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Research Article

An IoT-Based Home Energy Management System over Dynamic Home Area Networks

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A smart grid (SG) has attracted great attention due to recent environmental problems. SG technologies enable users, such as energy system operators and consumers, to reduce energy consumption and the emission of greenhouse gases, by changing energy infrastructure more efficiently. As a part of the SG, home energy management system (HEMS) has become increasingly important, because energy consumption of a residential sector accounts for a significant amount of total energy consumption. However, a conventional HEMS has some architectural limitations on scalability, reusability, and interoperability. Furthermore, the cost of implementation of a HEMS is very expensive, which leads to the disturbance of the spread of a HEMS. Therefore, this paper proposes an Internet of Things- (IoT-) based HEMS with lightweight photovoltaic (PV) system over dynamic home area networks (DHANs), which enables the construction of a HEMS to be more scalable, reusable, and interoperable. We suggest the techniques for reducing the cost of the HEMS with various perspectives on system, network, and middleware architecture. We designed and implemented the proposed HEMS and conducted a experiment to verify the performance of the proposed system.

1. Introduction

Emerging smart grid (SG) technologies have changed electricity infrastructure more efficiently [1]. The SG is a next generation power network and enables both electric power system operators and consumers to reduce energy consumption and greenhouse gas emissions through the fusion of the information technology and power electronics technology [2]. It has the capability to sense grid conditions, measure power, and control devices through two-way communications, which leads to improvement in energy efficiency and grid reliability to the electricity generation, transmission, distribution, and consumption part of the electric power grid [3].

A micro grid is a small-scale distributed power network. The main goals of the micro grid are a reduction in greenhouse gas emissions, enhancement of grid reliability, and energy self-sufficiency in distributed energy domains. In recent years, the technological progress of distributed renewable energy has enabled the household in the micro grid to independently generate and consume electricity [4]. In particular, photovoltaic (PV) energy has been under the spotlight as the distributed renewable energy source for residential energy consumers as shown in Figure 1, due to cost reductions in production, governmental incentives, and convenience in setting up [5, 6]. Despite the great attention of household PV systems, it is still challenging for most utilities to stabilize the quality of electric power, because of irregular generation [7]. As a countermeasure, the home energy management system (HEMS) is expected to ameliorate the instability of the power grids.

The HEMS is a consumer part of the SG and a demand side management technology, in which users efficiently manage their energy consumption, by monitoring and controlling their household loads [8]. The HEMS is employed to collect data from home appliances, renewable energy systems, and energy storage systems (ESSs) over home area networks (HANs) and to optimize power supply and management by using this collected information. The HEMS can select

Figure 1: Future green village.

an energy source from either the power grid or household PV system, according to the amount of household power demand, and manage the energy consumption of loads. Therefore, the HEMS is an essential technology in smart grid, in achieving the grid stabilization of a grid-connected PV system, and the efficient energy consumption of household loads.

However, a conventional HEMS has some architectural limitations. In respect of network topology, the HAN consists of various end nodes and fixed gateways (GWs) that are connected through wired or wireless communications [2, 8–10]. The static network topology of conventional HEMS ensures the reliability of data transmission. However, the fixed and static network topology is lacking in system scalability, and the preinstalled GWs inevitably increase costs of installation. Furthermore, most existing PV systems only perform a role in production of energy. In order to perform the sophisticated functions such as deterioration diagnosis, it is necessary to install additional servers (virtual or physical). Finally, such system architecture leads to the result that scalability and usability are reduced. In addition, the components for constructing the HEMS (such as home appliances, GWs, PV systems, and ESSs) are not compatible between companies, because protocols have been not yet fully standardized, which lowers interoperability. Furthermore, in respect of energy management service, existing systems mainly focus on saving energy. For example, in order to save energy, the air conditioner increases the reference temperature. These systems do not take into account the user's satisfaction. Therefore, we attempt to solve these limitations with the Internet of Things (IoT) paradigm and related technologies. This paper proposes an IoT-based HEMS with lightweight PV system over dynamic home area networks (DHANs), which enables the construction of a HEMS to be more scalable, reusable, and interoperable.

2. Related Works

The IoT is a new communication and network paradigm, and various studies of the IoT have been conducted. Fortino et al. [11] proposed a multilayered agent-based architecture for the development of proactive, cooperating, and context-aware smart objects through a JADE-based middleware. The multilayered agent-based architecture considered a wide range of smart objects from reactive to proactive, from small to very large, and from stand-alone to social. Gubbi et al. [12] present a new vision for Internet of Things based on cloud. This paper discussed key enabling technologies and applications of IoT in the near future. Atzori et al. [13] analyzed the major opportunities arising from the integration of social networking concepts into the Internet of Things. This paper also presented the various ongoing research activities around the world and discussed the most important technical challenges. Cirani et al. [14] proposed a scalable and self-configuring architecture for large-scale IoT. This architecture can provide autonomous services and resource discovery mechanisms with no human intervention to smart objects. This paper particularly focused on both local and global service discovery.

On the other hand, with the increasing importance of energy problems, many studies of an energy management system have been conducted. Various studies of a ZigBee-based HEMS have been done in the field of consumer electronics [15–17]. The proposed ZigBee-based HEMSs in these studies utilize IEEE 802.15.4 (ZigBee) as the standard for personal area wireless networks in order to construct HANs. Fortino et al. [18] presented the framework for multiplatform domain based on wireless sensor and actuator networks (WSANs) for enabling efficient and effective building management. Zhao et al. [19] presented the common architecture of energy management system in HANs and proposed an optimal power scheduling method for demand response (DR) in a HEMS. Niyato et al. [8] presented machine-to-machine (M2M) communications and network architecture for a HEMS to gather energy consumption demand and status from household appliances. Chavali et al. [20] proposed a distributed home energy management framework and a distributed algorithm of appliance scheduling for DR, based on the modeling of the cost function. Hu and Li [21] presented a hardware design and implementation of smart HEMS (SHEMS) with the functions of sensing, communications, and machine learning. Ozturk et al. [22] proposed a solution for DR for residential users. An adaptive neural fuzzy inference system-(ANFIS-) based home energy controller was developed to forecast energy demand according to the user's life style and environmental factors related to energy consumption. However, these studies have to assume fixed HANs. In other words, the proposed systems in these studies reduce energy consumption based on fixed network infrastructure of which end-components of HEMS such as home appliances, smart meters, PV system, and ESSs are connected with a central management server through fixed always-on GWs.

On the other hand, many studies of management of a PV system based on wireless communications have been done. In particular, the ZigBee wireless communication technology has been applied to PV systems because of its low cost and low power consumption when compared with the other available wireless communication technologies. Ranhotigamage and Mukhopadhyay [23] proposed a performance monitoring system for distributed solar panels based on a ZigBee wireless sensor network (WSN). Yu et al. [24] presented a three-level monitoring (i.e., system level, string level, and module level) scheme based on the ZigBee standard for fault diagnosis of PV systems. Other works have been carried out on a HEMS because of the propagation of household PV systems. Hong et al. [25] designed a HEMS integrated with a PV system. Here, the energy management system collects the information from the PV system and home appliances and manages the battery with solar energy. However, these ZigBee-based PV systems also should have several always-on GWs.

3. New Paradigm: Internet of Things

The IoT is a new communication and network paradigm in which a variety of things or objects (e.g., not only networked devices, but also people, vehicles, and bridges) become an integral part of the Internet. In other words, the objects become "*smart objects*" which are equipped with microprocessors and transceivers, which makes them able to communicate with each other and provide intelligent services to users autonomously [26, 27].

A variety of applications and services of IoT have begun to emerge in various fields of vehicles, healthcare, home automation, and SG framework [28–31]. In the field of the HEMS in the SG, communications infrastructure has been constructed in order to collect and analyze data in real-time by installation of smart meters and smart GWs. The smart meters and the smart GWs communicate with each other over intelligent M2M communications. It is, however, partial IoT rather than fully IoT, because it is only focused on making metering devices and GWs intelligent. In this architecture, there are several limitations such as low scalability, low reusability, and low interoperability. Therefore, the requirements of an IoT-based HEMS are as follows:

(i) *Distributed system architecture*: the existing sensor network usually operates under the three-tiered architecture. That is, the upper layer is a management server, the middle layer is a base station, and the lower layer is a sensor. It is not suitable for indoor environments such as a home or an office under this architecture because the service creation and execution time is very long. Therefore, we apply the IoT paradigm to HEMS in order to solve this limitation. The devices in service domain embed an adaptive rule-based engine; it generates the control signal directly according to rules, so that our system reduces the service creation and execution time.

(ii) *Smart objects by adaptive middleware architecture*: all components (objects) of the IoT-based HEMS such as appliances, smart meters, GWs, ESSs, and renewable energy system should operate intelligently. In other words, the objects should become smart objects. It is impossible to communicate with each other and create intelligent services to users autonomously unless the components of the IoT-based HEMS are smart objects. To meet this requirement, we equip the things with a middleware platform. However, to be equipped with the whole middleware causes a considerable waste of system resources. In order to solve this problem, we propose an adaptive middleware platform. The adaptive middleware platform autonomously configures middleware based on contextual information related to services, environments, and users.

(iii) *Dynamic network configuration by DHANs*: dynamic network configuration is one of the crucial characteristics of IoT. The IoT consists of different and heterogeneous objects which communicate with each other transparently and seamlessly. The proposed HEMS has the ability to configure the DHANs, which utilizes reusable nomadic agencies (NAs) to configure HANs. The reusable NAs refer to the applications of middleware in user's smart phones. In comparison with a conventional HEMS, the proposed HEMS enhances scalability and reusability and reduces implementation costs through DHANs.

(iv) *Enhancement of scalability and reusability by flexible platform design*: all components of the IoT-based HEMS should perform the various functions in order to create/provide intelligent services through the interaction with various objects. The functions performed by these objects are data sensing, extracting and processing, context-awareness, decision, security, authentication and authorization, discovery, object formulation, ontology-based modeling, virtualization, localization, process management, data mining, and so forth. It is difficult to set and update the functions on the platform of the conventional HEMS. The proposed HEMS is designed with flexible and reusable platform architecture to easily set and update the functions.

4. System Architecture

4.1. Overview of System Architecture. Figure 2 shows the typical architecture of the conventional HEMS. The HAN is constructed by using various wired and wireless network technologies. The various network-based devices in the home, such as smart appliances, smart meters, smart distribution panels, renewable energy systems, and ESSs, are connected by GWs in the HAN. These GWs have roles of aggregating data from the networked devices and transmitting the data to the central management server (CMS). These GWs of the conventional HEMS are fixed and are essential network components for reliable transmission in the HAN. Although this static network architecture enhances reliability of communication, it reduces scalability of networks, systems, and services. The fixed GWs, moreover, have another problem of a waste of energy. In the conventional HEMS, the GW's power needs to be always-on in order to collect data from appliances and sensors over the HAN, which results in constant power consumption.

To solve these existing problems, this paper proposes an IoT-based HEMS over DHANs. Figure 3 shows the architecture of the proposed system. There are several user-centric service domains. The user-centric service domain is defined as the service domain where the user-centric services are provided autonomously, based on the contextual information related to users and environments. When the user with a NA enters the service domain, the networked devices (e.g., networked appliances, networked lighting systems, smart meters, and networked PV systems) in HANs exchange data

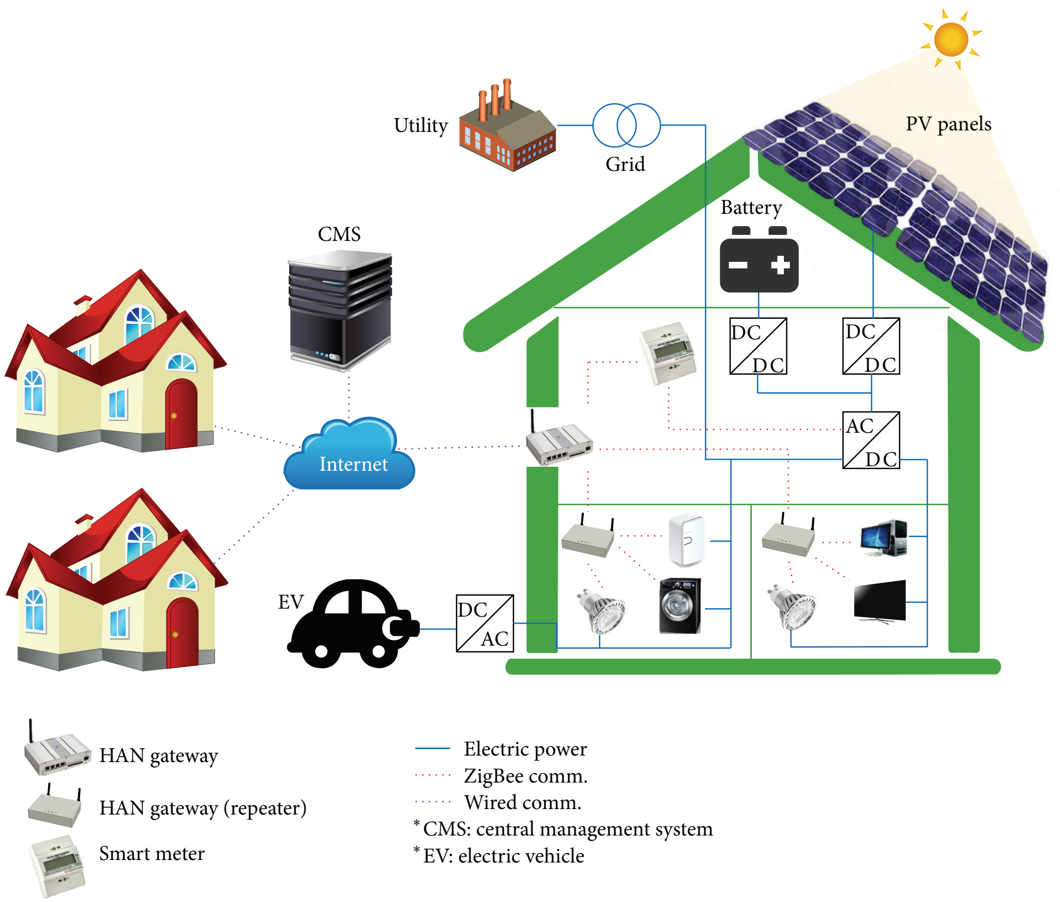


FIGURE 2: System architecture of the HEMS with PV system.

via the NA, by constructing peer-to-peer (P2P) connections. The important feature of the proposed HEMS is that the HAN can be dynamically configured by using the user's NA, without any fixed GWs. In other words, instead of the conventional GWs in the HAN, the NA is in charge of the role of interconnection between a CMS and an end device. We call this dynamically configurable network the DHAN. Another advantage of the DHAN is not only reducing the cost of system construction and management, but also providing user-centric services to users through the NA. In the conventional static network architecture, the user's mobile device is not one of the HEMS components, but a means of providing user experience for the user. There are various user experiences or services provided by the HEMS, such as the energy monitoring service. In the proposed system, the mobile device is used as a service provider, as well as the network resources. We use the Bluetooth technology for communications, because recently most mobile devices have adopted Bluetooth as a main wireless personal area network (WPAN). In this way, it is possible to construct HANs without installing additional GWs.

4.2. Information Fusion. We present information fusion scheme and the advantages we will have using it. Figure 4 illustrates the architecture of the information fusion scheme with adaptive middleware. We define that information is the one which combines the gathered contexts with useful data, such as time, day, environmental condition, executed service ID, and user profiles. Information fusion is the technique of the information management. Information convergence is defined as when creating new information, a system uses the information not only from its local domain but also from other domains. In this paper, we apply this scheme to gathering users' preferences between energy saving and comfort. An information fusion manager (IFM) (as shown in Figure 7) manages all the processes of information convergence. That is, it searches similar domains and also manages the interconnection with other domains. The NA can utilize information in other domains. This enhances the scalability and the service quality of the HEMS.

We present an adaptive middleware scheme which is applied to the energy saving device (ESD). The adaptive middleware architecture is defined that a system is aware of the user's state and environment and then modifies and reconfigures its middleware based on this information. There are some advantages of this scheme. The first advantage is scalability and adaptability. Common sensors mostly have a simple function. That is, they only sense the information such as the temperature, the humidity, and the user's movement. Furthermore these sensors have the fixed hardware and

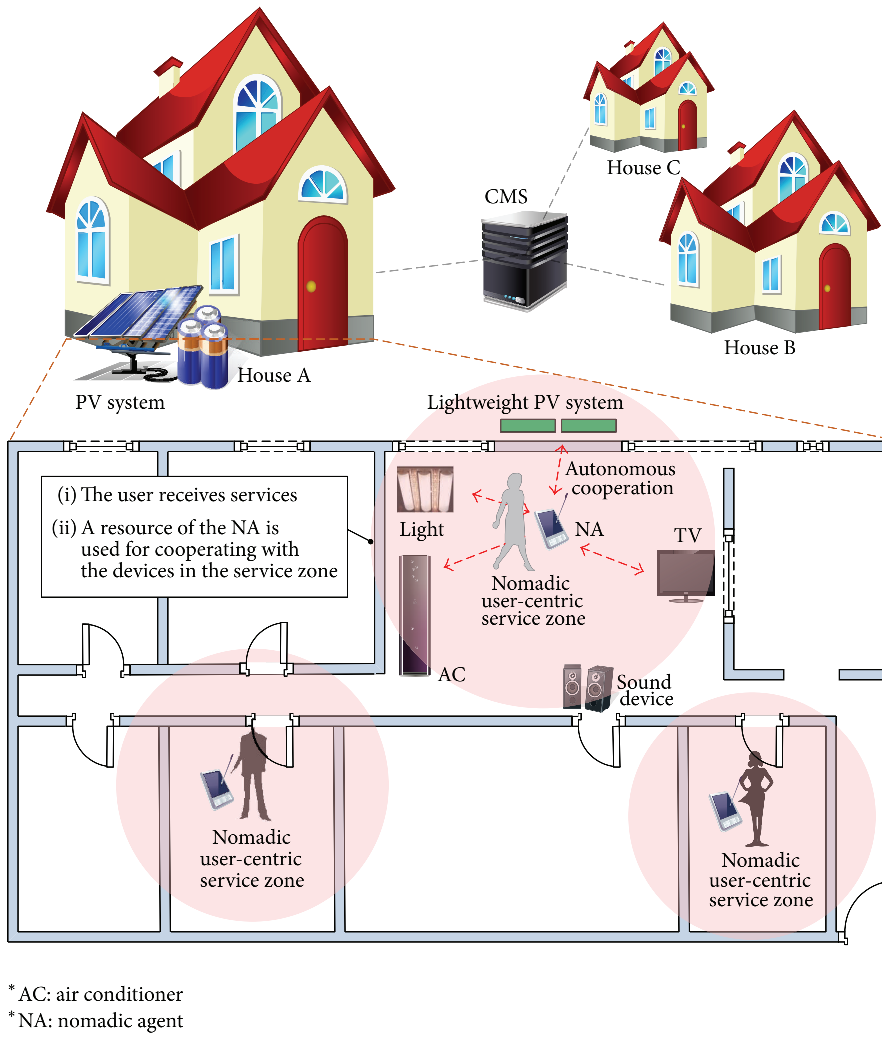


Figure 3: System architecture of the proposed HEMS.

software architecture, so that if we try to extend services we have to substitute the deployed sensors with the new ones, which is cost burden. However, the adaptive middleware architecture can be modified and updated freely. The second advantage is enhancement of the service quality. In order to create and provide the intelligent service, we need to deploy the intelligent sensors which effectively deal with complex events and situations. The adaptive middleware architecture offers various rules and functions to the system even though the system does not have all the middleware components.

The ESD reconfigures the adaptive middleware according to the characteristics of the space, the application, the environment, and the service. For the effective service creation and execution, the CMS sends the adaptive rules to the ESD with regard to the policies and machine learning. Therefore, the ESD is dynamically reconfigured and modified for enhancing the service quality such as the service response time, the hit ratio, the situation analysis, and the energy saving.

4.3. Energy Saving Scheme with Interaction Based on IoT

4.3.1. Energy Saving Based on the Interaction between Devices. The proposed HEMS provides an energy saving scheme through cooperation between home devices. A hierarchical relationship exists between home devices. For example, a PC, in general, is connected to a monitor, printer, and speakers, which are subordinated to the PC. When the PC is turned off, it is a waste of energy if monitor, printer, and speaker are turned on. Thus, a user can save energy by using this characteristic. The devices such as the PC are defined as the upper layered appliance and the devices such as monitor, printer, and speaker are defined as the lower layered appliance. When all upper layered appliances are turned off, the relevant lower layered appliances are turned off. For example, when the PC is turned off, the monitor, printer, and speaker are turned off. When the TV is turned off, all appliances, including the home theatre, set-top box, game machines, speakers, and DVD player, are turned off.

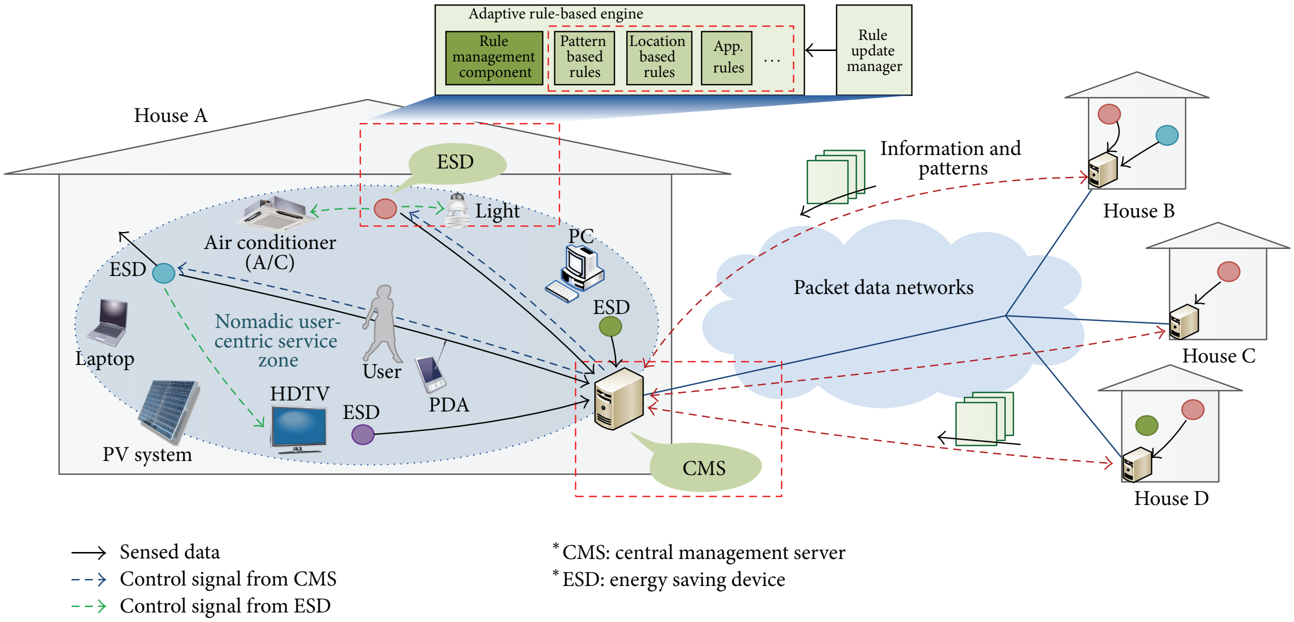


FIGURE 4: Architecture of information fusion scheme with adaptive middleware.

4.3.2. Energy Saving Based on the Interaction with User's Behavior Patterns. In order to reduce energy consumption, the proposed HEMS controls appliances based on user's behavior patterns in the service domain. The existing home energy management service conducts appliance control only based on user movement and not user's behavior patterns. The proposed HEMS generates user's behavior patterns based on the power feature data (gathered by ESD) and user movement data. The user's behavior patterns contain information on the purpose of user movement. The proposed HEMS has two methods to control devices in order to save energy consumption. The first method is rule-based control. The proposed HEMS generates various rules that connect a user's behavior pattern and location with device control. For example, if a user comes into a room, an ESD detects the user. Then, ESDs return all the appliances that were off in the room to standby mode. Depending on the operation of appliances and user movement, if a user completely leaves a room, energy saving is performed by cutting off standby power of appliances that are not operating. The second method is to utilize hierarchical relationship between the user's behaviors and home appliances. The user's behavior is defined as the highest layered appliance. The user's behavior is considered as ON when the user conducts a specific behavior and as OFF when the user finishes a specific behavior. For example, when the user leaves the bathroom, the lights and all electric devices such as electric bidet in a bathroom are turned off.

4.3.3. Energy Saving Based on the Interaction with User's Preference. The proposed HEMS can provide a new form of energy management services by using users' preference. The new form of energy management services is not only efficient energy management service but also enjoyable energy management service. It is possible to provide enjoyable energy management service through using user's preference. Therefore we developed a mobile application to vote on user's preference and conducted a simple experiment. The mobile application asked users to choose whether the users feel comfort or discomfort. Based on thousands of user votes, we are able to see which of the energy management services make people comfortable. The more data we collect and analyze, the more comfortable energy management service we provide.

5. Configuration of DHANs

A user can monitor and control devices in the HAN through a direct or indirect method. We will describe the configuration of DHANs by using some home appliances, a PV system, a NA, and a CMS. In the case of the PV system, the user can basically monitor an amount of real-time energy production, outside temperature/humidity, and the state of PV panels such as degradation, failure, and surface temperature.

5.1. A Direct Method. In this method, the proposed system constructs a P2P network between a PV system and a user's NA via Bluetooth technology. In the existing systems (e.g., the ZigBee-based HEMSs), a GW is a necessary component in order to monitor the PV system. In the proposed system, however, it is possible for a user to directly monitor a PV system through a mobile phone, by interconnection between a user's mobile phone and a PV system, after Bluetooth pairing processes.

Figure 5 shows a sequence diagram of the initiation and connection processes between the lightweight PV system and the NA. The PV system periodically broadcasts an advertising event. When the NA initially tries to connect with the PV system, an initiation process is needed. During the initiation process, the NA stores identification of the PV system, so that the NA is able to immediately connect with the PV system, without an initiation process. If the initiation process

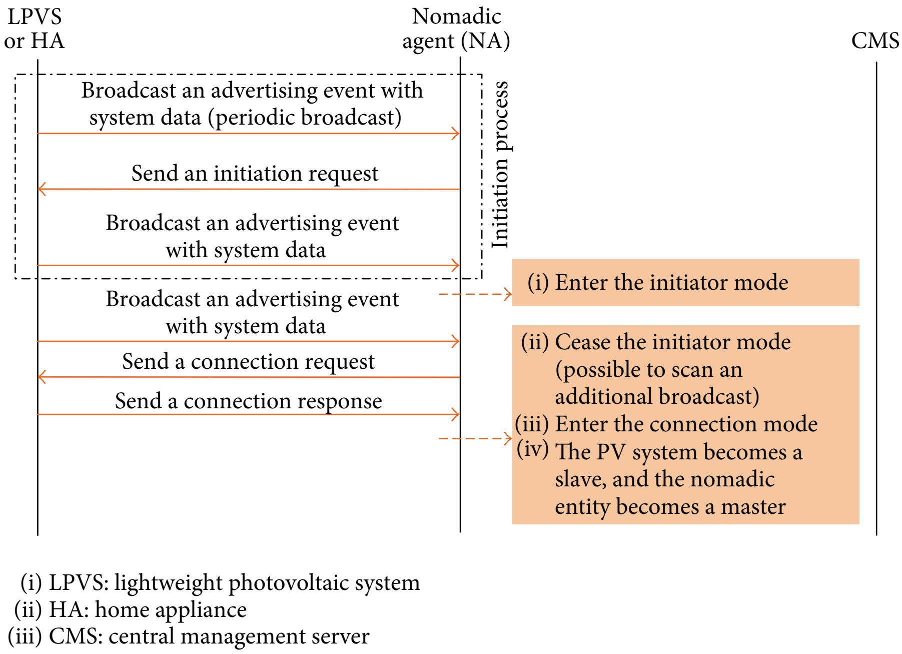


Figure 5: Sequence diagram of the initiation and connection processes.

is successfully performed, the NA sends a connection request to the PV system. If the PV system receives the connection request, the NA and PV system enter the connection mode. Then, the PV system becomes a slave, and the NA becomes a master. A master (i.e., the NA) can connect with other devices through a new initiation process.

5.2. An Indirect Method: Behavior-Based Routing Scheme. In this method, the proposed system constructs a client-to-server network between the PV system and the CMS. The user's mobile phone is utilized as the nomadic GW between the CMS and the PV system. In a conventional ZigBee-based system, several fixed GWs are necessary to communicate between the PV system and CMS. However, the proposed system utilizes the user's mobile phone as the nomadic GW for transmitting information of the PV system to the CMS, or controlling the PV system through the CMS. Since the mobile phone does not continuously maintain the connection to the PV system, a Bluetooth pairing process is executed, when the mobile phone detects the advertisement signal from the PV system. After the pairing process, the information stored in the memory of the PV system is transmitted to the CMS, through the user's mobile phone.

When the proposed PV system sends the information (e.g., power generation and state of the PV system) to the CMS in the autonomous node, a problem could arise, because the user utilizes the NA as the HAN GW. Due to the relatively short communication range, the PV system can transmit the information to the CMS only when the NA comes close to the PV system. If the PV system is installed in a space where the user does not go, the information of the PV system is not transmitted to the CMS. To solve this problem, we propose an information aggregation scheme, by using the frequency of the connection with the NA, based on machine-to-machine communications. Figure 6 shows the flowchart of information gathering, by using the NA in the autonomous mode. The process of information gathering is as follows:

(i) *Dynamic decision of the head-device in the M2M zone*: we define the M2M zone as a walled-in space. The frequency of the connection with the NA is calculated in the M2M zone. The device that has the most connections with the NA in the M2M zone becomes the head-device. The dynamic decision of the head-device performs autonomously, without the user intervention, through M2M communications.

(ii) *Connection between the head-device and the NA (A)*: if the device becomes the head-device, this device (i.e., home appliance 1 in Figure 6) frequently sends an information request to the PV system. Then, the PV system sends the information, and the head-device updates its database. If the user's NA enters the range of communication between the head-device and the NA, the NA connects with the head-device, the head-device transmits the information related to the PV system to the NA, and the NA transmits this information to the CMS. The CMS updates its database.

(iii) *Connection between the PV system and the NA (B)*: if the user's NA enters the range of communication between the PV system and the NA, the NA connects with the PV system, the PV system transmits the information to the NA, and the NA transmits this information to the CMS. The CMS updates its database. In this case, though the head-device has the information related to the PV system, the NA already

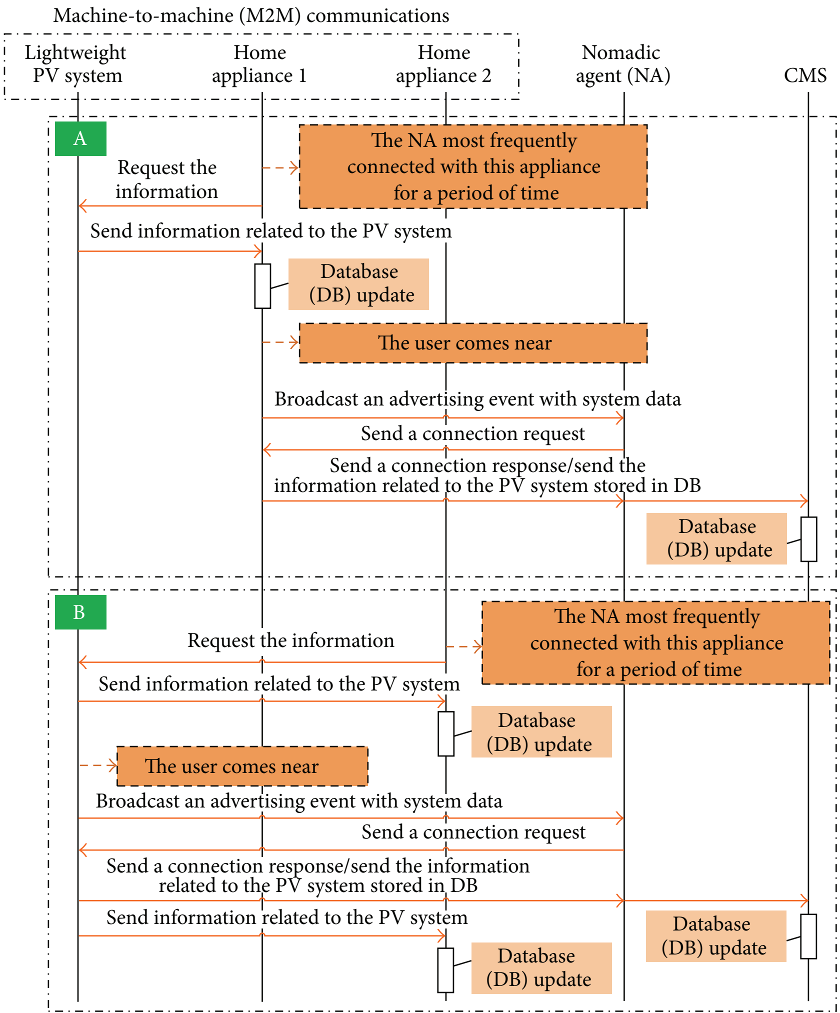


Figure 6: Sequence diagram of information gathering in the autonomous mode.

receives the information from the PV system and sends this information to the CMS. Thus, the head-device has to update its database.

6. Implementation

Figure 7 shows the middleware architecture and data flow of the proposed HEMS. The proposed HEMS consists of a lightweight PV system (LPVS), a NA, and an ESD. We designed and implemented the hardware and middleware of the proposed HEMS.

6.1. Hardware Implementation. Figure 8 shows the prototype of the LPVS. The proposed LPVS is a single-stage and grid-connected power control unit. It converts DC power generated from PV panels into AC power. The hardware of the LPVS consists of four major blocks: the power optimization block, the power conversion block, the communication block, and the energy monitoring block.

The *power optimization block* performs the function of optimizing the intermittent output power of PV panels. This block consists of three major components: the DC input filter, maximum power point tracking (MPPT) controller, and DC/DC converter. The input power generated from the PV panels has to be stable and constant, which improves the lifetime of the converter. For this reason, the DC input filter refines the input power by eliminating its noise and ripple. Moreover, the output of PV panels could be changed depending on several external variables such as partially shaded condition, solar irradiance, and temperature. These external conditions cause the fluctuation of maximum power point. The MPPT controller tracks the maximum power point and improves power efficiency. In particular, we used a perturb-and-observe (P&O) method for MPPT [32].

We measured the power efficiency (i.e., the power efficiency means the ratio of output power to input power) of the MPPT controller. In PV panels, a temperature is a crucial factor which influences the characteristics of a PV cell. When ambient temperature is high, the operating voltage of a PV cell is typically decreased, which reduces the power efficiency of PV system [33]. Thus, we constructed the test environment as shown in Figure 9. The input power of this block

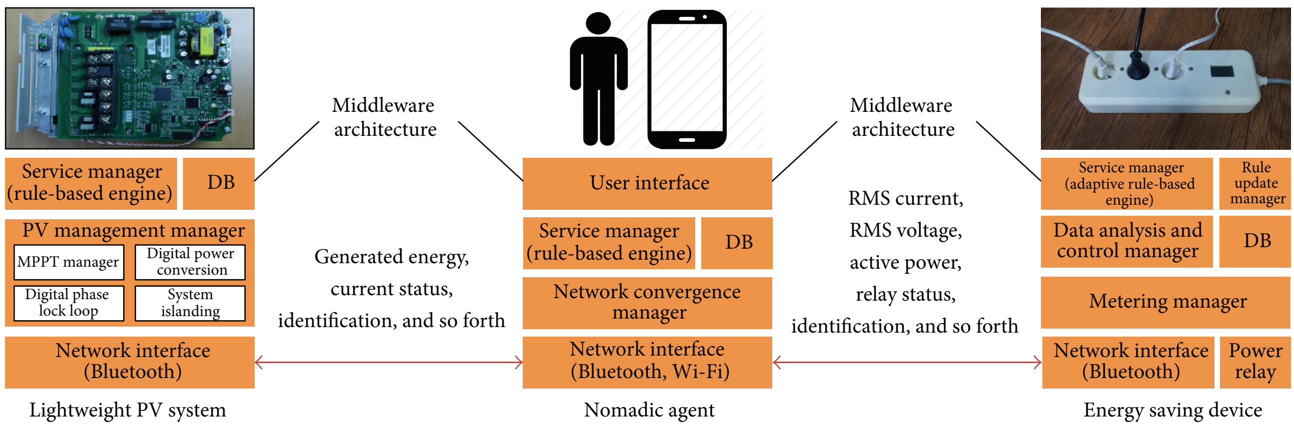


Figure 7: Middleware architecture and data flow of the proposed HEMS.

Table 1: The experiment results of the MPPT controller.

Temperature (degrees Celsius)	Power efficiency (%)
30	98.76
45	98.82
60	98.55
80	98.26

was generated by the PV panels in the temperature chamber. While varying the internal temperature of the chamber from 30 to 80 degrees Celsius, we measured the input and output power of the block for one hour. As a result, the power efficiency was maintained above 98% at each different temperature. Table 1 shows the results of the test.

The *power conversion block* performs the function of converting the DC voltage into the AC voltage required by loads and consists of two major components. One is the DC/AC inverter. It produces AC voltage by using PWM signals generated from 16-bit micro controller unit. The other is the DC output filter. As an electromagnetic interference filter, it protects the circuit from excessive external noise sources.

We built a test board in order to test the power conversion block. The output terminals of the test board were designed in form of three phases, because the proposed LPVS is intended for three-phase household power systems. When we applied the PWM signals to the test board, both high-side and low-side voltages were normally generated at all of the phases as shown in Figure 10(a). Similarly, when we applied the output power of PV panels to the test board, 230V AC voltage was normally generated as shown in Figure 10(b).

The *communication block* uses a Bluetooth 4.0 transceiver module for communication with an NA, or other smart devices. If ZigBee or WLAN technologies are used for configuring HANs, additional GWs are needed, as mentioned in Section 3. Currently, most smart phones have a Bluetooth transceiver module as a standard module for short-range wireless communication. Therefore, we utilized a Bluetooth 4.0 transceiver. In this way, we can reduce the cost of configuring HANs and enhance their scalability and availability.

The *energy monitoring block* performs the function of metering power generation. When the AC current transformer senses the power generation, the energy metering IC measures the amount of the generation. The power state of the LPVS is determined according to this measured power information by the MCU and transmitted to the NA through the communication block.

The ESD [34] in Figure 7 plays the role of shutting off the power, based on the user's command, or a rule-based engine. Thus, it is possible to save wasteful power consumption and standby power consumption.

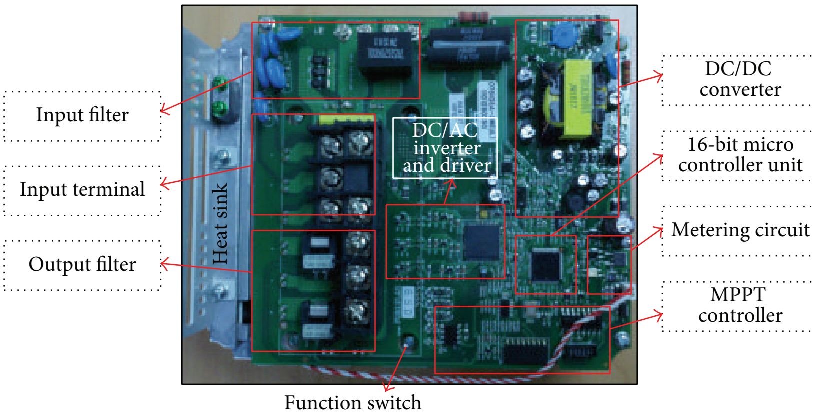
6.2. Adaptive Middleware Implementation. We designed and implemented the middleware platform using JAVA SDK 1.4 and an open service gateway initiative (OSGi) framework. The rules-based engine is implemented as a set of running applications, called bundles (Java archives (JARs)).

The middleware platforms of LPVS, NA, and ESD are shown in Figure 7. Main components of the middleware of LPVS are the PV management manager and the service manager. PV management manager plays a role in managing the PV system, and the primary roles are as follows:

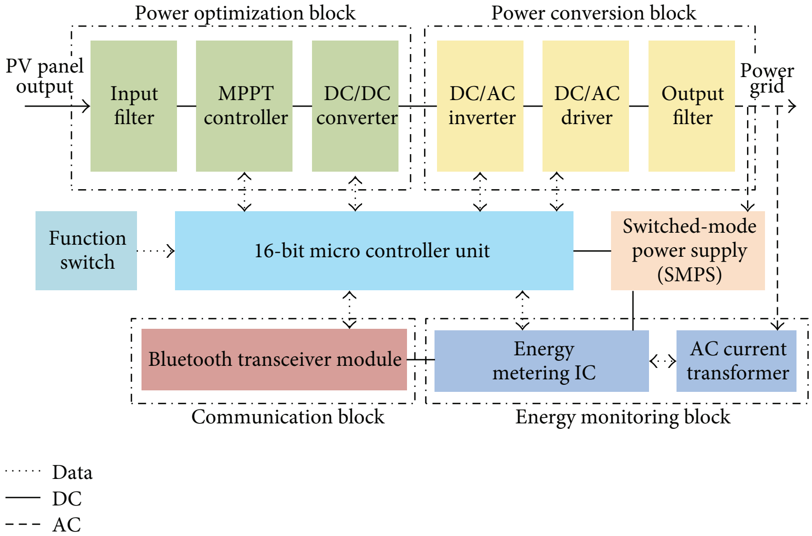
(i) *Digital power conversion manager*: this manager has the power conversion algorithms of a DC/DC converter and a DC/AC inverter; further, it efficiently converts power.

(ii) *Adaptive MPPT manager*: a PV system has nonlinear output characteristics. For example, its output varies according to environmental conditions, such as weather, or surface temperature of PV cells. Therefore, the adaptive MPPT manager determines which MPPT algorithm should be applied, by monitoring the external environment and the system state.

(iii) *Digital phase lock loop manager*: this manager is an important component in the control system of the inverter, which is connected to a grid, and has the function of synchronizing the output current of the inverter. This manager generates the frequency and phase of the grid voltage, which are used not only for generating the control signal, but also for protecting

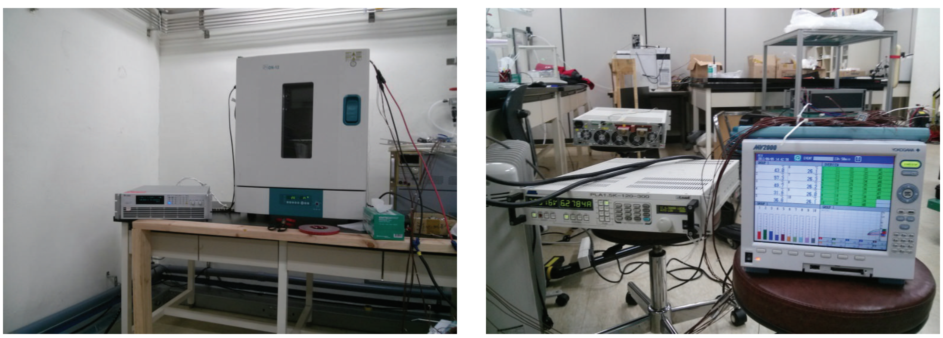


(a)



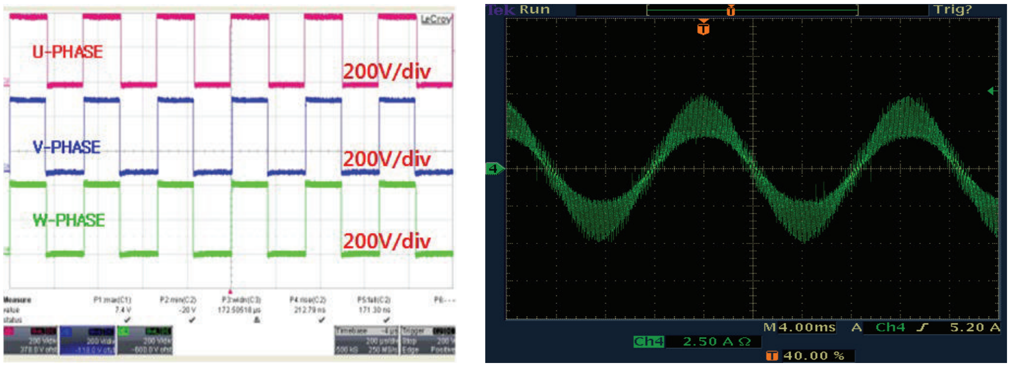
(b)

FIGURE 8: Prototype of lightweight PV system; (a) PCB layout and (b) hardware block diagram.



(a) (b)

FIGURE 9: Test environment; (a) temperature chamber and (b) temperature/power measuring instrument and DC load.



(a) (b)

Figure 10: Output wave of the power conversion block applied with (a) PWM signals and (b) PWM signals and the output power of PV panels.

the system at the island state. If this manager does not precisely synchronize the grid voltage, the efficiency of the output power factor could be adversely affected.

(iv) *System islanding handler*: its function is to detect and prevent islanding when the power system is shut down by some external disturbance, for example, when the system is suspended, because of system accidents, power failures, or the maintenance of electric lines.

(v) *The service manager*: this manager has the role of addition, modification, and deletion of service applications. This manager has a rule-based engine that is implemented as a set of running applications, called bundles. The service applications of LPVS are energy monitoring, system state monitoring, cell deterioration detection, and so forth.

The main components of the middleware of the NA are the network convergence manager and the service manager. Since the NA performs the role of the home GW, the network convergence manager modifies (encapsulates/decapsulates) the message transmitted over Bluetooth or Wi-Fi, in order to send the message to ESS, LPVS, and CMS. Likewise, the service manager is implemented as a set of running applications called bundles, and the service applications of the NA are device monitoring and control and message gathering and transmission, based on dynamic home area networks.

The main components of the middleware of ESS are the data analysis and control manager and the service manager. The data analysis and control manager has the role of controlling the power relay, based on cut-off mode, and standby mode learning mechanism. The service manager of ESS is also implemented as a set of running applications called bundles, and the service applications of ESS are automatic standby power cut-off, automatic returning to standby mode, cooperation based appliance control, and so forth. All application bundles of LPVS, NA, and ESS can be added, removed, and updated easily, due to the adaptive/flexible middleware platform architecture.

7. Performance Evaluation

Figure 11 shows our smart home test bed for experiments. The test bed is about 198 square meters and has eight rooms. Five people (researchers) live in the test bed. We deployed various household appliances, ESDs, and a LPVS in the test bed.

7.1. Installation Cost Reduction. The aspects of price will be discussed based on our test bed. In order for all appliances to be connected to the HANs reliably through Bluetooth communications, each room should have one or two GWs depending on the dimensions of a room. In theory, the system using the Bluetooth 4.0 technology has the communication range up to 100 m. However, the communication range is significantly reduced according to the environmental conditions. For example, if there is an obstacle such as the wall between the Bluetooth devices, if there is a wireless LAN device, and if there is a device that emits electromagnetic waves, the communication range is significantly reduced. Therefore, it is necessary to install one or two GWs in each room for reliable communications through the Bluetooth technology in experience. Thus, at least, eight GWs are required for all appliances to be connected to the HANs reliably in our smart home test bed. On the other hand, in order to install a GW, a socket that is connected to the Internet over Ethernet is also required. If there is no such socket, the additional cost for installation of Ethernet infrastructure occurs. Moreover, In this fixed architecture, it is difficult to adaptively deal with failure or changes in the system, and thus, when the system fails or changes, a large amount of cost also occurs. In addition, in the case of large buildings, many GWs are needed, which cause a greater installation cost.

7.2. Frequency of Data Transmission. Figure 12 shows the floor plan of the test bed and layout of appliances in the living room. The test bed in the living room has five devices including a LPVS, an air conditioner, four lighting system, a TV, and a sound device. Since each appliance is connected to the ESD, energy information is monitored. When an occupant who has a NA comes into Bluetooth communication range of the ESD,

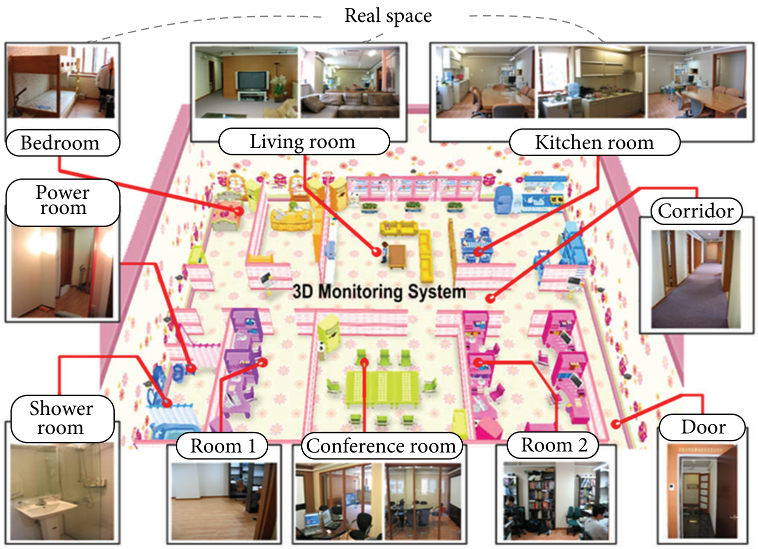


Figure 11: Smart home test bed for experiments.

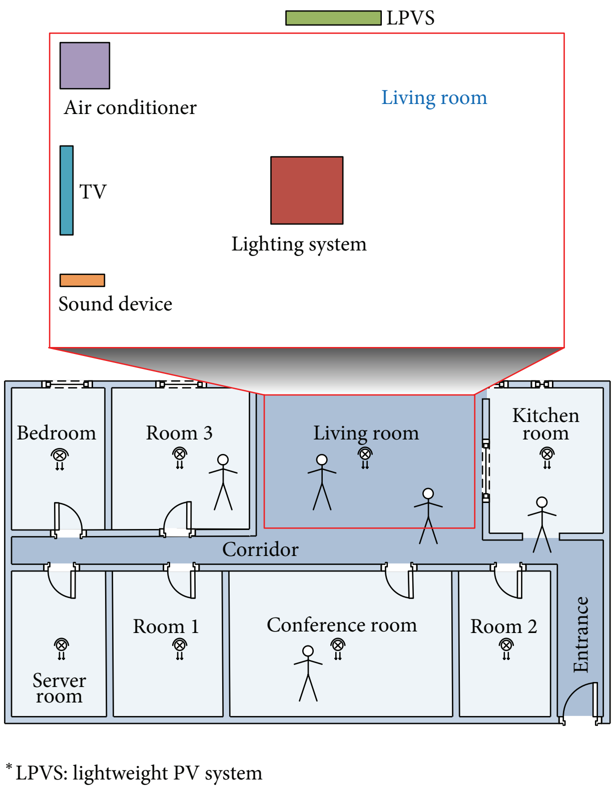


Figure 12: Floor plan of the test bed and layout of appliances in the living room.

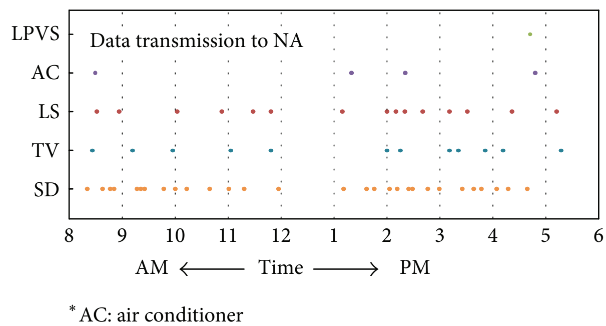


Figure 13: Experimental results; (a) the time to transmit the monitored energy information to the NA and (b) the frequency of data transmission per hour.

this ESD transmits the stored energy information to the NA; then the NA transmits it to the CMS. The smart phones of five occupants are used as the NAs.

Figure 13 shows the experimental results. Figure 13 shows the time to transmit the monitored energy information to the NA in each ESD. That is, the ESD that is connected to the appliance independently transmits the monitored information to the NA, when the NA comes into Bluetooth communication range. The number of data transmissions is different for each appliance, because the frequency of the occupant's access for each appliance is different, depending on where the appliance is installed. For example, we can see that the LPVS (i.e., installed outside the test bed) and the air conditioner (i.e., installed in a corner of the living room) sent almost no monitored energy information to the NA. Therefore, we proposed a dynamic HAN configuration scheme that considers occupant behavior patterns. If the proposed scheme is applied, an appliance that residents most frequently utilize becomes the head-appliance. The LPVS, air conditioner, TV, and lighting system periodically transmit the monitored information to the sound device, based on multihop routing protocol, and the transmitted information is stored in the database of the ESD of the sound device. When an NA comes into the Bluetooth communication range of the ESS of the sound device, the stored information is sent to the NA; then the NA sends the transmitted information to the CMS. In this way, all appliances installed in the living room

Table 2: An example of the prearranged schedules.

Time	Activity	Appliance/operating time
00:30–07:30	Sleep	Cellphone charger/7 h, air cleaner/7 h
07:30–08:00	Taking a bath	Bidet/1 m, hair dryer/10 m
08:00–09:30	Breakfast	Toaster/2 m, coffee pot/2 m, and microwave/2 m
09:30–12:30	Work	PC/3.5 h, monitor/3.5 h, speaker/1 h, shredder/2 m, and printer/5 m
12:30–13:30	Lunch	Electric cooker/30 m, electric fan/1 h, and microwave/2 m
13:30–15:00	Playing game	TV/1.5 h, game console/1.5 h, and electric fan/1.5 h
15:00–18:30	Work	PC/3.5 h, monitor/3.5 h, printer/5 m, laptop/30 m, and multifunction copier/5 m
18:30–20:00	Dinner	Electric cooker/30 m, juicer/5 m
20:00–21:30	TV watching	TV/1.5 h, set-top box/1.5 h
21:30–22:30	Taking a bath, laundry	Washing machine/1 h
22:30–00:30	TV watching	TV/1 h, set-top box/1 h

can transmit the monitored information to the CMS in the same period.

7.3. Energy Reduction. To verify the energy efficiency of the energy management service, the proposed HEMS was installed in a home test bed. The test bed consists of eight rooms, and each room consists of various home appliances and four LED lights. Furthermore, we deployed two ESDs in each room to measure the power consumption of appliances and control appliance.

The experiment was conducted for four weeks: the first and third week without the proposed HEMS and the second and fourth week with the proposed HEMS. In order to have identical experimental conditions, the residents in the home test bed performed on prearranged schedules during the experiment. There were seven different prearranged schedules, and seven residents conducted two-day experiment depending on their own prearranged schedules: one day without the proposed system and the other day with the proposed system. Table 2 shows an example of the prearranged schedules. During the prearranged schedule, users were able to move freely. However users had to use designated appliances for designated time.

Figure 14 shows the experimental result of energy reduction. Even though the amount of reduced power depended on the prearranged schedules, power consumption was reduced in the case of all prearranged schedules. The total power consumption of the appliances is reduced by 9.14–10.5% when applying the appliance control service using proposed HEMS.

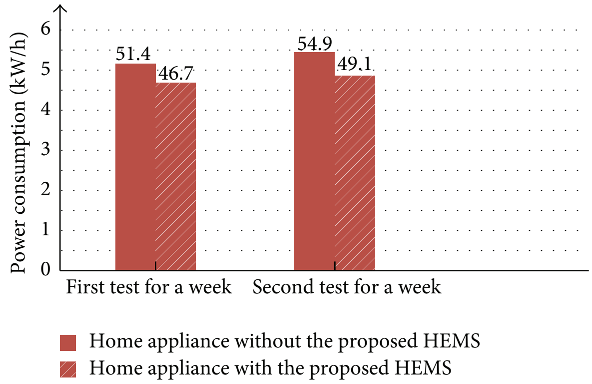


Figure 14: Experimental result of energy reduction.

8. Conclusions and Future Work

This paper proposed an IoT-based HEMS with lightweight PV system. Considering a new communication and network paradigm, the IoT, we presented the requirements of an IoT-based HEMS and designed and developed the HEMS by reflecting these requirements. We proposed DHANs that are autonomously constructed and reconfigured, by using a NA as a HAN GW. We presented the techniques for reducing the cost of the implementation of a HEMS with various perspectives on system, network, and middleware architecture. The proposed HEMS enables the construction of a HEMS to be more scalable, reusable, and interoperable. We implemented the proposed HEMS and performed an experiment to verify the performance and feasibility. We expect that this study will contribute to providing the guidance on the development of an IoT-based HEMS. As a future work, we will continue to research the technologies of context and situation awareness for energy management based on IoT. We will also carry out research on integration of social networking concepts into the IoT. In addition, we are developing the novel social IoT-based HEMS that reduces energy consumption through integration of social networking concepts.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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