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Power Monitoring and Control for Electric Home Appliances Based on Power Line Communication

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Abstract *– Home power consumption tends to grow in proportion to the increase in the number of large-sized electric home appliances. An embedded system without any new additional wiring has been developed for home power management. By using Power Line Communication (PLC) technology, electric home appliances can be controlled and monitored through domestic power lines. We describe a PPCOM (PLC Power-Controlled Outlet Module) which integrates the multiple AC power sockets, the power measuring module, the PLC module and a microcontroller into a power outlet to switch the power of the sockets on/off and to measure the power consumption of plugged-in electric home appliances. We have also designed an embedded home server which supports the Web page user interface, thus allowing the user to easily control and monitor the electric home appliances by means of the Internet. In addition, the field experiments reported have demonstrated that our design can be practically implemented and provides adequate results.*

Keywords *– Remote Measurement, Remote Control, Power Management, Power Line Communication.*

I. INTRODUCTION

Power monitoring and control through home networks is becoming important for electric home appliances. Together with the construction of access networks, several standards for wired home networks have been proposed and developed [1].

RS-232 hardware is an interface of easy design and in common use in today's industrial environment. However, RS-232 communications have some drawbacks in that floor environments often generate not only electrical noise but also transients that can cause errors in transmission and damage to the interface components. The other drawbacks of RS-232 are its point-to-point characteristic and a distance limitation of 15 m [2].

A typical IP-based device can remotely control power switches of electric home appliances. By using this device one can connect the Internet with an RJ45 and can be connected to any computer [3].

Radio frequency (RF) technology is more flexible and allows the user to link electric home appliances distributed throughout the house [4]. RF can be categorized as a narrow band or spread spectrum. Narrow band technology requires a clear channel uninterrupted by other digital appliances. Since each transmitter/receiver appliance transmits using its own frequency, it is unlikely to interfere with other RF appliances connected to the home network. However, if the wireless appliance is moved to another location in the house, it is possible that interference may occur. This limitation makes the use of this technology unsuitable for a number of home network applications [5].

Bluetooth technology provides a universal bridge to existing data networks, a peripheral interface and a mechanism to form small private ad hoc groupings of connected devices away from fixed network infrastructures. Designed to operate in a noisy radio frequency environment such as a home, the Bluetooth technology uses both a fast acknowledgement and a frequency-hopping scheme to make the link robust. Bluetooth technology, therefore, can replace the cumbersome cables used today to connect the PDA to any other digital device [6].

To implement home power management, both networked electric home appliances with control/monitoring capabilities and home networks without new wiring are indispensable [7]. Power line communication (PLC) is used to utilize a domestic power line as a communication cable. Home network devices are categorized as wired devices. The PLC provides high bit-rate data services by using the power grid residing in the vast infrastructure already in place for power distribution, which means that the potential effect of the service could be much higher than that of any other wire line alternative. Because PLC is a home network medium without any new additional wiring, it is easily installed in an existing residence [8]. In this paper we describe an embedded system using PLC technology which has been developed to remotely monitor/control the power of electric home appliances for home power management.

A home server is a hardware device connecting a home network with a wide area network (WAN) or the Internet. The residential gateway provides port translation (NAT), allowing all the computers in a small network to share the same IP address and Internet connection [9]. The home server sits between the modem and the internal network, or, as an alternate, a DSL or cable modem may be integrated into the home server. A home server often combines the functions of IP router, firewall, multi-port Ethernet switch and Wi-Fi access point. Home servers that include routing capabilities are converged devices and sometimes referred to as home routers or broadband routers with "broadband" in this case referring not to the router function but to the Internet access function. Home servers are under standardization by the Home Gateway Initiative [10].

Fig. 1 shows an overview of the embedded system which consists of three parts: the PPCOM (PLC Power-Controlled Outlet Module), the embedded home server and the remote control. For easy setup the entire hardware prototype of the PPCOM is now implemented in a box (18.5 cm × 15.5 cm × 3.8 cm). Any electric home appliance plugged into the socket of a PPCOM can be controlled and monitored without making any additional setting. The PLC and the asymmetric Digital Subscriber Line (ADSL) which has been selected for a wide area network have also been selected for the home network. By combining PLC and Ethernet technologies, PPCOM can connect to the embedded home server without any new additional wire lines.

The embedded home server connects to the Internet by means of the ADSL. Thus the user can manage electric home appliances and remotely monitor the power consumption status of the electric home appliances by means of the remote Web browser. The remote Web browser with a GUI allows the user to easily control/monitor the power status of electric home appliances.

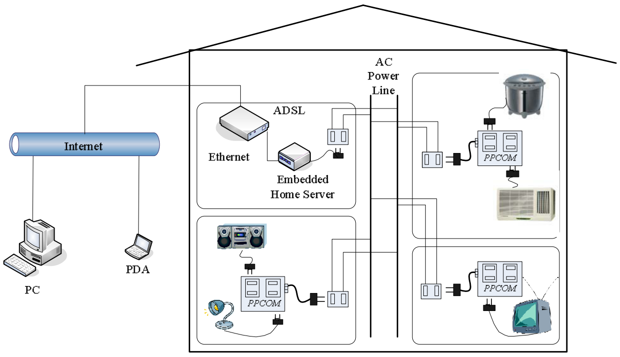


Fig. 1. The block diagram of the embedded system without any new additional wiring.

This paper is organized as follows. Section II introduces the PPCOM, Section III describes the embedded home server, Section 4 summarizes the evaluation results, and the final Section presents our conclusions.

II. PPCOM DESIGN

The PPCOM combines with the multiple AC power sockets. In the PPCOM a simple plug-in MCU performs the power on/off of the sockets and processes measured data. The PPCOM also includes a power measuring circuit to measure the power consumption of each electric home appliance. The circuit diagram of the PPCOM is shown in Fig. 2.

The PLC Module uses state-of-the-art CMOS design techniques to deliver the higher performance and flexibility. This highly integrated design combines the Media Access Control layer (MAC) and the Physical Layer (PHY) in a single chip. The PLC Module is a converter that connects electric home appliances to the Internet based on UDP protocol, thus allowing the user to control and monitor electric home appliances over the Internet.

We have used Solid State Relays (SSR) to switch each socket on/off for an electric home appliance. SSR have been used to replace mechanical relays because of their many advantages, including miniaturized configuration, elimination of contact bounce, low-energy consumption, decreased electrical noise and compatibility with digital circuit and high-speed switching performance. These SSR also provide isolation between a control circuit and a switched circuit.

To show the operational status of the electric home appliances, and to control the power on/off we use the Power Measuring Module, which is a measure circuit containing four parts: two current transformers (CT), an electrical power detector, a multiplexer and a power load microprocessor. The two CT are installed in the AC power outlet, as shown in Fig. 2. The load current of each socket is measured by the CT. By using the Hall Effect the charge carriers in the CT become deflected by the magnetic field and give rise to an electric field which is perpendicular to both the current and the magnetic field, as the load current changes the output voltage signal.

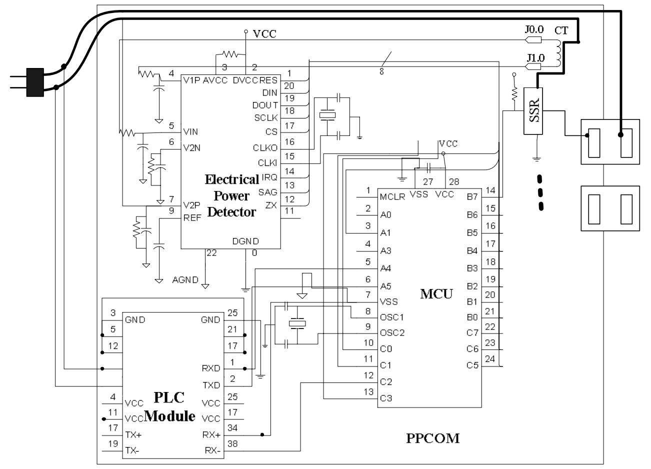


Fig. 2. Circuit diagram of the PPCOM.

The electrical power detector uses a high-accuracy electrical power measurement IC with a serial interface and a pulse output. The electrical power detector is comprised of two ADCs, a reference circuit and the signal processing necessary for the calculation of real (active) power. Circuitry is provided to null out various system errors including gain, phase and offset errors. Additional circuitry provides waveform sampling, programmable interrupts and power line monitoring [11].

The socket voltage is connected to the electrical power detector through the interface circuit which includes a filter. The socket current is converted from a current to a voltage by a CT. The electrical power multiplies the two voltage signals with the current signal and accumulates the results in the register. The electrical power detector measures the power consumption of each socket continuously.

The MCU is used to read the register of the electrical power detector cyclically through the communication port. Moreover, the MCU waits for the command from the embedded home server. If there are no control commands, the MCU stores the current power status. If the MCU has received a command, it checks to see whether or not the command is for the room controlled by the PPCOM. If the command is for that room, the MCU turns the power on/off or sends power data according to the command. If the command is not for any room controlled by the PPCOM, the command is broadcast over the PLC network. Fig. 3 shows the control flow chart of the PPCOM.

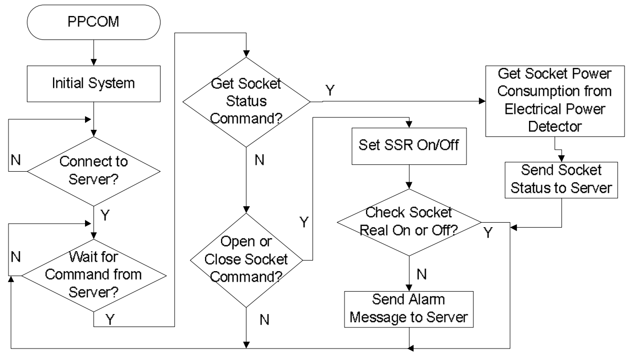


Fig. 3. The control flow chart of the PPCOM.

III. EMBEDDED HOME SERVER

The embedded home server is a centralized controller and human interface for an in-house system. It also provides a simple Web browser for information and guidance from the Internet. Application programs are used to control appliances in a house. Fig. 4 shows the block diagram of the embedded home server.

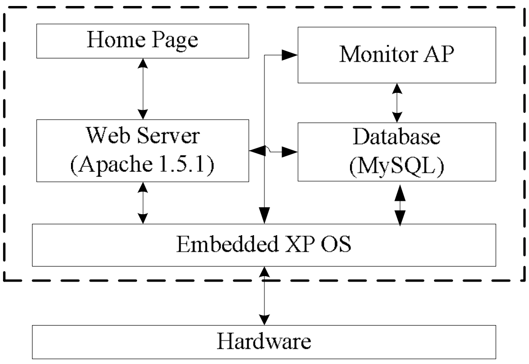


Fig. 4. Block diagram of the embedded home server.

Internet technologies such as TCP/IP, HTML, JavaScript, Web Server and Cipher Security are ported into the embedded home server which is controlled and monitored with HTML interface from both in-house and out-of-house via the Internet.

Property and status of appliances are expressed with their structure by HTML and JavaScript, whose description capability is excellent. Application service providers can monitor/control appliances remotely and can develop various application services for PPCOM with network access technique using HTML and JavaScript.

We have also designed a Monitor AP which supports the Graphic User Interface (GUI), so the user can easily configure the embedded home server status.

We built the Monitor AP to monitor the socket status and the power consumption. The user can use the columns of PPCOM numbers and socket numbers to select a specific power socket. Next, the IP of this PPCOM, the status of the power socket, watt consumption, voltage and current value will be shown. The on/off control of this power socket can be done directly, as shown in Fig. 5.

The user can use the columns of the PPCOM Number and the Socket Number to select a specific power socket. After this selection, the IP of this PPCOM, the status of power socket, the power consumption, the voltage and the current value will be shown; the on/off control of this power socket can be done directly.

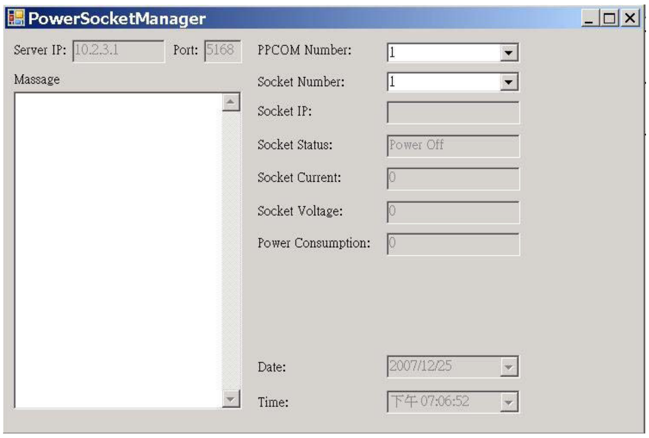


Fig. 5. Monitor AP.

We use the PLC to receive/transmit between the embedded home server and the PPCOM. The embedded home server offers an automatic system for power monitoring and control. It also collects information to produce an analysis of all power consumption including the daily, weekly and monthly electricity consumption of individual electric home appliances and the total consumption of the home. Fig. 6 shows the control flow chart of the embedded home server. If there are no control messages, the Web page displays the current power status. If the system has received a message, it checks the command format first. If the message is correct, the embedded home server sends the message to the PPCOM to turn the power on/off and waits for an "OK" message from the PPCOM. The embedded home server sends the most recent command message every three seconds until the embedded home server has received an "OK" message to guarantee that the PPCOM will work correctly. Our design also supports the Graphic User Interface (GUI) to let the user easily monitor and control the power on/off of each electric home appliance.

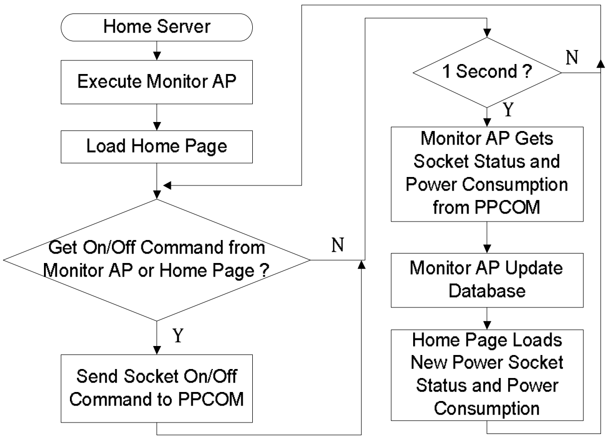


Fig. 6. The control flow chart of the embedded home server.

The Web browser is installed in a PC or a Notebook connected to the Internet. It can control electrical home appliances when the user is outdoors. The structure of the network connection of the remote control by Internet is a Host-Client structure. The client-installed Web browser sets IP address and PORT, sends a request to the PPCOM, creates a link and starts to link both client and PPCOM. The remote user can access a PPCOM from the Internet connection.

By means of the Internet the user can use a Web browser with a GUI to control and monitor the power consumption of the electric home appliances.

IV. IMPLEMENTATION RESULTS

The main goal is to be able to monitor and control the home power status anywhere whenever needed. In our design a web server is installed on the embedded home server to allow any device with a Web browser to connect to the embedded home server, typically, from outside the house. The remote control home page provides the user with a way when connected to the Internet to monitor and control the home power status by means of any Web browser.

The user can request the embedded home server to monitor and control the electric home appliances, as shown in Fig. 7. Our design provides three pages of home page for remote monitoring and control. The first page is the setup page, shown Fig. 7. This page lists the status of every power socket on the PPCOM connected to home server, namely on/off, power consumption, voltage and current value. This page can also control the on/off of each power socket, the setting of the time and the frequency of automatic on/off (once a week or once a day) and calculate the consumed power and fee for each power socket.

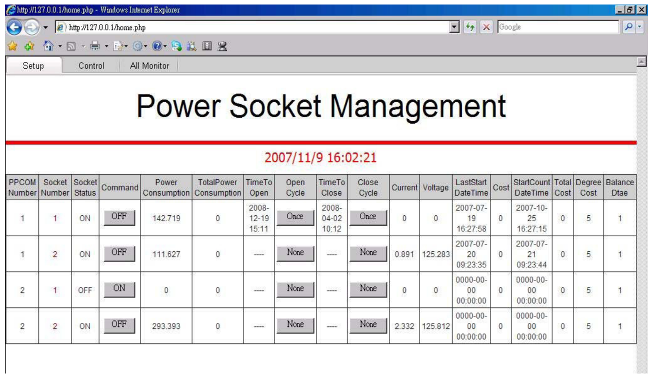


Fig. 7. Home Page for remote monitoring and control on home server.

The remote control home page displays not only the power consumption but also the real-time voltage and current of all PPCOMs connected to the embedded home server. The accumulated energy can be used to calculate the total cost starting from the launch time, as shown in Fig. 8.

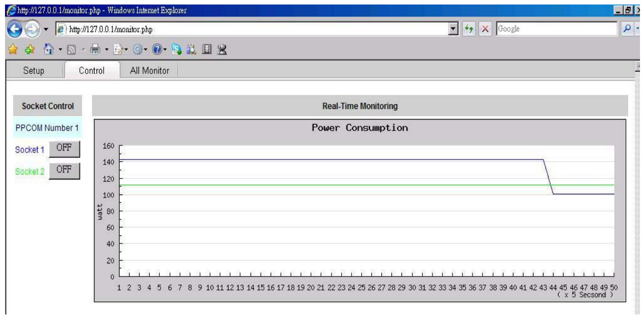


Fig. 8. User initiates requests to monitor and control electric home appliances by means of a Web browser.

The remote control home page supports up to 12 meters of real-time values. Each meter has the ability to display all PPCOM values. Selecting different items from the selection dialog area displays the selected item value, as shown in Fig. 9.

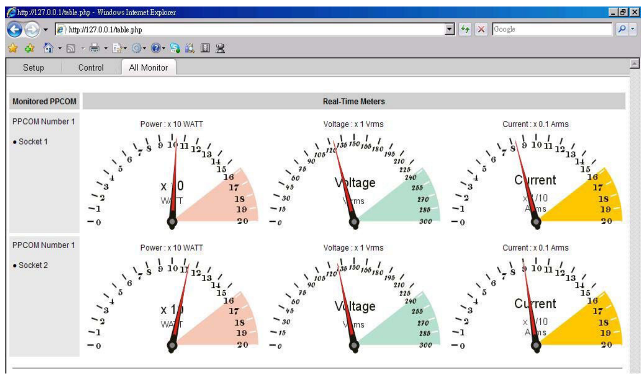


Fig. 9. Real-time monitoring of power consumption, voltage and current of all PPCOMs.

To validate their accuracy we have compared the results of our method with the meter measurement results. The electric home appliance used for the experiment was a 40" LCD TV with a full HD – 1,920 x 1080 pixels 16:9 screen format display resolution. The power of the LCD TV was measured by a power meter with both one week measurement intervals and a one-second resolution. Fig. 10 shows the measurement results obtained by use of our PPCOM and those obtained by use of a power meter. After conducting an experiment for one week, we found that there was an error of only about 8.2% between the estimated value and the measurement value.

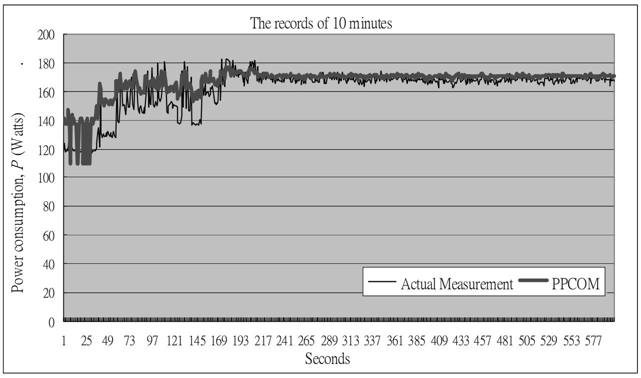
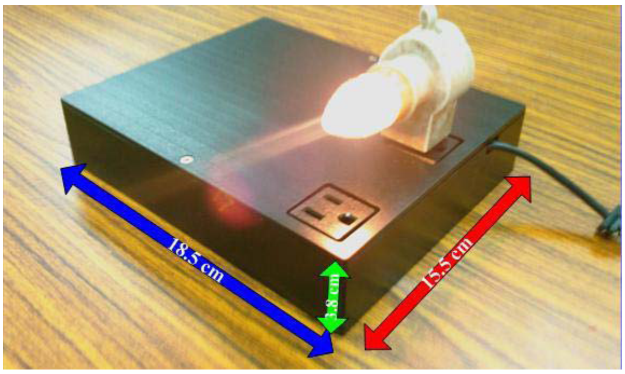


Fig. 10. Comparison of the measurements obtained by our system's design and by the power meter.

The final implementation of the PPCOM is shown in Fig. 11. The whole hardware prototype circuit of the PPCOM is now implemented on a 16.5 cm×12.5 cm printed circuit board (excluding the SSR and sockets).

In the prototype of our design the embedded home server was built with an embedded platform which had an 800-MHz Intel Processor, 512-MB RAM and a 60-GB hard disk. The embedded home server ran Microsoft Windows Embedded XP Service Pack 2 as its operating system and deployed the Apache 1.5.1 as its Web server which is designed by software using Visual C++ Studio [12].



(a)

(b)

Fig. 11. Outside (a) and inside (b) of the PPCOM

By using PLC the PPCOM enables the home network user to connect a wide range of electric home appliances easily, thereby eliminating the need of additional cabling to connect individual devices. The user needs only to follow three steps to finish installing the remote-controllable power outlet system indoors.

1. Replace the conventional outlet with a PPCOM to provide AC power for the electric home appliances.
2. Connect the embedded home server to the PPCOM by means of the PLC search.
3. Then the user can display and control the electric home appliance's power on/off by using the Web browser.

We also consider the power consumption of the PPCOM itself. Its average power consumption is measured as shown in Table 1. The point to observe is that the PLC Module and the electrical power detector consume maximal 22 mA and 24 mA separately while communicating. The total power consumption of a PPCOM is about 1 W and increases when the number of sockets of the PPCOM increases.

Table 1. Comparison of home power management designs.

Item	Average Current (mA)	Operation Voltage (V)	Average power Consumption (W)
PLC Module	22	12	0.264
Bluetooth Module	24	12	0.288
MCU and Essential Circuit	30	12	0.36
Total	66	12	0.912

An additional advantage of the Power Measuring Module is that it detects the status and measures the current consumption of an electric home appliance's power use in addition to controlling the on/off state of the sockets. In this experiment the Power Measuring Module detects and measures an electric home appliance's power consumption ranging from 1 W to 1200 W. We can extend the range to detect and measure lower and higher power consumption from 0.47 W to 2500 W by changing the CT which can increase its volume by half.

In addition we have compared our design with other home power management designs. The result of our experiment demonstrates that as our design has more integrated functions it is superior to other designs. The details of our comparison are shown in Table 2.

Table 2. Comparison of home power management designs.

	Method 1 [1]	Method 2 [2]	Method 3 [3]	Our design
Communica-tion	RF	PLC	Ethernet	PLC
Home server	X	PC	PC	Embedded home server
Server power consumption	X	156 Watts	156 Watts	17.3 Watts*
Length	10 m	Line	Line	Line
Setup	Compli-cated	Compli-cated	Easy	Easy
Scale out	Limited	Limited	Limited	Unlimited
Each socket controlling	X	X	X	Yes
Each socket monitoring	X	X	X	Yes
Total power monitoring	X	Yes	X	Yes
Remote control software	Local control	Specific software	Specific software	Web browser
Minimum power detection	X	About 5 Watts	About 5 Watts	About 0.1 Watt

*The power consumption can be reduced to below 1 Watt by including the embedded home server in the PPCOM.

V. CONCLUSION

By utilizing the PLC technique we have built an embedded remote electric power monitor/control system which is very easy to install and does not need additional wiring. This system enables the user to control the on/off and the power consumption remotely without bothering with extra wiring. Thus the system is very convenient and can be used at once after just plugging it in.

The embedded system and the key components for home power management have been developed, and in order to utilize remote control, the PLC technologies for power management have been integrated. The proposed PPCOM is designed for remote monitoring and controlling of different electric home appliances connected over a PLC network in a home environment. The embedded home server connects to the Internet by the ADSL. Thus the user can manage electric home appliances and remotely monitor their power consumption status by means of a remote Web browser.

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