Design and Implementation of a Smart Home Energy Management System with Hybrid Sensor Network in Smart Grid Environments

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***Abstract*— Green IT and smart grid technologies have changed electricity infrastructure more efficiently. Recent advances in wireless and mobile communications technologies facilitate context-aware power management systems which can offer situation-based services in digital home. In this paper, we propose a novel smart home energy management system (SHEMS) with hybrid sensor networks. Hybrid sensor networks consist of two types of sensors: the power information monitoring sensor (PIMS) and the environment information monitoring sensor (EIMS). To maximize the hybrid sensor network lifetime, we propose a new routing protocol based on cooperation between PIMS and EIMS, which we named the CPER. In order to verify the efficiency of our system, we implemented our system in real test bed and conducted some experiments. The results show that the reduction in service response time, the average number of packet transmissions, and energy consumption is approximately 29.8%, 42.3 and 17-22%.**

Keywords- home energy management system; smart Grid; wireless sensor networks (WSNs); pattern-based control, hybrid sensor networks

I. INTRODUCTION

Environmental problems, such as climate change or the exhaustion of natural resources are the one of the most important issues around the world in recent years. These problems are mainly because of the excessive use of energy. To deal with these problems, recently, smart grid technology is emerging and a lot of related works have been done by various researchers and scientists around the world.

Smart grid [1] is defined as a next generation power network that delivers electricity from suppliers to consumers based on two-way communications. This makes it possible for the suppliers and consumers to dynamically respond to changes in energy consumption, demand and grid condition, which improves grid reliability and energy efficiency.

As a part of the smart grid, the micro grid is a low voltage network that interlinks with small distributed power systems. The micro grid provides an independent power grid that interconnects the renewable energy plants with the power storage systems, such as load systems that govern device control in apartments and other dwellings. To enhance the function of micro grids, both energy management systems (EMS) and distributed automation systems (DAS) are needed.

The smart grid [2] designs a smart place which is defined as the energy-efficient place that provides the power-aware and user-centric services according to demand-response (DR) based on an advanced metering infrastructure (AMI) between the users and the power provider. The AMI is the infrastructure which monitors the digital meters, delivers the power consumption information, and controls the various devices. This infrastructure provides the cost and status of the power consumption to the users. The AMI offers an accurate demand forecast to the providers for load management and the revenue protection.

As renewable energy generation and storage systems increase, the power system should manage the demand-response and the power consumption load-balancing with the power storage device. These power systems merge the power provided from the power provider and the power generating from the renewable energy source. The different frequency and voltage are important issue when integrating renewable energy systems into the conventional power networks. Research on distribution and transmission considering integration of the renewable energy system is needed.

Recent studies of energy-aware systems focus on energy monitoring system [3], [4] and energy-savvy device design [5]. Energy monitoring systems [6], [7] allow inhabitants to see energy consumption and control electronic devices to minimize the power consumption of individual appliances. Such systems typically do not consider situation analysis or user satisfaction. Most studies of energy-savvy device design aim to decrease standby power consumption only for specific devices.

To enhance the scalability and effectiveness of power management, existing home network systems and energy-aware systems [3] should consider additional fundamental factors as follows:

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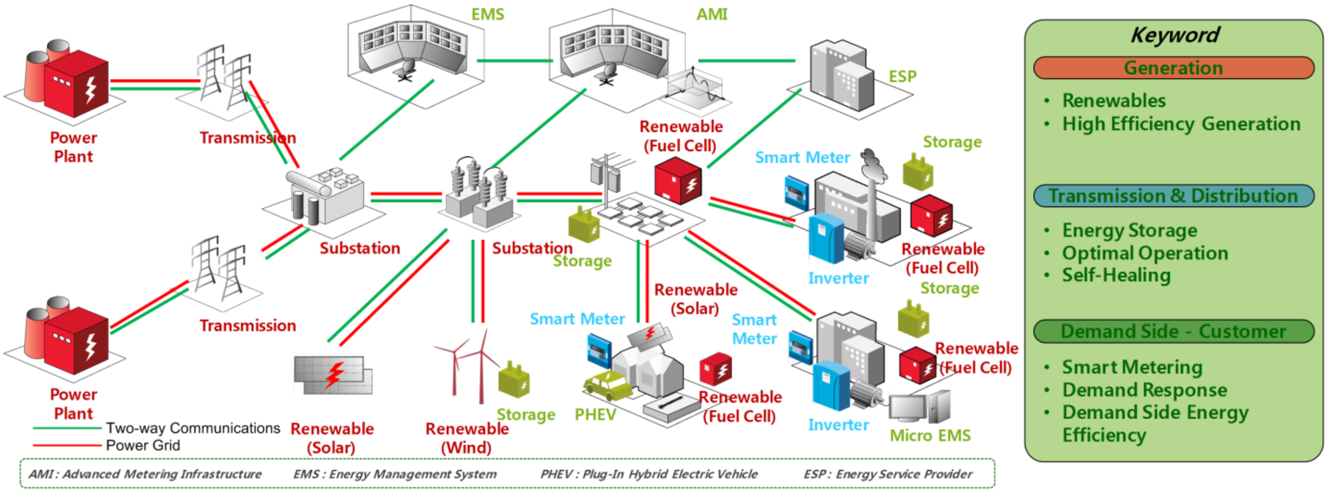

Figure 1. Concept of a smart grid (architecture and keyword)

1) *A deployment of wireless and mobile sensor-dependent environments*: To guarantee QoS and reason adaptive services, existing systems deploy a large number of sensors and then analyze the associated context. For example, crime and disaster prevention services depend on the continuous detection of sensor data. These services do not provide effective power consumption, and do not consider system resources or battery lifetimes, but they do guarantee high-quality service.

2) *The centralized or device-specific scheme*: To analyze contexts and provide service, existing systems use centralized server schemes or service-specific device schemes. However, centralized schemes require increased numbers of sensors to enhance the services that they provide. Moreover, to balancing the demands on system resources this scheme levels the QoS down according to the statuses of devices and sensors. Service-specific devices, which may deliver either static and predefined services are difficult to scale while maintaining appropriate responses to situational changes, such as environmental changes, interruptions, events, movements, or conflicts.

3) *The static rule-based inference*: Existing systems determine the services that they control according to predefined thresholds or on/off schedules. These systems have static policies and service rules with regard to the predefined event analysis and the service determination. Furthermore, due to the high dependency of the device intelligence, the previous systems are less efficient at device control and power consumption in situation management.

Therefore, an energy-efficient system needs to provide effectiveness in power management and user satisfaction for implementing the smart grid. Furthermore, such system must interconnect with intelligent devices, systems, networks, and service provider (SP) by network and information convergence.

Recent work on the smart grid focuses on the load management with AMI and wireless communications infrastructure. The smart grid only collects and monitors the energy status from a home without the consideration of the service management and the power consumption efficiency. Therefore, a power-aware home network system needs to interconnect with the smart grid and manage the energy-efficient services based on the demand-response for implementing the fine grid. Furthermore, the system has to cooperate with the AMI and the renewable storage for the reusability of the smart grid infrastructure.

Considering these requirements of the next generation power grid, we have designed a smart home energy management system (SHEMS). Our system is composed of a smart energy management gateway (SEMG), a smart energy management server (SEMS), and hybrid sensor networks. Our system automatically collects the sensed environmental information and efficiently controls the various consumer devices based on hybrid sensor networks.

II. Smart Grid's Background

A. Network Architecture of Smart Grid

Smart grid basically has the capability to sense power grid conditions, measure power consumption, and control devices with two-way communications. Smart grid makes it possible for the both SP and consumer to dynamically respond to changes in energy consumption, demand and grid condition. Furthermore, reliable and secure access to facilities is crucially important to the success of smart grid. Smart grid is typically composed of three network segments: home/building area networks (H/BANs), AMI or field area networks (FANs), and wide area networks (WANs). Smart grid consists of four parts, which are an electricity generation, transmission, distribution and consumer part (see fig. 1). Smart grid considers improvements in efficiency of all parts (i.e. from a generation part to a consumer part).

The generation part consists of various power plants such as a fossil fuelled power plant, nuclear power plant, hydroelectricity plant, and renewable power plant. Safety and reliability are most important factors in a generation part of smart grid. In smart grid, information about the

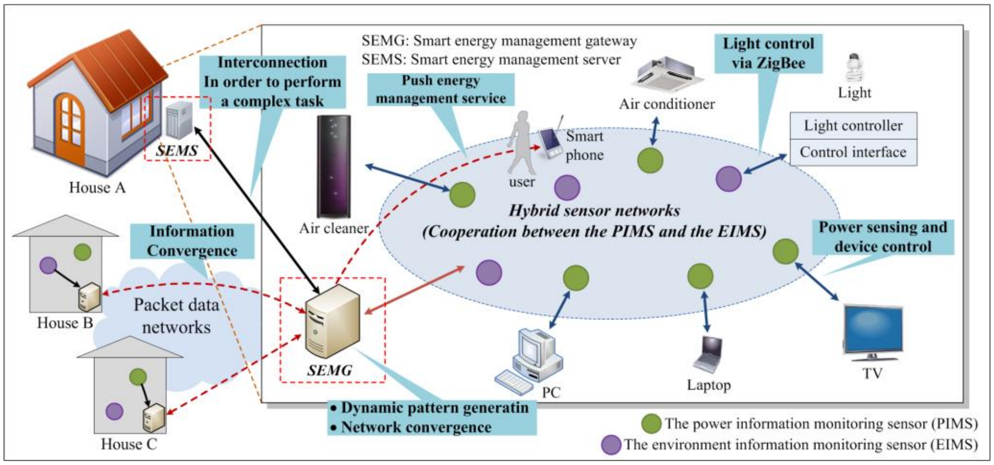

Figure. 2. Overview of the smart home energy management system

condition of the plant and environment is transmitted to administrators via IT infrastructure, thereby making the power plants more safe and reliable. Furthermore, smart grid is able to synchronize and adjust the voltage output of the added generation without damaging the whole system.

The transmission and distribution part play a role in optimizing the electricity transmission and distribution. That is, the loss and cost during transmission and distribution have to be minimizedm Alternating current (AC) is typically preferred since its voltage easily amplifies by a transformer, which minimizes resistive loss in the conductors used to transmit electricity over long distances. Recently, high-voltage direct current (HVDC) is used to deliver electricity due to the advantage of which is to transmit large amounts of electricity over long distances with lower costs and losses. In addition, key technologies enabling transmission and distribution part deployment are distribution automation system (DAS), supervisory control and data acquisition (SCADA), robust faulty detection, self-healing, and so on.

The consumer part is an end user (or consumer) of electricity and consists of many types of consumers such as home, building, and industry. Main role of this part is to gather and transmit various contexts such as power consumption or state of power system. Furthermore, this part manages electric vehicle (EV) charging and local renewable energy sources. In addition, because the smart grid's goal is enhancement of energy efficiency through response to many conditions in supply and demand, the smart meters are deployed to gather various contexts which are applied to calculate the supply and demand.

B. Communication Standardization for Smart Grid

There are some short and medium range wireless communications technologies emerged in the field of smart grid.

1) *IEEE 802.11 (WiFi)*: The IEEE 802.11 protocol is a set of standards for implementing a wireless local area network (WLAN), which is suited for high-data-rate applications over large areas. The IEEE 802.11 standard, commonly referred to as WiFi, is the most accepted technology for indoor wireless communications. The basic shortcoming of this standard is the high power requirement of devices.

2) *IEEE 802.15.1 (Bluetooth)*: IEEE 802.15.1 standard, commonly referred to as Bluetooth, is an open wireless technology standard for transmitting and receiving data over small areas. Bluetooth utilizes short wavelength radio transmissions in the ISM band from 2400 to 2480 MHz, creating personal area networks (PANs) with high levels of security. The Bluetooth protocol is well suited for low-power/low-data-rate applications. The main shortcoming of this standard is scalability. That is, Bluetooth networks support up to only eight devices. Another shortcoming is its periodical waking up and synchronization with the master device of Bluetooth networks.

3) *IEEE 802.15.3 (UWB)*: IEEE 802.15.3 is a MAC and PHY standard for high-rate WPANs. There are two major types of application that uses UWB communication. The first type of application is for high-data-rate (over 1 Mb/s) communications such as multimedia content transmission. The other type of application is for low-data-rate (below 1 Mb/s) such as wireless sensor networks. The main shortcoming of this technology is similar to that of WiFi. That is, the high power requirement.

4) IEEE 802.15.4 (ZigBee): ZigBee is a standard which is employed in many home networking solutions because ZigBee has a low-power and low-cost characteristics. The ZigBee provides various network topologies such as a cluster tree, self-healing mesh network, or star topology, according to application's requirements. In this way, the fixed and mobile devices can be configured flexibly. In addition, a ZigBee device using carrier sense multiple access with collision avoidance (CSMA/CA) does not require scheduling special wake-up events in order to communicate and maintain synchronization. Thus, ZigBee presents itself as a much better candidate (for wireless communication in the HAN) than UWB, WiFi, and Bluetooth [8].

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III. SYSTEM ARCHITECTURE

A. Overview of SHEMS

In this section, we present the overall system architecture of SHEMS. Fig. 2 shows an overview of the proposed smart building energy management system. The proposed system consists of hybrid sensor networks (the power information monitoring sensor + the environment information monitoring sensor), the smart energy management gateway (SEMG), and the smart energy management server (SEMS). We present our system in more detail below:

- The Hybrid Sensor Networks: To establish the proposed hybrid sensor networks, we utilize an intelligent sensor that is used for sensing the context as well as controlling the device according to rules or policies. For example, the environmental information monitoring sensor (EIMS) basically plays a role of information (e.g. the temperature, the humidity, the intensity of illumination, etc.) sensing and transmission to SEMG. However, it also directly controls a TV, a fan, and a light. In addition, the hybrid sensor networks consist of the two types of sensors: the power information monitoring sensor (PIMS) and EIMS. These sensors operate based on the proposed routing algorithm, the CPER.
- SEMG: SEMG can efficiently distribute various tasks related to the energy management service based on the hybrid sensor networks. It also interoperates with various mobile devices, such as smart phone, PDA, notebook PC using IEEE 802.15.4 (ZigBee), IEEE 802.11 (WLAN) technology.
- SEMS: SEMS performs complex tasks, such as load forecasting, user and device authentication /authorization, complex events analysis, etc. SEMS also manages the whole building energy and environmental information, user and device profiles. In addition, it performs a task of interconnection with other SEMSs.

B. Hybrid Sensor Network

In this subsection, we address the hybrid sensor networks architecture used for the proposed home energy management system. Our hybrid sensor networks consist of many smart sensor nodes. They can perform several tasks, such as gathering real-time energy consumption and building environmental information as well as controlling the various consumer devices. The proposed hybrid sensor networks are divided into two groups: PIMS group and EIMS group.

1) *PIMS*: This is mainly used for gathering the power consumption and the power state of the consumer device directly connected to PIMS. It is also used to directly control the consumer device. It has ZigBee and power line (PL) based communication capability in order to automatically establish sensor networks. The information about the power consumption and the power state collected by PIMS is transmitted to the SEMG. The SEMG analyzes this information and then generates a power consumption pattern. If an energy management operation is needed, the SEMG sends the control signal to PIMS in order to control and manage the consumer device. PIMS broadcasts its sensor identifier (SID) periodically once it enters the local hybrid network, so that the SEMG can recognize PIMS.

2) *EIMS*: This sensor monitors the environmental information, such as the temperature, the humidity, the gas (LPG and LNG), carbon monoxide (CO), the intensity of the illumination, the user's movement, etc. This sensor also generates a device control signal and directly transmits it to PIMS in order to control the consumer device. Like PIMS, EIMS has ZigBee-based communication capability in order to establish wireless sensor networks.

3) *CPER - Cooperation between the PIMS and EIMS based Routing protocol*

The main goal of the CPER protocol is to increase the lifetime of the hybrid sensor networks through the cooperation of the two types of sensors (PIMS and EIMS). The important difference between the two types of sensors is that one operates using the electrical power from the power socket directly and the other operates using that from a finite battery. We utilize these properties to route a packet from the source to the destination.

A number of existing wireless sensor network routing protocols, such as the ones found in [9] and in [10], do not consider an adaptive allocation of the system resources and the user-centric service aspects; they are not adequate in ubiquitous environments where novel services are provided for various users. Therefore, we propose a new routing protocol that is cooperative method between PIMS and EIMS, which is called CPER. We design our routing protocol suitable for home energy management services. The proposed protocol establishes the wired and the wireless sensor networks, based on cooperation between the two types of sensors in order to maximize the network lifetime. The protocol utilizes difference between the two types of sensors as mentioned above. The CPER protocol works as follows:

* Clustering: The SEMG determines a cluster-head depending on the node's power supply types. That is, the SEMG initially elects a node with a direct power source as a cluster-head. In the case of a node with battery-powered node, the SEMG applies the simplified LEACH [11] -based protocol to the cluster-head selection.

* Route discovery: (1) (default) If the source should discover a route to the destination, it broadcasts a route request packet (ROUTE_REQ) to its neighbors. If a node receiving a ROUTE_REQ does not know a route to the destination, the node inserts its own address into route tracking field of the packet and transmits a modified packet to its neighbors. In this way, paths are tracked. A typical problem for many ad hoc routing protocols is the needless packet flooding. To avoid the unnecessary packet flooding (e.g., endless packet circulation), each node only forward packets it has not yet seen. In addition, a ROUTE_REQ carries a form of expiration information, such as maximum number of hops in order to avoid unnecessary packet transmission. When receiving ROUTE_REQs that have different route, it selects a ROUTE_REQ with the minimum-

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Figure. 3. Prototype of the EIMS and the PIMS

hop path and sends a route reply a packet (ROUTE_RE) to the source node. (2) (cooperation with PIMS) If a node receiving a ROUTE_REQ has PIMS as its neighbor; does not know a route to the destination, it adds its own address to the packet and transmits (unicast) the ROUTE_REQ to PIMS. Long-distance transmission causes the significant energy consumption due to the attenuation characteristics of radio-frequency (RF) signals. Therefore, we use the battery-operated EIMS for short-distance transmission and use PIMS for relatively long-distance transmission. In addition, because PIMS also have the wired communication (i.e., PLC) capability, this makes the service response time faster.

* Data forwarding: Considering the requirements of network architecture for a home energy management service, we use the next-hop routing scheme. This approach supports some level of fault tolerance and makes our system more robust and resilient to node mobility.

4) *Implementation*: The hybrid sensor networks consist of two types of sensors: PIMS and EIMS (see fig 3). We designed each sensor node with sensing, controlling and networking abilities. Each sensor node automatically establishes the hybrid sensor network using proposed scheme and protocol. We designed PIMS using the 8-bit microprocessor, and a ZigBee transceiver for communication with other sensors and the SEMG. We use the ZigBee technology due to its low-cost and low-power characteristics [12]. PIMS also has a power line communication (PLC) module to communicate with the SEMG and other PIMSs. A wireless link has many advantages, such as high scalability and easy deployment compared with a wired link. However, since a wireless link also has a number of drawbacks, such as decreasing signal strength, frequent signal collision, and

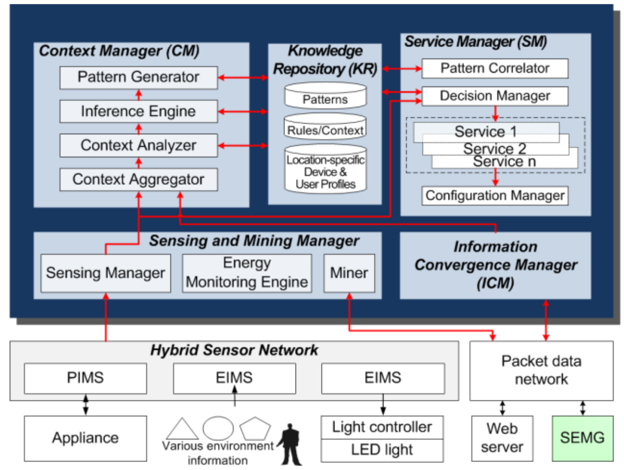


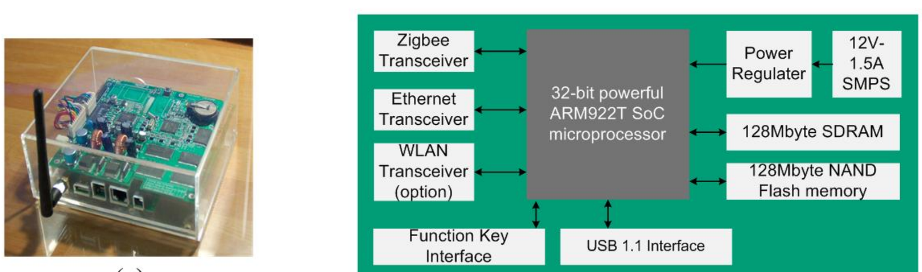
Figure 4. Middleware architecture of SEMG

fading, our system balances between the wireless link and the wired link. EIMS is equipped with a low power 8-bit microprocessor and a ZigBee module for communication with other sensors and the SEMG, much like PIMS. EIMS analyzes the user's situation and surroundings and operates the rule-based engine through the main processor group composed of the low-power 8-bit microprocessor and memory. EIMS has various sensor modules, such as temperature, humidity, gas detection (LPG, LNG, CO), Carbon dioxide, and object detection.

C. *Architecture of SEMG*

1) *Middleware Architecture*: Fig. 4 shows middleware architecture of the SEMG. It consists of various components. We will present the core modules in more detail.

- *Context Manager*: It gathers the sensor data and categorizes the situational events for the classification and storage to *Knowledge Repository*. This module assorts the meaning events that their values have the effects of the service status or the conflict situation. It transmits the meaning events to Inference Engine and requests the pattern verification to *Pattern Correlator*.
- *Inference Engine*: In order to reasoning and predicting the adaptive service, this module validates



(a) (b)

Figure 5. (a) Prototype and (b) hardware blockdiabram of the SEMG

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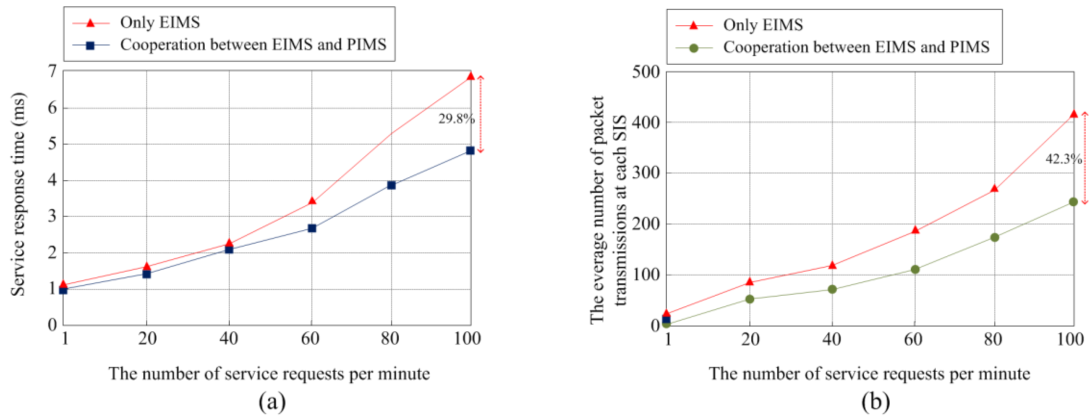

Figure. 6. Comparison of (a) the service response time, and (b) the everage number of packet transmissions at each EIMS

the correlation the events with the service pattern and analyzes the contexts receiving form *Knowledge Repository*. It decides whether or not to maintain the service and conflict solution to *Service Manager* with the pattern and policy.

- *Service Manager*: This module monitors the service status and maintains the personalized service. Moreover, this is used to determine the transmission of the service status according to the domain interconnection and correlation policy.
- *Configuration Manager*: For the convergence and the interconnection, this module manages the heterogeneous contexts which consist of the status of intelligent device, the system, and the network in a scalable fashion. When the environmental elements change in various situations, this module transmits the control signal that reconfigures the address and status.
- *Energy Monitoring Engine*: This module monitors the total and moment power consumption. Thus, this analyzes the pattern of consumption and verifies the correlation with service. When the power status suddenly changes or made up the novel pattern, this module interworking with *Inference Engine* actively organizes the differential service.
- *Pattern Correlator*: For the convergence of the network, the device, the service, and the system resource, this module generates the patterns and analyzes the correlations. In addition, this module influences the policy modification and the service prediction based on efficiency QoS requirements.

2) *Implementation*: Fig. 5 shows the prototype and hardware block diagram of SEMG. The main processor is based on 32-bit powerful ARM922T SoC (System on Chip) microprocessor. It is used for analyzing the complex events, operating the middleware, and processing the pattern generation. It also controls PIMS and EIMS. The communication group consists of a ZigBee transceiver, and Ethernet and WLAN modems. We used a 250kbps/2.4GHz ZigBee transceiver and 10/100Mbyte Ethernet modem for communication. A smart phone or a smart pad using IEEE 802.11 (WLAN) can receive the energy management service via a WLAN modem. The electricity monitoring group plays a part in monitoring the power consumption and the power state. Furthermore, when electricity leakage or overvoltage happens, the SEMG recognizes abnormal events and autonomously takes steps to counteract or alleviate these problems. The power group is composed of a SMPS and a power regulator.

We also implemented the SEMS to process various complex tasks (e.g. electric load forecasting, three-dimension (3D) simulation based on the energy management), a user and device authentication/authorization). There are various electric load forecasting methods and techniques, such as neural network based method [13] and time-series based model [14]. We adopted an ARIMA model, because in theory, it is the most typical model and possible to easy implementation.

IV. EXPERIMENT AND RESULT

Fig. 6 (a) shows the service response time by the number of information requests per minute. Even though the number of service requests increases, our system using CPER protocol maintains certain levels of delay of the request and response. Our system also gradually decreases the slope of the service response time according to a new routing

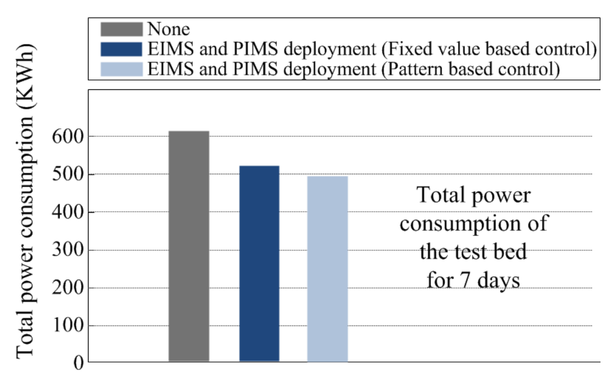

Figure 7. total power consumption of the test bed

protocol based on cooperation between PIMS and EIMS, whereas not cooperating with PIMS when routing rapidly increases the service response time due to the frequent packet collision and packet loss. The results show that the service response time reduction using our system is approximately 29.8% under conditions for generating 100 service requests per minute. Fig. 6 (b) presents the average number of packet transmissions at each EIMS by the number of information requests per minute. Similar to the result shown in Fig. 6 (a), proposed system using CPER protocol gradually decreases the slope of the average number of packet transmissions at each EIMS. The results show that the reduction of the every number of packet transmissions using our system is approximately 42.3% under conditions for generating 100 service requests per minute. Because the battery power consumption at a sensor node is proportionate to the number of packet transmissions, we can increase the network lifetime through our hybrid sensor networks. Fig. 7 illustrates the results of total power consumption for 7 days. The results show that the power saving using our system is approximately 17-22% by utilizing our energy management services, such as light control by using sensing data from EIMS, shutting up the standby power, the remote power control using a smart phone, etc.

V. CONCLUSION

Green IT technology is emerging and many related works have been done by various researchers around the world. In this paper, we propose a smart home energy management system (SHEMS) architecture based on hybrid sensor networks to make consumer devices more energy efficient and intelligent. We also present a new routing protocol to increase the hybrid sensor networks lifetime. We named this routing protocol the CPER, whose basic idea is in cooperation between the power information monitoring sensor (PIMS) and the environment information monitoring sensor (EIMS). We implemented our system, and we design and develop related hardware and software. We expect that our work will contribute to the development of novel home energy management system. In order to verify the efficiency of our system, we implemented our system in real test bed and conducted some experiments. The results show that the reduction in service response time, the average number of packet transmissions, and energy consumption is approximately 29.8%, 42.3 and 17-22%.

As a part of our future works, we are doing research into novel context awareness technologies and trying to apply them into an energy management system. Furthermore, we are developing a self-organized energy management system for various environments.

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