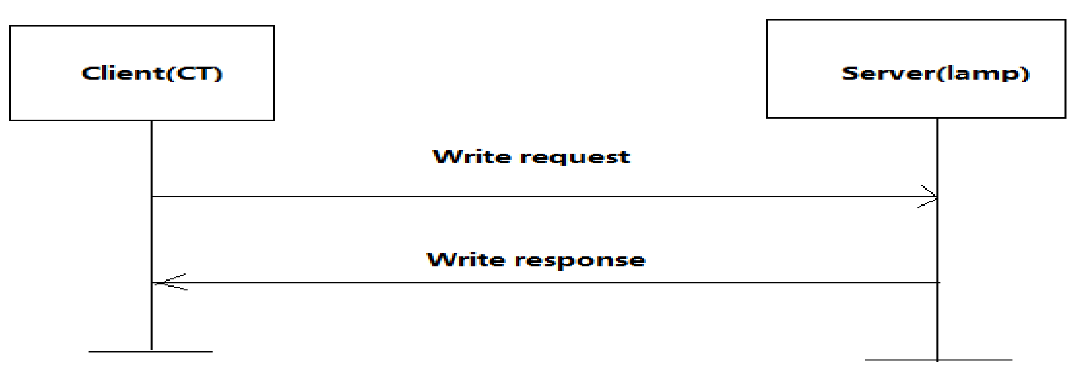

Figure 13: process of sending data from the CT to the lamp

C. Getting the address of Lamp

In this task, we need to use the CT to get the address of the lamp as shown in figure 14.

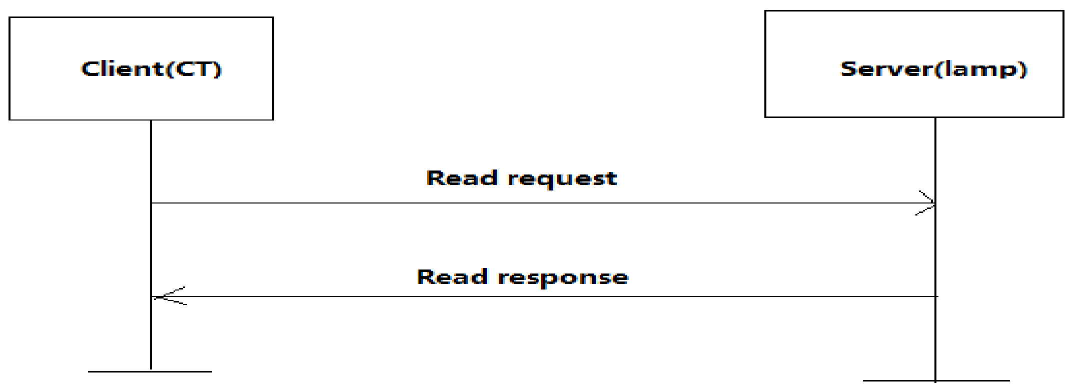

Figure 14: Process of getting the address of the lamp

This process is similar sending data from the CT to the lamp. But the difference being that the data is from the lamp to the CT. And this process is also related to GATT layer which is a layer for data exchanging.

The address of a Bluetooth low energy based device is defined by SIG which is an industry organization. Because each device has different address. As a result, this address can the confidential of a Bluetooth low energy based device. With this, the router can connect to the lamp that user want to migrate. The process of task1 is shown in Figure 15.

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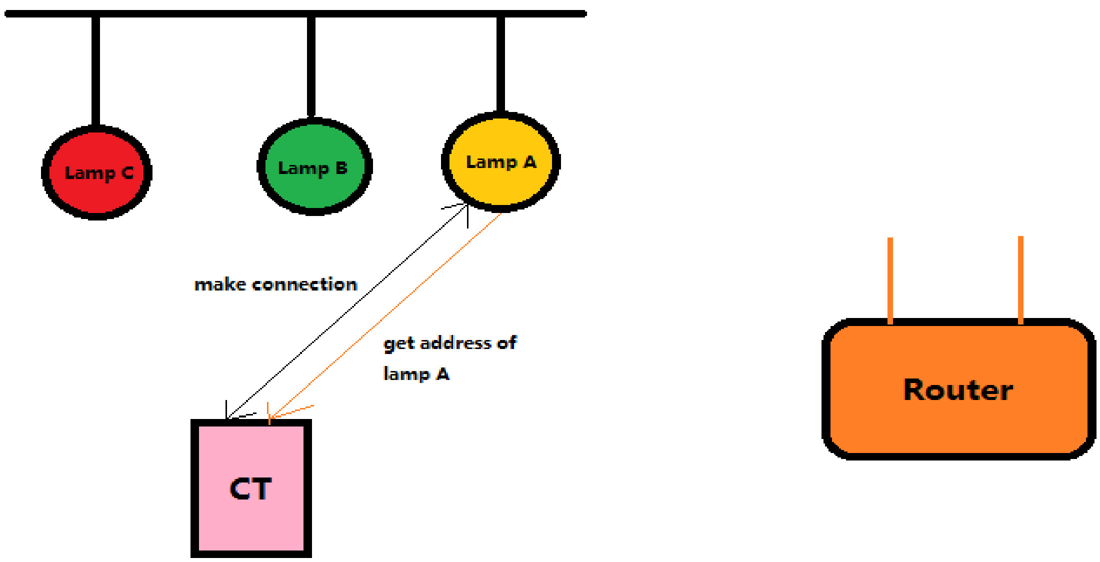

Figure 15: process of task 1

3.4.2 Task 2 Switching the role of CT and make it connect to the router

From the introduction of BLE stack, we know there are four roles in GAP layer [32]:

–Broadcaster –an advertiser that is non-connectable

–Observer –scans for advertisements, but cannot initiate connections.

–Peripheral –an advertiser that is connectable and can operate as a slave in a single link layer connection.

–Central –scans for advertisements and initiates connections; operates as a master in a single or multiple link layer connections.

Role of each device

In the task 1, we know the lamp takes the role of Peripheral (in this thesis, we also call it slave). The CT acts as a central (we can call it master). The reason why we choose these two roles for them is that they need to make connection and transmit data. Because two slaves cannot connect with each other, the router needs to choose the central role or the observer role. However, when a lamp migrates to the router, they still need to communicate and hence the router should act as master.

When the role of the lamp and the router are defined clearly, we find that there is still one problem. In task 1, the CT takes the role of the master while the router also acts as a master. Since two masters cannot connect, there is the question: how can these two devices connect with each other?

This is the question that we want to solve in task 2. The solution to this question is to change the role of CT. If the role of the CT is changed, the CT can act as slave in task2 and connect to the router. As a result, this question can be solved.

Challenge of this idea:

1.There remains a question: why do we switch the role of the CT, but not the lamp or the router? The answer is that the lamp and the router are constrained devices. If we add this switch function in these device, the complexity will be increased in them. However, if we add some functions at the CT side, we just need do some software update of smartphone. It is much easier to achieve.

2.Secondly, why do not we make the router to take the role of slave or the lamp take the role of the master. The reason being there may exist many Bluetooth low energy based lamps in user's house. One master can connect to many slaves but one slave cannot connect to many masters. If lamps take the role of master and the router takes the role of slave, the router can just connect to one of these lamps. Hence, we make the router act as master.

3. The third question being can we make the CT take the role of slave and master at the same time? If we can do that, the question remaining in task 2 can be solved as, the CT can communicate with the lamp and the router at the same time. However, this thought cannot be achieved since in link layer, there exists 5 states which are standby, advertising, scanning, initiating and connected [32].In the link layer (figure 16), there is a state machine which is used for managing these states..

Since the link layer state machine allows only one state to be active at a time, the link layer in the connection state shall not operate in the master role and slave role at the same time.. Due to this reason, we can conclude that it is hard to achieve multi-hop in Bluetooth low energy network.

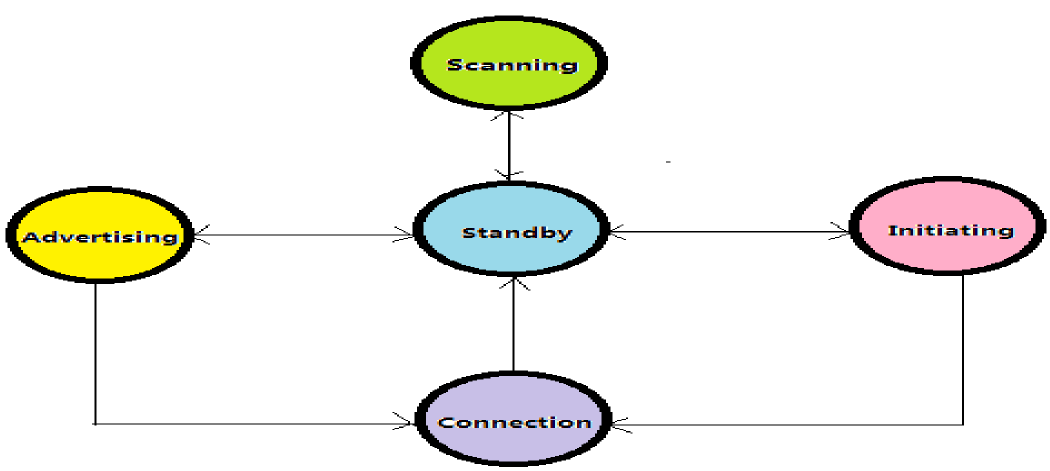

Figure 16:State diagram of link layer state machine

From the above discussion, it is clear that we need to add a switching function at the CT side. This function should be added in application layer of the original BLE stack. Since, the GAP layer is responsible for the role of the device our solution to this problem is to design a function in the application layer. The goal of this function is to change the GAP role of the device. In Figure 17, the communication between the application layer and the GAP layer (the profile is used for providing interface of these two layers) is shown.

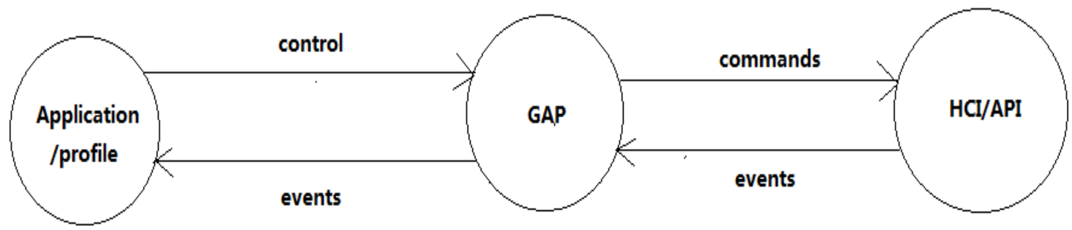

Figure 17: Communication between application layer and GAP layer

From the figure, we can see that by changing the original application layer of BLE we can switch the role of the CT. This can be proved by a demo which will be described in the chapter 4.

After changing the role of the CT, it can send advertisement and connect to the router. The connection process is the same as the task 1. When they have connected with each other, the CT can send the address of the lamp to the router. The router stores the address of the lamp when it receives the address from the CT as shown in figure 18.

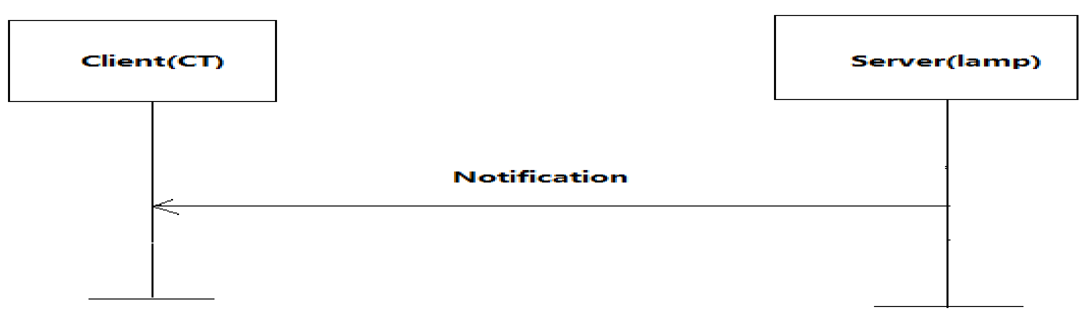

Figure 18: process of notification

From the figure, we know the data from the CT(slave) to the router(master) is different from the data from the CT(master) to the lamp(slave) in task 1. Because from the master to the slave, the master must wait for the response from the slave. However, from the slave to the master, the slave just sends notification and does not need any response. The relevant measurements have been done and will described in chapter 5. The change after task 2 is given in Figure 19.

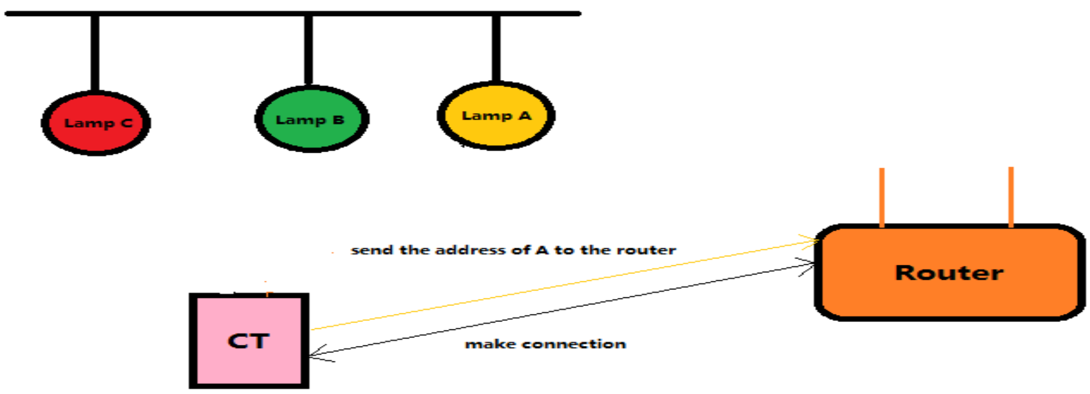

Figure 19: Process of Task 2

3.4.3 Task3 CT instructs the lamp to the Internet

After the CT disconnects to the router, the router will scan again. When it has found the advertisement of the lamp, the router can connect to the lamp. The connecting process is as same as connecting process in task 1 and task 2. After this process, we can see that the CT instructs the lamp to migrate to the existing Internet (the router) successfully. Via Internet, we can use a device to remotely control the lamp and the process is shown in Figure 26.

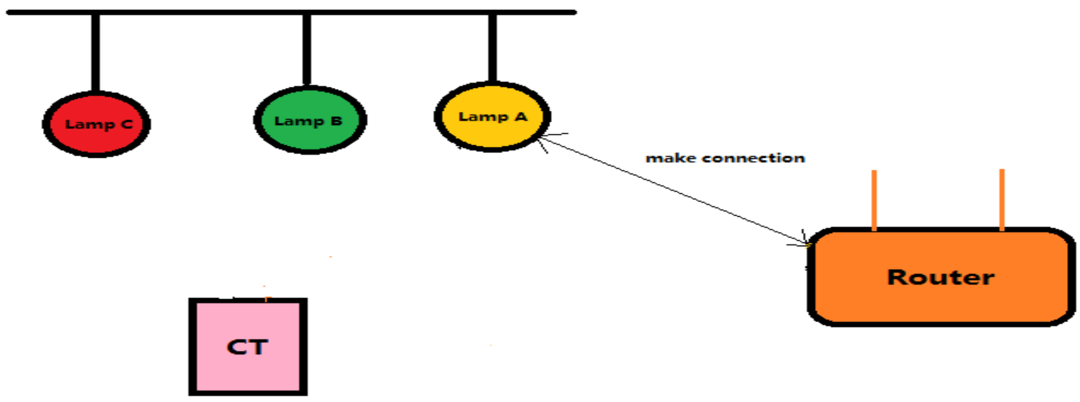

Figure 20: Process of Task 3

Chapter 4 Demo for evaluation

In chapter 3, we have introduced a solution to the commissioning problem. In this chapter, we prefer to show a demo which proves that the solution we have mentioned in chapter 3 is feasible.

4.1 Demo description

As we have discussed in chapter 3, we need at least 3 devices in this scenario. For the hardware part, this lab demo is built up by three BLE nodes namely the router, CT and the lamp. On the other hand, for the software part, we use IAR software to debug program of these devices and Packet Sniffer software to do some measurements. In the following part, we would like to introduce this demo in detail.

4.1.1 Hardware description

1.SmartRF05 Evaluation Boards

The evaluation board is a platform for the evaluation modules. In this project, we choose SmartRF05 evaluation boards. This evaluation has many user interfaces such as 3x16 character serial LCD, Joystick, USB interface can be connected to PC for user to control. Figure 21 shows this evaluation board.

Figure 21: Evaluation boards

2.CC2540 Evaluation Modules

In this project, we choose CC2540 [26] evaluation module which supports the stack of BLE protocol. This evaluation has an industry-standard 8051 MCU and enough programmable flash memory, 8-KB RAM. In addition, it can be connected to the SmartRF05 Evaluation Board for user to control via PC. Figure 22 shows CC2540 evaluation modules.

Figure 22: CC2540 evaluation modules

3.CC2540 USB dongle

CC2540 USB dongle is a tool which can be connected to PC and can be used for catching BLE packets in the air when we do measurements. These measurements we will describe in chapter 4. Figure 23 shows this tool.

Figure 23: CC2540 USB dongle

4.Antenna

We are familiar with this tool. It is used for transferring and receiving signals in the air. This is shown in figure 24.

Figure 24: Antennas

These are hardware part of demo. In this demo, one node contains one CC2540 Evaluation Module, one SmartRF05 Evaluation Board and one antenna.

4.1.2 Software description

IAR software

IAR system is a developing tool for embedded systems. IAR Systems develops C and C++ compilers, debuggers, and other tools for developing and debugging firmware for 8-, 16-, and 32-bit processors [16].

All software development on the CC2540 has been done using IAR Embedded Workbench for 8051 Integrated Development Environment (IDE). In this demo, the MCU of the CC2540 is 8051. So the IAR is suitable for software developing of this lab demo. In this thesis, we do all software work in IAR Embedded Workbench and download programs into CC2540 developing board.

4.2 Structure of CC2540 embedded software system

As we have discussed in chapter 3, we need to add some functions in application layer of BLE stack. So we would like to introduce the structure of CC2540 embedded software system first [17][18].

Five major parts of the application software:

1.Operating System Abstraction Layer (OSAL)

2.Hardware Abstraction Layer (HAL)

3. Application layer

4.BLE Protocol Stack

5.Profiles: GAP Role, GAP Security, and GATT Services

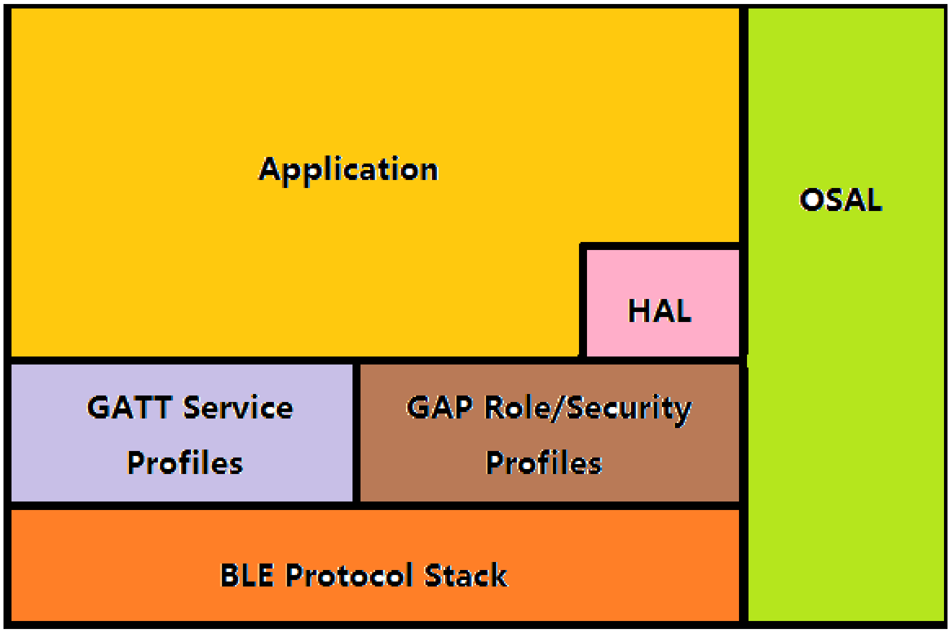

Figure 25: Structure of software system

In figure 25, we can see the relationship between these 5 parts. BLE protocol stack provides functions of each layer as object code. HAL layer provides some interfaces for user to control hardware platform. The profiles provide interfaces for user to control the whole BLE stack at application layer. So we know our project focus is on application layer. These four parts are related to BLE protocol and it is easy to understand. The OSAL layer is new layer for us so we would like to briefly introduce this new layer of embedded software. In the above figure, we can see that the OSAL layer is the foundation of the whole architecture. It is a control loop to set up for the execution of events. Every subsystem have their own task identifier(ID). For example, in this project, there are 12 OSAL tasks.

–Link Layer (0) –GAP (6)

–HAL (1) –SM (7)

–HCI (2) –Role Profile (8)

–OSAL Callback Timer (3) –GAP Bond Manager (9)

–L2CAP (4) –GATT Server (10)

–GATT (5) –Application(11)

We can see, each layer of BLE stack has its unique task ID and different layers have different functions. How do we use OSAL system to make each layer run well. For each task, we create a global variable which is tasksEvents. It is a unit 16 variable. When one of tasks, for example, task 6, its tasksEvents is not zero, the OSAL system can detect it and process this event which belongs to GAP layer. Because tasksEvents is a unit 16 variable, each task can define max 15 events(one of event is for communicating with other task). From this introduction, we can see how this embedded software system works.

4.3 The whole process of experiment

Because there are three components in this lab demo. They are the lamp, the mobile phone and the router. Each of them is represented by a CC2540 developing board. In this part, we explain the whole process of this lab.

Task1. The lamp can be controlled by the mobile phone.

At first, three developing boards are all flashed in programs. The lamp takes the slave role. When the lamp is powered up, it can send an advertisement. And when the mobile phone is powered up, it takes the role of master. As a master, it can scan for advertisement of slave. When it has found the advertisement of the lamp, we can press a key(down[1]) of the mobile phone to make it connect to the lamp and store the address of the mobile phone. In addition, we can use another key(down)to make the mobile phone send data to the lamp. And this proves that the lamp can be controlled by the mobile phone.

PS1:Because there is a joystick in the CC2540 developing board, we can use it for triggering events. The joystick has 5 keys which are up, down, center, left and right. Some of them are also used in this lab demo.

Task 2.Migrate the lamp from the mobile phone to the router.

At the beginning of this task, we press a key(up)of the mobile phone. This will lead to two effects. One is to terminate the link between the lamp and the mobile phone. The other is to make the mobile phone take slave role. As a result, the lamp and the mobile phone can send their advertisement. At this time, we switch on the router. Due to the router's master role, it can scan for advertisements of slaves. When it finds the advertisement of the mobile phone, it can connect to the mobile phone automatically. After they have built the connection, we press another key(center) which can lead to two effects. One is to terminate the link between the mobile phone and the router. The other is to send the address of the lamp to the router. After this process, the router will scan again. When it has found the advertisement of the lamp, it can connect to the lamp. Now, the lamp has been migrated from the mobile phone to the router.

Task3. The lamp can be remote controlled by the mobile phone.

At the start of this part, we can press on a button of the router. As a result, the router can connect to the mobile phone. Now, the system contains three components. The router, takes master role, connects to the lamp and the mobile phone at the same time. We can use a key(right)of the mobile phone to send data to the lamp. The data will be sent to the router first. And if the router has received this data, it will forward it to the lamp. And this proves that the lamp can be remote controlled by the mobile phone. However, in this task, the lamp is remote controlled by the CT via BLE. In the real world, this function will often not be used.

4.4 The work flow of experiment

The whole experiment we can use a work flow to explain. Figure 26 shows this workflow of experiment.

4.5 Experiment setup

To give a simple analogy, as a third device, the CT is an instructor. The router is like a room and lamps like people. People want to come into the room. However, the owner of room does not want everyone come in and he just trusts his friend, the CT. If CT tells him that A is a good man, the owner of the room will open the door and let people A come into the room. However, if the CT does not mention a few people, for example, people B, the owner of the room will not open the door.

As we have discussed in last part, the lab demo is made up of three CC2540 developing boards. Because a good technical design should also be user friendly. The developing boards can be used for testing. However, they are not the products in the real world. In other word, there are some differences between lab and real products. So in this section, we prefer to show how this application works if we can apply it in the real world. The following section shows the scenario users experience in this application.

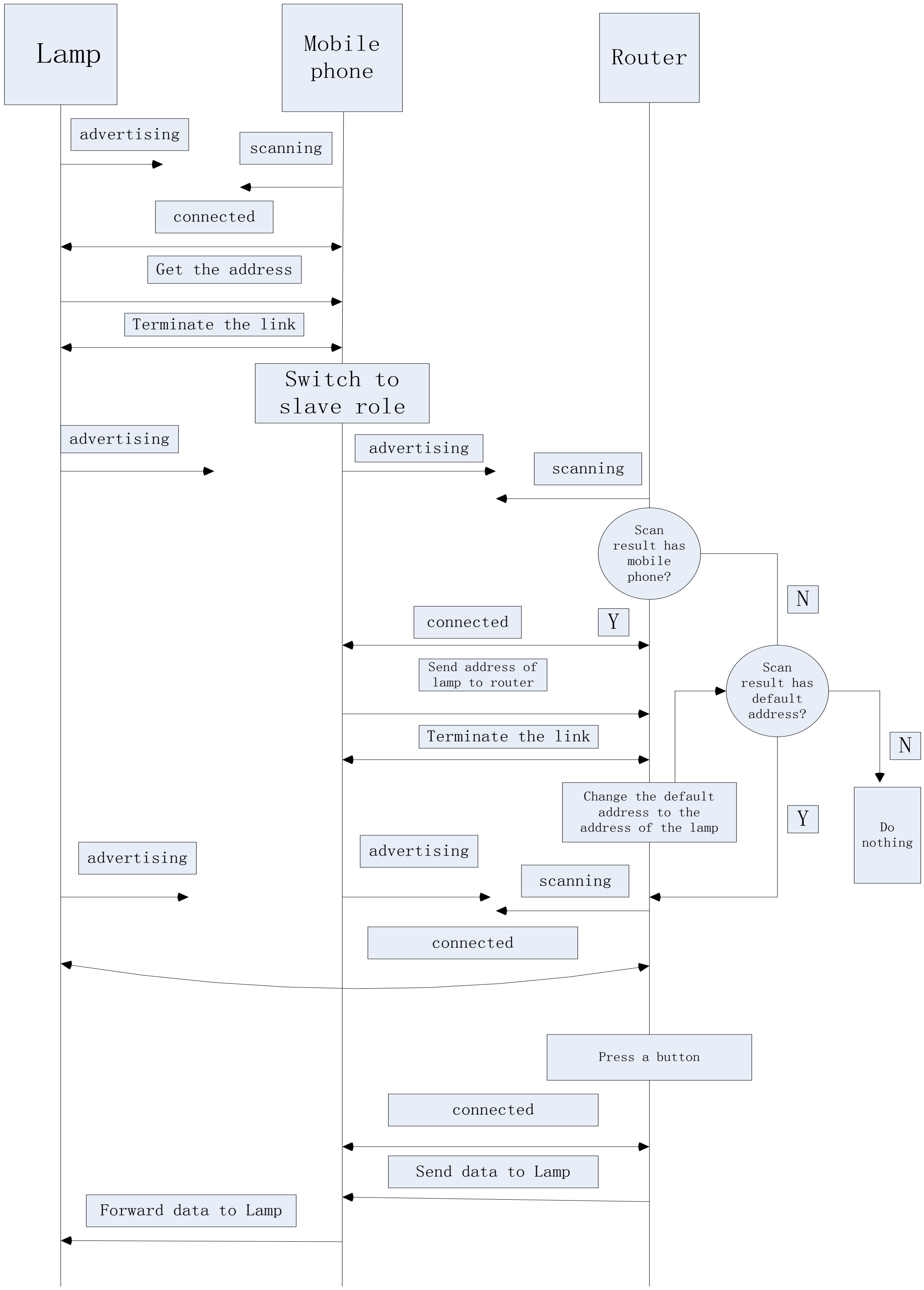

Figure 26: Workflow of experiment

Make constrained devices join the network

Scenario: A user has brought a Bluetooth low energy based lamp and downloaded the modified Bluetooth low energy application protocol in his(her) smartphone. In addition, there is a router which support Bluetooth low energy in his(her) house. The user wants to migrate lamps to the Internet by his(her) smartphone.

Steps:

1. User turns on lamps.

2. User turns on the smartphone. User uses the smartphone to discover lamps and connect to them. Through some commissioning commands, lamps can be controlled by the smartphone.

3. When user wants to leave and remote control lamps via Internet, he(she) can use a virtual button of smartphone to store addresses of the lamp(s) he want to remote control and terminates the link between the smartphone and lamps.

4. User switches smartphone into slave mode by using another virtual button. User turns on the router and the smartphone can be connected to the router automatically.

5. Through pressing another virtual button on the smartphone, user can send addresses of lamps which he(she) wants to migrate to the Internet to the router. After that, the link between the smartphone and the router is terminated.

6.The router scans again and connects to the lamps which user want to remote control via Internet.

Figure 27 shows this process

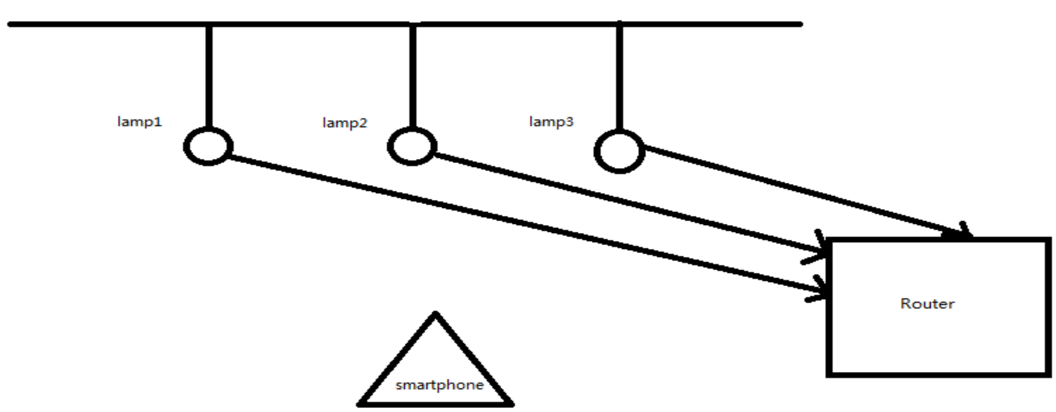

Figure 27: Make constrained devices join the network

Chapter 5 Performance Analysis

In this chapter, we present some measurements to evaluate the BLE network and prove that technology has a good performance which satisfies the requirements of wireless lighting control system.

5.1 Introduction of experiment

In this experiment, we prefer to do research on three parts namely roundtrip latency, throughput and scalability.

Significant works have been reported in literature with regard to throughput and scalability [34,36,38]. In [34] and [36], authors use a simulation tool to test the max throughput and energy consumption. In [38], average latency has been estimated. In this thesis, we prefer to do our tests with CC2540 which comes from TI company. This is the developing board we have discussed in chapter 3 which we use to build a demo. The reason why we choose this developing board is that the module of CC2540 developing board itself comes from TI company and is widely used. Thus, the experiment which is made up by these developing boards is a representative lab. In addition, we use the USB dongle [19] which takes an important role in this experiment. The function of this device is catching packets in the air.

In the following parts, we will describe these three experiments in detail.

In BLE network, there is a parameter which is connection interval. This parameter can influence roundtrip latency and throughput. So I will introduce this parameter first.

The connection interval is the amount of time between two connection events. Because all communications between two connected devices occur in "connection events". Connection events occur periodically, with the connection interval parameter specifying the period. The following figure 28 can be used for explaining this parameter.

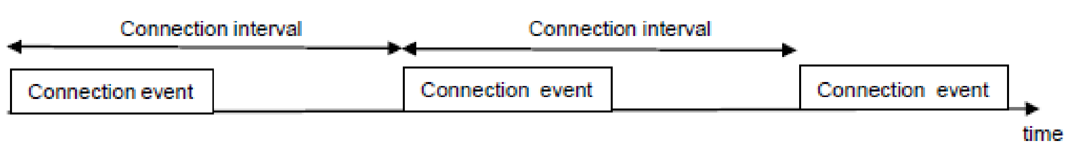

Figure 28: Connection interval

5.2Process of experiments

5.2.1 Roundtrip latency

5.2.1.1 Roundtrip VS connection interval

In this experiment, we have changed connection interval to different values and tested the roundtrip between these two devices. In the experiment, we use packet sniffer to catch packets and get the roundtrip latency. Figure 29 shows how we get roundtrip latency in an example.

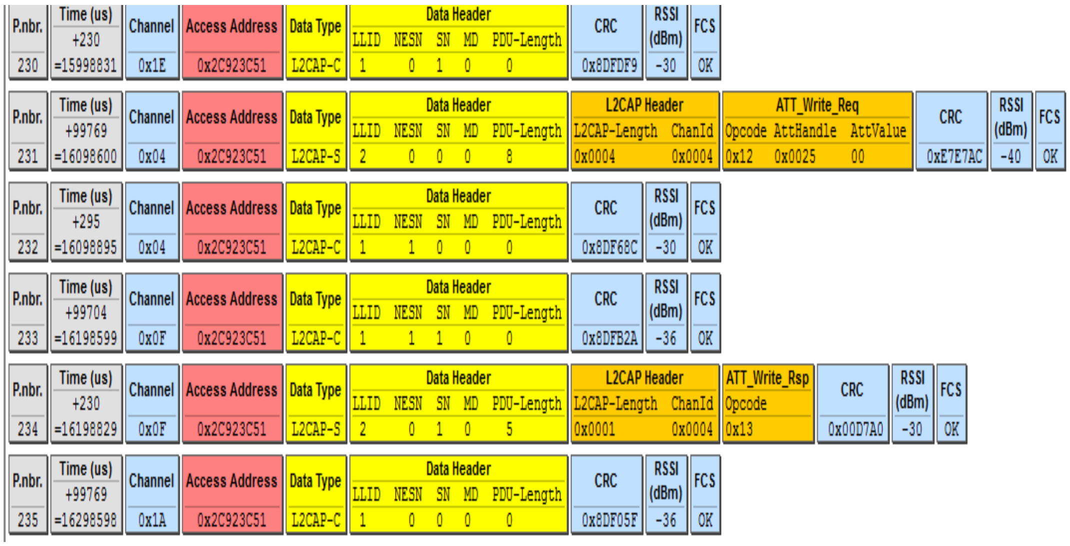

Figure 29: Example for catching packets in the air(connection interval =100ms)

In this example, the connection interval is 100ms as the roundtrip latency between the master and the slave is between the master sending data, to the master receiving response from the slave. In the figure, we can see the roundtrip latency is (16198829-16098600)us=100229us.

Like the above example, we have tested ten different connection intervals. The following table shows the relationship between roundtrip and connection interval.

Table 2: Relationship between connection interval and roundtrip latency

Connection interval	Roundtrip
10ms	10231us
20ms	20230us
30ms	29769us
40ms	40231us
50ms	50230us

60ms	60230us
70ms	70231us
80ms	80230us
90ms	90230us
100ms	100229us

We use data of table to draw the figure 30.

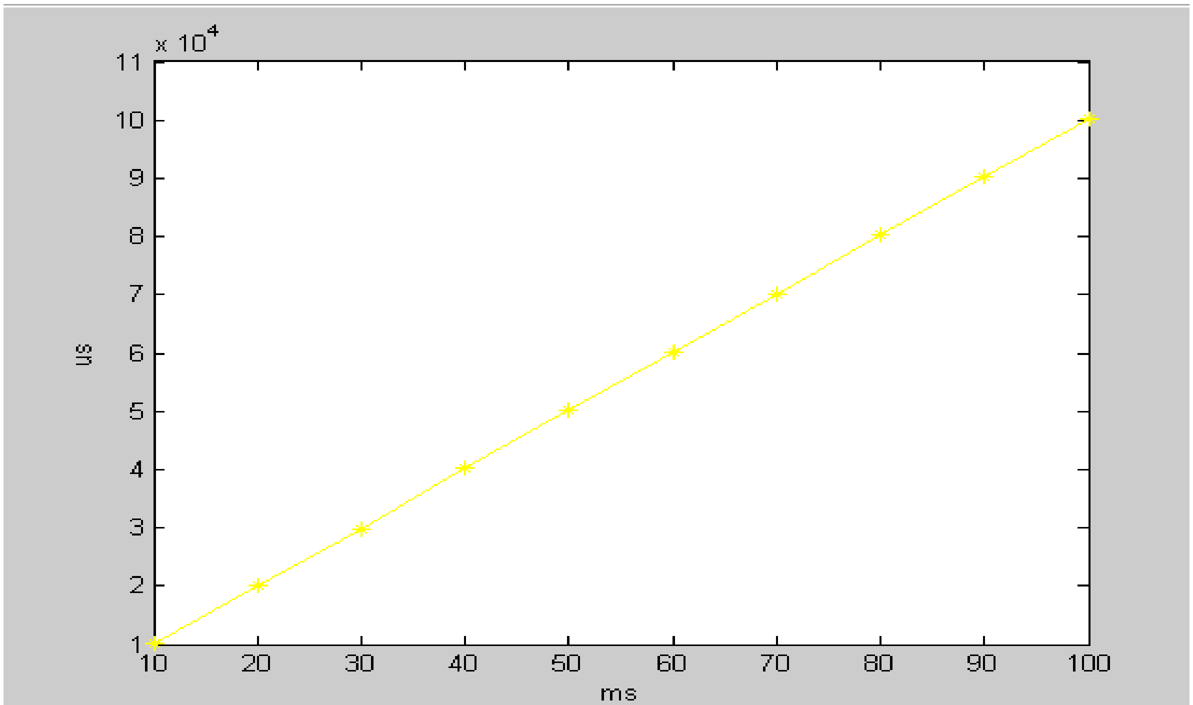

Figure 30: Relationship between connection interval and roundtrip latency

From figure 30, we can see roundtrip latency is linearly related to connection interval. Roundtrip latency increases with increasing connection interval.

5.2.1.2 Roundtrip latency VS data size

In this experiment, we use two devices to build up a system to test the roundtrip between these two devices. One of these two devices is a master and the other is the slave. First, we use the master to send data to the slave. By using different type of data sizes, we can see results of the roundtrip. The following table shows results of roundtrip latency for different data sizes.

Table 3: Relationship between data size and throughput

Data size	1 byte	2bytes	10bytes	20bytes	30bytes	100bytes
Roundtrip latency	20230us	20230us	20230us	20230us	60230us	120230us

From table 3, we can see there is no significant relationship between roundtrip latency and data size when the data size is smaller than 20bytes. However, when it is over 20bytes, the roundtrip increases with data size. The reason will be explained in the last section of this chapter.

5.2.1.3 Conclusion

This experiment is mainly focused on the roundtrip latency of Bluetooth low energy network. In the real world, when we want to apply this technology in the wireless lighting control area, we need to design reasonable roundtrip latency for users. If the roundtrip is too large, users are not satisfied with it. However, power saving is one of most important advantages of Bluetooth low energy technology. If we choose a small connection interval which leads to small roundtrip latency, the power consumption will become large which is also not desirable. These parameters can provide designers to choose between reasonable connection interval, data size and strike an optimal balance between roundtrip latency and power consumption. In addition, when the roundtrip latency is very small, it proves that BLE technology can satisfy the delay requirement of intelligent lighting control system(200ms).

5.2.2 Throughput

5.2.2.1 Connection interval VS throughput

In this experiment, we use two boards to test throughput of the system. One is the master and the other is the slave. Our test for throughput is divided into 2 steps:

i) We make the master send data to the slave at different bit rate.
ii)By finding the highest bit rate at which data can be received successfully, we can use a tool named packet sniffer to catch packets and calculate the throughput.

Table 4 shows the result of connection interval VS throughput(from master to slave)

Table 4: Relationship between connection interval VS throughput(from master to slave)

Connection interval	Throughput
10ms	8kbit/s
20ms	4kbit/s
30ms	2.7kbit/s
40ms	2kbit/s
50ms	1.6kbit/s
60ms	1.3kbit/s
70ms	1.1kbit/s
80ms	1kbit/s
90ms	0.89kbit/s
100ms	0.8kbit/s

Figure 31 shows content of table 4.

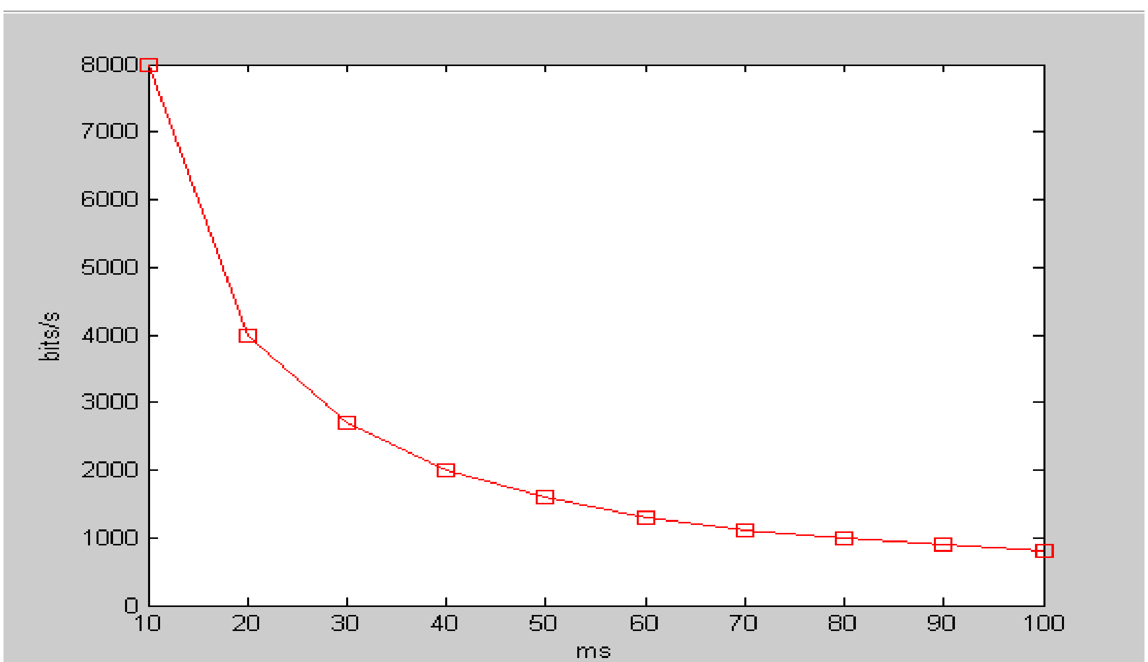

Figure 31: Relationship between connection interval and throughput (from master to slave)

When we change the direction of transmission, from slave to master, we can see different results. The process is the same as last lab. We make the slave send data to master at different bit rate and test the highest bit rate the slave can receive successfully. The results are shown in following table.

Table 5: Relationship between connection interval and throughput(from slave to master)

Connection interval	Throughput
10ms	48kbit/s
20ms	24kbit/s
30ms	16kbit/s
40ms	12kbit/s
50ms	9.6kbit/s
60ms	8kbit/s
70ms	6.7kbit/s
80ms	6kbit/s
90ms	5.3kbit/s
100ms	4.8kbit/s

The figure 32 shows the relationship between connection interval VS throughput(from slave to master)

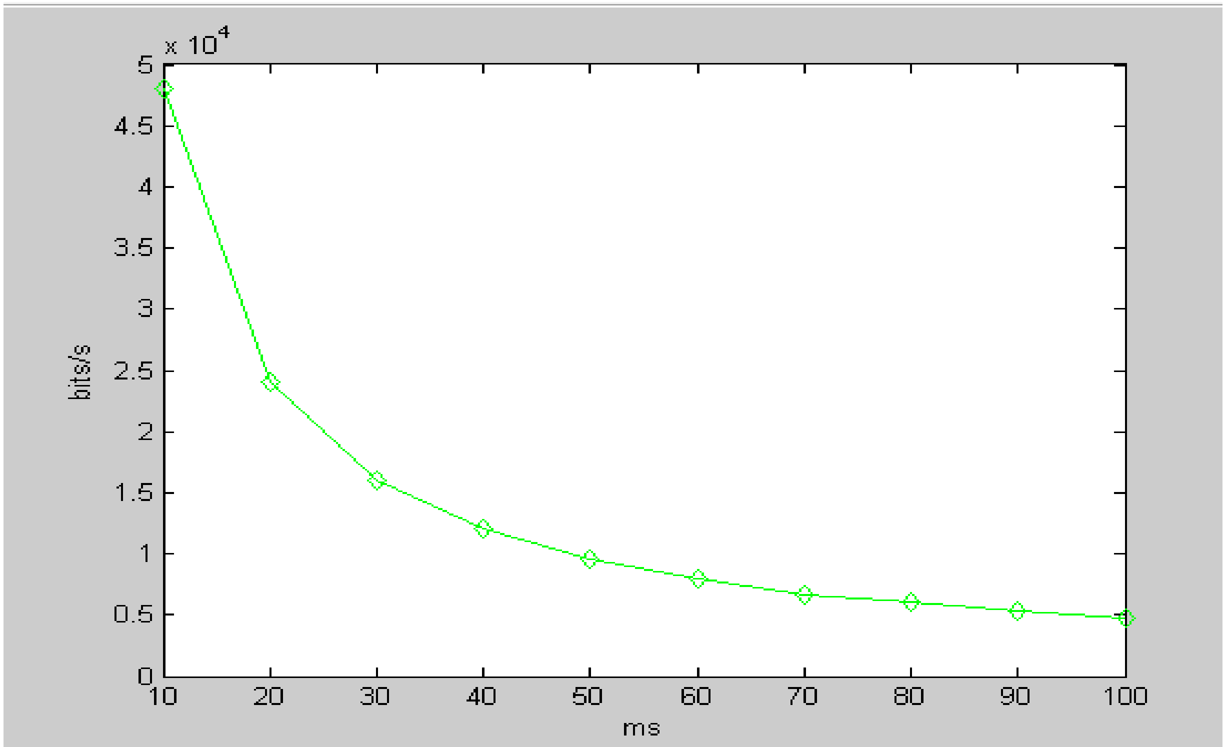

Figure 32: Relationship between connection interval and throughput(from slave to master)

From figure 32, we can see that throughput increases with the decrease in connection interval.

5.2.2.2 Conclusion

Similar to conclusion in last lab, we should make a tradeoff between throughput and power consumption. Larger connection interval means smaller power consumption, but smaller throughput. This experiment shows the relationship between throughput and connection interval. This provides data for designers to choose reasonable parameters and satisfy the users. In addition, the throughput is high enough for requirement of intelligent lighting control system.

Another conclusion is that throughput is different in different directions. We can see that the throughput from slave to master is more larger when we choose the same connection interval. That means data transfer from slave to master takes place in a more efficient way. So we can make light(slave) do more things like sending data. On the other hand, it means Bluetooth low energy technology can be applied in many other areas. For example, many kinds of sensors as in these applications slaves will send more data.

5.2.3 Scalability

5.2.3.1 Process of experiment of scalability

In this experiment, we focus on the scalability of BLE network. The aim of this experiment is to research on the number of slaves which can be controlled by a single master at the same time. Researching on scalability can provide useful data for lighting designer to choose suitable parameter to build up Bluetooth low energy based network.

This experiment can be divided into two steps.

1.We use two CC2540 boards to build up a network. One is the master and the other is the slave. After these two devices make connection with each other, the master can send data to the slave. We change some communication parameters to test the throughput of this network. When connection interval=10ms, data size=20bytes, we have obtained the throughput of this network to be 8k bit/s.

2.After we have tested the throughput in last step, we use three boards to build up another network. In this network, there is one master, two slaves and data transmitting direction is the same as step1, from master to slaves. From experience, we know that if a master(central device) wants to well control a slave(light), the lowest bit rate is 1k bit/s. Here, well control means that the master can send many commissioning commands like switching on/off, changing color, lightness. So at first, we make the master send data to each slave at 1k bit/s. As a result, it works well. After that, we improve the bit rate and test the highest bit rate the master can transmit to each slave. Finally, we have found that the highest bit rate that the master can transmit to each slave is 4k bit/s. In conclusion, the master can well control 8 slaves at the same time and this is enough for a small lighting network.

5.2.3.2 Conclusion

In this experiment, we wanted to see how many slaves can be controlled by a master at the same time. The results show the relationship between scalability and throughput. As the throughput is related to connection interval, we can get the relationship between scalability and connection interval. From our results, we see that the master can well control 8 slaves at the same time when we choose connection interval of 10ms. However, if we increase the connection interval, the throughput will decrease which has been proved in the last experiment. As a result, the amount of slaves that can be well controlled will decrease. For example, if we choose connection interval of 20ms, the throughput is reduced to 4kbit/s and it means the master can well control only 4 slaves at the same time. Finally, the smaller the connection interval, better the scalability, but higher the power consumption.

5.3 Questions in this experiment

1. Why largest data size in the experiment is 20bytes? Is it defined in the BLE protocol?

A: In BLE protocol, there is a layer named Logical Link Control and Adaptation Protocol (L2CAP). This layer is like data link layer in OSI model which has a function of segmentation and reassembly. It permits upper level protocols and applications to transmit and receive upper layer data packets up to 23 bytes in length. In the experiment, when we call function to send data in application layer, the data will be divided into several parts in L2CAP if the data is over 20bytes. For example, when we want to transfer the data and its size is 46bytes, it will be divided into 3packets. These three are 20bytes, 20bytes and 6bytes. So when we use sniffer to catch packets, the largest data size is 20bytes.

2. Why the write request and response in different connection interval?

A: This question I have not found a answer in BLE protocol, but I think I have a reasonable explanation through experiment. In BLE protocol, I have found that there should be a connection event between master and slave in each connection interval. During each connection event, the master transmits first, and the slave responds 150us later. In the experiment, this time interval is about 230us, a little different from the BLE protocol. However, it is too short for slave to receive write request from master and response to mater. As a result, writing request and response are in different connection interval.

Chapter 6 Conclusion

In this chapter, we first give an overview of contribution for this study in section 6.1.In section 6.2, we give limitations of this thesis project and some possible direction of future work.

6.1 Contributions

Through the whole thesis project, our contributions are as follows

First of all, through comparing different communication protocols, we choose the most suitable communication protocol, BLE, for next generation architecture of intelligent lighting control system.

Secondly, we solve a commissioning problem of BLE based intelligent lighting control system from stand point of BLE protocol. The solution is that we design a new protocol, developed on BLE protocol, and utilize it in a third device. This device can be used for instructing specific BLE based lamps securely connect to a Wi-Fi router which supports Bluetooth low energy protocol.

Thirdly, we set up a demo to test the solution to the commissioning problem is valid. The demo is composed of CC2540 developing kit which come from Texas Instruments company. The program of this demo is developed in IAR 8.20.

Finally, we do some experiments to evaluate performance of BLE network. There parameters which are roundtrip, throughput and scalability have been tested. These experiments are used for doing research on performance of BLE network and proving that these parameters are satisfied with requirements of intelligent lighting control system.

6.2 limitations and future work

As a primitive solution, this system has its limitations:

1.The router in this project is assumed a device which both support Wi-Fi protocol and BLE protocol.

2.The chipset for this application is expensive. Suppliers need to drop price of BLE based chipset.

3.If there are many lamps, it is difficult to instruct two or more lamps to the router at the same time. Because the router(master) can connect to a lamp(slave) at one time. The solution to this problem is to add a button at router side. However, it will increase the cost.

There are some future wok we need to do.

1. The topology of BLE is star and multi-hop cannot be applied in BLE network. It can influence the range of the BLE network. So how to improve range of BLE network has to be developed.

2. In the security side, BLE is very weak. Attacker can obtain messages through catching and analyzing packets.

3.As we mentioned in limitation 1, BLE need to improve the compatibility with AP(Wi-Fi). If they want to join in the Internet, BLE based devices need to connect to existing access points. And this is also a direction of development for BLE.

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