Energy Monitoring System using Sensor Networks in Residential Houses

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***Abstract*—The energy consumption of consumer electronics has been increasing over the past half century. Due to the growing importance of energy saving, many researches about the energy savings of information and communication technology have been presented. Providing residents with information on their energy use has become a feasible option to promote energy savings in the residential sector. In this paper, a home energy management system, particularly an energy monitoring system using sensor networks, is described. The authors designed and developed a smart power strip sensor network and evaluated its accuracy and energy saving efficiency.**

***Keywords*-Home energy management system (HEMS), energy monitoring system, smart home, sensor networks.**

I. Introduction

The energy consumption of consumer electronics has been increasing over the past half century, mainly due to the increasing populations and economic development around the world. In order to meet the Kyoto Protocol, reducing the energy demand and CO_2 emission is very important. Particularly, in Japan, the 2011 Tohoku earthquake and tsunami severely damaged several electric generating stations and caused a lack of electric power. This disaster increased the requirements for energy saving not only in emergencies, but also in daily life.

A home energy management system (HEMS) incorporates sensors and home appliances in a residential house through a home network. Energy monitoring systems based on home networks have been evaluated as next-generation energy saving solutions. Actually several experiments on energy visualization systems revealed that the visualization of power consumption could reduce the entire energy consumption of residential areas by 10–30 % [1] [2] [3]. On the other hand, it is costly and difficult to introduce a HEMS in older houses and legacy home appliances.

We developed a HEMS, particularly an energy monitoring system. Our developed system requires no electric construction when introduced into old houses and legacy home appliances. This system aggregates the power consumption data through wireless communications so that users can avoid hard-wiring. Figure 1 shows an overview of the proposed system.

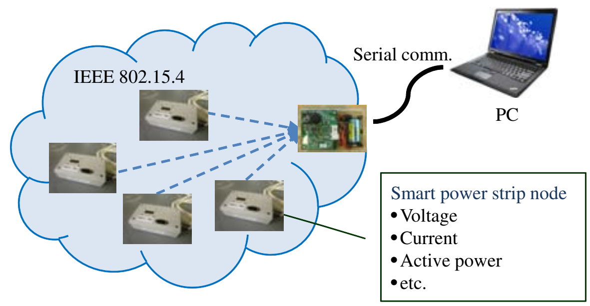

Figure 1. The overview of proposed system

The rest of this paper is organized as follows. Section 2 outlines the related issues. In Section 3, we describe the requirements and features of our proposed energy monitoring system in detail. Section 4 discusses the implementation of our developed system, and Section 5 shows the experimental results. Section 6 concludes the paper with a brief summary and mentions our future work.

II. Related Issues

As described in the introduction, various technical researches have been conducted. In an energy monitoring area, T. Ueno found that an energy saving of 10% was achieved using a monitoring system providing real-time energy information [1]. J. E. Petersen reported that an energy saving of 32% was achieved using a real-time visual feedback system [2]. In C. Fischer's research, an energy saving of 12% was achieved [3]. In an appliance control area, M. Nakamura presented home network systems that converge various appliances and sensors [4]. They incorporated heterogeneous networks and proposed various services, for example, an illumination control for entering or leaving a room, and a DVD theater system with several appliances. J. Han implemented automatic standby power cut-off outlets and reduced the standby powers of connected appliances [5]. Standby power saving is effective, but normal operation power saving is also important because home appliances and consumer electronics account for about 30% of home energy consumption [6]. Y. S. Son proposed a HEMS based on

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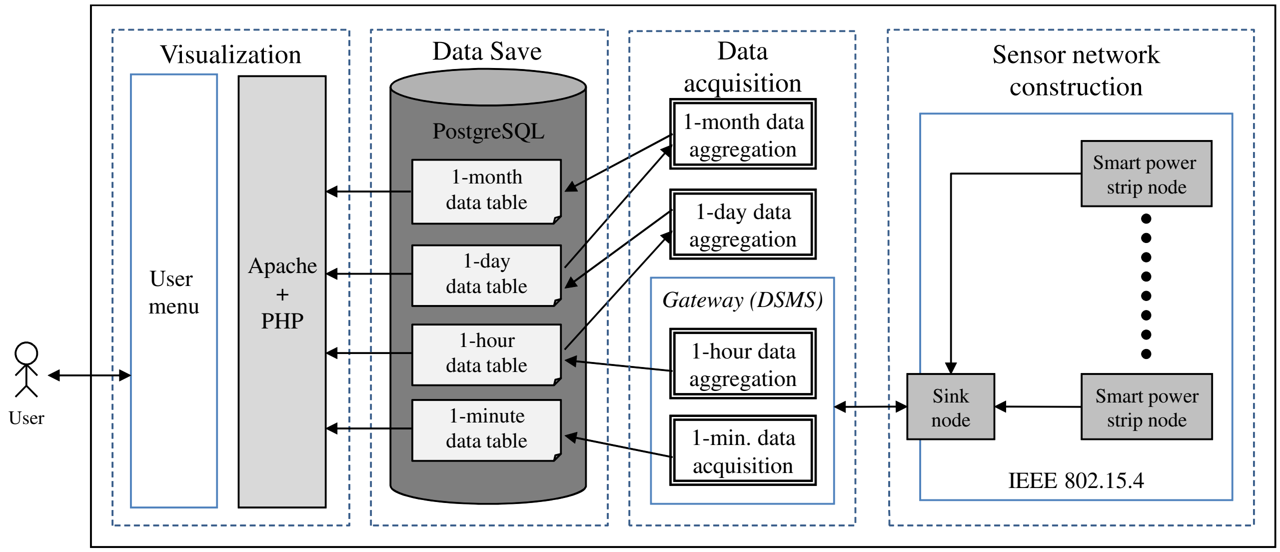


Figure 2. Architecture of proposed system

PLC [7]. Power lines are everywhere, and therefore, a PLC-based system is available to any house. However, when the availability of a PLC is high, the communication quality is affected by noise from the connected appliances. When a PLC-based system is used, it is very important to consider the quality of service.

These researches purpose only energy savings for home appliances and do not take into consideration the energy usage of the HEMS itself. In order to meet the necessary amount of energy savings for an entire house, the system operational cost must be taken account. If the system cost is greater than the saved cost, the introduced system is inefficient in respect to energy saving. In the following sections, we propose a HEMS implementation and discuss the system energy consumption itself.

III. Proposed system

A. System requirements

Our proposed system targets residential homes. The system aggregates the energy consumption data for home appliances and visualizes it into comprehensible forms. Visualizing the fine-grained data enables residents to understand the details of their energy consumption and use behavior. For example, if there is a digital signage that presents residents with the energy consumption for their own appliances, the residents would think more carefully about their daily energy usage and savings. Several requirements that achieve the goal described above are discussed below.

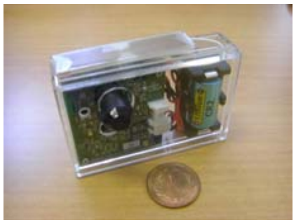
1) Specialized sensor nodes are used to monitor the energy consumption of appliances. The authors call them smart power strip nodes. A smart power strip node measures the energy consumption of the connected appliance and sends the measured data to a sink node. Fine-grained data are required to conduct a detailed analysis of the energy uses. In addition, a low power wireless communication technology is required to reduce the maintenance costs of these nodes.
2) The energy consumption of each electric appliance is monitored the smart power strip we developed. In order to help residents to better understand the details of their energy usage, the smart power strip nodes have to collect fine-grained data. The smart power strip nodes can measure the energy consumption for a connected appliance every second.
3) There must be many requests from the visualization component. In order to instantly respond to various requests, the data save component has to write the measured data to the DB in a proper form.
4) The visualization component shows the residents several charts of the saved data. There are four types of charts: column, pie, line, and integrated charts. These charts have to show not only the present values but also the past ones.

B. System architecture

Figure 2 shows the architecture of our proposed system. This system consists of the following four components.

1) Sensor network construction
2) Data acquisition
3) Data save
4) Visualization

The sensor network construction component includes the smart power strip nodes and a sink node. The smart power strip nodes measure the energy consumption for each connected appliance and send the data to the sink node through an IEEE 802.15.4 wireless communication. The sink node



(a) Sink node

(b) Smart power strip node

Figure 3. Developed nodes

receives the data from the smart power strip nodes and sends it to a gateway through an RS-232 serial communication.

The data acquisition and the data save components include a gateway and a Data Stream Management System (DSMS) that enables for real-time data processing at a low latency. The DSMS works on the gateway. The gateway sends the energy consumption data to the DSMS in a stream format. The DSMS processes the data and writes the results to a DB server.

The visualization component includes a web server and a DB server. The web server receives the data from the DB server and visualizes it. Residents can see the trend charts of the energy consumption on their web browsers.

IV. Prototype development

A. Sensor network construction

Our sensor network consists of two types of nodes: the sink node and the smart power strip node. Figure 3 shows our developed power-saving, small-sized IEEE 802.15.4 sensor nodes [8]. We used Renesas Technology Co.'s R8C as an MCU. These nodes can be operated by either CR2 batteries or an AC adapter.

In order to reduce the energy consumption of the proposed system itself, we have to save the energy used for wireless communications. IEEE 802.15.4 and Zigbee are known as low-power wireless communication protocols and several researches have used them [5] [9]. When considering the network flexibilities, IEEE 802.15.4 has more advantages than Zigbee. For example, many routing protocols for wireless sensor networks have been researched [10]. There are network coverage oriented protocols, energy saving oriented protocols, or other goal oriented ones. Zigbee has its own routing protocol, so we can't implement another protocol. On the other hand, IEEE 802.15.4 is only implemented under the MAC layer. Therefore, we can choose any desired protocol based on the given purpose and we can add network flexibilities to the system. Due to the requirement for energy saving and the network flexibilities described above, we chose IEEE 802.15.4 for our wireless communication protocol.

```
MASTER clock_1m
SELECT powerStrip.id, avg(powerStrip.power)
FROM   powerStrip[60000]
WHERE  powerStrip.id = target
```

Figure 4. Example of CQL

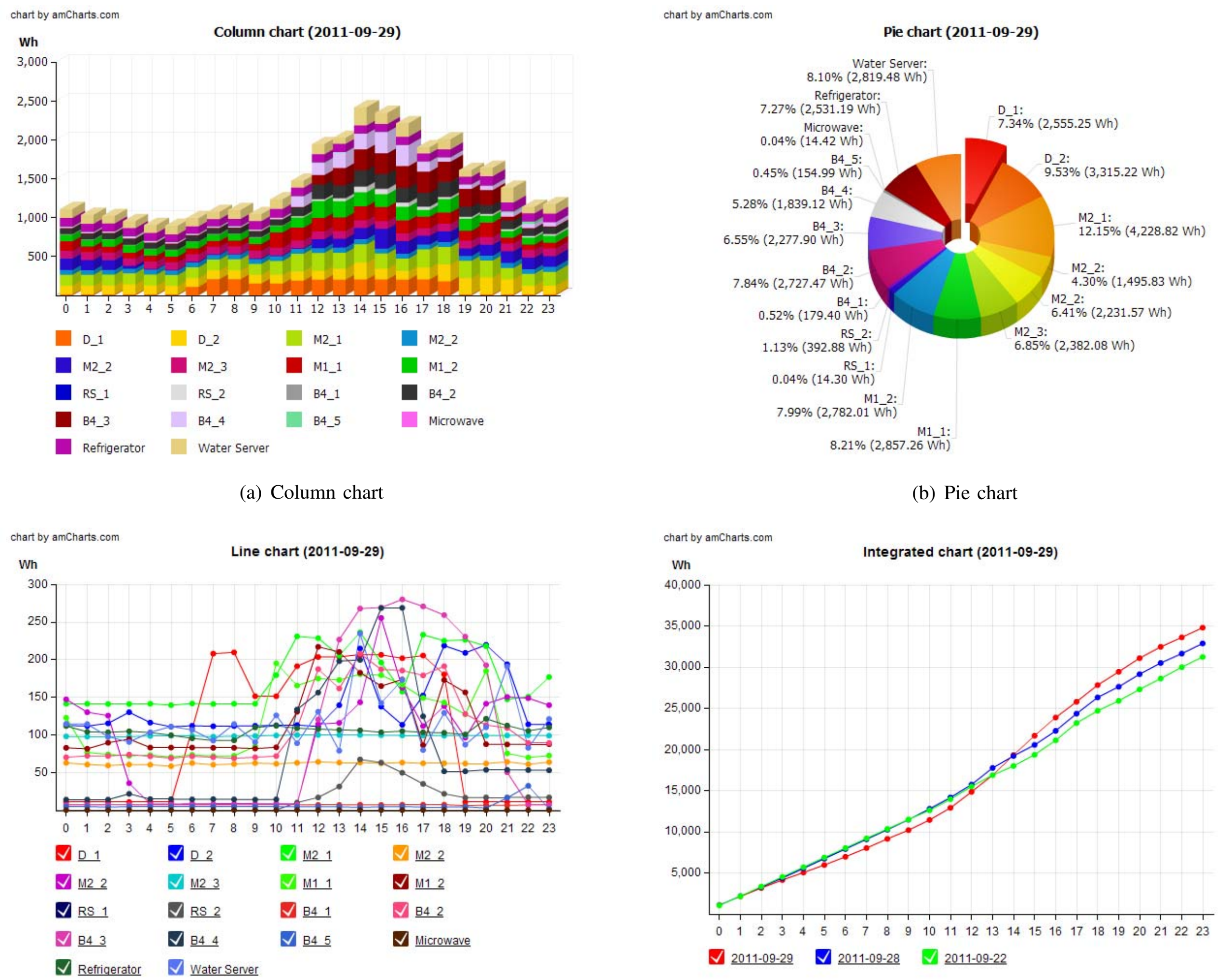
B. Data acquisition

The smart power strip nodes send the energy consumption data for a connected appliance every second. The sink node receives the data from all the smart power strip nodes and sends it to a gateway. The gateway sends the received data to a DSMS in a stream form. In the DSMS, the data processing is executed by a continuous query (CQ). CQ is one of the specialized functions of the DSMSs. When a user sends a query message (like an SQL), the CQ registers it to the system. After the registration, the CQ executes a registered query whenever the data arrives. This function enables real-time data processing.

We choose the StreamSpinner [11] as the DSMS for this system. The StreamSpinner has two main features: multiple query optimization and event driven continuous query execution. When there are multiple queries, the multiple query optimization function picks out the more common parts from the queries and executes them at one time. The multiple query optimization enables for the handling of huge queries. The event driven continuous query execution function sets the timing for the query execution. The StreamSpinner can query whenever new data arrives, or at fixed intervals, or a mixture of both. The event driven continuous query execution enables for an adaptable query execution. In the next subsection, the queries of the proposed system are described.

C. Data save

The DSMS executes the CQs to process and save the data to a DB (PostgreSQL). Figure 4 presents an example of the Continuous Query Language (CQL). A query description of StreamSpinner is like SQL. A timer control query is used in Fig. 4. The MASTER phrase sets the events and clock_1m fires every minute. Then "MASTER clock_1m" means that this CQ is executed every minute. The SELECT and WHERE phrases of the CQL are same as in SQL. The FROM phrase not only sets the data tables but also the interval. "[60000]" means that this CQ deals with the data from the past 60,000 ms. Therefore, Fig. 4 means that if a smart power strip node ID of the received data is a targeted ID, the DSMS averages the data in the past 60,000 ms and writes a result to the DB every minute. These data are called 1-minute data and the DB table that the 1-minute data are inserted into is called a 1-minute table. In a similar way to the 1-minute data, 1-hour data are created. In addition, 1-day data and 1-month data are calculated and inserted by



(a) Column chart

(b) Pie chart

(c) Line chart

(d) Integrated chart

Figure 5. Several trend chart samples

a crontab. These data are referred to by the visualization component.

D. Visualization

The visualization component shows the energy consumption trend charts. We developed several Web interfaces to convert the aggregated data into user-friendly formats, as shown in Fig. 5. This figure shows the sample trend charts in column, pie, line, and integrated formats with amCharts [12] that can display the graph in JavaScript and Flash. This component visualizes the data of the selected period: an hour, a day, a week, a month, and an year.

The volume of the data from the smart power strip nodes is large, so when all the data is downloaded for each case, the infrastructure between the Web server and the PostgreSQL server is overloaded. We designed the DB tables described last subsection to solve this problem. For example, if a selected period is an hour, the Web server requests only the 1-minute data from the DB server. Table I shows the relations between the selected period and the requested data. The Web server (PHP) requests information from the tables on the PostgreSQL database in accordance with the timestamp, and then the PostgreSQL sends it back to the PHP. The PHP makes an XML file from the PostgreSQL data and reads it using a drawing program.

Table I
SELECTED PERIOD AND CALLED DATA

Selected period	Requested data
Hour	1 minute
Day	1 hour
Week or month	1 day
Year	1 month

Table II
DIGITAL POWER METER WT-230

Measuring load	Voltage [V]	Current [mA]	Power consumption [W]	Power factor [%]
	95.6	883.5	84.5	100
Filament lamp	101.3	906.4	92.1	100
	110.4	949.4	104.9	100
Drier (cool)	103.8	326.4	32.8	97.1
Oscilloscope	104.6	146.0	9.29	60.6

Table III
SMART POWER STRIP NODE

Measuring load	Voltage [V]	Current [mA]	Power consumption [W]	Power factor [%]
	95.9	870.0	83.6	100
Filament lamp	101.9	899.2	91.6	100
	110.9	942.8	104.5	100
Drier (cool)	103.9	321.0	32.9	98.4
Oscilloscope	104.0	145.0	9.1	61.1

Table IV
ERROR RATE BETWEEN WT-230 AND SMART POWER STRIP NODE

Measuring load	Power error [%]	Voltage error [%]	Current error [%]
	-1.07	0.31	-1.53
Filament lamp	-0.54	0.59	-0.79
	-0.38	0.45	-0.70
Drier (cool)	0.30	0.10	-1.65
Oscilloscope	-2.05	-0.57	-0.68

V. EXPERIMENTAL RESULTS

A. Accuracy of our developed node

We measured the accuracy of our smart power strip node using a Yokogawa Electric Corp.'s digital power meter WT-230. The measuring loads are a filament lamp, a drier, and an oscilloscope. We measured the voltage, current, power consumption, and power factor. Tables II, III, and IV present the experimental results. First, the power error rates between WT-230 and our node are within $\pm 3\%$. Next, the voltage error rates are within $\pm 1\%$. The current error rates are within $\pm 2\%$. The accuracy of our node seems to be a non-factor based on these results.

B. Energy consumption of proposed system

Considering the energy saving efficiencies of the system, the energy consumption of the system itself had to be measured. If the system energy consumption exceeds the reduced energy, the proposed system is not effective in respect to energy saving. Our proposed system requires at least one sink node and one gateway. We implemented the gateway function, the DB server function, and the Web server function to a notebook computer Acer Aspire 3820-F54D/F. We connected the sink node to the gateway, and then we measured the power consumption of both of them. We also measured the power consumption of the smart power strip node. Table V lists the result.

Table V
ENERGY CONSUMPTION OF PROPOSED SYSTEM

Item	Power consumption [W]
Sink node & gateway	13.9
Smart power strip node	9.8

If there is one gateway and k smart power strip nodes, the power consumption of the system itself P_{system} is as follows.

$$P_{system} = P_{gateway} + \sum_{i=1}^{k} P_{node} \tag{1}$$

Next, if there are k home appliances connected to a smart power strip node and the energy saving efficiency rate of the system is R, the saved power consumption P_{save} is as follows.

$$P_{save} = R \cdot \sum_{i=1}^{k} P_{app_i} \tag{2}$$

Therefore, if a targeted residential house satisfies the next formula, the house can save energy due to introduction of our proposed system.

$$P_{system} < P_{save} \tag{3}$$

C. Discussion for energy saving node

When we take the energy saving for our developed node into consideration, the energy monitoring algorithm on the node must be improved. Algorithm 1 is a naive algorithm that works on our smart power strip node. The current smart power strip node measures the power consumption every 10 ms and averages the measured data and sends it to

Algorithm 1 Naive algorithm of smart power strip node

```
repeat
  if 1 ms past then
    timer = timer + 1
  end if
  if timer/10 = 0 then
    tmpValue = tmpValue + powerConsumption
    if timer = 1000 then
      avgValue = tmpValue/100
      send avgValue to sink
      tmpValue = 0
      timer = 0
    end if
  end if
until power-off
```

the sink node every second. These frequent measurements, calculations, and data sending improve the accuracy of the node. However these operations also increase the power consumption for the node. The power consumption and the measurement accuracy are trade-offs. Therefore, when we take the energy saving for the node into consideration, we have to search for an adapted frequency for the target applications.

VI. Conclusion

We proposed an energy monitoring system that uses sensor networks in residential homes. The configured system is composed of the smart power strip nodes, the sink node, the gateway, the DB server, and the Web server. The smart power strip nodes measure the energy consumptions for the connected home appliances. The sink node aggregates the energy consumption data from the smart power strip nodes. The gateway receives the data from the sink node then processes it and writes the calculated data to the DB. When the Web server is accessed, it gets the required data from the DB server and visualizes the trend charts from the received data.

The experimental results for our developed system showed that it is possible to measure high accuracy data and visualize it in user-friendly formats. We took into consideration the energy consumption of our proposed system because the system's operational cost is important in respect to the energy savings. If the operational cost of the system exceeded the saved costs, the system was ineffective. Finally, we discussed the energy savings of our developed nodes. There is a trade-off relation between the measurement accuracy and power consumption. We can save energy using our nodes to reduce the measurement frequency.

In our future work, we will introduce our system into residential homes and confirm the effectiveness of our system with respect to energy savings. In addition, we will improve the algorithm of the smart power strip node. We will also attempt to reduce the energy consumption of the node by maintaining its measurement accuracy.

Acknowledgment

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