A Smart Grid Testbed using Wireless Sensor Networks in a Building

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Abstract—**This paper describes the implementation and results of a field demonstration that monitors the usage and the generation of electricity in a two-story building. The field demonstration took place in Jeju to increase energy efficiency and to evaluate the stability of the developed system including 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 based on ZigBee. A centralized 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 charge. This testbed provides valuable insights about design decisions of a smart grid using wireless sensor networks.**

Keywords-wireless sensor networks; smart grid; testbed; home area; energy efficiency

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][2][3].

A smart grid refers to a next generation electric power network that combines information technologies and power technologies. The smart grid includes all functions of a utility such as power generation, electricity distribution, electricity transmission, and energy trading. Some of these functionalities related to utilities are already implemented through some automation systems such as SCADA (Supervisory Control and Data Acquisition) and DAS (Distribution Automation Systems) [4]. Recently, the smart grid is extending to include customers. Therefore, it becomes a system that enables two-way communications between consumers and suppliers [5]. Through the communications, the energy consumption of a consumer is transmitted to an electric power company and the company sends control messages to reduce the energy consumption to the consumer. The energy consumption is measured by a smart meter on the consumer side and the energy control is executed by smart appliances. In addition to the devices, the smart grid includes distributed energy such as renewable energies.

There are several competing technologies for capturing and transmitting the electricity usages of consumers in the smart grid, such as wired technology, power line communication (PLC) technology, and wireless sensor network (WSN) 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]-[15]. 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.

The ZigBee technology is one of the most popular wireless standards to implement the monitoring and controlling of the energy consumption for the smart grid. The ZigBee Alliance published the smart energy profile for interoperable products that monitor, control and automate the delivery and use of energy. The profile includes several specifications related to the advanced metering, the demand response and load control, pricing, and text message [16].

We implemented several devices based on the ZigBee standards and some of them were certified by the ZigBee Alliance. They were installed at a testbed in Jeju Island, South Korea. Our system focuses on measuring, monitoring, and controlling the energy consumption on the customer side.

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 South Korea the demand of electricity is growing faster every year. If the peak electricity demand grows higher than

 ISBN: 978-1-61208-144-1

the power generation, then the power network is broken down. Figure 1 shows the increasing trend of the power production and the consumption in South Korea from 2005 to 2009. We can clearly see in Figure 1 that the electricity consumption is growing every year. To supply the energy for consumers without outage, the utility company, KEPCO (Korea Electric Power Corporation), can do two activities: constructing a new power plant and reducing energy consumption. The construction of a new plant may not be reasonable in a certain aspect. It requires a lot of costs and time to construct a new power plant. Also, the new plant might operate and generate the electricity only when the energy consumption approaches peak load. This situation is ineffective for utilities. Therefore, many utilities have sought to decrease the energy consumption, in other words, they want to balance the power generation and the power consumption by controlling the energy consumption.

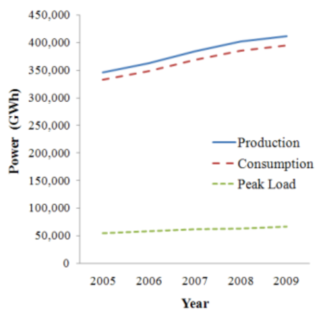


Figure 1. Trend of energy production and consumption in Korea (Source: KEPCO's Statistics, May 2010)

III. SMART GRID TESTBED DESIGN

The building in which the system was installed is a two-story building and the area of each story is about 30m × 20m. The system consists of five main components: (i) application, (ii) server, (iii) gateway, (iv) electric devices, and (v) information networks connecting all devices. They are shown in Figure 2.

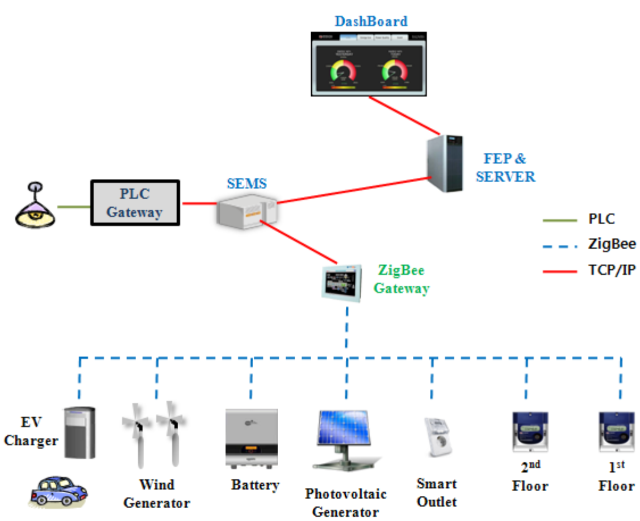
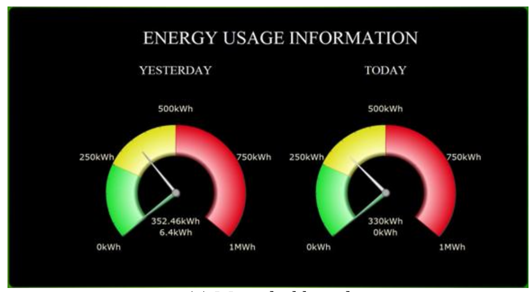


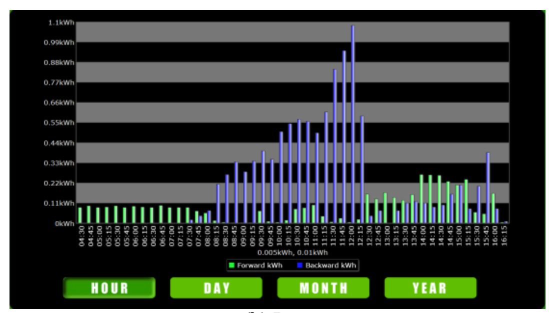
Figure 2. System configuration

A. *Application*

The main function of the application is to display all measurements according to the requirements of users. Two examples are shown in Figure 3. Figure 3-(a) indicates the main dashboard that displays and compares the electricity usages of today and yesterday. If the electricity gauge is displayed in red, then the user had better control the electricity usages because the electricity usage is over a threshold. Figure 3-(b) displays the electricity usages according to the specific period. The electricity usage has been measured and transmitted on every 15 minutes by the smart meters and the smart outlet. The graph based on hour will be changed according to the search condition such as day, month, or year.



(a) Main dashboard



(b) Power usage

Figure 3. Power usage information

Figure 4. SEMS's user interface

 ISBN: 978-1-61208-144-1

B. Server

The server is divided into SEMS (Smart Energy Management Server) and FEP (Front End Processor). The functionalities of SEMS and FEP are similar; however, their coverage is different. SEMS is installed a relatively narrow area such as a home, a building, a university campus, a factory, an apartment, etc; on the other hand, FEP covers a wide area such as a city by connecting to a lot of SEMSs. Therefore, SEMS gathers and manages the electricity usage at the fine-grained level, in other words, it captures directly the electricity usage of each electricity device. FEP summarizes the values gathered by SEMSs. Figure 4 displays the user interface of SEMS. The electricity usages of lighting, EV (Electric Vehicle) chargers, a battery, and renewable power generators are displayed separately. SEMS sends a query at 15-minute intervals to gather the electricity usage to all electric devices and sends the gathered data to FEP. In addition, SEMS sends a control message (e.g., turn a device on/off, charge/discharge the battery) to the smart outlet, the battery, and the light controller. The control message is generated by a demand response program in SEMS according to predefined rules. For example, if the electricity usage exceeds a threshold, the demand response program sends a turn-off message to the outside lighting devices. If the usage exceeds the threshold again, then it sends another message to those near to windows.

C. Gateway

The gateway becomes a bridge between the wireless sensor network and SEMS through an IP-based network. The gateway provides the gateway device interface and the smart energy profile 1.0 announced by ZigBee Alliance [16][17] as well as provides the functions that connect and manage all electric devices within HAN (Home Area Network). The gateway includes PANC (Personal Area Network Coordinator) starting the network formation and routing messages between the gateway and each electric device. The gateway is implemented on Linux 2.6 in the C programming language, and uses PHP (Personal Hypertext Preprocessor) for the web application to exchange data with SEMS. The gateway and SEMS exchange XML messages following REST (Representational State Transfer) specification [17]. Figure 5 shows the gateway hardware and the main window.

Figure 5. Gateway

D. Electric Devices

The electric devices consist of five smart meters, two wind power generators, a photovoltaic power generator, a rechargeable battery, two electric vehicle chargers, two light controllers, and a smart outlet. The light controllers exchange their data and control messages through PLC and the other devices exchange those through a wireless sensor network. The smart meters measure the electricity usage of the first and second floor, the two electric vehicle chargers, and the smart outlet as well as the electricity generation of two wind generators and one photovoltaic generator. The wind and the photovoltaic generator produce 0.8KWh and 6 KWh of energy, respectively. The measurements of the meters are transmitted to the gateway. The meters send LP_Data (Load Profile Data) including forward active power, backward active power, reactive power, etc. 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 outlet measures the electricity usage of an appliance (e.g., TV, air conditioner, refrigerator, etc.) which connects to it and transmits the measurement to the gateway. The rechargeable battery is a storage device which repeats charging and discharging according to the predefined conditions. It can store the power generated by the wind and the photovoltaic generator and dispatch power to supply electricity for streetlights over a night. Its current state and the charge level are transmitted to the gateway. Depending on a battery type and capacity, the high speed and the low speed EV charger can take about 3 hours and 12 hours to fully recharge a battery. The light controller measures the electricity usage of the first and the second floor, and transmits them to the PLC gateway.

TABLE I. COMPARISON RESULTS OF COMMUNICATION SCHEMES

Competitiveness Items	ZigBee	Narrowband PLC	Z-Wave
Communication Range	1~75m+	Max 1Km(bet. PLC modems)	30~500m
Data Transfer Speed	40K~250Kbps	1Kbps~20Kbps	10-40Kbps
Communication Stability	Partly Limited	Very Limited	Limited
Interoperability with HAN Devices	Very High	Low	Medium
Standardization Support	Global Standard	De facto Standard	Local Standard
Security	Very Good	Good	Good
Scalability(Number of Device Adders)	255+	20-255	232
Convenience in Deployment	Non-line-of-sight feature is suitable for various environment	needs to deploy repeaters and modems on the wire	Non-line-of-sight feature is suitable for various environments
Battery Support(One AAA battery with network activation on a minute basis)	Weeks	No capability of battery support	Weeks ~ Months
Mobility	High	Low	Medium

E. Information Networks

In a smart grid, two-way communication allows the data exchange between the customer side and the supply side.

There are several technologies that can be used in the smart grid [6]. We compare the technologies in terms of communication range, data transfer speed, interoperability with HAN devices, standardization support, etc. The result is shown in Table I.

We select PLC and the ZigBee technology. As PLC uses the existing power line infrastructure, it is used to capture and to control the electricity usage of lighting devices in our testbed. On the other hand, newly installed devices are developed based on ZigBee because it is one of the most popular wireless standards to implement the monitoring and controlling the energy consumption for the smart grid through the smart energy profile. Therefore, our wireless sensor network system is developed based on ZigBee specification and IEEE 802.15.4. The sensor network installed on each floor consists of one gateway and several nodes corresponding to the electric devices respectively. In this building environment, the devices can exchange messages via one-hop communication with star topology because every device is within the radio range of the gateway. After PANC included in the gateway starts the network formation, a node willing to associate with the network starts the association procedure by requesting for a beacon with channel scanning. A joined node permits the association by beaconing with setting permit-joining flag on. Once a node 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 within a small building. To monitor and control the usage and the generation of the electricity in the building, we installed two monitoring servers and several electric devices including five smart meters, two wind power generators, a photovoltaic power generator, a battery, two electric vehicle chargers, two light controllers, and a smart outlet. The light controllers exchange their data and control messages through PLC 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, the building owner could reduce the amount due on the electricity bill because most of the consumed energy has been supplied by the renewable power generators.

In the future, we will execute a demand response program combining with a real-time pricing policy. In addition, we will perform the economic analysis on the smart grid testbed to apply the devices to other households and buildings.

Acknowledgment

This work is supported by Development of Self-Powered Smart Sensor Node Platform for Smart and Green Building [10035570] funded by the Ministry of Knowledge and Economy, Republic of Korea. The authors would like to thank KEPCO-KDN members for working together.

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