Concurrent Simulation Platform for Energy-Aware Smart Metering Systems

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Abstract — *We propose a simulation framework that can model a house equipped with various home appliances and next-generation smart metering devices. This simulator can predict the power dissipation profiles of individual appliances as well as the cumulative energy consumption of the house in a realistic manner. We utilize SystemC, a concurrent system-modeling methodology originally developed and populated in the design automation community. According to our experiments with various consumer electronics devices, the simulated and measured power profiles match very closely, producing the average correlation of 0.973. The deviation of simulated energy consumption from the measurement was also negligible. Using the proposed simulation platform, any electricity consumer interested in energy saving as well as the designer of a new smart metering system will be able to simulate and test their system from energy perspectives. As a case study, we show how the size of the accumulative power peak of a house can be reduced significantly by using the information provided by the proposed simulator.*

Index Terms — Advanced metering infrastructure, home appliances, simulation, smart grid.

I. INTRODUCTION

To reduce carbon dioxide emission, the power generation methods that exploit renewable energy resources such as wind and sunlight have been gaining much attention. Unfortunately, controlling power generation from such renewable energy resources is often more difficult than managing conventional methods such as atomic or thermal power generation. Since we should not blindly generate more power than needed, it remains critical to have an effective means to predict future power usage, even in the era of renewable energy. To this end, many people expect that the Smart Grid system [1] will play a key role. Smart Grid is an emerging energy generation and management system that combines the traditional electricity supply infrastructure with information technology (IT) for enhancing energy utilization and reducing wasted resources. Technological, economic and social interests in Smart Grid are skyrocketing these days.

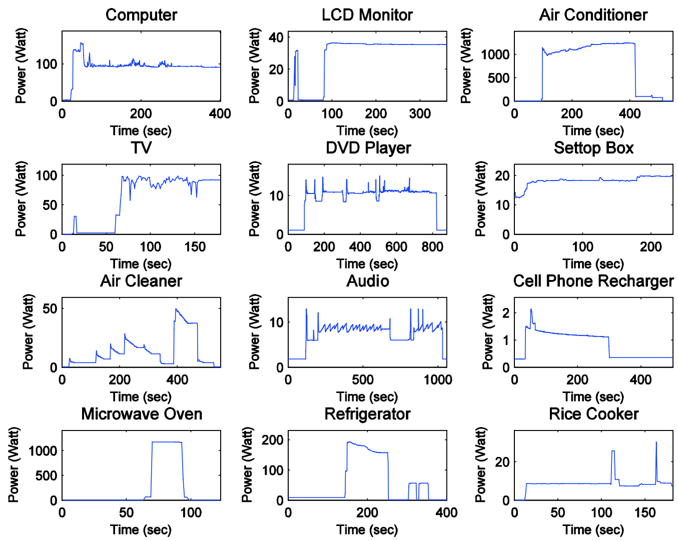

Fig. 1. The power dissipation patterns of typical home appliances.

The idea of Smart Grid can be applied to not only large-scale electrical power transmission infrastructures but also small-scale systems such as individual houses. Just as electricity suppliers continuously monitor and predict country-level energy requirements in order to prepare for future energy demands more effectively [2], we can improve the energy efficiency of a house by measuring and profiling the power consumption of individual appliances inside the house. We cannot manage what we cannot measure.

In this regard, a few online services have been introduced that can give information on house-level energy consumption. For instance, Google PowerMeter [3] can show the total power consumption of a house using a user-friendly web interface. Microsoft Hohm [4] is another web-based platform similar to PowerMeter. Although PowerMeter and Hohm are useful to a certain extent but are limited in that they can report only the total energy consumption of a house, without detailed power profiles of individual appliances inside the house. As shown in Fig. 1, the power dissipation profiles of appliances are diverse and complicated. Without monitoring individual appliances, it would be difficult to determine how to optimize the appliance usage for energy reduction, even if the user is informed of excessive total consumption.

To monitor the power consumption of individual appliances, it is needed to attach a metering device to each appliance. This has been traditionally possible by placing a wattmeter between

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an appliance and the power outlet that feeds the appliance. Recently, more advanced types of wattmeters have been introduced that are equipped with communication capabilities for automatic measurement and management. In this paper, we refer to this type of wattmeter as a *smart socket*. In some systems [5], it is possible to not only monitor but also control specific appliances through smart sockets. By constructing a home-wide network of smart sockets, we will be able to monitor and control all appliances in the near future.

Despite this promising outlook of smart socket based metering systems, there still remain technical challenges to be addressed. Building a home-wide network of smart sockets corresponds to implementing a full-fledged information system having nontrivial complexity. For instance, there exist multiple possibilities for selecting the communication method for smart sockets, such as power-line communication (PLC) [6], (wireless) Ethernets and ZigBee [7]. A typical smart socket is equipped with various components such as communication devices, sensors, microprocessors, and the power consumption of each component should be optimized to minimize overhead. The number and placement topology of smart sockets also needs to be optimized. Given the complexity of such a system, optimizing its design parameters will be highly challenging.

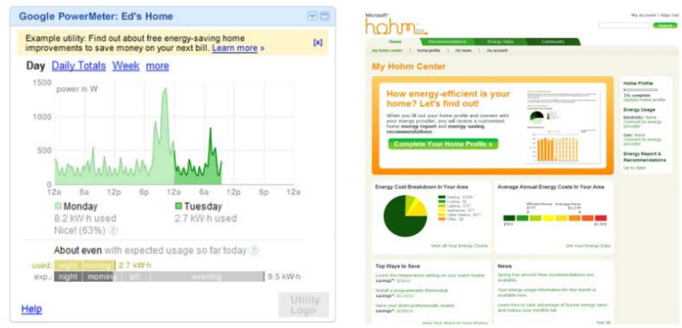
To alleviate this problem, we propose in this paper a simulation platform that is useful for designing and verifying complex smart metering systems. On this platform, the designer can model a system, which consists of various home appliances and smart sockets, and simulate its behavior from energy perspectives. To simulate the complex interplay among multiple objects in the system, the proposed simulation platform exploits SystemC [8], a powerful system-modeling methodology originally developed and populated in the design automation community. We tested this simulation platform in a variety of scenarios and present some results in this paper to demonstrate the effectiveness of our approach.

The remainder of this paper is organized as follows. Section II provides the background information that should facilitate understanding the proposed simulation platform. More details of this simulator are presented in Section III. Our assumptions and approaches can be found in Section IV. Section V then gives experimental results to show the effectiveness of the proposed simulator, and Section VI concludes the paper.

II. Background

A. Advanced Metering Infrastructure

In Smart Grid, information on energy consumption at various levels needs to be gathered, integrated and analyzed, and a new type of metering system that has a certain level of intelligence and communication capabilities is accompanied. The advanced metering infrastructure (AMI) [9] is such a system for real-time monitoring and control of electricity usage. The smart socket is an example of an AMI device. The buildings and residences employing AMI send energy usage information automatically to their electricity supplier. By acquiring the information on energy requests and balancing energy loads, energy suppliers can decrease the cost that would otherwise be spent on generating extra energy supply and/or expanding the infrastructure. In return, the consumers are provided with real-time pricing and analyzed usage information. The potential benefits by adopting AMI are tremendous, and the governments in many countries are preparing for the nation-wide deployment of various AMI devices [10].



(a) (b)

Fig. 2. Example smart metering systems. (a) Google PowerMeter [3] (b) Microsoft Hohm [4]

B. Related Work

Google PowerMeter [3] is a house-level energy monitoring service that enables the user to watch the energy usage of a house periodically and to predict and reduce upcoming service charges so that she can meet her energy saving goals. Fig. 2(a) shows a screenshot of the PowerMeter service. To subscribe this service, a house should be equipped with an AMI device that can transmit measurement data to a local electricity supplier, which then forwards the data to Google. As of July 2010, a limited number of electricity suppliers in the US, Germany and the UK provide this service. Google recently released the application programming interface (API) that allows access to PowerMeter data for fostering its adoption.

As shown in Fig. 2(b), Microsoft Hohm [4] is another on-line service for managing household energy consumption and providing useful energy saving recommendations. Unlike PowerMeter, Hohm does not require an individual residence to have an AMI device, since the measurement data is directly obtained by participating energy suppliers. Hohm can provide information on not only electricity but also gas and oil consumption, and location-specific optimizations are also provided. Hohm is currently available only in the US.

The Homer platform [11], shown in Fig. 3, is for simulating a small-scale hybrid power system composed of conventional and renewable energy sources, such as wind turbines and photovoltaic (PV) arrays, as well as batteries. The three key features of Homer are simulation, optimization and sensitivity analysis. It is known that renewable energy sources can be unstable from time to time and are normally used in harmony with conventional power grids. Homer can simulate such unpredictability of renewable energy sources. The running expenses and fuel prices can also be considered during simulation. By analyzing simulation results, Homer can optimize the system configuration given a power consumption scenario. Furthermore, Homer can analyze the sensitivity of a given system and predict how it is influenced by the fluctuations in fuel prices, wind speeds and power grid prices.

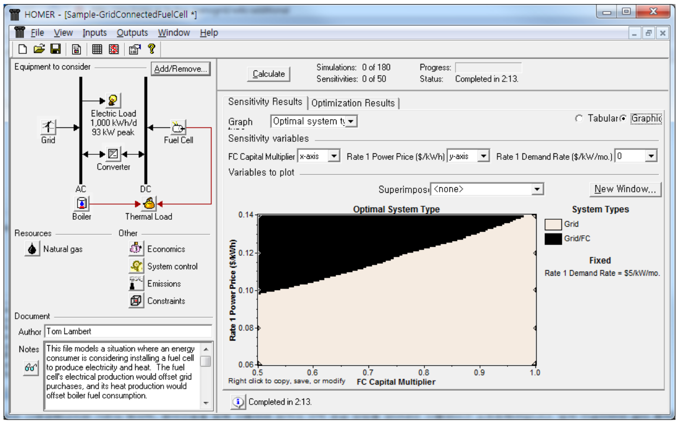


Fig. 3. The Homer simulator [11].

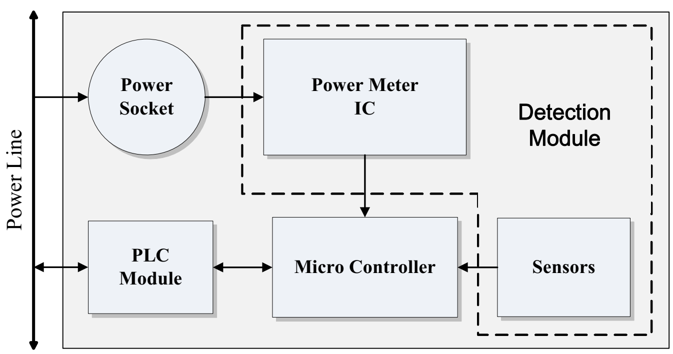


Fig. 4. The block diagram of RMCPS [12].

Fig. 4 shows the block diagram of a type of smart socket named the *remote monitoring and controlling power socket* (RMCPS) [12]. This device consists of several components such as a power socket, a microcontroller unit (MCU), a power meter IC, light/temperature sensors and a PLC module. RMCPS can measure energy consumption in real-time and store the measured data into its internal memory. Using IT devices that can access the Internet, the user can acquire from RMCPS the information on the current temperature, the status of ambient lights and the usage of electricity. The user can even remotely turn on or off an appliance connected to the RMCPS.

Although the aforementioned approaches can provide the user with useful information from energy saving perspectives, there still remains room for improvements. For example, Google PowerMeter and Microsoft Hohm can report only the total amount of energy consumption of a target building, and the user cannot see the detailed power consumption profiles of individual devices. For more accurate prediction and analysis of energy consuming patterns, it is desirable to measure the energy consumption of individual appliances. To this end, an electricity outlet should have a power metering circuit and a communication module. RMCPS is such a smart metering device but provides only basic functionalities due to its limited processing and memory resources. For integrating and analyzing energy usage data more effectively, the RMCPS device needs to be augmented by additional hardware and

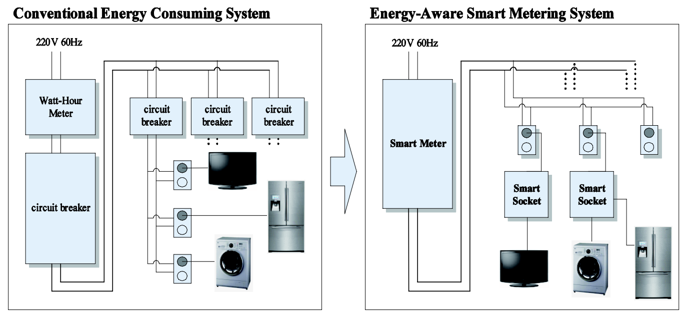


Fig. 5. A conventional system (left) versus a next-generation system with smart metering supported (right).

software supports. Homer provides a powerful software platform capable of performing accurate simulation and optimization of complex power systems but is more for engineers at electricity suppliers rather than for home users. This is because the main objective of Homer is to facilitate designing and configuring a large-scale power system, rather than suggesting how to reduce energy consumption from a consumer's viewpoint.

We expect that a system that can overcome the limitations of these existing approaches will eventually appear in the near future. To facilitate designing such a system, it would be helpful to have a simulation platform for modeling, analysis and optimization.

III. Objectives and Assumptions

The main objective of the proposed approach is to develop a simulator that can model a network of home appliances and smart meters and that can predict detailed power profiles of these appliances and cumulative energy consumption. Any electricity consumer interested in energy saving as well as the designer of a new type of smart metering system would significantly benefit from using this simulation platform.

The key component of a next-generation smart metering system would be the ability to measure the energy consumption of individual appliances and to transfer this information to a metering server, which can communicate with the electricity supplier about the cumulative usage and real-time price information. In the conventional electricity supply system, as shown in the left pane of Fig. 5, this type of smart metering functionality is usually not supported.

The proposed simulator assumes a smart metering system as shown in the right pane of Fig. 5. The Smart Meter block show in the figure plays the role of the server mentioned above as well as the roles of the watt-hour meter and the circuit breakers in the conventional system depicted in Fig. 5. As discussed earlier, the Smart Socket block represents a new type of electric socket that can measure and transfer the electricity usage information of an individual appliance to the

Smart Meter. A smart socket is assumed to be placed between an appliance and an electricity outlet. In this paper, we assume that the Smart Meter and the Smart Sockets exchange information by using the power line communication (PLC) technique [6]; other types of communication methods can also be simulated by reflecting the characteristics of the specific method used into simulation parameters.

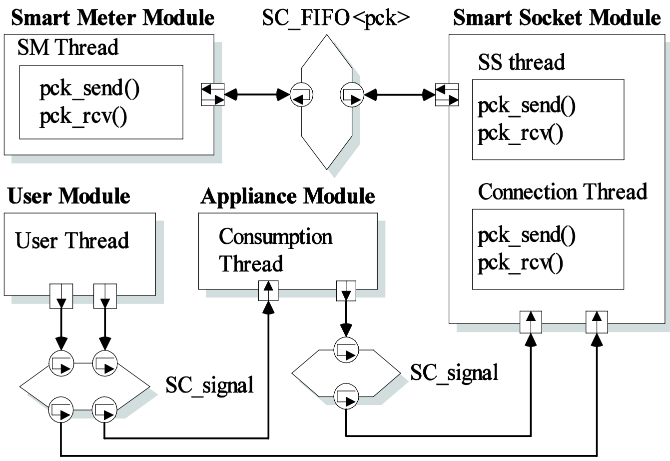


Fig. 6. Block diagram of the proposed simulator.

IV. PROPOSED SIMULATION PLATFORM

A. Overview

Fig. 6 shows the block diagram of the core of the proposed simulator. For clarity, the auxiliary blocks for data integration and visualization are not shown in the figure. The simulator core consists of the following four modules: the Smart Meter module, the Smart Socket module, the User module and the Appliance module. The roles of the first two modules (*i.e.*, Smart Meter and Smart Socket) should be clear from the discussion in the previous section. The User module is to simulate the behavior of the user such as turning on and off an appliance or changing its operational state. The Appliance module is to model the operation of a specific appliance. Note that there can be multiple instances of the Smart Socket and the Appliance modules, but only one of each is shown in the diagram for clarity. More details of each module will be given in Section IV.B.

To model the concurrent behavior and complex interactions of multiple objects in a realistic manner, we employ the SystemC platform [8] as the simulation kernel of the proposed simulator. SystemC is a system-level modeling methodology that consists of C++ classes and an event-driven simulation kernel for modeling concurrent processes in a complex electronic circuitry. A typical simulation flow using SystemC is shown in Fig. 7. Although SystemC was originally developed and populated in the design automation community, its effectiveness and versatility have made its deployment widespread in other disciplines as well [13, 14].

In particular, we found the following features of SystemC most appealing to our purpose: First, SystemC provides a systematic and elegant way of simulating multiple objects concurrently, as a tool developed for modeling hardware, in which concurrency is inherent. A large number of energy-consuming appliances and smart metering devices can be modeled easily and accurately using SystemC. Second, SystemC is not only a programming language but also a simulation kernel. Utilizing this kernel allows the developer to focus on the domain-specific functionalities, thus eliminating the need for debugging and optimizing the kernel. We could

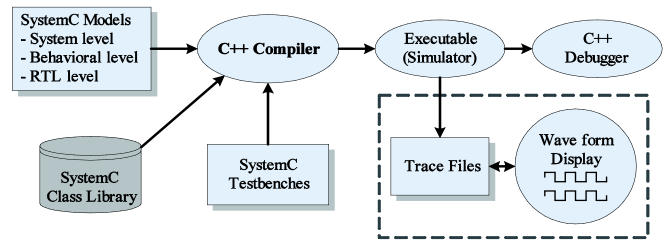


Fig. 7. Simulation flow in SystemC [15].

reduce the development time significantly by exploiting the SystemC platform.

B. More Details of the Four Modules

The four modules shown in Fig. 6 were implemented at the behavioral level, one of the four simulation levels SystemC supports. Each module has one or more threads running inside. The modules can communicate with each other using *channels* and *ports*, which constitute the inter-process communication mechanism SystemC provides. In Fig. 6, such a channel and a port are represented by a hexagon and a square with an arrow inside, respectively. Section IV. C will present more details on the communication protocols used.

The Smart Meter module collects the measurement data sent by the Smart Socket module(s), stores the collected information and analyzes it. A first-in first-out (FIFO) queue is used between the Smart Meter module and an instance of the Smart Socket module for packet exchange. Every packet from the Smart Socket module is stored in the queue and is processed sequentially. A FIFO queue is called `sc_fifo` in SystemC. Every Smart Socket module has its own ID and state managed by the Smart Meter module, which utilizes registers to save these IDs and states. The collected measurement information is stored in the industry-standard value change dump (VCD) format [16] by using a SystemC function called `sc_trace` for visualization and analysis.

The Smart Socket module is connected to the User and the Appliance modules, measures the electricity usage of the appliances attached and sends the measurement data to the Smart Meter module. The Smart Socket module thus has three ports. One port is used to connect to the Smart Meter module via the FIFO queue therein. Another port is used to receive data from the User module. The data received from this port has only two states, namely plugged or unplugged, and another type of channel called `sc_signal` is used, which is simpler than the `sc_fifo` type. The third port is used to receive data from the Appliance module, which also sends binary on/off information.

The Appliance module is to model the behavior of an appliance. Several operational states or modes are assumed for each appliance depending on its type, and the energy consumption of an appliance varies according to which mode it is currently operating in. For instance, Fig. 8 shows the four different operational modes (*i.e.*, high, middle, low and standby) of an electric fan and the corresponding powerTABLE I

OPERATION SEQUENCE DEPICTED IN FIG. 8

Duration (sec.)	Operational mode	Power consumption (W)
19	Standby	0.61
22	Low	30.2
27	Middle	35.8
24	High	43
58	Low	30.2
42	High	43
45	Middle	36.8
23	High	43
12	Standby	0.61
45	Low	30.2
18	Standby	0.61

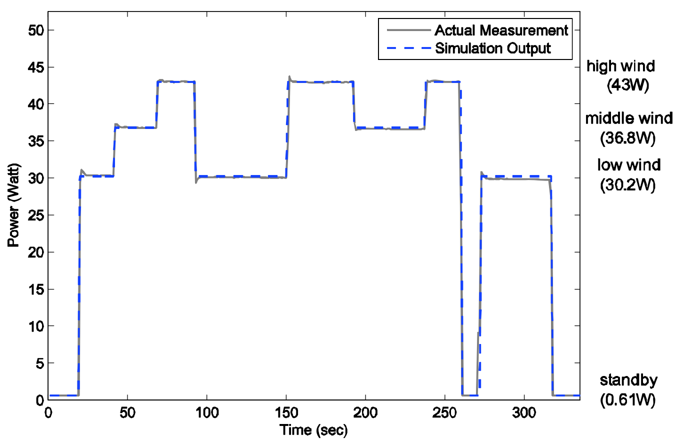


Fig. 8. Four operational modes of an electric fan (model: EFE-434R, Hanil Electric Co., Ltd., Korea) and the corresponding power consumption.

consumption, and Table I lists the sequence of operation represented in Fig. 8 with detailed power dissipation values. We selected a set of representative appliances commonly used at home and characterized them in terms of their operating modes and the corresponding energy consumption values. The standby power of each appliance was also taken into consideration, since some devices consume nonnegligible power in their off state unless they are completely unplugged.

Lastly, the User module is to model the behavior of the user, who connects/disconnects and changes the operational mode of an appliance according to a certain scenario. An example of such a sequence of operation is listed in Table I. This behavior of the user is captured by the Smart Socket module, which detects the signals sent by the User module over the `sc_signal` channel, as drawn in Fig. 6.

C. Communication Protocol Design

This subsection describes how the Smart Meter and Smart Socket modules communicate with each other. Fig. 9(a) shows the overall communication protocol layers used in the simulator. We use a 3-layer protocol stack, which consists of physical, network and appliance layers. Just as in most communication systems, the physical layer is for the fundamental transmission technology used, and the network layer is responsible for delivering packets from a source to destination. In the appliance layer, the Smart Meter and Smart Socket modules play their roles using the information stored in the packets delivered.

TABLE II

PACKET TYPES AND DESCRIPTIONS

Packet Type	Description
SS_CONNECTION_REQ	Request for confirmation of connection of Smart Socket to Smart Meter
SS_CONNECTION_ACK	Acknowledgement of SS_CONNECTION_REQ
SS_LOCATION_REQ	Request for confirmation of location of connected Smart Socket to Smart Meter
SS_LOCATION_ACK	Acknowledgement of SS_LOCATION_REQ
APP_CONNECTION_REQ	Request for confirmation of connection of appliance
APP_CONNECTION_ACK	Acknowledgement of APP_CONNECTION_REQ
APP_CONSUMPTION_REQ	Request for confirmation of amount of power consumption of a appliance
APP_CONSUMPTION_ACK	Acknowledgement of APP_CONSUMPTION_REQ
APP_DISCONNECTION_REQ	Request for confirmation of disconnection of a appliance
APP_DISCONNECTION_ACK	Acknowledgement of APP_DISCONNECTION_REQ

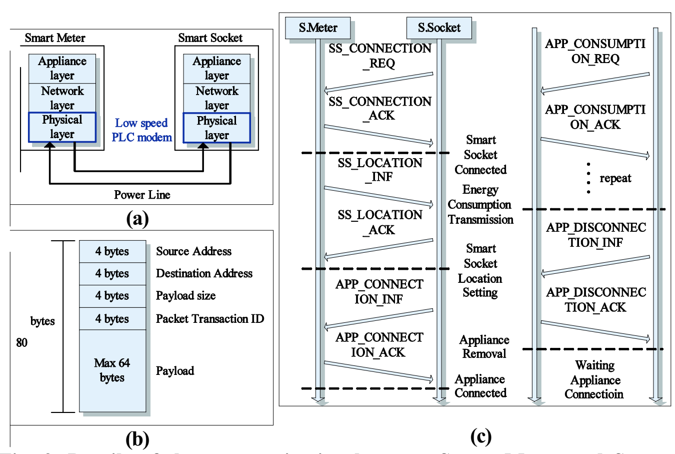


Fig. 9. Details of the communication between Smart Meter and Smart Socket modules. (a) Protocol layers (b) Packet definition (c) Packet exchange diagram

For the physical layer, we assume that the simulated system uses the PLC method [6], which fits well with the idea of smart metering. If PLC is used, no separate communication channel is needed to exchange measurement information. PLC is thus one of the most favorable communication methods in smart metering. The energy consumption measurement does not demand much bandwidth (only a few bytes for each reading), and a low-speed PLC modem should thus suffice.

Fig. 9(b) shows the definition of the packet used in the network layer. Every packet is 80 bytes long and is composed of a 16-byte header and a 64-byte payload. The header has

Fig. 10. Graphical user interface (GUI) of the proposed simulator.

four 4-byte subfields, namely the source and the destination addresses, the payload size and the packet ID. There are 10 types of packets as listed in Table II, which also shows the brief description of each type of packet.

The protocol to exchange information between the Smart Meter and Smart Socket modules is depicted in Fig. 9(c). This diagram represents the sequence of packets exchanged between these modules. The packet exchange begins when an instance of Smart Socket is newly connected and finishes when the instance is disconnected. In the middle, the two modules exchange information such as plugging in and out an appliance, the socket location and the power consumption.

D. Integration and Visualization

For enhanced user experience, the simulation modules are integrated with the tools for analysis and visualization using the C# environment [17]. Fig. 10 shows the graphical user interface (GUI) of the proposed simulator. A floor plan of a house equipped with a variety of appliances is provided, and the user can select the list of appliances to simulate by clicking and selecting their icons. The user can conveniently specify simulation parameters and options such as simulation time and resolution, the number and configuration of Smart Sockets and the usage pattern and operating schedule of appliances. The simulator shows the accumulative energy consumption as well as detailed power profiles of individual appliances. The Zedgraph library [18], an open source charting class library for .NET framework [19], was used to visualize power consumption waveforms (shown at the bottom of the GUI window), which are exported by the Smart Meter module in the VCD format.

V. Experimental Results

A. Verifying Simulation Accuracy

We modeled the 12 appliances listed in Table III using the procedure described in Section IV.B. As shown in Fig. 11, the actual power consumption of these appliances was measured and stored into a laptop computer by using a measurement device called HMP-100A [20]. Fig. 12 shows the prediction results obtained by running the proposed simulator for these

TABLE III Appliances Used in Experiments

Duration (sec.)	Appliance	Manufacturer and model
401	Air conditioner	SAMSUNG A9W152HD
361	Air cleaner	WOONGJIN AP-1007AH
549	Audio	PHILIPS MC157/61
179	DVD player	LG LC-605M
878	PC	INTEL Q6600 2.4GHz
232	LCD monitor	LG L197WHP-PF
549	Cell phone charger	LG SV-100
1060	Microwave oven	SAMSUNG RE-MS20
501	TV	SAMSUNG CT-25D8E
123	Set-top box	SAMSUNG SMT-H3020
400	Rice cooker	CUCKOO CRP-HB1015FG
182	Refrigerator	SAMSUNG SRS575GC

TABLE IV Correlation Coefficients and Error Rate of Watt-Hours

Appliance	Correlation coefficient	Error rate (Watt-Hour)
Computer	0.968	0.002
LCD monitor	0.982	0.001
Air conditioner	0.987	0.011
TV	0.958	0.032
DVD player	0.986	0.001
Set-top box	0.973	0.001
Air cleaner	0.986	0.005
Audio	0.957	0.001
Cell phone charger	0.967	0.003
Microwave oven	0.989	0.029
Refrigerator	0.935	0.018
Rice cooker	0.990	0.015

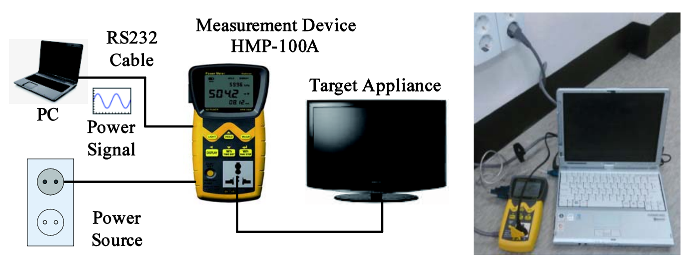


Fig. 11. Measuring power consumption of home appliances using HMP-100A (Adpower Co., Korea) [20], which allows the user to store the measurement data into a computer.

appliances. In this figure, the actual and simulated waveforms are drawn in gray and black, respectively. The simulation time resolution used was 1 second in all cases, whereas the total simulation time was different from case to case.

As expected, the degree of discrepancy between the simulated and the actual waveforms depends on how actively an appliance can change its operational mode. For instance, the simulation results match the actual curves almost perfectly for the appliances that do not change the operational modes frequently (such as a cell phone charger, an LCD monitor and a microwave oven). In contrast, relatively higher deviation from the actual values was observed for those appliances that have internal sensors and/or can change the operational mode actively and frequently (such as a refrigerator and an air conditioner).

Nonetheless, we observed that the actual and simulated waveforms are very similar in all the cases tested. For more quantitative comparison, we calculated, for each appliance, the

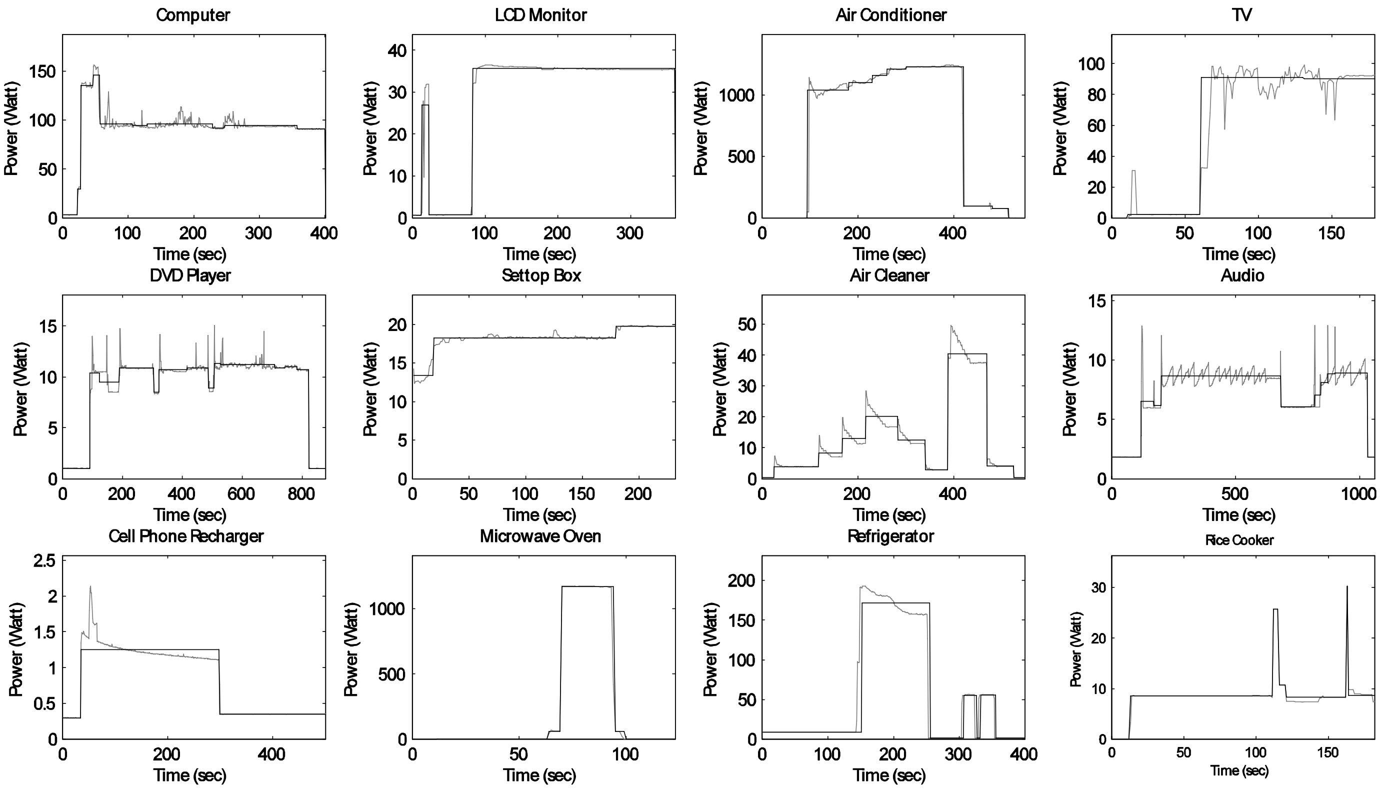


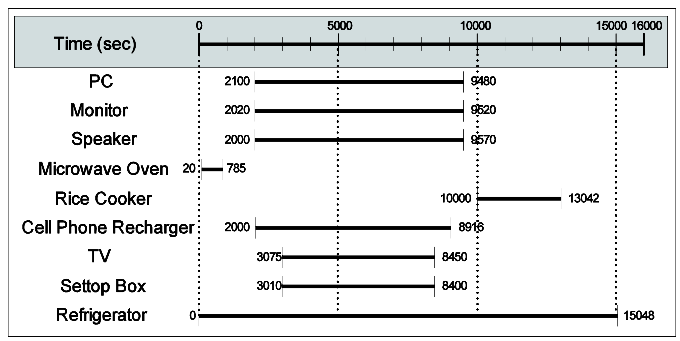
Fig. 12. Comparison of actual (gray) and simulated (black) waveforms for 12 different appliances.

correlation coefficient between the two power waveforms and the error rate of the simulated energy consumption with respect to the actual value, as listed in Table IV. The correlation coefficients in all the cases were very high, ranging from 0.935 to 0.990. Also, the error rate values were all negligible, topping at 0.32%. This result indicates that the simulated values closely resemble the measurement. Note that there are sharp peaks in the actual measurements, but the duration of such a peak is very short, giving little effect to computing correlation coefficients and error rates.

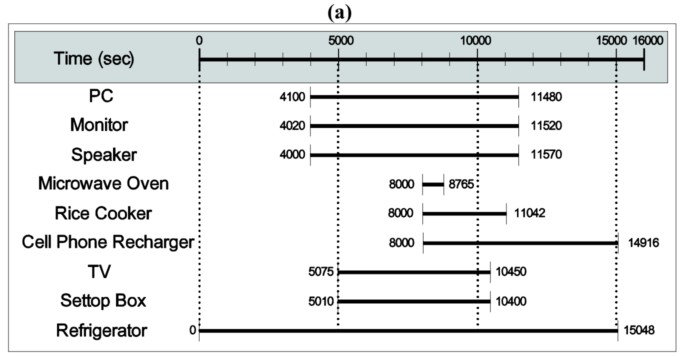
B. *Leveling Energy Usage by the Proposed Simulator*

From the viewpoint of the nation-wide electricity resource management, it is critical to reduce the amount of peak power consumption [21]. In countries under inclement weather conditions, the nation-wide peak power consumption occurs usually in summer or winter. These countries do every effort to fulfill the peak power demand by, for instance, building additional power plants and broadcasting advertisements on energy saving. Being the building block of such a nation-wide power grid, every household can contribute to the efforts to reduce the peak of nation-wide power consumption.

The proposed simulator can be useful for making the shape of power dissipation pattern flatter, thus lowering the house-wide power peak. Fig. 13(a) shows an example schedule of using nine different appliances. The predicted power consumption waveform of this scenario is shown in Fig. 14 (solid line). Since the simulator provides the user with the detailed information on how much power each appliance dissipates, the user can adjust her schedule so that the peak power consumption can be reduced. Fig. 13(b) shows the



(a)



(b)

Fig. 13. Two schedules of using 9 appliances. (a) Original schedule (b) Revised schedule that has lower power peak

revised schedule, whose simulation result is shown in Fig. 14 (dotted line).

To automate this re-scheduling process, the simulator employs the following guideline: Those appliances that need to be always on (such as a refrigerator) are scheduled first. Then, those appliances that consume a large amount of

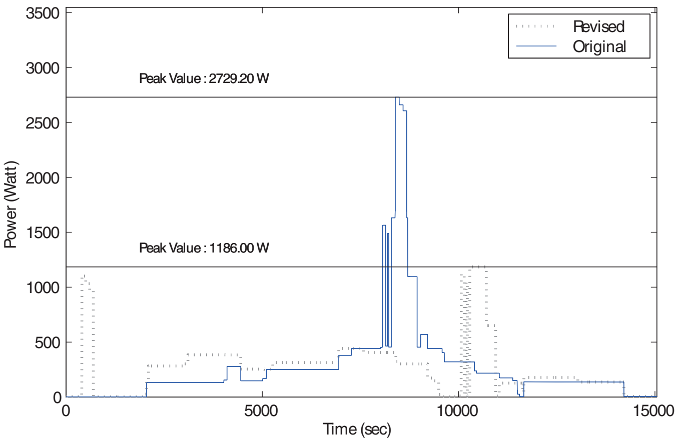


Fig. 14. Comparing power consumption patterns of the two schedules shown in Fig. 13.

energy or whose schedule cannot be changed arbitrarily (such as an air conditioner, an electrical heater, microwave oven and a hair dryer) are scheduled next. Last in the scheduling are the remaining appliances. For the example shown in Fig. 14, the peak power can be reduced by this procedure from 2.73kW to 1.19kW (over 50%). Of note is that this rule is only a simple heuristic used for a pilot study. More sophisticated scheduling algorithms could be employed for even greater reduction.

VI. Conclusion

We have described a simulation platform that can be used for predicting the energy consumption of a house with a variety of appliances. This simulator is based on SystemC, a powerful concurrent system-modeling language, and can model a next-generation metering system that utilizes an advanced type of socket with communication capability. According to our experiments, the proposed simulator can predict the actual power dissipation profiles of the tested appliances accurately, and the average correlation between the simulated and the real waveforms was 0.973. Also, the average error rate of simulated energy consumption with respect to the actual measurement was 0.009. Moreover, the simulator can be used to reduce the peak power consumption by giving insight into how the schedule of using appliances should be adjusted. Using the proposed simulation platform, the designer of a new smart metering system will be able to test, verify and optimize the system in a realistic manner. Anyone interested in reducing energy at home can also benefit from using the proposed simulator.

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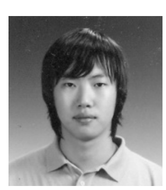
Biographies



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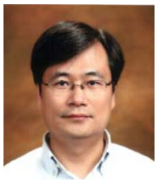

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