Monitoring and Management of Power Consumption in Apartment using ZigBee

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***Abstract*—This paper describes a field demonstration system that monitors the power consumption in an apartment. To evaluate the effectiveness of the system, 20 houses selected from Mudeung Park Apartment have participated in this project. The system includes 20 smart meters, 20 in-home displays, 2 data collection units, 20 energy service interface servers, and one meter data management server. A wireless sensor network based on ZigBee is used to exchange metering data between smart meters and data collection units as well as between an in-home display device and an energy service interface server in a home; the meter data management server exchanges data with data collection units and energy service interface servers through an IP network. The meter data management server has operated to collect periodically the power consumption from all meters and to send the amount of power usage and charge as well as additional data such as weather and price policy to each in-home display device. This testbed provides valuable insights about the operation of the system in an apartment that has a lot of obstacles which interfere in the wireless communication.**

Keywords- smart grid; WSNs; apartment; power monitoring

I. INTRODUCTION

The rapid industrialization and indiscriminate development in a lot of countries have increased greenhouse gas emissions, caused environmental degradation, and depleted natural resources. To overcome these problems, many counties have sought to develop technologies to reduce the use of natural resources as well as the greenhouse gas emissions. A smart grid is considered one of innovative technologies that reduce the greenhouse gas emissions by increasing energy efficiency [1]-[3].

Korean Government has constructed a smart grid testbed on Jeju Island [4][5]. About 10 consortiums in five areas have participated in the testbed project to test technologies and develop business models. The areas are smart place, smart transportation, smart renewable, smart power grid, and smart electricity service. The smart place is related to customers directly and includes customers as a part of a smart grid to increase energy efficiency. As a utility provides power usages and charges that customers have consumed for the customers, the utility encourages consumers to save energy. The smart transportation constructs a charging infrastructure for electric vehicles. There are two types of electric vehicle chargers: high speed charger and low speed charger. The former can be used at electric vehicle charging stations and the latter can be used at a house. Therefore, a utility should consider the number of electric vehicles, the amount of battery installed in each electric vehicle, and the time when an electric vehicle starts the charging in order to balance the power generation and the power consumption. The smart renewable develops renewable power generation technologies and builds power generation complexes to reduce CO_2 emissions. Also, the smart renewable can construct a micro-grid that generates and consumes the power by itself. The smart power grid constructs open power grids that can allow various interconnections between power suppliers and consumers. By using the open power grids, many new business models will be developed. The smart electricity service is to improve consumer's right-to-choose by introducing various price policies and demand response programs.

There are several competing technologies for capturing and transmitting the electricity usages of consumers in the smart grid, such as wired technology, PLC (power line communication) technology, and WSN (wireless sensor network) technology [6]. Although each technology has its own advantages, the WSN technology is very promising candidate among these technologies for several reasons. The WSN technology represents an emerging set of technologies that will have profound effects across a range of industrial, scientific, and energy management applications [7]-[14]. The WSN can reduce wiring cost and time for the smart grid deployment. Also, the WSN technology can reduce labor costs by simplifying installation. Moreover, it is one of key solution for facilities that frequently reconfigure spaces and places where a wire communication is difficult to apply. Meanwhile, in the residential area, the WSN is regarded as a part of the home network system. Accordingly, various service concepts which integrate the smart grid with home networks can be derived [6][7][8]. By introducing WSN technologies which assure network flexibility and mobility, it is easier to provide value added services like electricity equipment control.

In Korea, the ZigBee and the PLC are the popular communication technologies to implement the monitoring and controlling of the energy consumption for the smart grid. We selected the Zigbee technology because it provides the high interoperability as well as is the defacto standard in the smart grid. Also, a ZigBee Device can be moved to another place easily. The ZigBee Alliance published the smart energy profile for interoperable products that monitor,

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control and automate the delivery and use of energy [15]. The profile includes several specifications related to the advanced metering, the demand response and load control, pricing, and text message.

We installed several devices at 20 houses whose residents expressed the participation in this project. They were selected from Mudeung Park Apartment to evaluate our system in a city environment with a lot of obstacles that interfere in the wireless communications. The system is shown in Figure 1. Every house has one smart meter and one IHD (in-home display), and one ESI (energy service interface) server. Two houses from those have additional devices: PCT (programmable communicating thermostat) and LCD (load control device). MDMS (meter data management server) installed in a utility collects the power usage of each customer through DCUs (data collection units), calculates the charge on the usage, and sends them to IHD periodically. A customer can check them on the screen of IHD.

The remainder of this paper is organized as follows. The motivation is discussed in Section II. The detailed design of the testbed is described in Section III. Finally, Section IV provides the conclusion and the future work.

II. Motivation

In this section, we discuss the motivation of this study. In 2010, we implemented several devices based on the ZigBee standards [16]. They were installed in a two-story building in Jeju Island, South Korea. Our system focused on measuring and monitoring the amount of power consumption and generation, and controlling the energy consumption on the customer side. The system consists of smart meters, a wind power generator, a photovoltaic power generator, a rechargeable battery, electric vehicle chargers, light controllers, and a smart outlet. The light controllers exchange data through a power line communication; the other devices exchange those through a wireless sensor network. A central monitoring server has operated to collect periodically all data such as the amount of the electricity consumption and generation and to control the amount of electricity consumption and charges.

However, the system test in Jeju Island has a shortcoming because the system was installed on a typical rural village. It is difficult to prove the efficiency of the system and the reliability of the wireless communication. As the people in the village go to work early in the morning, return to their home at sunset, and go to bed early in the evening, they almost do not use the power during the day and use a little at night. Therefore, it is very difficult to prove that the system saves the power consumption or increases the power efficiency. Furthermore, there are few structures that interfere with the wireless communication because most houses built in a single layer and are relatively far apart. Therefore, it also is hard to prove that the wireless communication used to exchange metering data among devices is stable. To evaluate the efficiency and the reliability of the system, we selected another testbed where a lot of barriers exist and the power usage is relatively high. We have worked with LS Industrial System, KEPCO (Korea Power Corporation), KEPCO Data and Network, ADTechnology, Wooam Corporation, KERI (Korea Electro Technology Research Institute), KETI (Korea Electronics Technology Institute).

III. Testbed Design

The system consists of six main components: (i) MDMS, (ii) DCU, (iii) ESI, (iv) IHD, (v) load control devices (LCD and PCT), (vi) smart meter, and (vii) an information network connecting all devices.

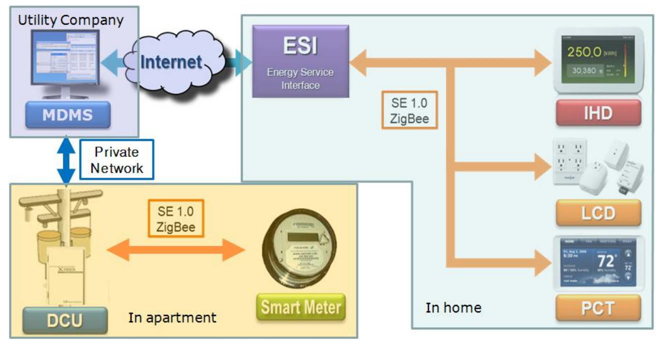

Figure 1. System configuration

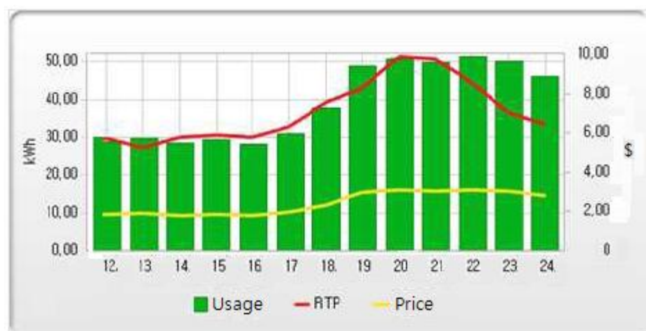

Figure 2. Power usage and charge

A. Meter Data Management Server

MDMS is the key component of our system. MDMS collects metering values from all smart meters through DCUs, and sends power usage and charge of each customer to IHD installed in the house of the customer. MDMS manages not only metering values and charges but also customer information, weather, CBL (Customer Baseline) for billing, power factor, price, etc. MDMS gathers the weather from Korea Meteorogical Administration and sends it to customers according to their residential area one a day, about 5 AM. MDMS calculates CBL that indicates a baseline load shape of the power usage of each customer. It is used to calculate the billing for each customer. Figure 2 shows the power usages and the charges from the noon to the midnight on 25 October. The bar chart indicates the usages, and the red and the yellow line curves indicate RTP (Real Time Price) and general price, respectively. Also, MDMS can send a load control message to a customer while the amount of power consumption is increasing dramatically. A load control device which receives the load control message reduces the power usage of an appliance by adjusting an operating condition of it or turns off an appliance, for example, increasing the set temperature of an air-conditioner.

MDMS uses CIM (common information model)-based XML messages to collect metering data from DCUs and to send billing information to each IHD. CIM is a standard defined as IEC (International Electrotechnical Commission) 61968 for exchanging information among electrical systems and devices [17]. Figure 3 is an example of customer billing information. The customer billing information is consisted of daily or monthly charge of a customer, billing date, billing cycle, meter identifier, type of billing, billing period, etc.

Customers can check their power usage and charge on a portal that MDMS provides. The type of users of the portal is divided into two groups roughly. One is customers and the other is administrators. For customers, the portal provides customer information including name, address, energy usage, charge, etc. For administrators, it provides the device information, network state information, statistics on the energy usage and charge. Authorized customers on the system can check their own information through the Internet. The Portal assigns different access rights to each user in order to limit the available information according to the user authority. For example, a customer cannot access the network state information. On the other hand, an administrator can access all information related to both customers and administrators. All information the Portal uses is stored and managed by MDMS.

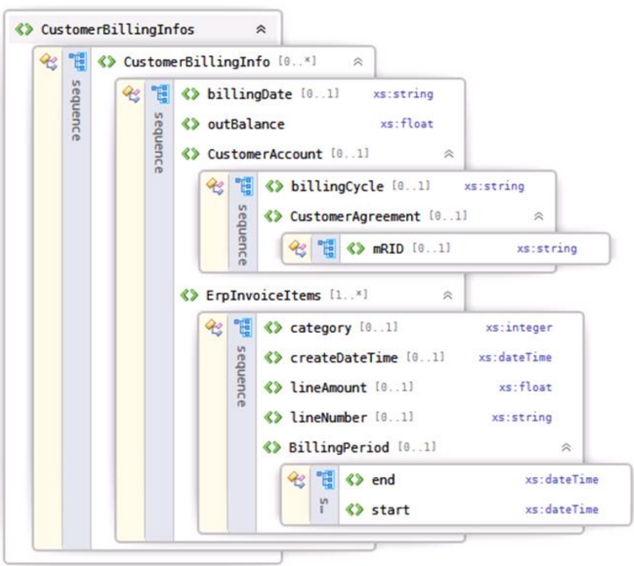

Figure 3. Customer billing information

B. Data Collection Unit

DCU locates between a smart meter and MDMS and distributes the load of data collection of MDMS. If MDMS collects metering values from a thousand of meters directly, it gives much of a burden on MDMS. To collect metering values, a variety of communication methods such as ZigBee[18], PLC[19], and WiFi[20] are implemented in DCU.

In this project, DCU is installed on a utility pole outside the apartment and acts as a gateway in a wireless sensor network. The goal of DCU design is to collect metering values from 200 meters within 15 minutes. In this testbed, one DCU connects to ten smart meters and collects a metering value from each smart meter periodically. The data received from smart meters are transmitted to MDMS according to a transmission schedule. The size of data which DCU can sent at a time is designed less than 680 Bytes. During the operation of the system, there are many missing data due to collisions among data transmissions sent by smart meters. Therefore, the success rate of metering data collections is about 96 percent due to the collisions. To overcome these limitations, we adapt a query scheduling method which collects simultaneously two metering values. A query scheduling assigns a report time to each smart meter to avoid the collisions. Each smart meter sends its two values, the current metering value and the value which was measured 15 minutes ago, at the time assigned by the scheduler. However, this method increases the success rate to only 99 percent. The missing values are collected by a batch process in which MDMS executes one per day.

C. Energy Service Interface

ESI becomes a bridge between the wireless sensor network and MDMS through an IP-based network. ESI provides the gateway device interface and the smart energy profile 1.0 announced by ZigBee Alliance as well as provides the functions that connect and manage all devices within a home area network [15][18]. ESI includes PANC (personal area network coordinator) starting the network formation and routing messages between the gateway and each electric device. ESI is implemented on Linux 2.6 in the C programming language, and uses PHP (personal hypertext preprocessor) for the web application to exchange data formatted in XML with MDMS.


```
G 15:37:11 + BeClient:post url http://129.254.82.171:1792/restifc/zgd/net/defaul
t/localnode/services/10/wsnconnection/message?timeout=10000
---
<Info>
  <Detail>
    <ZCLCommand>
      <DestinationAddressMode>2</DestinationAddressMode>
      <DestinationAddress>
        <NetworkAddress>43525</NetworkAddress>
      </DestinationAddress>
      <SourceEndpoint>10</SourceEndpoint>
      <DestinationEndpoint>10</DestinationEndpoint>
      <Profile>265</Profile>
      <Cluster>65243</Cluster>
      <Radius>10</Radius>
      <TxOptions>
        <SecurityEnabled>false</SecurityEnabled>
        <UseNetworkKey>false</UseNetworkKey>
        <Acknowledged>true</Acknowledged>
        <PermitFragmentation>false</PermitFragmentation>
      </TxOptions>
      <CommandID>0</CommandID>
      <Command>081f000100</Command>
    </ZCLCommand>
  </Detail>
</Info>
```


Figure 4. Example of ZCL message

The data transmitted through the home area network is formatted in ZCL (ZigBee cluster library). We use different clusters according to the type of transmitted data. When we receive the metering data from a smart meter, we use the simple metering cluster. If we want to control LCD, we use the demand response and load control cluster. They are included in SEP (smart energy profile). ESI coverts a CIM-based XML message into a ZCL message and vice versa. An example of ZCL message is shown in Figure 4. The message is sent to LCD to collect the energy usage that an appliance connected to the LCD has consumed.

D. In-Home Display

IHD is a portable device installed in a home. Therefore, a customer can move it to another home. In this situation, we have to prevent this IHD from joining to another ESI installed in the home where the customer visits. If this IHD connects to ESI of another home, it might receive the power usage and charge of the home that the customer visits. To prevent the situation, we make ESI, IHD, PCT, and LCD within the same home share the same unique key.

IHD receives several data such as power usage and charge, weather, CBL, price, etc., from MDMS and displays them on the screen. Table 1 shows the attribute of CBL curve. IHD draws a CBL curve when it receives the data. The user interface of IHD is shown in Figure 5. A customer can see the amount of power consumption, hourly power price, the trend of them, and weather on the same window.

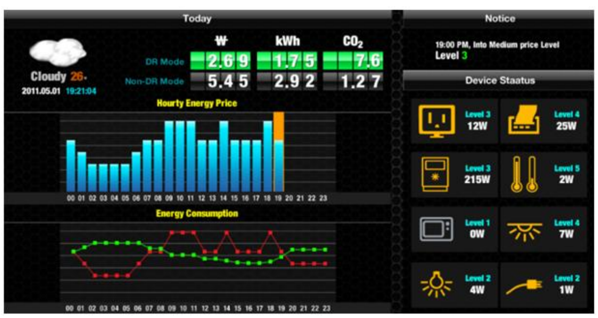

Figure 5. User interface of IHD

E. Load Control Device

A load control device is divided into two groups: PCT and LCD. They receive a load control message and return the result to MDMS. LCD has been implemented in the form of a switch and an outlet. Their roles are a little different. PCT can control an air conditioner with ZigBee functions; however, PCT does not have a metering capability. On the other hand, LCD controls an appliance such as an electric pan; and it can measure the power usage of an appliance that connects to itself because it has a metering capability. Furthermore, LCD can send its metering value to MDMS through ESI. Therefore, our system can measure a fine-grained power usage that each appliance has consumed.

F. Smart Meter

A smart meter measures the electricity usage of a home in which it is installed. It has recorded the electricity usage and sent the data formatted in the smart energy profile [15] to DCU on every 15 minutes. The meter also sends LP_Data (load profile data) including forward active power, backward active power, reactive power, etc as well as power quality. The forward power indicates that it is supplied for a customer by a utility; the backward power indicates that it is supplied for the utility by the customer. The power quality consists of the set of electrical properties such as power quality, frequency quality, and voltage quality.

The meter provides several different tariffs including time-of-use, real-time-pricing, critical-peak- pricing, and progressive-pricing. In Korea, the progressive pricing policy is applied to most of electric users. However, the Korean government seeks to change the tariff from the progressive pricing to the real-time-pricing to reduce the electricity usage.

TABLE 1. ATTRIBUTE OF TODAY CBL

Name	Data Type
CreatedYear	unsigned 8bit Integer
CreatedMonth	unsigned 8bit Integer
CreatedDay	unsigned 8bit Integer
ReferenceYear	unsigned 8bit Integer
ReferenceMonth	unsigned 8bit Integer
ReferenceDay	unsigned 8bit Integer
xMultiplier	unsigned 16bit Integer
xUnit	8 bit Enumeration
yMultiplier	unsigned 32bit Integer
yUnit	unsigned 8bit Integer
yValueTrailingDigit	8 bit Bitmap
NumberofValues	unsigned 8bit Integer
yValue	unsigned 32bit Integer

G. Information Network

An information network called SUN (smart utility network) can be divided into three categories. One is HAN (home area network) that is a residential local network for communicating among ESI, LCD, and IHD deployed in a home; another is NAN (neighborhood area network) that communicates between DCU and either ESI or smart meter; the third is WAN (wide area network) that communicates between DCU and MDMS operated by a utility company. In this project, ZigBee is used in both the home area network and the neighborhood area network, and the Internet is used in the wide area network. HAN devices such as IHD and LCD cannot communicate with NAN devices such as DCU and a smart meter due to the wall of the house.

Our wireless sensor network is developed based on ZigBee specification and IEEE 802.15.4. The sensor network installed in each house consists of one ESI, one LCD, one IHD, and one PCT. In this project, the devices can exchange messages via one-hop communication with star topology because every device is within the radio range of ESI. Also, DCU exchanges messages via one-hop communication with a smart meter.

After PANC included in ESI starts the network formation, a device willing to associate with the network starts the association procedure by requesting for a beacon with channel scanning. A joined device permits the association by beaconing with setting permit-joining flag on. Once a device has associated the network, it maintains three data tables: routing table, neighbor list table and link cost table. The maintaining of those tables allows the further expanding of the network up to the mesh topology, and the size of each table is resizable according to the network size.

IV. Conclusion And Future Work

This paper describes a smart grid testbed using a wireless sensor network at 20 houses in an apartment to evaluate the efficiency and the reliability of the system. To monitor and control the usage and charge of the electricity in each home, we install MDMS, DCUs, smart meters, and several devices including ESI, IHD, LCD and PCT in which locate a house. MDMS, DCU and ESI exchange their data and control messages through the Internet, and the other devices exchange those through a wireless sensor network. By visualizing the electricity usage and running a demand response program based on the electricity usage, the energy consumption could be saved. Also, a customer could save the electric bill by checking the charge in real time. One of the most difficulties is to collect the metering values from smart meters through the wireless sensor network. When we have collected the values on every 15 minutes, the success rate is about 96 percent because the data collision in the air. Therefore, we collect simultaneously two metering values on every 15 minutes, the last two metering values including the current value, to increase the success rate of the data collection. MDMS also collects a missing value one per day if necessary.

In the future, we will operate the system more than one year, accumulate the metering data to analyze the efficiency of the system, and perform the economic analysis on the smart grid testbed to apply the devices to other households and buildings. In addition, we have to solve several security issues, because the power consumption measured in a sensor network is directly related to the amount due on the electricity bill of the user.

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