การพัฒนามาตรอัจฉริยะที่เชื่อมอุปกรณ์ 6LoWPAN เข้ากับเครือข่าย IEEE1888 แบบไว-ไฟ

นายดง ฮวง ลี

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมไฟฟ้า ภาควิชาวิศวกรรมไฟฟ้า
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2556

DEVELOPMENT OF SMART METER BRIDGING 6LOWPAN DEVICES TO WI-FI IEEE1888 NETWORK

Mr. Duong Hoang Le

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Electrical Engineering
Department of Electrical Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 2013

Thesis Title	DEVELOPMENT OF SMART METER BRIDGING 6LOWPAN DEVICES TO WI-FI IEEE1888 NETWORK
By	Mr. Duong Hoang Le
Field of Study	Electrical Engineering
Thesis Advisor	Assistant Professor Wanchalerm Pora, Ph.D.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

....Dean of the Faculty of Engineering

(Professor Bundhit Eua-arporn, Ph.D.)

THESIS COMMITTEE

....Chairman

(Associate Professor Ekachai Leelarasmee, Ph.D.)

....Thesis Advisor

(Assistant Professor Wanchalerm Pora, Ph.D.)

....Examiner

(Assistant Professor Chaodit Aswakul, Ph.D.)

....External Examiner

(Assistant Professor Kittiphan Techakittiroj, Ph.D.)

ดง ฮวง ลี : การพัฒนามาตรอัจฉริยะที่เชื่อมอุปกรณ์ 6LoWPAN เข้ากับเครือข่าย IEEE1888 แบบไว-ไฟ. (DEVELOPMENT OF SMART METER BRIDGING 6LOWPAN DEVICES TO WI-FI IEEE1888 NETWORK) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ. ดร. วันเฉลิม โปรา, 4 หน้า.

ในวิทยานิพนธ์นี้ต้นแบบมาตรอัจฉริยะได้ถูกพัฒนาขึ้นสำหรับระบบบริหารจัดการพลังงานในอาคารโดยเฉพาะ นอกจากนี้โพรโตคอลในชั้นโปรแกรมประยุกต์ที่รู้จักในนาม IEEE1888 ได้ถูกพัฒนาอีกด้วย เพื่อที่จะขจัดข้อจำกัดเกี่ยวกับจำนวนที่อยู่ทางอินเตอร์เน็ตในกรณีของ IPv4 และเพื่อที่จะลดการใช้พลังงาน กองโพรโตคอล 6LoWPAN และ กองโพรโตคอล Wi-Fi IPv6 ได้ถูกเลือกให้รองรับการทำงานของ IEEE1888 การได้รวมคุณประโยชน์ของ IEEE1888, 6LoWPAN และ Wi-Fi IPv6 ไว้ในมาตรอัจฉริยะตัวนี้ช่วยให้งานวิจัยชิ้นนี้สร้างต้นแบบมาตรอัจฉริยะที่ทำหน้าที่เป็นเกตเวย์ไปในตัว กล่าวคือมันช่วยเชื่อมต่ออุปกรณ์ขนาดเล็กที่สื่อสารแบบ 6LoWPAN เพียงอย่างเดียว เข้ากับระบบ IEEE1888 ที่ทำงานอยู่บนกองโพรโตคอล Wi-Fi IPv6 ได้

เพื่อที่จะทดสอบการทำงานของเกตเวย์ อุปกรณ์ขนาดเล็กที่มีเซ็นเซอร์หลายแบบและสื่อสารแบบ 6LoWPAN ได้ถูกสร้างขึ้น โปรแกรมประยุกต์ที่ทำงานอยู่บนโทรศัพท์มือถือที่ใช้ระบบปฏิบัติการ Android สามารถอ่านข้อมูลในอดีตจากคลังข้อมูลของ IEEE1888 หรือข้อมูลล่าสุดของอุปกรณ์ดังกล่าวจากเกตเวย์โดยตรง โปรแกรมนี้ยังสามารถควบคุมสถานะเปิด/ปิดของสวิทซ์ที่อยู่บนอุปกรณ์เหล่านั้นได้อีกด้วย

ภาควิชา วิศวกรรมไฟฟ้า ลายมือชื่อนิสิต ....

สาขาวิชา วิศวกรรมไฟฟ้า ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก ....

ปีการศึกษา 2556

5570528421 : MAJOR ELECTRICAL ENGINEERING
KEYWORDS: IEEE1888 / 6LOWPAN / SMART METER / WI-FI IPV6 / SMART GRID

DUONG HOANG LE: DEVELOPMENT OF SMART METER BRIDGING 6LOWPAN DEVICES TO WI-FI IEEE1888 NETWORK. ADVISOR: ASST. PROF. WANCHALERM PORA, Ph.D., 4 pp.

In this dissertation a Smart Meter (SM) prototype was developed specifically for Building Energy Management Systems (BEMS). Furthermore, an application-layered protocol, known as IEEE1888 was implemented. To overcome the restriction on the number of Internet addresses in the case of IPv4, and to reduce energy consumption, IPv6 Low power Wireless Personal Area Network (6LoWPAN) and TCP/IPv6 Wi-Fi protocol stacks were selected as the IEEE1888 supporting layers. Integrating the advantages of IEEE1888, Wi-Fi IPv6 and 6LoWPAN into SM helped this research to prototyped successfully a smart meter which functions as a gateway of 6LoWPAN nodes to the Wi-Fi IPv6 IEEE1888 network.

In order to test the gateway function, three 6LoWPAN nodes with a few sensors were also developed. An IEEE1888 Application on mobile devices running on Android operating system was employed to read 6LoWPAN nodes' history data from the IEEE1888 Storage or their latest data from the SM/gateway. The application may also control the on/off status of switches, located at the 6LoWPAN nodes.

Department:	Electrical Engineering	Student's Signature	....
Field of Study:	Electrical Engineering	Advisor's Signature	....
Academic Year:	2013		

ACKNOWLEDGEMENTS

This thesis was done to fulfill the JICA scholarship on Master of Engineering at Chulalongkorn University, Bangkok, Thailand in collaboration with the University of Tokyo, Japan. It makes up the last step in my Master study in Department of Electrical Engineering, Faculty of Engineering, Chulalongkorn University.

This thesis has been under supervision by Assistant Professor Dr. Wanchalerm Pora (Chulalongkorn University), with Professor Dr. Hiroshi Esaki (the University of Tokyo) as co-supervisor.

I would like to express my deepest gratitude to Assistant Professor Dr. Wanchalerm Pora for his endless motivation, kind instructions, and valuable advices since the first days when I developed this topic until now. During the last two years, I feel very lucky to be his student and to be given a lot of opportunities for my intellectual development through a variety of international conferences and projects. Along the way completing this thesis, I am very grateful to his supports at any time when I am in need.

I would also like to thank Professor Dr. Hiroshi Esaki and Assistant Professor Dr. Hideya Ochiai for their consideration, enthusiastic explanations, and useful documents for my research.

This thesis could not have been accomplished without the advices and comments from the committee, including my committee chair, Associate Professor Dr. Ekachai Leelarasmee; Assistant Professor Dr. Chaodit Aswakul; Assistant Professor Dr. Kittiphan Techakittiroj.

Specially thanks for M.E. Sarawut Dechijarusyothin who conscientiously shares knowledge and experiences on some parts in my thesis. Also, all of my friends in ESID laboratory (friendly, crazy, talkative, helpful, generous, and super intelligent), thanks!

And finally I want to thank my great father, my beloved mother, and my little lovey brother for their caring and encouragement in every steps of my thesis completion. Beside I am also happy to receive supports from my respectful grandmothers and my uncle Dr. Nguyen Chi Truong. Last but not least, my heartfelt thanks to my sweet partner and life companion who always keep giving trust and encouragement to me. I dedicate this thesis to my family.

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CHAPTER 1: INTRODUCTION

1.1 Motivation

Undoubtedly, the world is running out of natural resources. Facing this challenge, it is suggested that reducing energy consumption should be a solution. Governments has been implemented a variety of policies to show its commitments to cut down on energy using. With the advantage of energy-saving technology, commercial buildings are one of the greatest contributing sectors in the effort to reduce energy [19]. This is also beneficial for companies because energy efficiency can help reduce their daily business cost. In regards of technology, innovative solutions are called on to solve the issue of energy exhaustion. At this point, Smart Grid is on the top of the list. Among several issues that Smart Grid deals with, i.e. energy generation and transmission, and rethinks business models, Building Energy Management Systems (BEMS) is of great importance.

In BEMS, Smart Meter (SM) has a function of assisting users to sense and identify energy consumption. Realizing its usefulness, a great deal of efforts has been made to improve its function so as to save energy towards a green economy and sustainable development. In addition to SM, development of other protocols to get a smart, convenient and secure management and control among buildings and buildings blocks have been carried out. One of these protocols is the IEEE1888 standard which is developed on top of the TCP/IP one. It has been in successful use in the University of Tokyo, Japan. This research is taking this prominent concept into consideration.

While Internet-connected devices become popular nowadays, it is not a good choice to integrate millions of devices into the IPV4 internet because of the lack of IPv4 addresses. IPv6 is the solution to this problem since it allows a big number of Internet-based devices. However, one disadvantage is that IPv6 is more complicated and consumes more power than IPv4. To address this limit of the system, IPv6 Low power Wireless Personal Area Network (6LoWPAN) was created to reduce energy consumption. It is suitable for battery-operated nodes including temperature and light sensors. Integrating the advantages of two protocols - IEEE1888 and 6LoWPAN into SM helps it fulfill its function as a Gateway (GW) in BEMS.

This thesis aims at showing the implementation of a smart meter functioning as an IPv6 IEEE1888-6LoWPAN gateway. Specifically, Smart Meter/Gateway (SM/GW) plays the role of sensing the consumption and relaying the data from 6LoWPAN sensors in building blocks to other places in IEEE1888 Storage. This SM/GW includes motion sensor that can monitor the environment. Additionally, this SM/GW works as the temporary Storage to store the latest values of the 6LoWPAN Nodes data such as temperature and motion data, motion sensor, and energy. It also assists the data retrieving from other devices through the Wi-Fi communication. As a result, the IEEE1888 Application operating on mobile Android OS device is useful to access the latest values for sensor reading from this temporary Storage. This temporary Storage can be implemented on SM/GW and operates on the actuator commands to control.

1.2 Research Objectives

1.2.1 To develop a smart meter which functions as a gateway of 6LoWPAN Devices to a Wi-Fi IEEE1888 network

1.2.2 To develop 6LoWPAN temperature sensors.

1.2.3 To test the communication between 6LoWPAN sensors and an IEEE1888 Storage.

1.3 Scope of Research

1.3.1. Two simple temperature

1.3.2. An energy meter prototype

1.3.2.1. Single-phase

1.3.2.2. Accuracy Class 1

1.3.2.3. 220V, 5A rated

1.3.2.4. Two communication modules for Wi-Fi and 6LoWPAN communication

1.3.2.5. Post measured energy and temperature to a IEEE1888 storage every minute

1.3.3. An investigation of the communication between 6LoWPAN sensors and the Storage

1.4 Structure of Research

This thesis is organized as follows. The first chapter is the introduction of BEMS, Smart meter, IEEE1888 and 6LoWPAN and why this research chooses these standards. In this chapter also includes the Research Objectives and the Scope of research. The second chapter looks at the Theoretical Background this research is related to, it consists of the introduction of some current protocols, studies about IEEE1888 Protocol, 6LoWPAN and Smart meter. Design and Implementation is covered in the third chapter; it concludes the system hardware and system software and the implementation issues in using IEEE1888 and 6LoWPAN in Smart meter. The Experiments and Results are given in Chapter 4. Finally, the Conclusion with the future challenges is discussed in Chapter 5.

CHAPTER 2: THEORETICAL BACKGROUND

2.1 Related Protocols

2.1.1 BACNet

Building Automation and Controls network (BACNet) is the data communication protocol or communication rules. This standard protocol is used in building automation system components to standardize communication. Many different vendors such as HVAC&R control, fire systems, lighting, and security use this protocol BACNet to communicate each other with the purposes as object-oriented presentation, interpreting, requesting and transporting information used in the buildings digital control technology.

2.1.2 Bluetooth

Nowadays, many devices are using Bluetooth technology such as mobile phones and personal computers. Low cost, low range and low power supply are the main purposes of design for this technology. The unlicensed 2.4GHz (2400 – 2483 MHz) is the frequency used in Bluetooth, which is also shared with IEEE 802.15.4 and Wi-Fi as well. For solving the collision when using the same 2.4GHz band between other Bluetooth networks, Wi-Fi, ZigBee and other wireless communications, Bluetooth uses the Frequency-Hopping Spread Spectrum as the solution which implements jumping from one channel to another from time to time. The Adaptive

Frequency-Hopping used to implement in its devices to listen to new channel, and a new channel is chosen if it is occupied [14].

Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is also implemented in Bluetooth to avoid the collision between a shared channel with another wireless communication. Master – slave mode is chosen for working on Bluetooth. The Bluetooth topology supports one master with 7 Slaves up to 255 Slaves in parked mode (this mode uses for waiting to be awakened by the master). Clock and time slots are defined by the master device, moreover the master can change his roles (master to be slave and vice versa) to all slave devices [14].

2.1.3 Wi-Fi

The Wireless Fidelity (Wi-Fi) is the term referred to the IEEE 802.11 communication standard which supports for Wireless Local Area Networks (WLANs). There are some versions of Wi-Fi are available:

+ 802.11a: this is the first version operates in 5GHz band

+ 802.11b/g: this is the developed version from the first one with the faster data transmission rate (11 Mbps and 54 Mbps respectively) which operates in 2.4 GHz band.

+ 802.11n: this is the most popular version is using and many Wi-Fi devices now, it can be configured and operated in both 2.4GHz and 5GHz frequency band.

Orthogonal Frequency-Division Multiplexing is used in Wi-Fi which supports for the performance a full-duplex communication in a channel. For avoiding the collision between overlapping channels, CSMA/CA is used as the solution. Wi-Fi network architecture uses an Access Point (AP) and multiple clients, these clients communicate on network through the latter. Furthermore, because of working on wireless networking, the security is also very important. With low-security applications, WPA is considered to be sufficient protection. For the applications require most secure, WPA2 is referred to use [14].

2.1.4 ZigBee

With the huge increase of embedded systems, Wi-Fi and Bluetooth are very power-greedy. Following the needs, the communication protocol is required to be more and more autonomous and convenient. For this requirement, IEEE 802.15.4 is the solution which is intended for wireless networks with small dimensions, consumption and cost.

In this IEEE 802.15.4 standard, only physical layer (PHY) and medium access control (MAC) are defined [14]. The implementations of ZigBee must be defined in higher Layer; a standard for WPAN is specified for Network and an Application layer to complete the IEEE. ZigBee Alliance is named by a number of industrial companies, points to the low cost, low consumption wireless communication.

ZigBee is able to run on the data rate of 250kbs with the reaching up to 500m, the typical consumption is between from 125 to 400 μW. The security is also provided based on IEEE 802.15.4 [14].

2.1.5 The 6LoWPAN

As the Internet standard, 6LoWPAN is enabled to use IPv6 over low-power wireless area networks (such as the IEEE 802.15.4 radio). This serves to realize the Wireless Embedded Internet [11].

To facilitate the utilization the IPv6 in low-power, the limitation of processing in embedded devices over wireless networks with low-bandwidth, 6LoWPAN with IPv6 is employed to replace IPv4 due to the increasing number of Internet address [17]. The wireless communication IPv6 is put over the standardized IEEE 802.15.4 low-power radio assists devices with the limitation of space and power such as sensor nodes.

As shown in Figure 1, the 6LoWPAN Protocol Stack which provides a wireless sensor network node with IP embedded. The 6LoWPAN is put above the IEEE 802.15.4 data link layer as the adaptation layer and also the TCP/IP communication is provided above the data link layer.

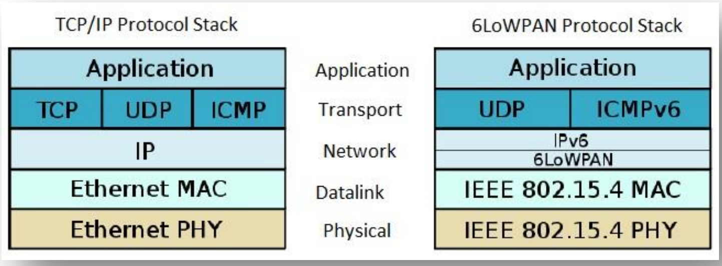


Figure 1 6LoWPAN Protocol Stack

In home networking, building automation and industrial control, IEEE 802.15.4 is the important standard and also includes three modes:

+ 20 kbps at 868MHz

+ 40 kbps at 915MHz

+ 250 kbps at 2.4GHz

Inside the 6LoWPAN protocol stack, the IEE802.15.4 compliant is located in the Physical layer which provides the basic communication. For more detail is found in section 2.3.

2.1.6 IEEE1888

IEEE1888 is the internet communication protocol suite based on TCP/IP using HTTP and XML for the sensor exchanged data and actuator commands. IEEE1888 could be applied in digital city networks and also intelligent building groups. According to this standard, the different electrical appliances in home area networks communicate via a same language and protocol [4]. IEEE1888 exploits communications and IT so that the energy savings and environment protection are achieved. This standard describes architecture of digital device community which can be controlled and monitored locally or remotely. IEEE1888 specifies not only the interactive data format between servers and devices, but generalizes communication methods. For more detail is found in section 2.2.

2.2 The IEEE1888 Protocol

2.2.1 Overview

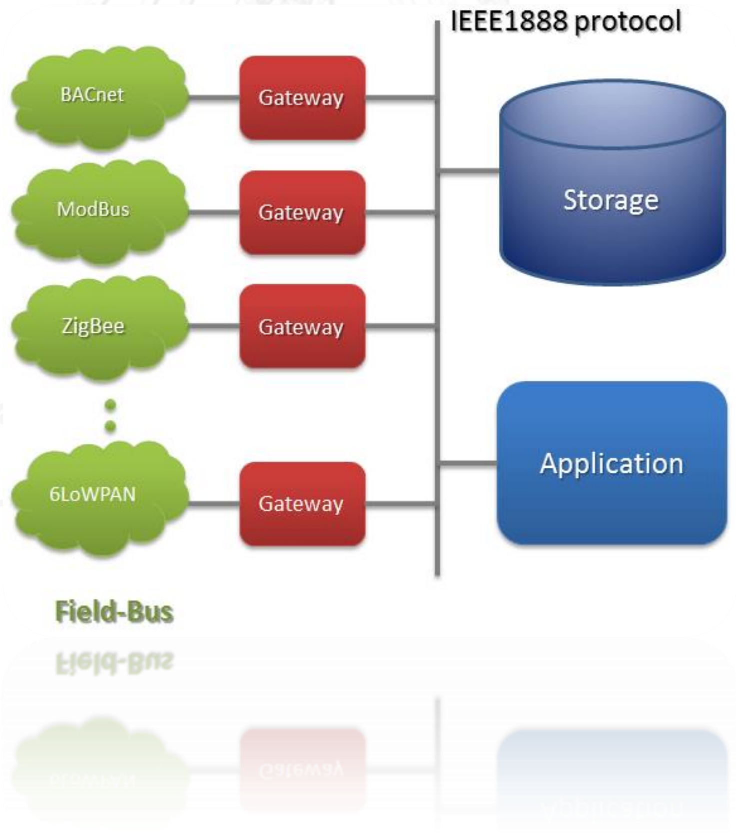


Figure 2 IEEE1888 Architecture

Figure 2 illustrates the IEEE1888 networking architecture which includes Gateway (GW), Application (APP) and Storage. Three of them are called "Component". Specifically, GW is the translator in IEEE1888 frame builder of some low-power sensors and actuators located in Field Buses (FB). Storage stores the history of data sequences. The data can be written from the components and be permanently stored in the disks, and it is also provided to the components by requesting from the components [16]. APP is used to work on sensor reading and actuator commands; it also has the user interface to display the data of latest environment state. Through APP, it allows user to put schedules for the actuator settings, it can well manage in real-time some sensor data and also provide the result. The Registry serves as the go-between of GW, APPs and Storage; it functions mainly to link all components above autonomously and appropriately. There is no operation on sensor readings and actuators settings by Registry [4].

IEEE1888 communication is based on HTTP and Remote Procedure Call (RPC). IEEE1888 contains Component-to-Component Communication three handshake Procedures [4]:

+ *WRITE Procedure*: Transmission of data to the remote component and the invocation of data method

+ *FETCH Procedure*: Retrieval of existing data from the remote component and the invocation of data method

+ *TRAP Procedure*: Receiving of upcoming data from the remote component and the combination of query and data methods.

In addition, IEEE1888 includes Component-to-Registry Communication protocol [4]:

+ *Registration Protocol*: for registration of the role of components and semantics of Points

+ *Lookup Protocol*: for searching appropriate components and Points.

2.2.2 Deployment

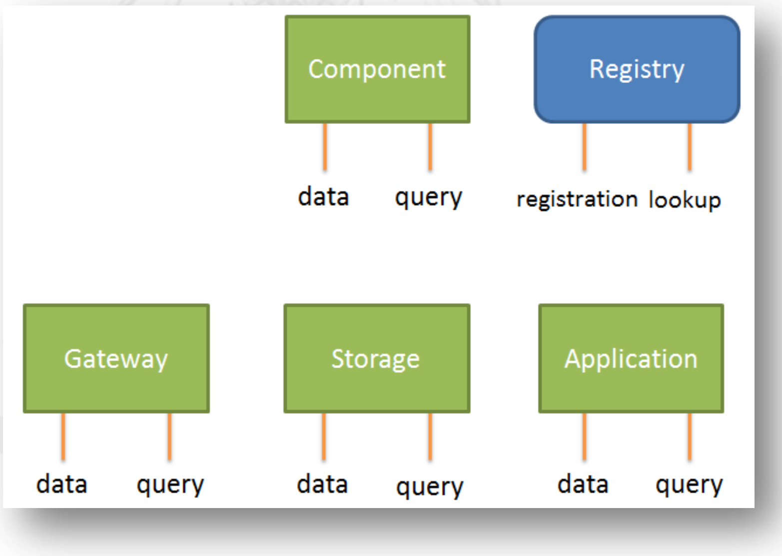


Figure 3 System model

Figure 3 illustrates the IEEE1888 system model, which concludes three kinds of components are gateway, storage and application. Component supports data method and query method.

+ *Query method*: for retrieving data from other component and reading data from the indicated Points

+ *Data method*: for transferring data into the component and writing data into the indicated Points

Registry has registration method and lookup method, which works as the go-between of components. It also manages the connection between components and Point ID.

+ *Registration method* does the role registration of the components Points semantics.

+ *Look up* method works as the finder for correct components and Points

A Point has URI-based globally unique identifier which identifies the data flow exchanged between components. The IDs will be assigned for all of physical sensors and actuators. The PointSet is the hierarchical management of Points [4]. The example of Point ID and PointSet are shown in Chapter 4.

2.2.3 Common Communication protocol

There are three kinds of components (Gateway, Storage, Application) whose communications are based on IEEE1888 protocol. Also, Simple Object Access Protocol (SOAP) is used in this protocol [4].

There are three procedures which are WRITE, FETCH, and TRAP have the structure defined in XML format. Two of them WRITE and FETCH procedures are applied into my research.

WRITE: For transmission of data to the remote component and the invocation of data method.

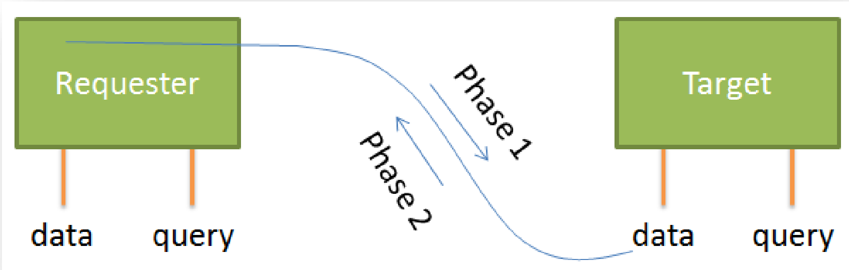


Figure 4 Write protocol

This protocol is used to transfer data to a remote component. Figure 4 describes the communication between a Requester and Target.

+ Phase 1: Requester uses data method with data contents to invokes Target

+ Phase 2: After receiving, Target will reply a confirmation successful or failure message to Requester.

FETCH protocol: Retrieval of existing data from the remote component and the invocation of data method

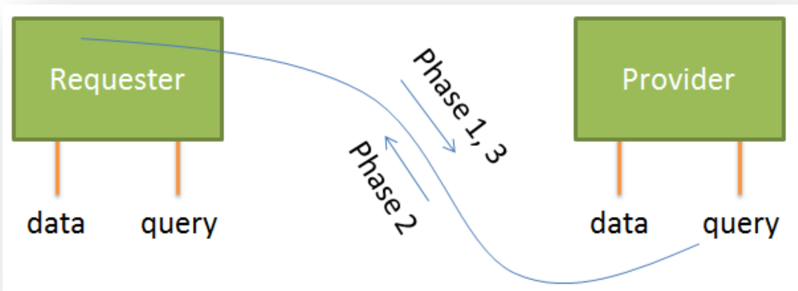


Figure 5 Fetch protocol

This protocol supports to retrieve data from a remote component. Figure 5 illustrates the communication between two components, one of them is Requester which inquires data, and another is Provider which replies with the data.

+ Phase 1: Requester uses the Query method to send the query information, and also the size of acceptable data at the RPC-response should be sent at the same time. 100 should be applied for default setting by Server if the acceptable size is not available.

+ Phase 2: All of dataset will be sent by the Provider by the RPC-response. If the size of requested data is exceeding the acceptable size or the Provider has to compute a lot of resources, a cursor will be associated to a returned subset of the whole data.

+ Phase 3: If the previous response has a cursor with 60 seconds validity of time for recommendation, a query method is invoked by Requester at the Provider again. And this process will be back to Phase 2.

+ Phase 4: Fetch process will be ended, if dataset is retrieved without any cursor.

TRAP protocol: Receiving of upcoming data from the remote component and the combination of query and data methods. This protocol is used for event query and data transfer. This research does not focus on this kind of protocol.

2.3 The 6LoWPAN

2.3.1 Overview

IEEE 802.15.4 is intended for wireless network with small consumption, small dimensions and the small cost. In this protocol, only PHY and MAC layer are defined.

This standard defines 3 frequency bands to use:

+ 2400 – 2483.5 MHz: includes 16 channels, and available worldwide

+ 902 – 928 MHz: includes 30 channels, available in the USA

+ 868.0 – 868.6 MHz: only using 1 channel, available in Europe

IEEE 802.15.4 consumes low power with the small batteries for year operation. It can apply to low-end embedded system of limited hardware performance. The distance for communication is from 10m to 100m.

IEEE 802.15.4 supports multiple types. One of these types is Full Function Device (FFD) which includes coordinator and router. The coordinator can configure and form the network information through configuration channel, and router has responsibility in routing the packet. Both of them can be other types is Reduced Function Device (RFD) which is the end device. This device is limited in its performance, and stays at the sleep mode most of the time [20].

2.3.2 Deployment

Furthermore, there are some kinds of topologies are used in this standard: Star Topology, mesh topology as shown in Figure 6:

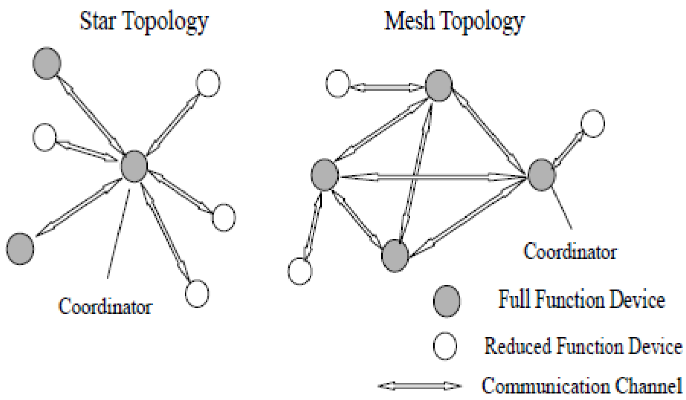


Figure 6 the IEEE802.15.4 Network Topologies

The PHY and MAC layer of IEEE802.15.4 standard is adopted by 6LoWPAN bottom layer. IPv6 has chosen as the networking technology leads to the wireless sensor networks. The IPv6 payload length in MAC layer (1280 bytes) is much more than one provided by 6LoWPAN bottom layer (not over 127 bytes), so for the seamless connection of MAC layer and network layer, the LoWPAN adaptation layer as shown in Figure 7, is added between MAC and network layer to support for header compression, fragmentation, and reassembly [20].

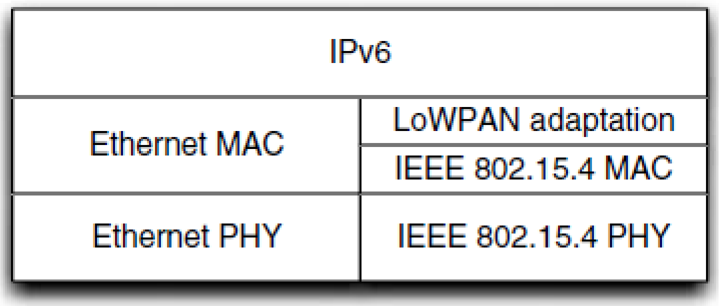


Figure 7 LoWPAN Adaptation Layer

The dynamic assignment is available in 6LoWPAN for 16-bit short addresses. Then, the transport protocol is used with 6LoWPAN is the UDP which can be compressed using the LoWPAN adaptation format. In this adaptation layer, because all compressed fields of each node are known, the host (server) node or router does not need to work with full formats of IPv6 or UDP header [15].

Furthermore, in data link layer for 6LoWPAN is recommended for unique addresses by using 64-bit extended unique identifier (EUI-64) because of stateless auto-configuration. The payload size in link layer is provided at least 30 bytes in length [20].

Security is also a concern for 6LoWPAN. A security mechanism always needs more processing and more bandwidth resources. Leading to the low-power, embedded devices with limitation of processing over wireless networks with low-bandwidth, 6LoWPAN is not suitable. IEEE 802.15.4 also provides AES security mechanism, but it is not enough strengthen. The strong authentication and encryption is always recommended to include in this link layer [15].

2.4 Smart meter

2.4.1 Overview

As an electronic device, a smart meter is assigned with gaining all data consumption in a smart grid. It is also in charge of enabling consumers to monitor, analyze, and control the energy consumption in their places [18]. For example, the smart meter informs users of higher rates of energy used during the peak in hot or cold weather. In this way, consumers can keep track of all details in their energy consumption and avoid big energy bills. Notably, if well used, it is shown that the energy consumption can be reduced by one-half.

As a result, smart meters become vital for the development and construction of smart grids. Without this new measure device, the goal of user-friendly system in which interactivity and participation of clients are encouraged cannot be fulfilled. It is highly recommended that customers should be aware of the status of their energy consumption. Smart meters are created to facilitate this task by informing clients of their energy consumption, energy costs and carbon emission; providing clients with capacity to become smart energy users, and offering equipment with accurate data on energy and water consumption for energy saving.

In short, smart meters are intelligent in functioning these tasks: (1) providing a measurement of used energy, (2) switching the customer off from a distance, (3) controlling electricity consumption from a distance.

2.4.2 Definitions

In AC electric circuit, the voltage and current has the formulas as shown in equations (0.1) and (0.2) as follows:

$$U = U\sqrt{2} \times Sin\omega t \tag{0.1}$$

$$I = I\sqrt{2}\ \times Sin(\omega t - \ \varphi) \tag{0.2}$$

+ Active Power (W):

$$P = U \times I \times Cos\varphi \tag{0.3}$$

+ Apparent Power (VA):

$$S = U\ \times I \tag{0.4}$$

+ Reactive Power (VAR):

$$Q = \ \sqrt{S^2 - P^2} = U\ \times I\ \times Sin\varphi \tag{0.5}$$

+ Power Factor PF:

$$PF = Cos\varphi = \ \frac{P}{S} \tag{0.6}$$

+ Electric Energy (Wh):

$$E = P\ \times t \tag{0.7}$$

Where:

U, I: are the effective values

$\varphi = \ \varphi_u - \ \varphi_i$: Phase angle from Current to Voltage

φ_u, φ_i is the voltage and current to the same reference phase angles

t: time (hours)

CHAPTER 3: DESIGN AND IMPLEMENTATION

3.1 Hardware

3.1.1 Central Processing Unit

In this study, the system requires high performance to implement some communication protocols such as IEEE1888 working as Client and Server, 6LoWPAN data analysis, and also built in smart meter with the addition of some actuators, and the implementation of system status monitoring. Besides, the cost to build this system is also important. Because of these above reasons, the ARM-Cortex M4 Microcontroller STM32F407VG has been chosen.

Figure 8 STM32F407VG

This Microcontroller Unit (MCU) STM32F407VG is shown in the Figure 8 has 144 pins working as the main core. This MCU is equipped with high performance ARM Cortex-M4 32-bit RISC core with the frequency of operation up to 168MHz. The MCU core has a Floating Point Unit single precision with the assistance for all of ARM single precision data processing instruction and data types. The full set of digital processing instructions and the protection unit for improvement of the application security has also been equipped [7].

With 100 pins, this MCU supports a large range of Input/Outputs and peripherals. They are connected into two Advanced Peripheral Buses, three Advanced High-performance Buses (AHB) and a 32-bit multi-AHB bus matrix [7].

The MCU has a 12-bit Analog to Digital Converters, two Digital to Analog Converter, a low-power Real Time Clock, and the true Random number generator. In addition, this MCU also has some advanced communication listed as follows:

+ Two CANs

+ Three SPIs, two I2S full duplex

+ A USB OTG high-speed with full-speed capability

+ Four USARTs plus two UARTs

+ An SDIO/MMC interface

+ Up to three I2Cs

+ The Ethernet and the camera interface for CMOS sensors.

STM32F407VG has the range of operation temperature is from -40°C to +105°C with the power supply ranges from 1.8V to 3.6V. From 0°C to 70°C the external power supply can drop to 1.7V [7].

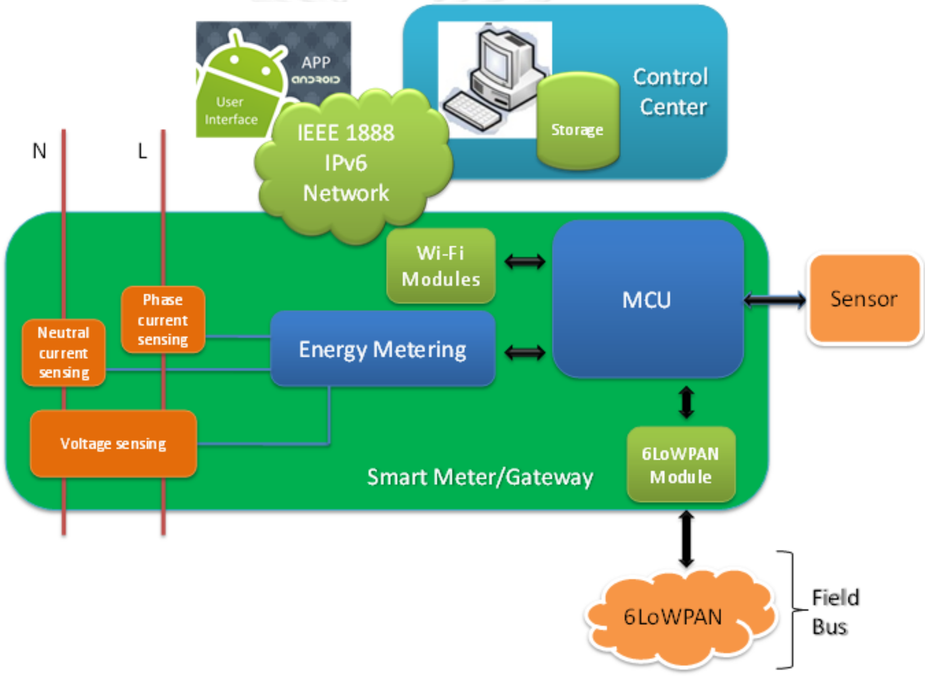


Figure 9 System Architecture

As shown in the Figure 9, MCU is connected to two Wi-Fi Modules (detailed descriptions of these modules will be provided in section 3.1.2) through USART communication supporting for IPv4/IPv6 IEEE1888 communication working as the IEEE1888 Gateway. Also the 6LoWPAN module (details in section 3.1.3) is connected to the MCU through USART communication working as the 6LoWPAN Server Node in collecting all of 6LoWPAN Client Node data from Field Bus. The Energy Metering

Module is connected to MCU through SPI interface to supports for power consumption measurement. PIR motion sensor in sensor part is connected to the MCU through GPIO pin.

3.1.2 Wi-Fi Modules

3.1.2.1 CSW-M85

CSW-M85 is the Wi-Fi Module which supports TCP/IP wireless LAN IEEE 802.11b/g communication. This module (as shown in Figure 10) has responsibility to implement the converting process using TCP/IP protocol for users in order to get to the network [8].

Figure 10 CSW-M85 module

CSW-M85 has some features that support to the system:

+ Using serial devices connection to connect to IEEE 802.11b/g wireless LAN.

+ Built-in compact type

+ Embedded TCP/IP stack works stable

+ Ability to use both internal (Chip), external (Socket) antenna

+ Support IPv4/IPv6 dual stack

+ Support wireless signal strength indication mode

+ WLAN security support: WPA, WPA2

Inside this system, CSW-M85 is connected to MCU by serial communication as shown in Figure 11. It supports the AT-Command language, so MCU can configure and control this module by using this command for TCP connection. CSW-M85 works as the IPv6 IEEE1888 Client, it connects to IEEE1888 Storage/Server through Wireless Access Point in order to transfer its data to Server by IPv6 TCP connection follows IEEE1888 protocol every minute or in the interval of time which is changeable.

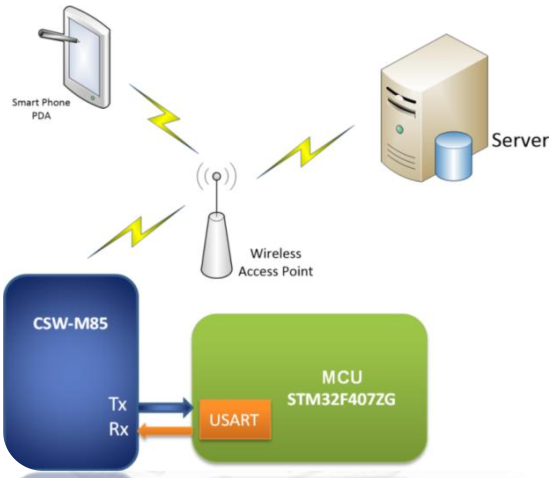


Figure 11 CSW-M85 MCU Connection

In addition, this module also can be implemented to work as the IPv4/IPv6 IEEE1888 Server for retrieving its data from other client devices such as Smart phone, PDA, computer, etc.

3.1.2.2 RN-171

Figure 12 CSW-M85 Module

Figure 12 shows the small Wi-Fi standalone module with embedded wireless 802.11b/g from Roving Network Company. This module is built in the small form factor and consumes very low-power. RN-171 consists of processor, TCP/IP stack, a 2.4GHz radio, real time clock, analog sensor interfaces, and power management. RN-171 uses ASCII command language for programming and control. Some typical features are listed as follows [6]:

+ Operation at 2.4 GHz, IEEE802.11b/g transceiver

+ Small, compact type with surface-mount

+ Low-power: 4μA at sleep, 40 mA RX, 210 mA TX

+ UART interface

+ Accepts 3.3V regulated power, and 2-3V battery.

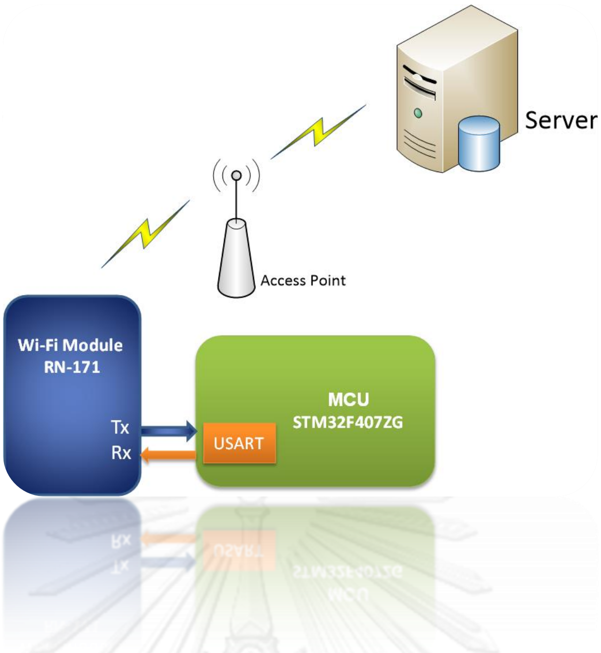


Figure 13 RN-171 MCU Connection

RN-171 is also connected to the MCU through Serial communication as shown in Figure 13. MCU can configure and control RN-171 by using ASCII command language which supports for UDP connection. In system, this module has responsibility in NTP Synchronization; also it is programmed to synchronize the time with IEEE1888 Storage/Server every hour to ensure that the update time interval is always correct.

3.1.3 The 6LoWPAN module

The wireless networking from DiZiC Company capabilities with IEEE 802.15.4 standard radio frequency module which is applied to applications need long time battery life with very low-power consumption at high RF performance in sensitivity and transmitting.

Figure 14 the 6LoWPAN module

In addition, ARM Cortex M3 STM32W108 wireless system on chip (SoC) from STMicroelectronics (as shown in Figure 14) works as the main core in this module; it operates smoothly and also integrates Radio Frequency for Consumer Electronics and low level MAC/PHY protocol stack IEEE802.15.4 standard radio frequency [9].

Some typical features are equipped in this module as:

+ STM32W108 / IEEE 802.15.4 System on Chip (SoC) integrates 128kB Flash, 8kB of SRAM supports for debugging and programming.

+ Data rate can reach at 250kbit/s

+ Supports Serial interfaces UART, I2C, and SPI

+ 6 inputs 12-bit ADC

+ RX Sensitivity from -99dBm to -105dBm

+ TX Power from 3dBm and 20dBm

Figure 15 illustrates the connection of microcontroller STM32F4 with a red 6LoWPAN module which works as the 6LoWPAN Server node. There are three blue 6LoWPAN nodes working as the 6LoWPAN Client nodes that are located in different places, they have responsibility to update all of collected data (such as temperature, motion data) by wireless UDP connection. These modules powered by Contiki OS with IPv6 TCP/IP stack, this IP stack is put at the network layer combines with IEEE802.15.4 standard radio frequency in data-link layer.

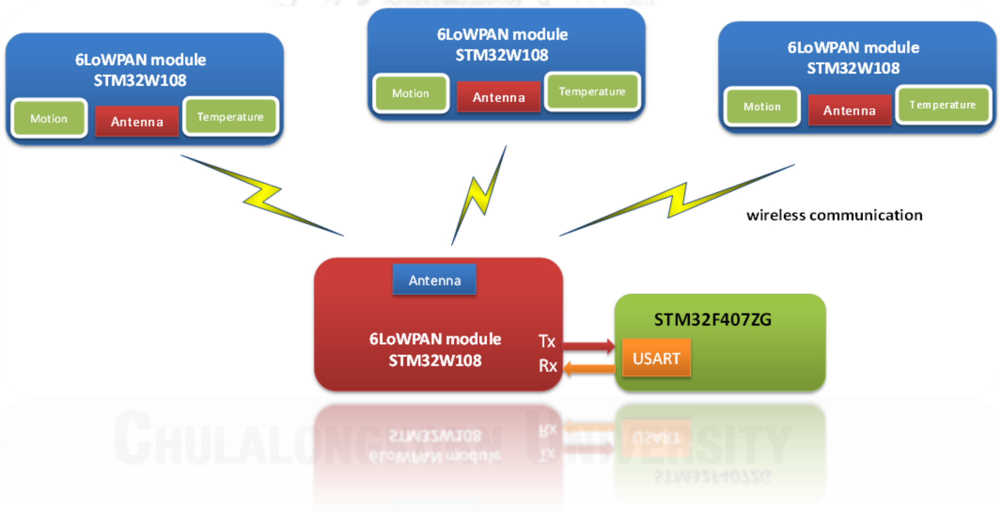


Figure 15 6LoWPAN MCU Connection

3.1.3.1 Temperature Sensor

The temperature sensor is used in 6LoWPAN Client node is STLM20W87F from ST Microelectronics.

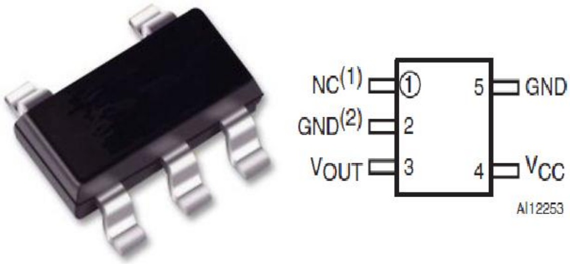


Figure 16 STLM20W87F

This temperature sensor with the precision analog voltage output consumes ultra-low current such as 4.8 μA (typical) and 0.8 μA (max), and the operating voltage ranges from 2.4V to 5.5V. The operating temperature ranges from -55 ˚C to 130 ˚C. The temperature accuracy is ±1.5 ˚C (±0.5˚C typical) [3].

V_{CC} pin is connected to the analog pin of microcontroller. Following the manufacturer's datasheet, the value of temperature is calculated follows this equation:

(0.8) $$T = -1481.96 + \sqrt{2.1962 \times 10^6 + \frac{(1.8639 - V_0)}{3.88 \times 10^{-6}}}$$

The equation (0.8) shows the way we calculate the temperature T (°C) from the output voltage V_0 [3].

3.1.3.2 Motion Sensor

Each 6LoWPAN client module also integrates one Passive Infrared sensor (PIR sensor) is one kind of electronic sensor that measures the radiation of object's infrared light in the field of view.

Figure 17 PIR Motion sensor

Figure 17 shows the motion sensor is used in 6LoWPAN Client Node, it has some features [10] as follows:

+ 3 main pins, header 2.54mm: V_{CC}, Output, GND. This Output pin is connected to a GPIO pin of each 6LoWPAN Client node.

+ Power supply: 3V – 24V

+ TTL output

+ High sensitive

+ Delay time: 0.5 seconds to 18 minutes

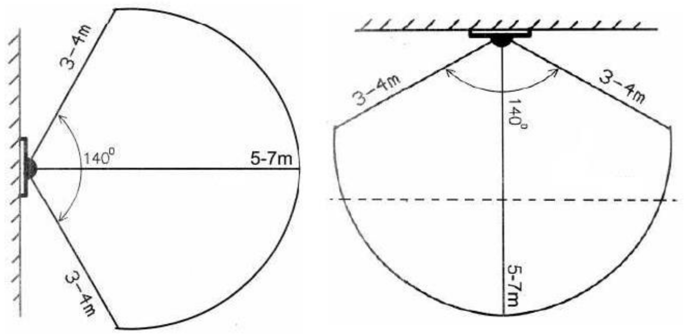


Figure 18 PIR operation range

Figure 18 shows the operation range of this PIR Motion sensor. This sensor can be hung on the wall or ceiling.

3.1.3.3 DIP Switch

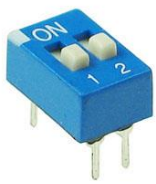


Figure 19 DIP Switch 2 positions

Figure 19 shows the dip switch with 2 positions that is integrated in each 6LoWPAN Client node. Pins on DIP Switch are connected to some GPIO pins of each

6LoWPAN Client node to change the time for updating to 6LoWPAN Server node. The updated-time interval can be one of two values is 30 seconds and 60 seconds.

3.1.4 Energy Metering Module

Figure 20 STPM01

The energy metering module is used in this study has a STPM01 metering IC working as the main core of the module as shown in the Figure 20. This IC works as the single phase energy metering which plays in the important role in effective energy measurement. This IC supports for measurement of active, reactive and apparent energy in the power line system [5]. A current transformer is used in this study.

STPM01 includes 2 parts are analog and digital part. It also has an OTP block for calibration, configuration and testing. The OTP (One Time Programmable) block is controlled through Serial Peripheral Interface Bus (SPI) by means of dedicate command set and be written permanently. The RMS and instantaneous values of voltage and current are also measured. This IC has a powerful Digital Signal Process (DSP) unit to compute the energy, current and voltage as well. The results appear on the output of DSP the pulse frequency proportional to the energy consumption. Also, this pulse is provided to calibration purpose. All of states of digital output or the available data bits in some registers which can be read through SPI interface [5]. STPM01 has some typical features which are useful for this study is listed as follows:

+ Energy Measurement (active, reactive, apparent energy, RMS values)
+ Active energy pulse output
+ Selectable crystal oscillator or RC
+ Support 50 to 60 Hz
+ Error is less than 0.1%.
+ Precision voltage reference: 1.23V

The data record map of STPM01 is shown in the Figure 21. These internal registers keep all of useful information of the meter system. There are two kinds of active energy: all of harmonic content (type0) is included in the total active energy called type 0 and the 1^{st} harmonic is the limitation of the active energy called type 1 [5]. The both active energy registers concludes 20-bit. In addition, the resolution of Reactive and Apparent energies is also 20-bit.

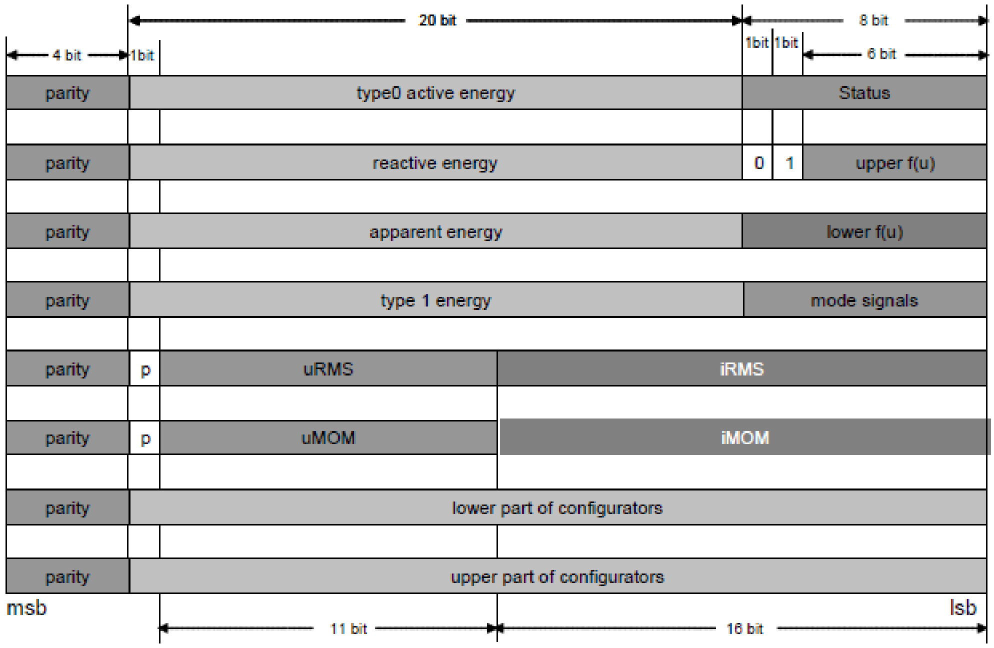


Figure 21 STPM01 Registers

The RMS values of current and voltage are also available. The RMS value of voltage occupies 11-bit resolution because of the insignificant dynamic variation. While the RMS value of current is available with 16-bit resolution. The momentary sample (MOM) of voltage and current value are also 11 and 16-bit respectively. Furthermore, the register for frequency value is also available with 14-bit resolution [5].

Due to the operation of Smart meter, it has to be calibrated before. All of the calibration parameters are available in OTP block which located in “lower part of configuration” register.

Figure 22 illustrates the connection between Energy Metering Module to the MCU STM32F407VG. The SPI communication interface is chosen due to the requirement of STPM01 chip and the high performance in real-time reading energy values. In this study, current transformer is chose to use instead of Shunt for current sensing part. The current and voltage are sensed by current transformer and voltage divider circuit.

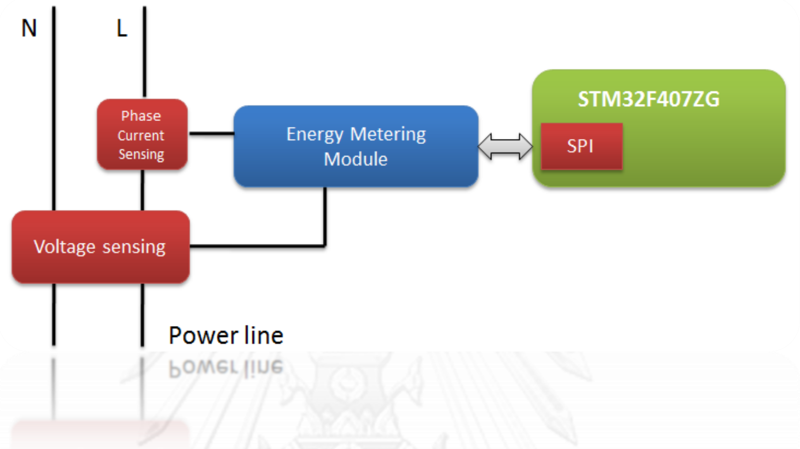


Figure 22 STPM01 Module

Figure 23 Current sensor

Figure 23 shows the current sensor (TZ2L9) using in smart meter. This current sensor has turn ratio is 1:1000, and supports frequency range 50/60Hz.

3.1.5 Sensor & Actuators

3.1.5.1 Sensor

The system has also integrated a motion sensor (as shown in the previous section 3.1.3.2) applies to moving detection, it can support for many useful purposes. In this study, when smart meter is hung on the wall or put in the small electrical box, this sensor can help to identify when the electrical box is opened. In the future, this sensor can be applied to turn on/off the light which is located in the electrical box or make a loud sound when someone tries to open the system illegally, etc. The connection with MCU is shown in section 4.1.1.1.

3.1.5.2 Actuators

3.1.5.2.1 Relay

In this system, there are 2 Relays which have responsibility to switch on/off the electricity from 2 electrical outlets using in system.

Relay HRS4H-S-DC3V is used as shown in the Figure 24. The power supply for this relay is 3V DC. Figure 25 shows the connection between a relay to the MCU.

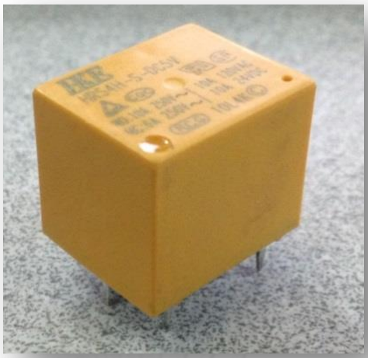


Figure 24 Relay HRS4H-S-DC3V

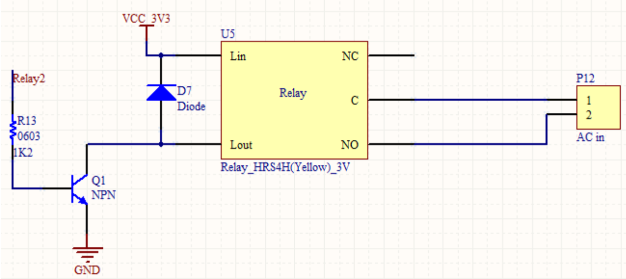


Figure 25 Relay-MCU connection

Above Figure 25 shows the connection between Relay and MCU. One NPN transistor and diode are used to perform this function.

3.1.5.2.2 Buzzer

Figure 26 Buzzer

Figure 26 shows a Buzzer used in system. This Buzzer can be controlled by system or IEEE1888 application on mobile device. This will automatically make a loud sound when the system gets over-load. One pin of this buzzer is connected to the GPIO pin of MCU, another one is connect to Ground. The connection with MCU is shown in section 4.1.1.1.

3.1.5 Power Supply

The system is powered by 5V and 3.3V. It uses two 3V3 regulators LM1117T (as shown in Figure 27) to supply to system as shown in the Figure 28.

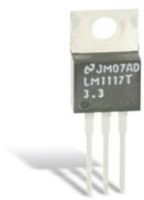


Figure 27 LM1117T 3.3

One of LM1117T supplies 3.3V to the CSW-M85 Wi-Fi module, Energy metering module, and relays. Another one supplies 3.3V to the MCU and RN-171 Wi-Fi module, and 6LoWPAN module.

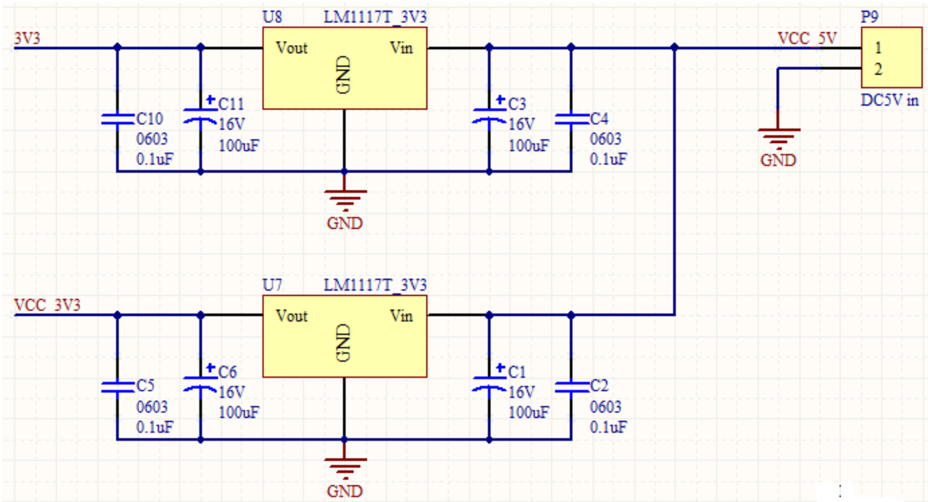


Figure 28 3.3V Power Supply

3.2 Software

3.2.1 Overview

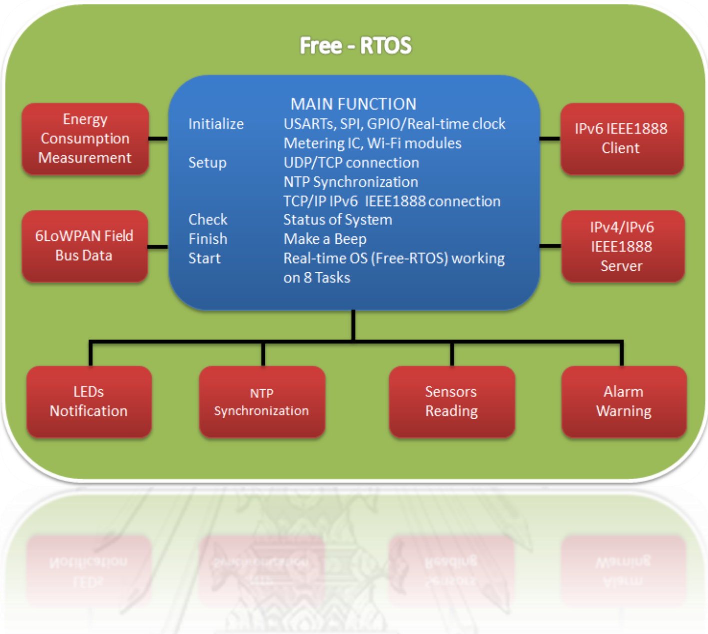


Figure 29 Software Overview

The system software is powered by an open source Free Real-time Operating System (Free-RTOS). This OS is supports for embedded systems with much different architecture. Free-RTOS is made to be simple, portable, and easy to use [1].

The software part includes the Main function and eight execution Tasks. All of Tasks has the same priority. As shown in Figure 29, the main function (blue block) is to:

+ Initialize the hardware such as USARTs, SPI, GPIOs, Metering IC, real-time clock, and two Wi-Fi Modules.

+ Setup the IPv4/IPv6 addresses, TCP/IP connection. System uses static IP address.

+ Synchronize the time from IEEE1888 Storage from control center (Server)

+ Check all the status of system hardware (all of relays, motion sensor, updated time interval, alarm)

After all of above initialized steps is finished preparing to run all of Tasks (as shown in Figure 30), a short loud sound like a beep will be heard. There are total four main Tasks will be performed as follows:

+ *IPv6 IEEE1888 Client:* this Task executes the IEEE1888 write-client procedure. It will collect all of data and the time, and then update these values to Storage by using IPv6 IEEE1888 format message.

+ *IPv4/IPv6 IEEE1888 Server:* the System will be run as IEEE1888 Server; it is implemented IEEE1888 Write-Server and Fetch-Server. This system also works as the Temporary Storage; its data can be accessed by IPv4/IPv6 IEEE1888 client devices.

+ *Energy Consumption Measurement:* This Task has responsibility to read all of metering data from energy metering data and calculate it, prepare to display or upload these data to IEEE1888 Storage.

+ *6LoWPAN Field Bus Data:* All of 6LoWPAN client nodes will send data to Server node built in system in the period of time, this Task will process these data and prepare to display or upload these data to IEEE1888 Storage.

```
Starting system...
        CPU: STM32F407VG
        System clock: 168 MHz

Initializing Hardware interfaces, Metering module... DONE!

Initializing Wi-Fi modules... RN-171... CSW-M85...
Network SSID: ESID_LAB
Local IPv6 address: 2001::6666/64       Local Port: 80
Local IPv4 address: 192.168.5.123       Local Port: 80
Server IPv6 address: 2001::8888/64      Server Port: 80
IEEE1888 ID prefix: http://green-apple.chula.th/
---->DONE!

NTP Server IPv6 address: 2001::8888/64  Port: 123
NTP requesting... DONE! Time now = Thu Apr 10 18:01:09 2014

Initializing TCP connection... DONE!

Checking status of System... OK!

Tasks is started running!
Waiting for DATA to upload...
Planning time for NTP Sychronization after: 1 hour
```

Figure 30 Main Function

In addition, this system also has more four Tasks that supports for system operation in a safer manner, smarter, more accuracy, and easier to monitor and control. All of these Tasks are listed as follows:

+ *NTP Synchronization:* This Task performs the time synchronization with IEEE1888 Server every hour to make sure that the time for update to IEEE1888 Storage always be accurate. Once the system goes wrong in NTP Synchronization because of without internet, this process will be implemented in every thirty minutes. Until NTP Synchronization is finished, every hour for NTP Synchronization of this process will be planned again.

+ *Alarm Warning:* This Task will be implemented to check the over-load case. If this case happens, a loud sound will be heard in three seconds and all of electrical devices which are connected to this system at that time will be also extracted from smart meter. If the over-load problem ends, this smart meter will automatically turn on the last connected devices.

+ *LEDs Notification:* There are seven LEDs that are equipped into the system will be programmed to give the user or system maintainer some useful notifications. They will be able to know where system is working and the system status as well.

+ *Sensors reading:* This Task is performed to read all of Sensors which are equipped into the system for monitoring. In this study, only motion sensor is performed. This Task will be further applied to add more sensors in future case.

3.2.2 IEEE1888 system deployment

This system works on two mode that are client mode and server mode. On client mode, it will collect all of measured data and then post these data to the Storage. All the rest of the time, it runs as server (also works as temporary storage) allows other IEEE1888 client devices (Application) access its latest data.

3.2.2.1 IEEE1888 Client mode

In this mode, smart meter has a function to collect all of measured data such as metering data, 6LoWPAN nodes data, sensor data, and also some hardware status in system (see Chapter 4 for details) and then post these data to the Storage follows the IEEE1888 protocol in an exact length of time. The time for update data to Storage is a minute for default time. This time is changeable, so it can be adjusted from 1 minute to 999 minutes by using other IEEE1888 control devices (see in Chapter 4).

The flow chart of the Task "*IPv6 IEEE1888 Client*" as shown in Figure 32 describes how system works for sending data to Storage using IPv6 address. At first, the system will wait for all of 6LoWPAN data nodes. If the 6LoWPAN data nodes come all, this Task will start running. After that, the system will collect all of measured data, take the current time and also reset the energy value (see in section 3.2.4). All of these data will be packed in an IEEE1888 Message. Before sending this message, the system will check the TCP connection with client device. If the system is connected to another client device (in Server mode), it will disconnect that client device from the system as shown in Figure 33. Then it tries to establish the TCP client connection to IEEE1888 Storage.

When IEEE1888 Storage is not available because of without the internet, system will try to connect to the Storage 3 times in 6 seconds. If the time for trying to connect to Storage is over, system will be change to IEEE1888 server mode (also works as temporary storage) and wait for 45 seconds for the next update (as shown in Figure 31). With the availability of the internet, the system will go on of updating its data to the Storage. After successful message delivery from system, Storage will send back the response message to inform the system how successful this update process is. Unless the message is well delivered, the system will try to convey the data 3 more times in 6 seconds. All going well, this system will subsequently reach the final point of process to wait for the next update. The duration of this process which is dependent on the installation by user can be 1 minute to 999 minutes. Otherwise, the system will be change to IEEE1888 server mode (also works as temporary storage) and wait for 45 seconds for the next update.

```
Start IEEE1888 Write Data...
Stop TCP Server...
Start TCP Client...
--> No Connection to Server_noClient!!

Start TCP Client...
--> No Connection to Server_noClient!!

Start TCP Client...
--> No Connection to Server_noClient!!

Start TCP Server...
```

Figure 31 Internet connection error

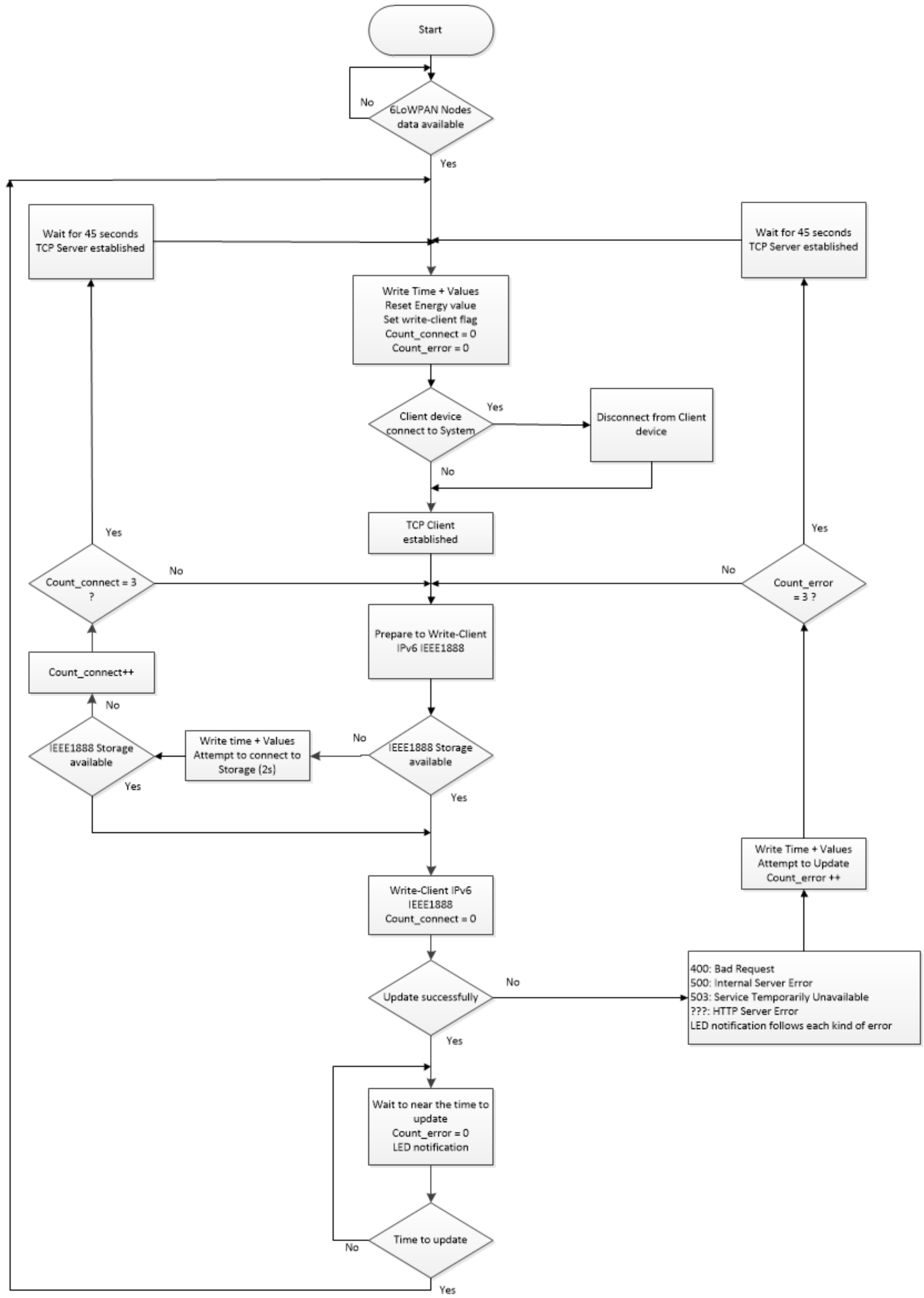


Figure 32 Flow-chart IEEE1888 Write-Client

```
Start IEEE1888 Write Data...
Disconnected to Client devices!
Start TCP Client...
--> No Connection to Server_noClient!!

Start TCP Client...
--> No Connection to Server_noClient!!

Start TCP Client...
--> No Connection to Server_noClient!!

Start TCP Server...
```

Figure 33 Internet connection error (2)

3.2.2.2 IEEE1888 Server mode

In this mode, smart meter works as the IEEE1888 server and also the temporary storage. The system will be accessed the data and also be controlled by the other IEEE1888 client device using with IPv4 and IPv6 address. Two kind of IEEE1888 procedures which are implemented in this mode are Write server and Fetch server with Data method (control) and Query method (access the data).

From Figure 34 to Figure 37 illustrate the example of WRITE and FETCH messages. These messages consist of PointSet, Point ID, Key ID, Query ID, Time, and value of Point ID.

```xml
<transport xmlns="http://gutp.jp/fiap/2009/11/">
 <body>
  <pointSet id="http://green-apple.chula.th/">
  <point id="http://green-apple.chula.th/6LoWPAN_nodes/node1/temp">
   <value time="2014-04-21T16:15:00.000+07:00">25.7</value>
  </point>
  <point id="http://green-apple.chula.th/Sensors/motion">
   <value time="2014-04-21T16:15:00.000+07:00">detected</value>
  </point>
  <point id="http://green-apple.chula.th/Smartmeter/energy">
   <value time="2014-04-21T16:15:00.000+07:00">0.21</value>
  </point>
  <point id="http://green-apple.chula.th/System/status">
   <value time="2014-04-21T16:15:00.000+07:00">NORMAL</value>
  </point>
  </pointSet>
 </body>
</transport>
```

PointSet

Point ID

Time, value

Figure 34 WRITE query message

```xml
<transport xmlns="http://gutp.jp/fiap/2009/11/">
 <header>
  <OK />
 </header>
</transport>
```

Figure 35 WRITE response message


```xml
<transport xmlns="http://gutp.jp/fiap/2009/11/">
 <header>
  <query id="da95134a-4935-4158-28d8-8c8f3d9269b2" type="storage">
   <key id="http://green-apple.chula.th/6LoWPAN_nodes/node1/temp" attrName="time" select="maximum" />
  </query>
 </header>
</transport>
```

Query ID

Key ID

Figure 36 FETCH query message

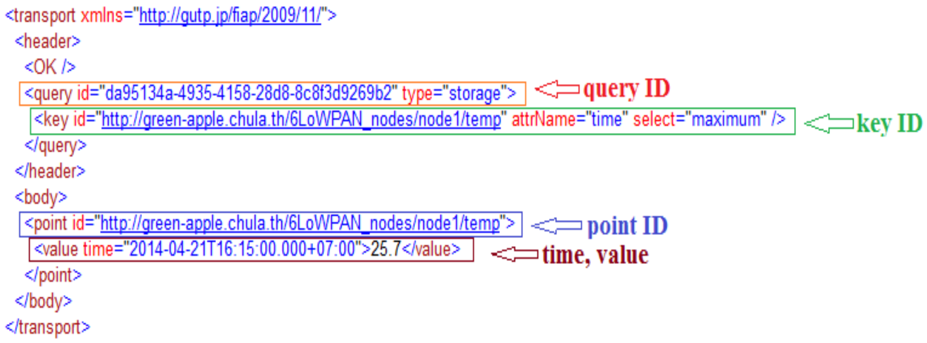


Figure 37 FETCH response message

Figure 38 shows all of works this Task *"IPv4/IPv6 IEEE1888 Server"* has to perform. In this server mode, the system will wait for the incoming IEEE1888 message from client device. Once it receives the message from client device, this message will be parsed. The first step for this process is for message header. From the Header of HTTP message, the system is able to know what kind of method. If a method which is not Data method and Query method can't be recognized, the system will skip it and goes back to wait for a new incoming IEEE1888 message.

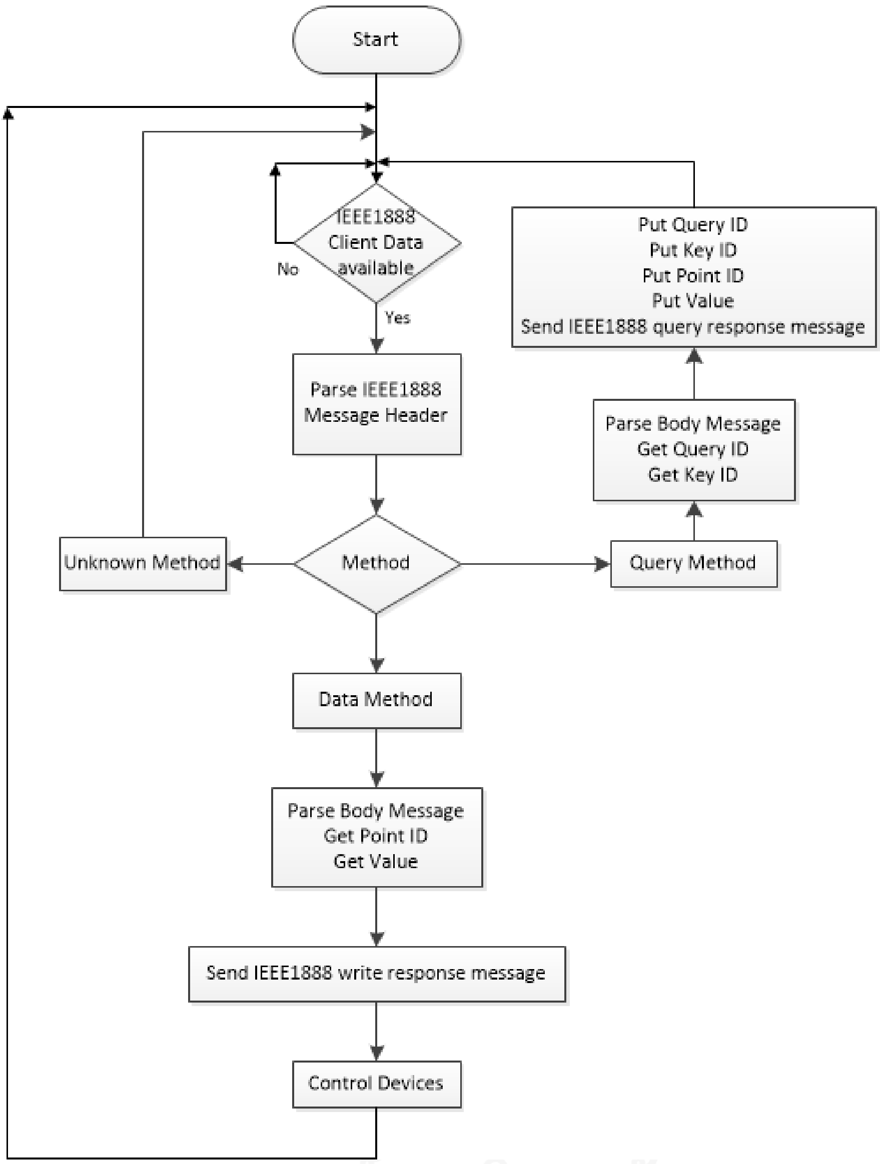


Figure 38 Flow chart of IEEE1888 Write-Sever & Fetch-Server

After the successful Header parsing, the Data method is recognized. This process will go on to parse the Body of message to get the Point ID, and the value of this Point ID. As the result of recognizing the Point ID and the value, the system will send back the response message following the IEEE1888 protocol message form to the client device for confirmation. All going well, this system will go on to control the component which is assigned with the Point ID has been recognized. Figure 39 shows an example about data method used to control an electrical outlet 1 socket on smart meter. Finally, the system will go on to wait for a new incoming IEEE1888 message. Figure 40 shows example process to change the updated time interval to Storage. Figure 41 shows the confirmation about error value from the system when the time is setting wrong. When the time is set that is the same with the current updated time interval, the system will inform that the time is not changed.

```
>---------<DATA METHOD>------------------------------------------------------------>
--> Point ID = http://green-apple.chula.th/Switches/outlet1
--> Value = 1
>>>> SWITCH ON
>----<Results on Mobile's Screen - END>-------------------------------------------->

>---------<DATA METHOD>------------------------------------------------------------>
--> Point ID = http://green-apple.chula.th/Switches/outlet1
--> Value = 0
>>>> SWITCH OFF
>----<Results on Mobile's Screen - END>-------------------------------------------->
```

Figure 39 IEEE1888 Write-Server example (1)

```
>---------<DATA METHOD>------------------------------------------------------------>
--> Point ID = http://green-apple.chula.th/System/uTime
--> Value = 1
>>>> TIME UPDATE
>----<Results on Mobile's Screen - END>-------------------------------------------->

OK! Up-Time changed to = 1 minute

>---------<DATA METHOD>------------------------------------------------------------>
--> Point ID = http://green-apple.chula.th/System/uTime
--> Value = 5
>>>> TIME UPDATE
>----<Results on Mobile's Screen - END>-------------------------------------------->

OK! Up-Time changed to = 5 minutes
```

Figure 40 IEEE1888 Write-Server example (2)

```
>---------<DATA METHOD>------------------------------------------------------------>
--> Point ID = http://green-apple.chula.th/System/uTime
--> Value = 5
>>>> TIME UPDATE
>----<Results on Mobile's Screen - END>-------------------------------------------->

Up-Time does NOT change!

>---------<DATA METHOD>------------------------------------------------------------>
--> Point ID = http://green-apple.chula.th/System/uTime
--> Value = 0
>>>> TIME UPDATE
>----<Results on Mobile's Screen - END>-------------------------------------------->

Error! Up-Time can NOT be changed to 0!
```

Figure 41 IEEE1888 Write-Server example (3)

Otherwise, the Query method is recognized after header parsing process, the system will go on to parse the body to get Query ID and the Key ID. Finally, the

IEEE1888 response message which is packed with Query ID, Key ID, Point ID and value of Point ID is sent to client device. Figure 42 shows an example about the implementation of Fetch-server on the system.

```
>---------<QUERY METHOD>------------------------------------------------------------>
--> Query ID = dd82403a-4986-4129-8d82-7c3247ea41b9
--> Point ID = http://green-apple.chula.th/Switches/outlet1
>----<Results on Mobile's Screen - END>--------------------------------------------->
```

Figure 42 IEEE1888 Fetch-Server example

3.2.3 6LoWPAN Field Bus

The communication of each node in network using 6LoWPAN communication is performed by Contiki OS [12]. Contiki OS which is the open source OS is turned to embedded hardware with the limitation memory and processing resources [13]. It provides the IP connectivity with the integration of µIP stack which is consists of IPv6 implementing with LoWPAN and UDP connection. Its core system runs on event-driven kernel with supporting the preemptive multithreading on-demand to manage sharing memory resources between processes. A process is employed as a service or an application program which provides functions. Events have been posted by inter-process communication [15].

All of 6LoWPAN nodes are performed with Contiki OS. One of node is deployed as 6LoWPAN server node, other nodes is deployed as the client node. Both kinds can be able to perform as router. These nodes are also implemented multicast Domain Name Server (mDNS) which makes ease of network configuration and to enable devices to view and search other devices. The identifiable information such as the name is used in hostname. Whereas corresponding device tend to give response with its list of DNS resource records, the devices investigate network addresses with requests to the multicast group [15]. The results for communication between each node will be practically illustrated in section 4.3.

3.2.4 Smart meter

All of energy metering module values will be read from the metering data registers as shown in the section 3.1.4 through SPI interface. The energy value will count up follow the energy consumption.

Following the calibration procedures [2], the number of pulse of LED's blinking is 75,740 pulses per kWh. In this study, K_{AW} represents the LSB value of active energy register, which has unit is Wh.

$$K_{AW} = \frac{1000}{2^{11} \times P} \tag{0.9}$$

Equation (0.9) represents how K_{AW} is calculated [5]. In this study:

$$K_{AW} = 6.44681 \times 10^{-6}\ \text{Wh}$$

From the given K_{AW}, it means that reading the active energy register of 0x00001 will be represented 6.44681 μWh.

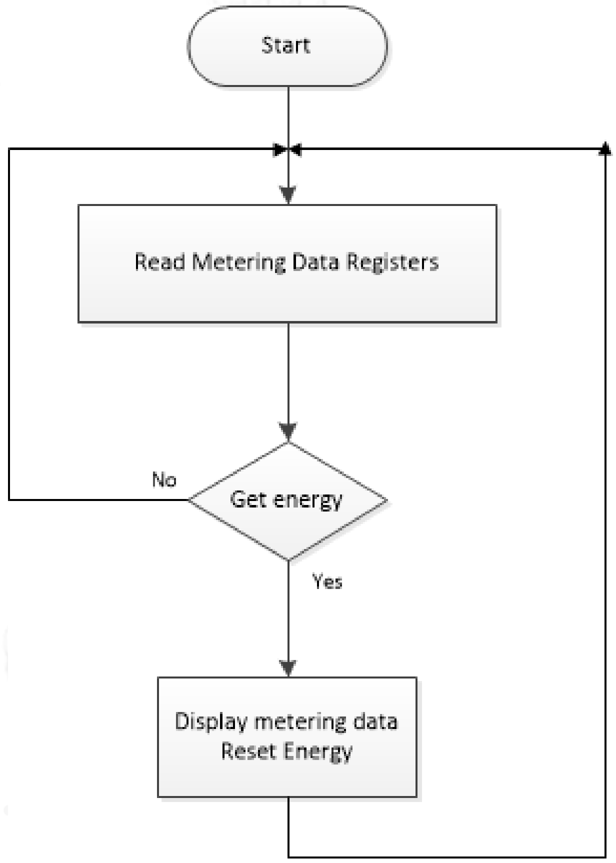


Figure 43 Flowchart of Energy Metering

As shown in Figure 43, all of the metering data registers will be read and counted up following the consumption. All of these values (voltage, current, power, energy, frequency) will be updated and prepared to send to Storage through IEEE1888 protocol.

CHAPTER 4: EXPERIMENTS & RESULTS

4.1 System hardware

4.1.1 Main system Circuit

4.1.1.1 Schematic

Figure 45 illustrates the system schematic concludes all parts of the system. There are total eight parts are shown in Figure 44, and from Figure 46 to Figure 52.

The energy metering module is shown in Figure 53.

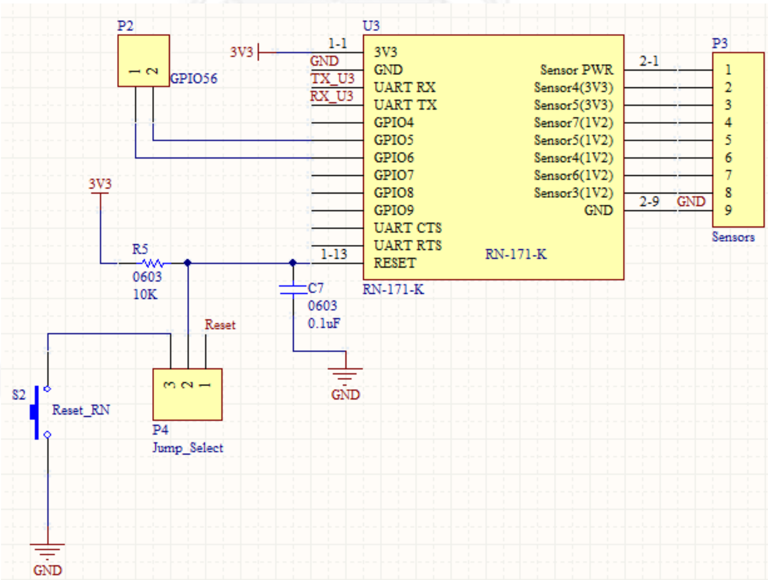


Figure 44 RN-171 Wi-Fi part

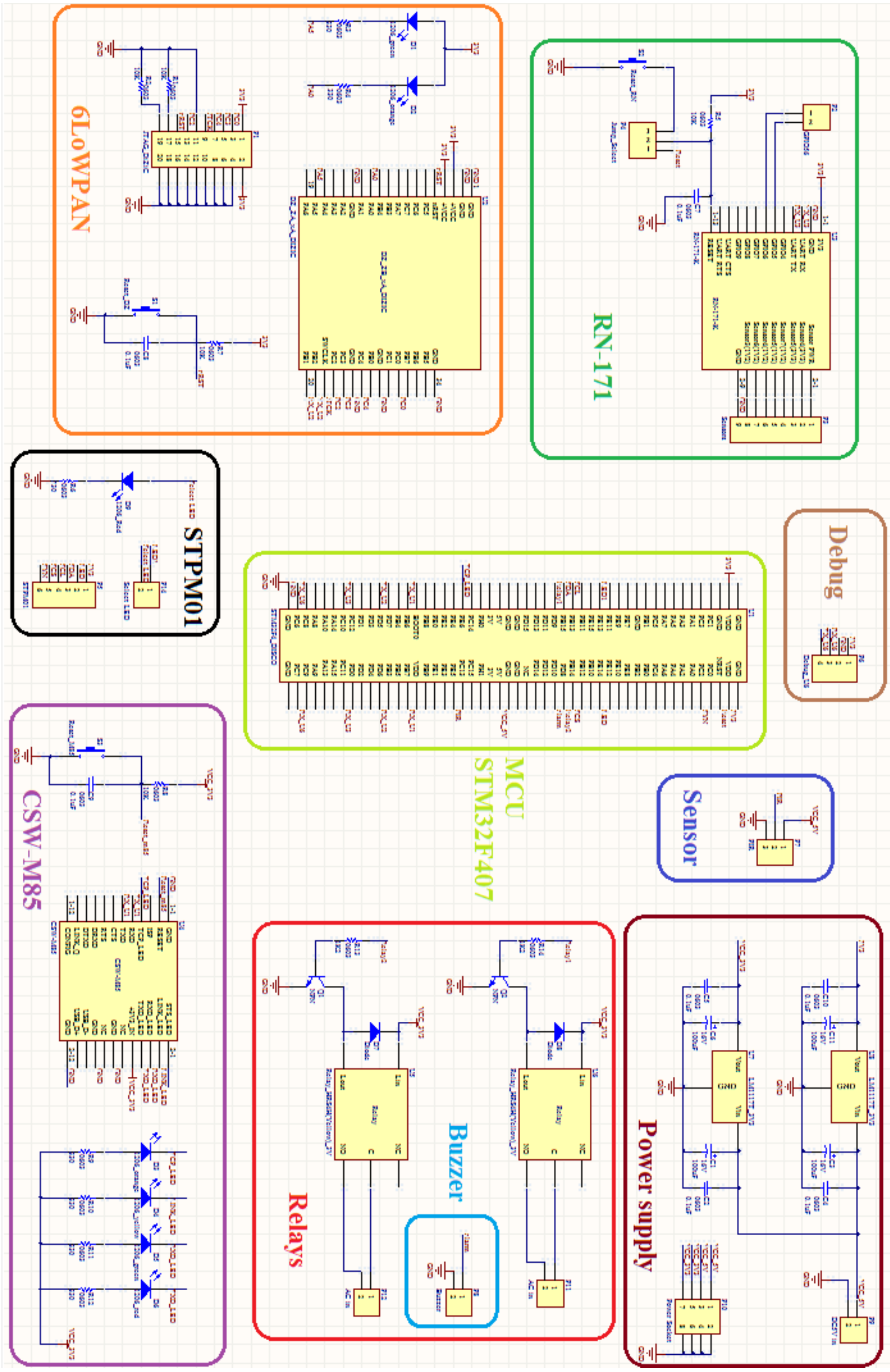


Figure 45 System schematic

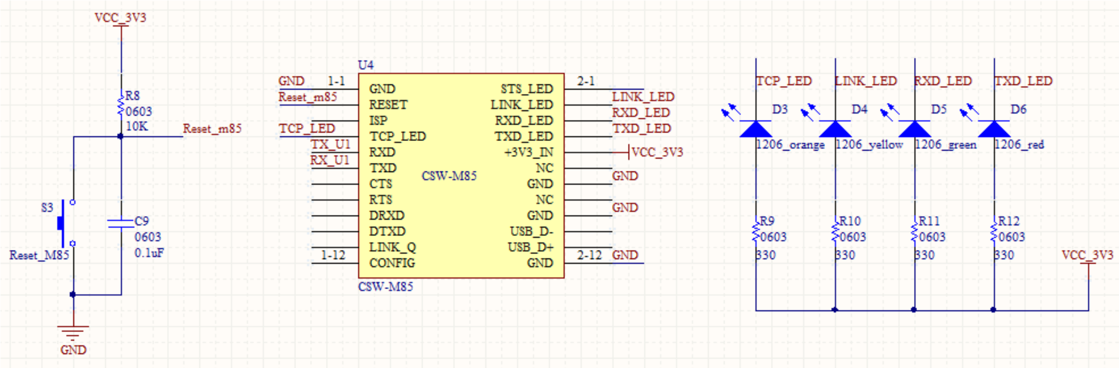


Figure 46 CSW-M85 Wi-Fi part

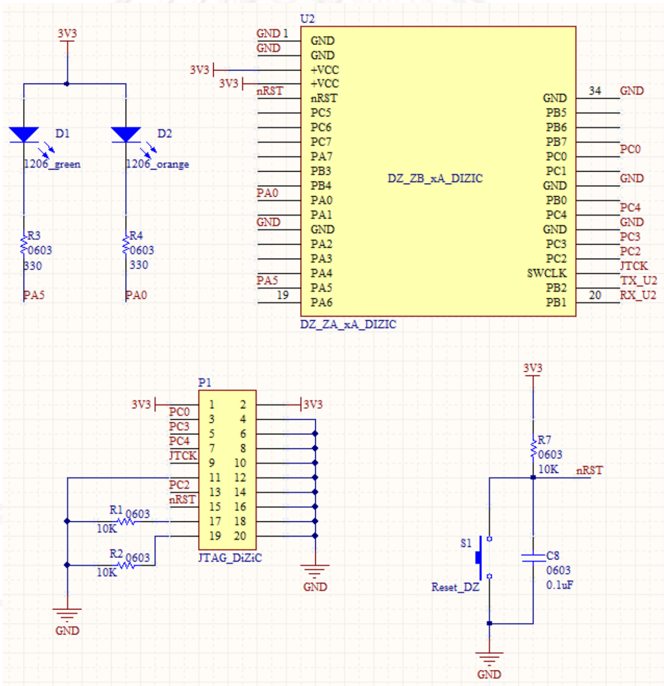


Figure 47 the 6LoWPAN part

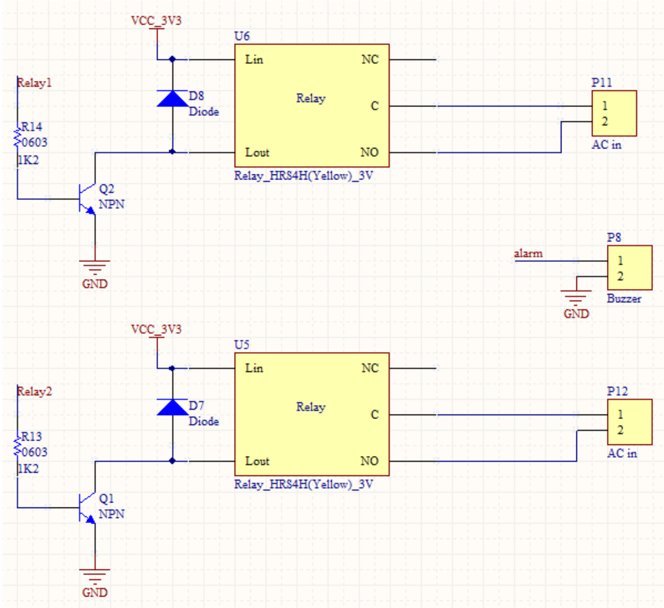


Figure 48 Actuators part

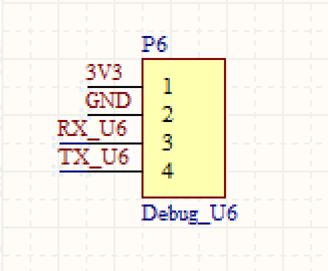


Figure 49 Debug part

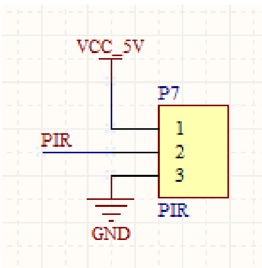


Figure 50 Motion sensor part

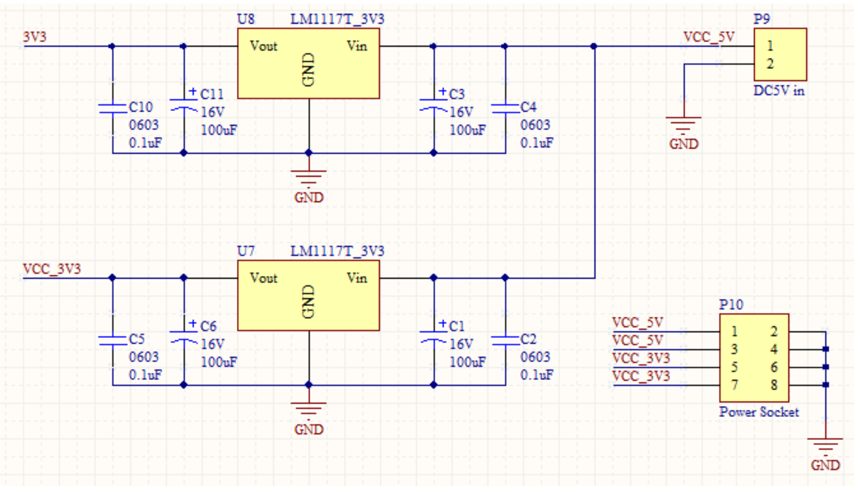


Figure 51 Power supply

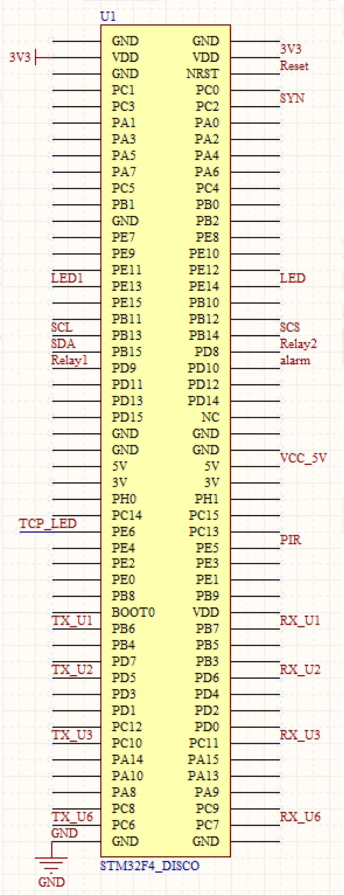


Figure 52 MCU Pins connection

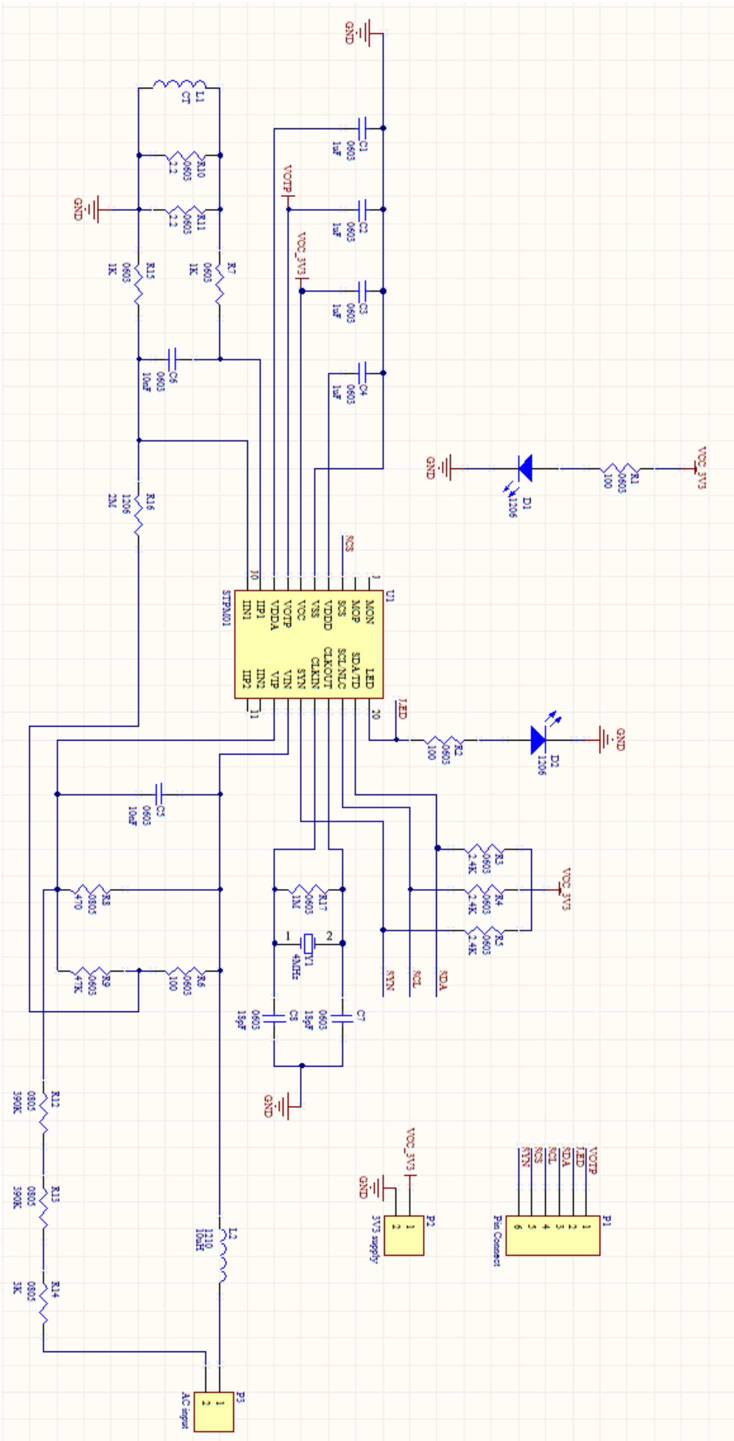


Figure 53 STPM01 Module Schematic

4.1.1.2 Real Circuit

In this Figure 54 shows the real system circuit which includes some parts listed as follows:

+ MCU: STM32F407VG, the heart of system is put in Yellow Square

+ 6LoWPAN Module Server Node: put in Red Rectangular

+ CSW-M85 Wi-Fi module: put in Violet Rectangular

+ RN-171 Wi-Fi module: put in Brown Rectangular

+ Power Supply: supplies 3.3VDC put in Orange Rectangular

+ 2 Electrical Outlets: outlet1, outlet2 support 1 socket for each one that put in White Rectangular as shown in the figure (as shown in Figure 57)

+ 2 Relay: Relay1, Relay2 used to switch ON/OFF the electricity goes through 2 Outlets which are put in White Rectangular (as shown in Figure 57)

+ Fan: also used to cool the system circuit, because CSW-M85 Wi-Fi Module consumes more current so it radiates more heat. It is put in White Rectangular

+ Buzzer + LEDs: used for system notification. Buzzer will make an alarm when the over load happens. There are 4 LEDs (Orange, Red, Blue, and Green) that will blink in different kinds to make the user monitor the system operation easier

+ GPIO: Some pins from MCU support for Sensor and USART debugging.

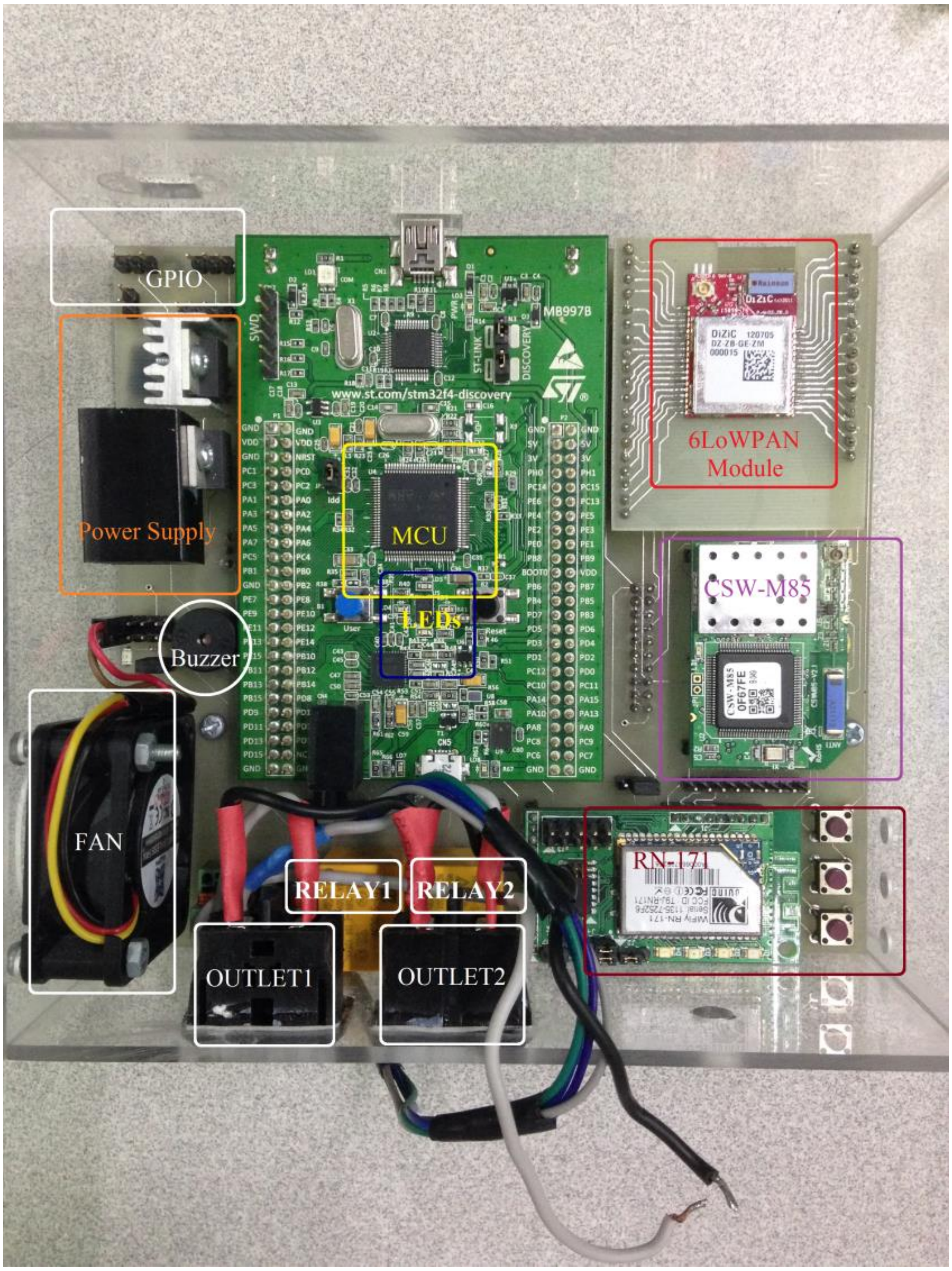


Figure 54 System Circuit

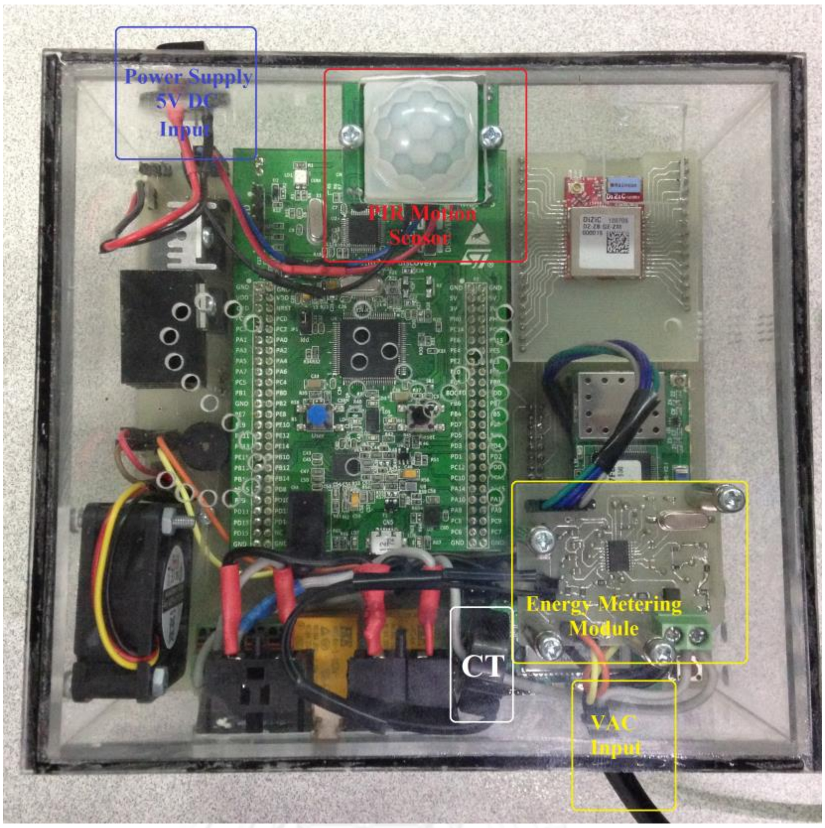


Figure 55 System Circuit Layer 2

Figure 55 shows the second Layer of system circuit. This layer includes the Energy Metering module, Motion sensor, Current transformer (CT), power supply inputs 5V DC, and the input of AC Voltage (220VAC ~ 245VAC).

As shown in Figure 56, Wi-Fi LEDs includes 4 LEDs to notify the operation of CSW-M85 Wi-Fi module of TCP communication. The 6LoWPAN LEDs are programmed to show the 6LoWPAN module status:

+ Green led: it is ON when 6LoWPAN module finishes all of configuration, prepares for communication to 6LoWPAN client nodes.

+ Orange led: it blinks when receiving data from other 6LoWPAN nodes

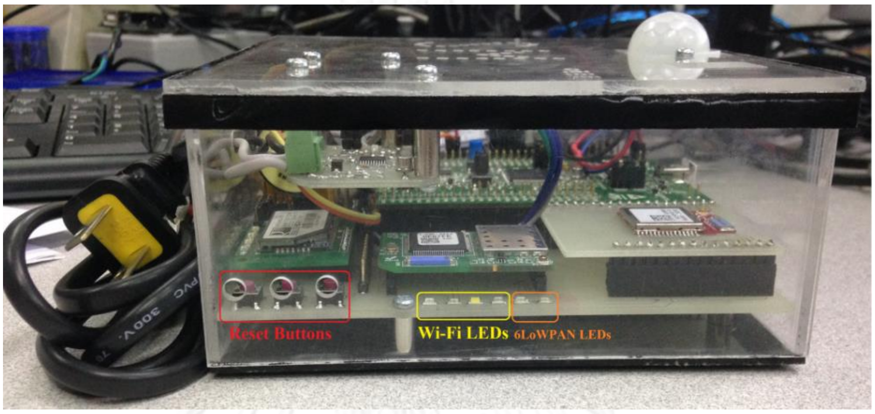


Figure 56 System Circuit side

All of buttons supports for reset all of modules in lower layer (CSW-M85, MCU, RN-171, 6LoWPAN module).

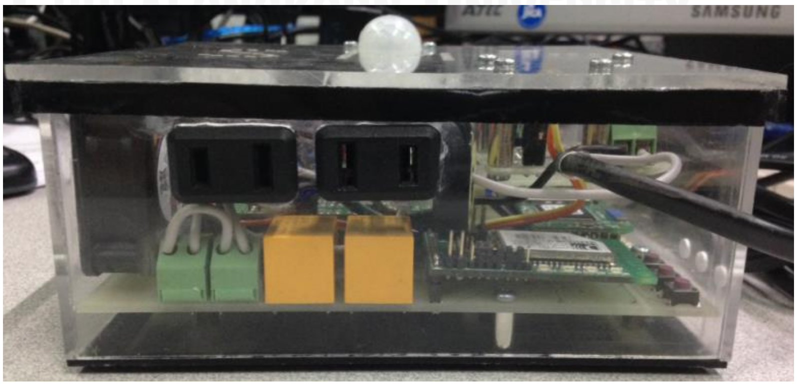


Figure 57 System Circuit side 2

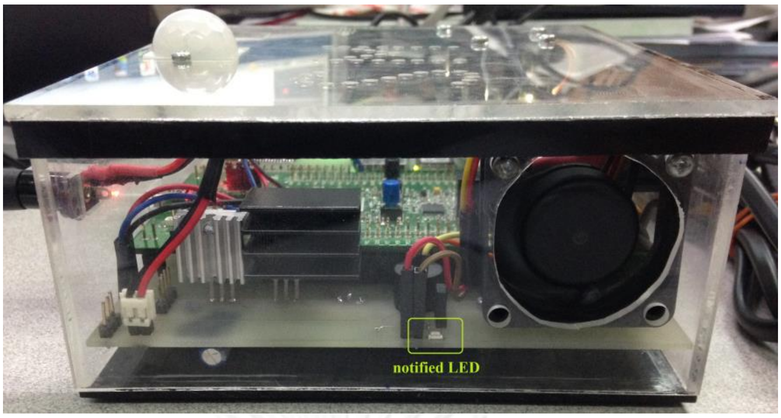


Figure 58 System circuit side 3

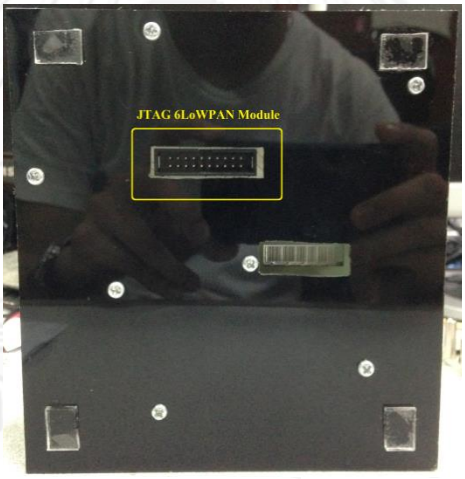


Figure 59 System Circuit bottom

Figure 58 shows other side of device. At this side, a notified LED is located which notifies to the user about the connection status to the power AC line. Figure 59 shows the System Circuit Bottom which is included a JTAG port of 6LoWPAN module to reprogram or debug.

4.1.2 The 6LoWPAN nodes

Figure 60 6LoWPAN Client Nodes using in system

Figure 60 shows three 6LoWPAN Client nodes using in this system. Each node is equipped a temperature sensor, motion PIR sensor, switches for changing updated time interval, and notified LEDs (Green and Orange) to notify the operation of node (as shown in Figure 61). This 6LoWPAN node is powered by 5V DC input.

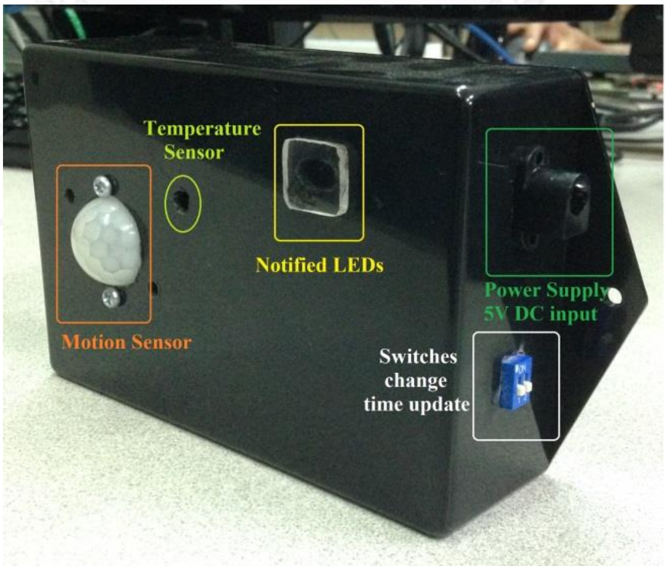


Figure 61 6LoWPAN Client Node box

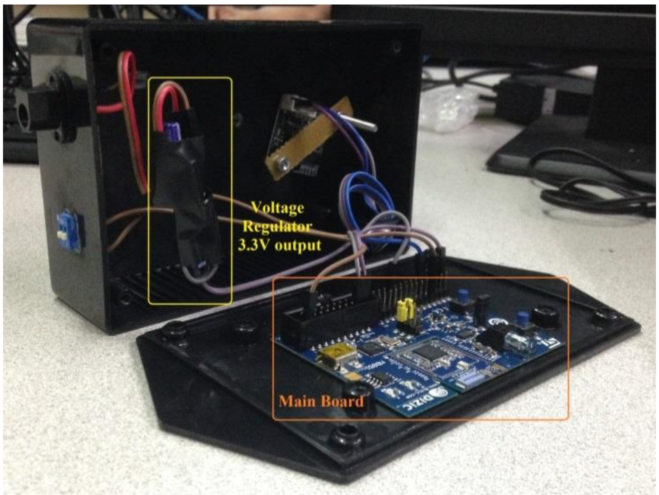


Figure 62 Inside 6LoWPAN client node box

Figure 62 shows all of components inside a box of 6LoWPAN client node. This box includes a main board, voltage regulator 3.3V DC output.

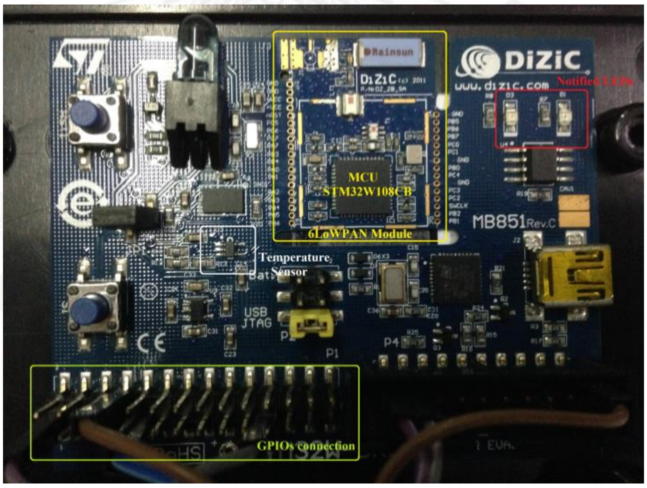


Figure 63 6LoWPAN node main board

6LoWPAN main board shows in Figure 63 is the development board from ST Microelectronics Company. This main board includes the MCU STM32W108CB, GPIO connections, and 2 LEDs (Green and Orange). This mainboard has re-programmed to work on 6LoWPAN, the orange LED will blinks 2 times when it receives a response from 6LoWPAN Server node that means sending data successful.

4.2 Operation

Smart meter/Gateway (SM/GW) met all of expectations. It gets the data such as temperature, motion from 6LoWPAN nodes; also measures the voltage, current, power, frequency and energy consumption from Load connected to AC electrical line.

This SM/GW also integrates a motion sensor; this sensor takes the motion data for monitoring environment at the location it located in.

Moreover, this system can monitor its overload status for safety. It will upload all of collected data to control center through IEEE1888 protocol every minute, the time for uploading to control center is changeable (from 1 minute to 999 minutes) by using IEEE1888 application on Android mobile OS device.

In addition, the SM/GW also functioned as IEEE1888 temporary Storage. It can be accessed to take the data and also controlled by using IEEE1888 Application on mobile Android OS devices.

4.3 Communication testing

All of tests are done by using the Wireshark Network Analyzer v1.10.2 (SVN Rev 51934 from /trunk-1.10) application on Personal Computer (PC).

As shown in Figure 64, the system time is synchronized to IEEE1888 Server using UDP connection. The UDP packet is delivered to system (192.168.5.74) from Server (192.168.5.2).

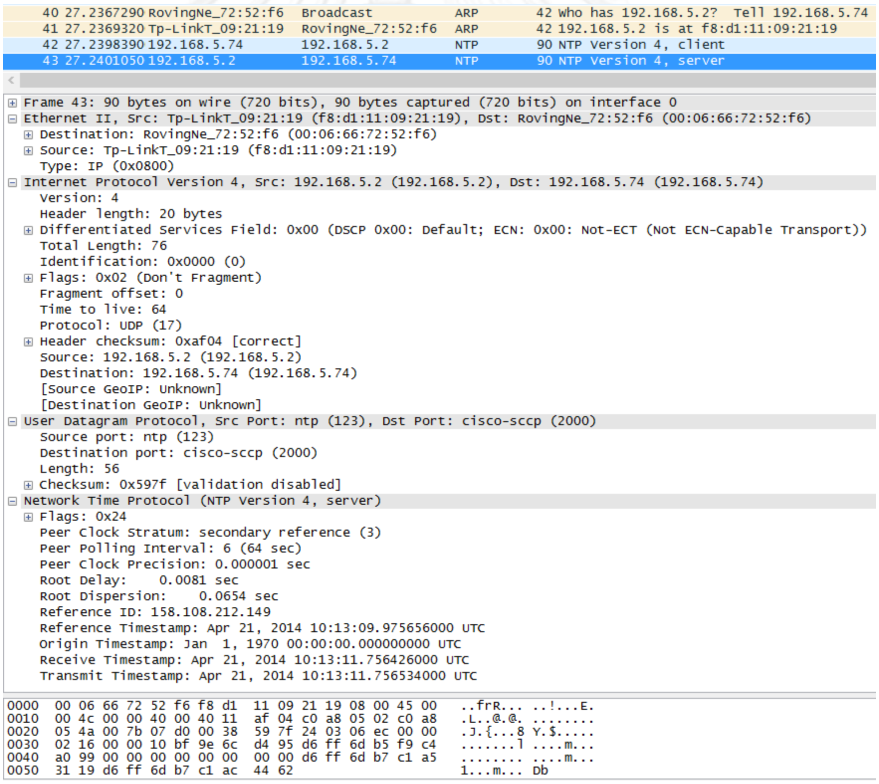


Figure 64 NTP Synchronization

Figure 65 and Figure 66 show the IEEE1888 data requested message for uploading data to Server and the successfully responded message from IEEE1888

Server (Storage) after system has finished uploading data to Storage. The system IPv6 address is [2001::6666], and the Storage IPv6 address is [2001::8888]

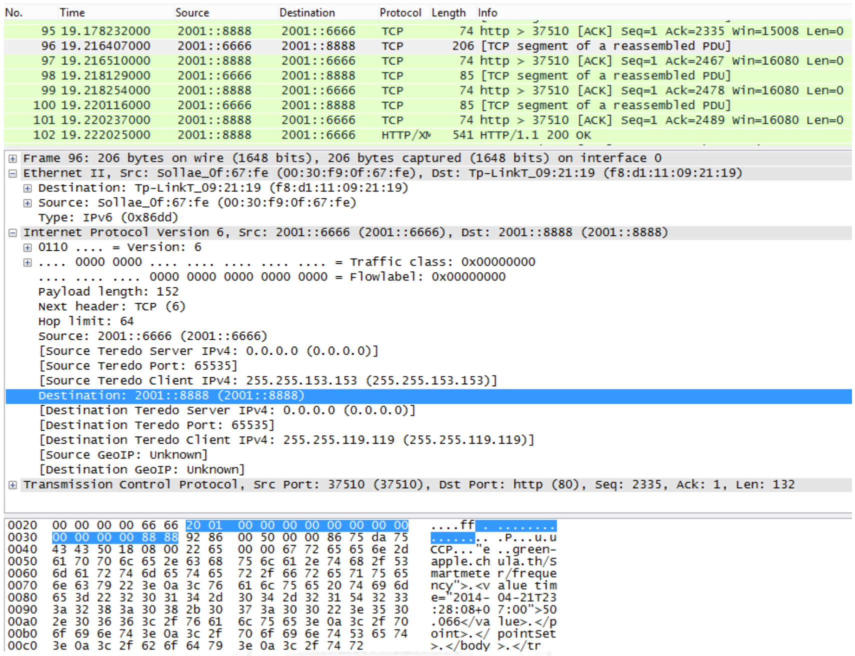


Figure 65 IPv6 IEEE1888 DataRQ Message

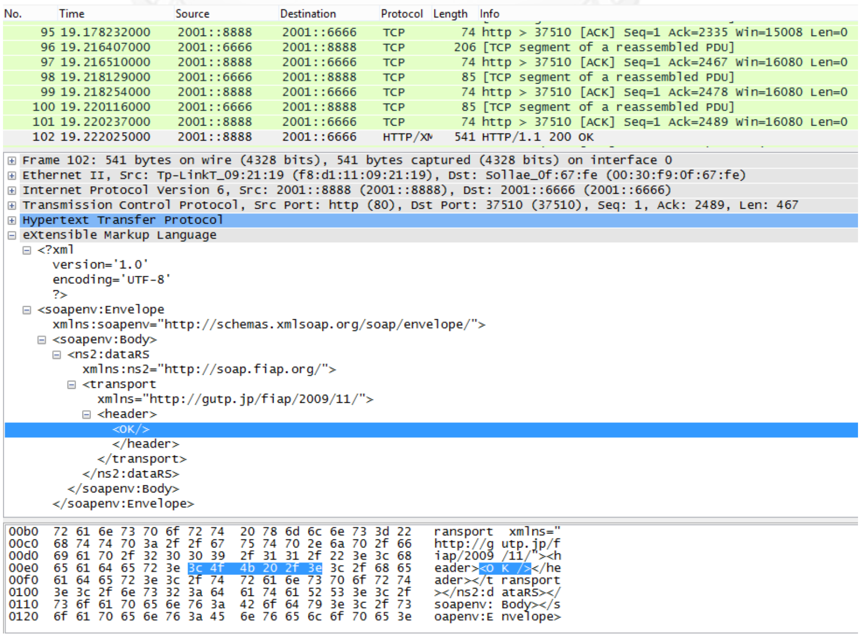


Figure 66 IEEE1888 DataRS Message

All of 6LoWPAN Client-nodes (Node 1, Node 2, and Node 3) packets included temperature, and motion data which are shown in Figure 67 to Figure 69 respectively, are sent to 6LoWPAN Server-nodes.

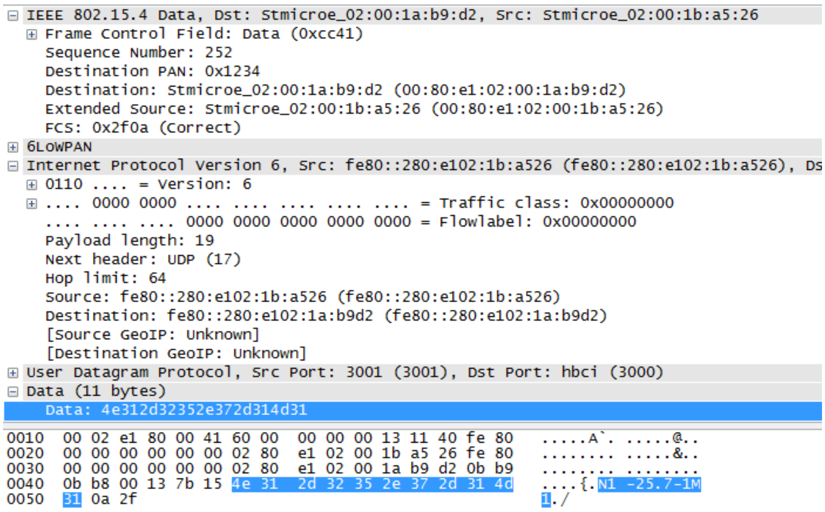


Figure 67 6LoWPAN Node 1 data

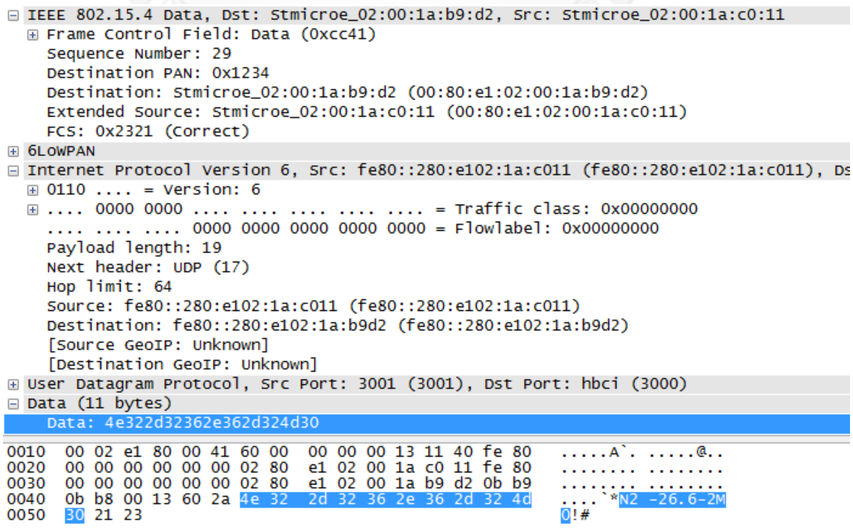


Figure 68 6LoWPAN Node 2 data

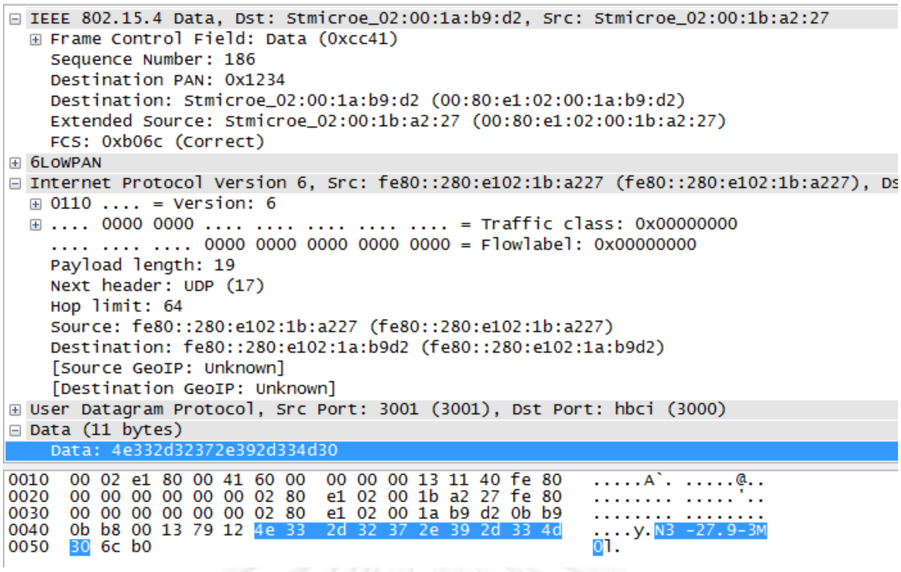


Figure 69 6LoWPAN Node 3 data

4.4 Results

Figure 70 illustrates all of Point ID, Time and Value of each Point ID is available in IEEE1888 Storage. It includes all of Point ID from 6LoWPAN nodes, sensors data, Smart meter value (current, energy, frequency, power and voltage), the state of two Outlets, the status of system and the interval time for update data.

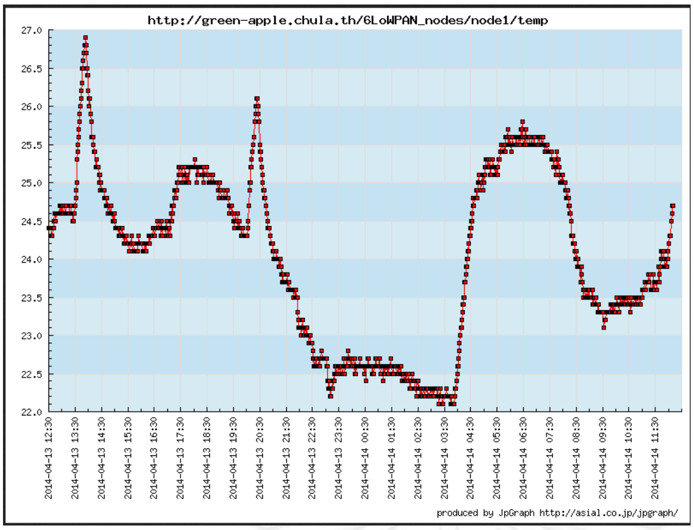
There are six Point ID used for 6LoWPAN nodes (as shown in Figure 71) such as node 1, node 2, and node 3. Each node includes the temperature value and motion value. In this study results, 6LoWPAN Node 1, Node 2, and Node 3 are located in the study room for Graduate students, Meeting room, and study room for undergraduate student respectively in ESID Laboratory, Department of Electrical Engineering, Chulalongkorn University.

Point ID	Time	Value
http://green-apple.chula.th/6LoWPAN_nodes/node1/motion	2014-04-16T07:23:58.000+07:00	detected
http://green-apple.chula.th/6LoWPAN_nodes/node1/temp	2014-04-16T07:23:58.000+07:00	23.3
http://green-apple.chula.th/6LoWPAN_nodes/node2/motion	2014-04-16T07:23:58.000+07:00	OFF
http://green-apple.chula.th/6LoWPAN_nodes/node2/temp	2014-04-16T07:23:58.000+07:00	29.8
http://green-apple.chula.th/6LoWPAN_nodes/node3/motion	2014-04-16T07:23:58.000+07:00	OFF
http://green-apple.chula.th/6LoWPAN_nodes/node3/temp	2014-04-16T07:23:58.000+07:00	27.6
http://green-apple.chula.th/Sensors/motion	2014-04-16T07:23:58.000+07:00	detected
http://green-apple.chula.th/Smartmeter/current	2014-04-16T07:23:58.000+07:00	0.061
http://green-apple.chula.th/Smartmeter/energy	2014-04-16T07:23:58.000+07:00	0.20
http://green-apple.chula.th/Smartmeter/frequency	2014-04-16T07:23:58.000+07:00	50.052
http://green-apple.chula.th/Smartmeter/power	2014-04-16T07:23:58.000+07:00	11.838
http://green-apple.chula.th/Smartmeter/voltage	2014-04-16T07:23:58.000+07:00	228.855
http://green-apple.chula.th/Switches/outlet1	2014-04-16T07:23:58.000+07:00	OFF
http://green-apple.chula.th/Switches/outlet2	2014-04-16T07:23:58.000+07:00	ON
http://green-apple.chula.th/System/status	2014-04-16T07:23:58.000+07:00	NORMAL
http://green-apple.chula.th/System/uTime	2014-04-16T07:23:58.000+07:00	1

Figure 70 Sensors in FIAPStorage

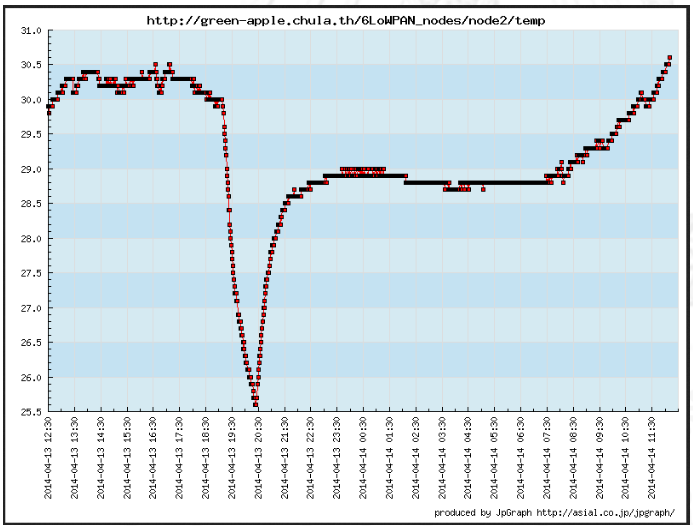
http://green-apple.chula.th/6LoWPAN_nodes/node1/motion	2014-04-16T07:23:58.000+07:00	detected
http://green-apple.chula.th/6LoWPAN_nodes/node1/temp	2014-04-16T07:23:58.000+07:00	23.3
http://green-apple.chula.th/6LoWPAN_nodes/node2/motion	2014-04-16T07:23:58.000+07:00	OFF
http://green-apple.chula.th/6LoWPAN_nodes/node2/temp	2014-04-16T07:23:58.000+07:00	29.8
http://green-apple.chula.th/6LoWPAN_nodes/node3/motion	2014-04-16T07:23:58.000+07:00	OFF
http://green-apple.chula.th/6LoWPAN_nodes/node3/temp	2014-04-16T07:23:58.000+07:00	27.6

Figure 71 the 6LoWPAN Point ID



Time	Value
2014-04-13 12:30:00	OFF
2014-04-13 12:31:00	OFF
2014-04-13 12:32:00	OFF
2014-04-13 12:33:00	OFF
2014-04-13 12:34:00	OFF
2014-04-13 12:35:00	OFF
2014-04-13 12:36:00	OFF
2014-04-13 12:37:00	OFF
2014-04-13 12:38:00	OFF
2014-04-13 12:39:00	OFF
2014-04-13 12:40:00	OFF
2014-04-13 12:41:00	OFF
2014-04-13 12:42:00	OFF
2014-04-13 12:43:00	OFF
2014-04-13 12:44:00	OFF
2014-04-13 12:45:00	OFF
2014-04-13 12:46:00	OFF
2014-04-13 12:47:00	OFF
2014-04-13 12:48:00	OFF
2014-04-13 12:49:00	OFF
2014-04-13 12:50:00	OFF
2014-04-13 12:51:00	OFF
2014-04-13 12:52:00	OFF
2014-04-13 12:53:00	OFF
2014-04-13 12:54:00	OFF
2014-04-13 12:55:00	OFF
2014-04-13 12:56:00	OFF
2014-04-13 12:57:00	detected

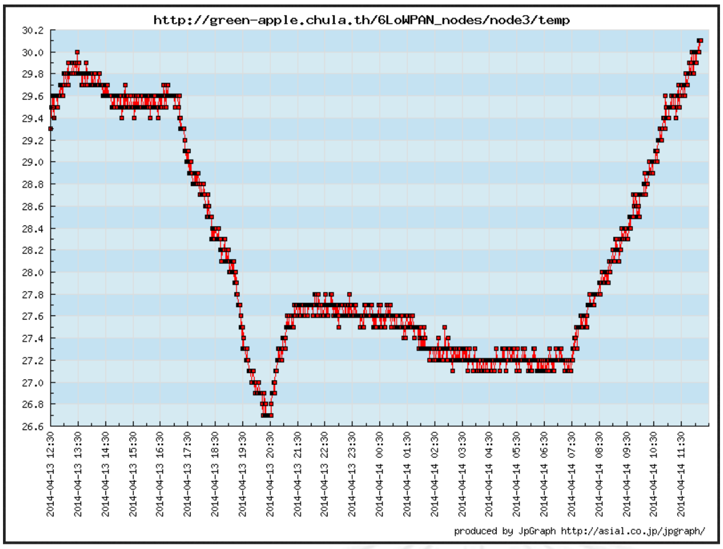
Figure 72 the 6LoWPAN Node 1 Temperature & Motion



Time	Value
2014-04-13 12:30:00	detected
2014-04-13 12:31:00	detected
2014-04-13 12:32:00	detected
2014-04-13 12:33:00	detected
2014-04-13 12:34:00	detected
2014-04-13 12:35:00	detected
2014-04-13 12:36:00	OFF
2014-04-13 12:37:00	detected
2014-04-13 12:38:00	detected
2014-04-13 12:39:00	detected
2014-04-13 12:40:00	detected
2014-04-13 12:41:00	detected
2014-04-13 12:42:00	detected
2014-04-13 12:43:00	detected
2014-04-13 12:44:00	detected
2014-04-13 12:45:00	detected
2014-04-13 12:46:00	OFF
2014-04-13 12:47:00	detected
2014-04-13 12:48:00	OFF
2014-04-13 12:49:00	detected
2014-04-13 12:50:00	detected
2014-04-13 12:51:00	detected
2014-04-13 12:52:00	detected
2014-04-13 12:53:00	detected
2014-04-13 12:54:00	detected
2014-04-13 12:55:00	detected
2014-04-13 12:56:00	OFF
2014-04-13 12:57:00	OFF

Figure 73 the 6LoWPAN Node 2 Temperature & Motion

From the Figure 72, Figure 73, and Figure 74 show the graphs of temperature (Unit: °C) and the tables of motion value (Unit: OFF, detected). As shown in the graphs, the temperature value reaches the highest value of 30.5°C.



Time	Value
2014-04-13 12:30:00	OFF
2014-04-13 12:31:00	OFF
2014-04-13 12:32:00	OFF
2014-04-13 12:33:00	OFF
2014-04-13 12:34:00	OFF
2014-04-13 12:35:00	OFF
2014-04-13 12:36:00	OFF
2014-04-13 12:37:00	OFF
2014-04-13 12:38:00	OFF
2014-04-13 12:39:00	OFF
2014-04-13 12:40:00	OFF
2014-04-13 12:41:00	OFF
2014-04-13 12:42:00	OFF
2014-04-13 12:43:00	OFF
2014-04-13 12:44:00	OFF
2014-04-13 12:45:00	OFF
2014-04-13 12:46:00	OFF
2014-04-13 12:47:00	OFF
2014-04-13 12:48:00	OFF
2014-04-13 12:49:00	OFF
2014-04-13 12:50:00	OFF
2014-04-13 12:51:00	OFF
2014-04-13 12:52:00	OFF
2014-04-13 12:53:00	OFF
2014-04-13 12:54:00	OFF
2014-04-13 12:55:00	OFF
2014-04-13 12:56:00	OFF
2014-04-13 12:57:00	OFF

Figure 74 the 6LoWPAN Node 3 Temperature & Motion

http://green-apple.chula.th/Sensors/motion	2014-04-16T07:23:58.000+07:00	detected

Figure 75 Built-in Sensor

As shown in Figure 75, the Point ID illustrates the motion value of PIR sensor which is integrated inside the SM/GW.

http://green-apple.chula.th/Smartmeter/current	2014-04-16T07:23:58.000+07:00	0.061
http://green-apple.chula.th/Smartmeter/energy	2014-04-16T07:23:58.000+07:00	0.20
http://green-apple.chula.th/Smartmeter/frequency	2014-04-16T07:23:58.000+07:00	50.052
http://green-apple.chula.th/Smartmeter/power	2014-04-16T07:23:58.000+07:00	11.838
http://green-apple.chula.th/Smartmeter/voltage	2014-04-16T07:23:58.000+07:00	228.855

Figure 76 Smart meter data

All values of this smart meter are sent to the IEEE1888 Storage such as current (A), energy (Wh), frequency (Hz), power (W), voltage (V) value. This Smart meter follows the IEC International Standard for checking the Accuracy of Smart meter, has the accuracy in Class 2 as shown in Table 1.

Table 1 Testing result of smart meter accuracy

Value of current	Power factor	Error limit (%)	Smart meter error max	Result
$0.25 \leq I < 0.5$	1	±2.5	2.313	Pass
$0.5 \leq I \leq 10$	1	±2	1.803	Pass
$0.5 \leq I < 1$	0.5 inductive	±2.5	2.378	Pass
$1 \leq I \leq 10$	0.5 inductive	±2.0	1.865	Pass

For this study results, this Smart meter is plug in to electrical outlet with six sockets, people can connect their devices to this electrical outlet to charge their phone, laptop, tablet, running the board, or using the Lamp. Figure 76 shows all of smart meter data that Storage receives in every minute for default updated time interval. From Figure 77 to Figure 81 give us an overview about the changes of Smart meter values by using graph.

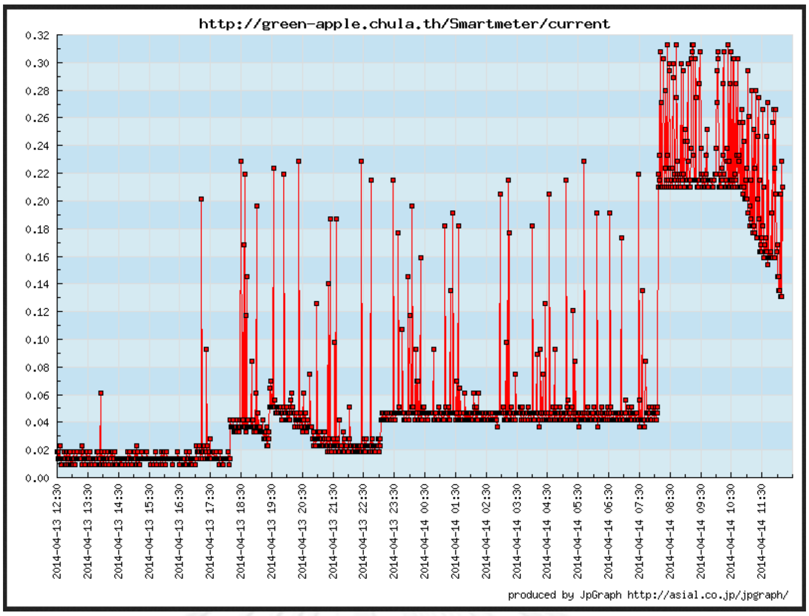


Figure 77 Smart-meter Current

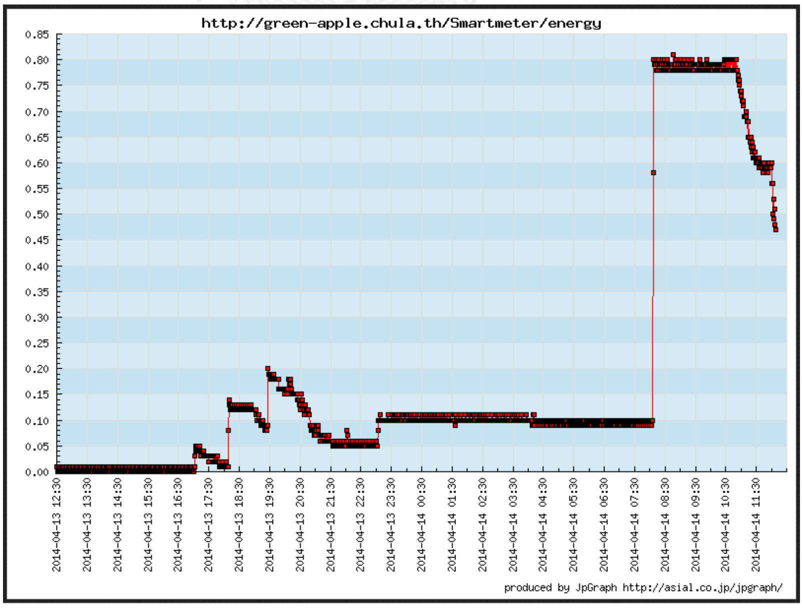


Figure 78 Smart-meter Energy

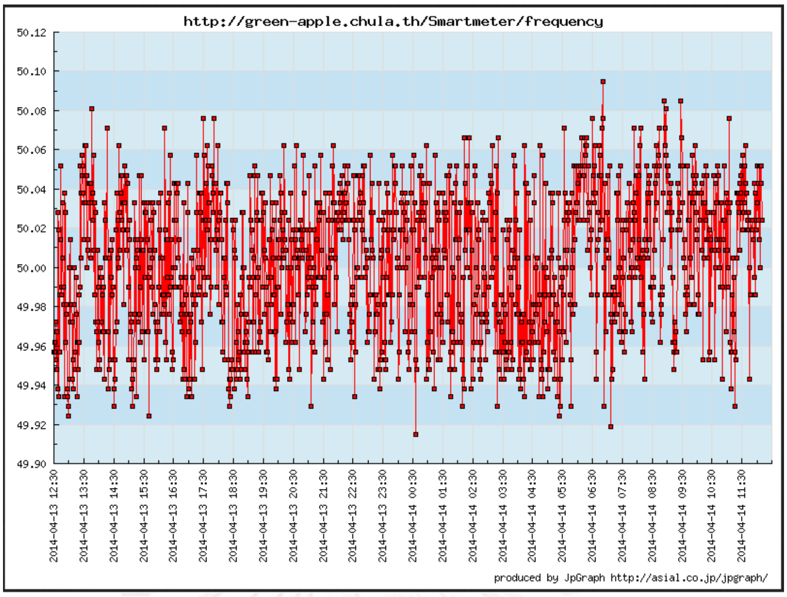


Figure 79 Smart-meter Frequency

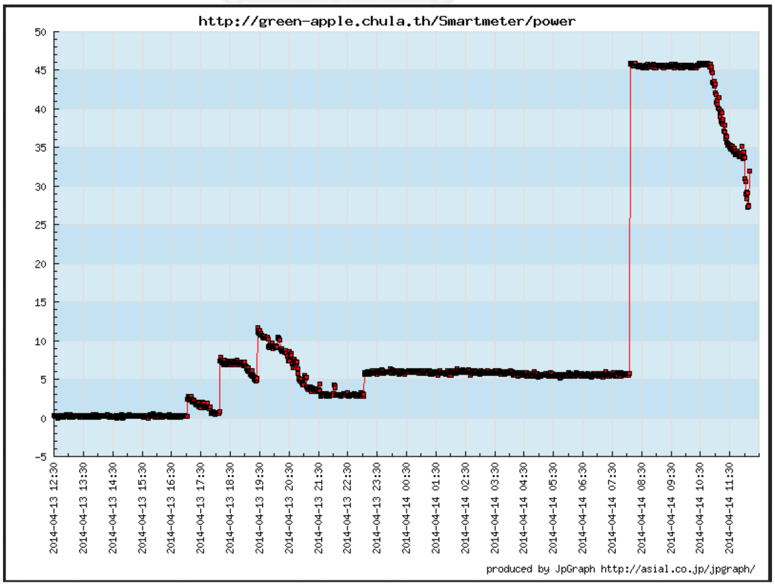


Figure 80 Smart-meter Power

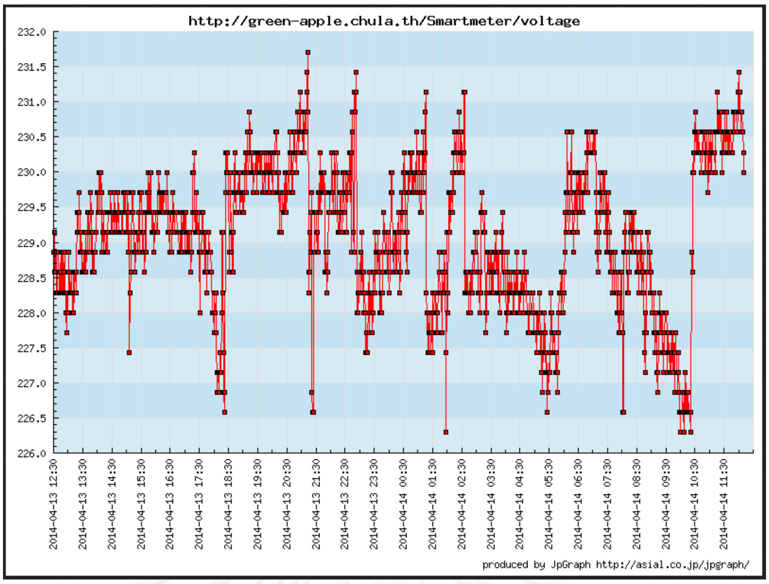


Figure 81 Smart-meter Voltage

On this smart meter is equipped with two electrical 1 socket outlets, user can control to switch on/off these outlets remotely by using application on mobile devices.

http://green-apple.chula.th/Switches/outlet1	2014-04-16T07:23:58.000+07:00	OFF
http://green-apple.chula.th/Switches/outlet2	2014-04-16T07:23:58.000+07:00	ON

Figure 82 Switches

Figure 82 describes the states of two electrical outlets, outlet1 is switched OFF, and outlet2 is switched ON to supply power to external electrical outlets.

http://green-apple.chula.th/System/status	2014-04-16T07:23:58.000+07:00	NORMAL
http://green-apple.chula.th/System/uTime	2014-04-16T07:23:58.000+07:00	1

Figure 83 System status

Figure 83 shows the system monitoring. The status of system is NORMAL; it means that smart meter works on the normal conditions without overload, and the update time interval to the IEEE1888 Storage is 1 minute. If the overload status happens, this smart meter will automatically switch OFF two built-in electrical outlets and make an alarm to notify that it is getting to over-loaded status. All of electrical outlets status before over-loading will be remembered. The value shows error status of system is ALARM. Alarm will be turned off after two seconds.

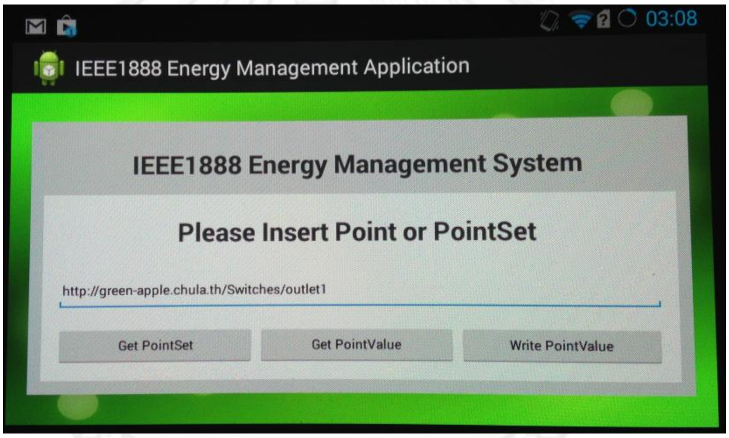


Figure 84 Application interface

IEEE1888 application running on Android OS v4.3.1 is shown in Figure 84 was created to supports for testing the accuracy of system operation. This main activity interface gives us three buttons and one input line for Point ID input (i.e. http://green-apple.chula.th/Switches/outlet1).

+ *Get PointSet*: to get all of Point IDs has the same PointSet (i.e. http://green-apple.chula.th/)

+ *Get PointValue*: implement the FETCH procedure, access data from Server for monitoring, analyzing, computing, etc.

+ *Write PointValue*: implement the WIRTE procedure; write data to system to control actuators to connect/disconnect the electrical outlets.

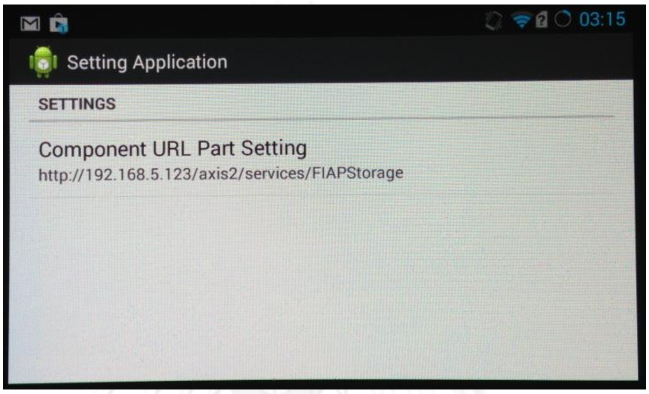


Figure 85 Application Setting

Figure 85 shows the application setting. At this activity, the IEEE1888 server address is set (i. e. http://192.168.5.123 is smart meter IPv4 address). This application was created to perform IPv4 connection.

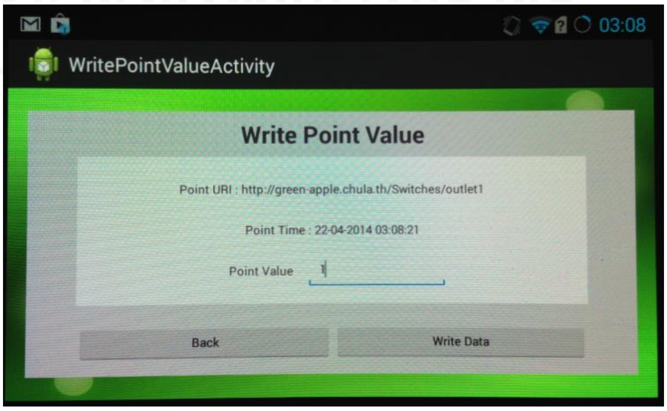


Figure 86 Application Write Client

The user can access to another activity through Write PointValue button on the main activity interface. Figure 86 illustrates the example for control interface for switch ON (Point value equals 1)/OFF (Point value equals 0) the electrical outlet1 on smart meter. The information will be appeared if the application receives successful confirmation message from system as shown in Figure 87.

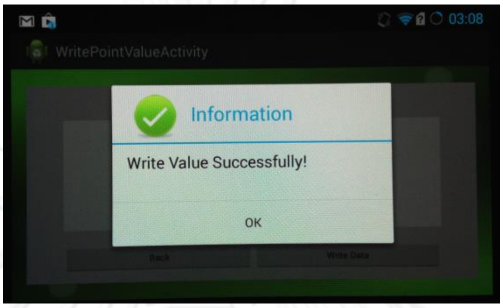


Figure 87 Application Write Client successfully

Furthermore, the system also allows application to access its data by implementing Fetch Client on application. All of results are illustrated in Figure 88 and Figure 89.

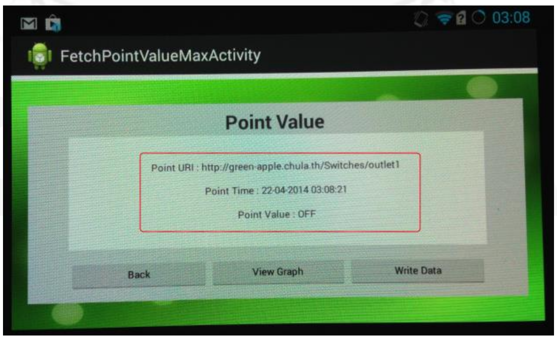


Figure 88 Application fetch value (1)

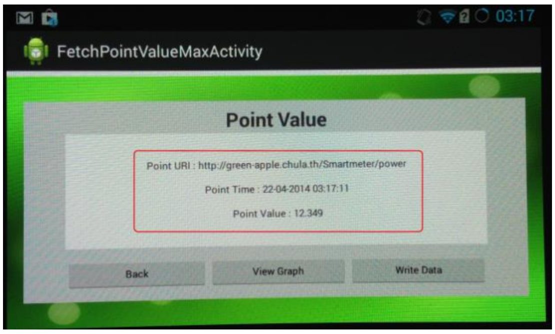


Figure 89 Application fetch value (2)

CHAPTER 5: CONCLUSION

This research basically aims at developing a smart meter which functions as a gateway of 6LoWPAN Devices to a Wi-Fi IEEE1888 network. In order to achieve this objective, this research relies on the theory of IEEE1888, 6LoWPAN, IPv6 Wi-Fi communication, and smart meter. In regards of IEEE1888 protocols, it is the internet communication protocol suite based on TCP/IP. This standard describes architecture of digital device community which can be controlled and monitored locally or remotely. Concerning the 6loWPAN, it is the internet standard which is enabled to use IPv6 over low-power wireless area networks (such as the IEEE 802.15.4 radio). This serves to realize the Wireless Embedded Internet. When it comes to Wi-Fi, this term refers to the IEEE 802.11 communication standard which supports for Wireless Local Area Networks (WLANs) using IPv6. As shown in Chapter 2, these three protocols are integrated in the smart meter which measures the energy consumption in buildings or building blocks.

Chapter 3 illustrates the design and implementation of system hardware and software. This chapter also describes the selection, connection, and the operation of hardware to sustain the system.

In Chapter 4, the study finds the implementation of smart meter based on IPv6 IEEE1888 standard protocol using Wi-Fi communication and also integrates 6LoWPAN (IPv6 Low power Wireless Personal Area Network) is the internet protocol based on IPv6 that could be applied to the smallest devices such as temperature sensor, and motion sensor. The smart meter is the gateway to transfer the data from each node in 6LoWPAN network into the internet follow IEEE1888 standard protocol using IPv6. Furthermore, this smart meter also functions as the temporarily Storage to store the latest values of 6LoWPAN nodes and the value of sensor that integrates in this Smart Meter/Gateway such as motion sensor. With the IEEE1888 Application on mobile device running on Android operating system which can access all of data from IEEE1888 Storage in control center or the latest values and also control the operation of this Smart meter/Gateway based on IEEE1888 standard protocol.

At this point, the results go beyond the scope of the research by developing smart meter working as the temporary Storage to allow not only other IPv4/IPv6 IEEE1888 application devices to retrieve all of the latest data but also support actuator commands. Instead of IPv4, it also applies IPv6 in uploading data from smart meter to IEEE1888 Storage every minute, and this time is changeable. The system integrates three 6LoWPAN nodes, each of which has temperature sensor, motion sensor, and DIP Switch for changing updated time interval. Additionally, smart meter is equipped with some useful functions. The first function is to synchronize NTP server in an hourly basis to ensure the accuracy in the time for updating measured data to IEEE1888 Storage. Secondly, this smart meter is also able to check if over-loaded status is found. This function of alarm warning is used for safety purposes. The third function serves for user and system maintainers by giving useful notifications by using notified LEDs. This has to identify the working status of the system. Last of not least, smart meter also performs to read motion sensor. More sensors can be added by users in implementing this function. Given this, this system can operate in the safer, smarter, and more accurate manner and it is easier for users to monitor and control this system remotely. Yet, when it comes to energy measurement, the result only reflects the Accuracy Class 2.

In respect to the results mention about, the research fulfills all the research objectives by developing a smart meter which functions as a gateway of 6LoWPAN Devices to a Wi-Fi IEEE1888 network, and 6LoWPAN temperature sensors, and examine the communication between 6LoWPAN sensors and an IEEE1888 Storage.

Based on the results in this research, this smart meter can be used in buildings and building blocks to save energy towards a green economy and sustainable development. This also contributes to get a smart, convenient and secure management and control among buildings and buildings blocks. Further researches can be implemented in a larger scale with higher accuracy.

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APPENDIX

VITA

Duong Hoang Le was born in Hanoi, the capital of Vietnam. He gains his Bachelor of Engineering in Control Engineering and Automation from Hanoi University of Science and Technology in 2011. During his study in university, he had experiences in working at National Center for Technological Progress Vietnam, and FPT-Software under FPT corporation Vietnam. After graduation, He participated in Language course in De La Salle University, Manila, the Philippines. After that, he got the Scholarship from JICA to follow his Master in the Department of Electrical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok Thailand from June 2012 to May 2014.