# Hardware Demonstration of a Home Energy Management System for Demand Response Applications

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***Abstract*—A Home Energy Management (HEM) system plays a crucial role in realizing residential Demand Response (DR) programs in the smart grid environment. It provides a homeowner the ability to automatically perform smart load controls based on utility signals, customer's preference and load priority. This paper presents the hardware demonstration of the proposed HEM system for managing end-use appliances. The HEM's communication time delay to perform load control is analyzed, along with its residual energy consumption.**

***Index Terms*—Demand response (DR), home energy management (HEM), smart grid, home automation.**

## I. Introduction

TRADITIONALLY, in the U.S. and in many parts of the world, there is a persistent problem of inefficient use of electric power generation and transmission assets. For example, in the Dominion Virginia Power's service area, roughly 20% of generation assets are used 5% of the time [1]. This problem has partially been tackled by demand side management, which was introduced in the early 1980s [2], [3]. With the introduction of the smart grid, it is now possible to perform demand response at customer premises to get a finer control of the available resources.

Demand response (DR) is defined as "changes in electricity use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" [4]. According to FERC, DR activities in the U.S. are classified as either incentive-based (e.g., direct load control) or time-based (e.g., dynamic pricing, critical peak pricing) programs. FERC has also pointed out that almost 80% of the total U.S. peak load reduction potential comes from incentive-based DR programs [4].

Due to this reason, and the fact that there has not been a mature time-varying tariff for residential customers, the DR concept for our hardware demonstration is based on the incentive-based DR program—which involves a customer receiving some sorts of load control signals from a service provider. This DR concept is thoroughly discussed in [5], in which we describe algorithm to manage multiple power-intensive loads in a house to meet certain peak reduction targets, taking into account homeowner preset load priority and comfort level preference. In this case, a homeowner has the freedom to choose what loads to manage and for how long. This is different from a pre-set load (kW) reduction target set by a local electric utility company in direct load control programs. Note that for this kind of DR programs, economic incentives should have already been written into the contract between consumer and the utility.

In order to realize the proposed DR feature, it is necessary to deploy a fully automated DR solution, or auto-DR [6], which can be made possible through the use of a Home Energy Management (HEM) system. Today, interests in HEM systems have grown significantly. Various HEM systems are designed based on different communication schemes, such as ZigBee [7] and power-line carriers [8]. In [9], authors implement an HEM system using a task-scheduling approach; while in [10], authors propose an HEM system that can display energy usage information of individual appliances. In [11], authors propose an in-home energy management (iHEM) system to reduce energy expenses and peak loads. In [12]–[14], authors focus on scheduling and controlling in-home appliances to provide economic advantages for residential energy management.

Most of the HEM implementations discussed in the literature are designed to schedule appliance operation based on price signals. There is yet another implementation of an HEM system that can manage power-intensive loads to limit the household peak demand, while taking into account homeowner's load priority and comfort preference. This topic is the subject of this paper. It presents the HEM hardware demonstration in a laboratory environment using the previously developed DR algorithm. Emphasis is placed on the HEM system setup and electrical measurements of the loads that are controlled by the HEM unit, together with measurements of communication time delays between the HEM unit and load controllers, along with the HEM system's residual power consumption.

## II. Description of the Proposed HEM System

### *A. Overview of the Proposed HEM System*

The concept of the proposed HEM system is shown in Fig. 1. The overall system comprises ~~an HEM unit~~ that provides monitoring and control functionalities for a homeowner, and ~~load controllers~~ that gather electrical consumption data from selected appliances and perform local control based on command signals from the HEM system. A gateway, such as a smart meter, can be

Manuscript received March 30, 2012; revised July 04, 2012; accepted August 25, 2012. Date of current version December 28, 2012. This work was supported in part by the U.S. National Science Foundation under Grant IIP-1114314. Paper no. TSG-00152-2012.

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Digital Object Identifier 10.1109/TSG.2012.2216295

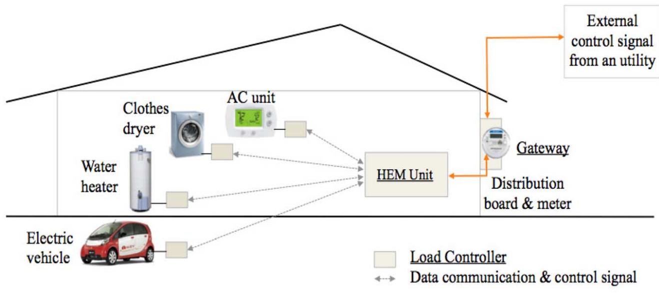



Fig. 1. Overview of the proposed HEM system.

used to provide an interface between a utility and a homeowner in a real-life HEM deployment. In such a scenario, the gateway receives a DR signal from a utility, which is used as an input for our HEM unit.

As shown in Fig. 1, we focus on controlling power-intensive household appliances, namely water heaters, air conditioners, clothes dryers, and electric vehicles. Other household loads, such as lights, TVs, computers, and other plug loads, will not be controlled because turning OFF these loads will result in noticeable impacts on customer's lifestyle.

### B. Architecture of an HEM Unit

In general, an HEM unit comprises: *a) An embedded PC running a GUI software application*, which includes a DR algorithm that serves as the brain of the HEM system. It makes a decision to switch ON/OFF selected end-use appliances based on the utility signal received, as well as homeowner's load priority and preference settings. It is also responsible for collecting electrical consumption data from all load controllers and providing an interface for homeowners to retrieve appliances' status and review their power consumption; and *b) An HEM communication module*, which provides communication paths between the HEM unit and its load controllers. This module is attached to the HEM unit and enables the HEM unit to send load control commands to all load controllers, and receive responses back.

A laptop computer with a ZigBee-enabled communication module is used as the HEM unit for this demonstration.

### C. Architecture of a Load Controller

A load controller provides an interface between the HEM unit and a selected appliance. It provides basic power management functions (i.e., monitor, control, communicate) via a standard electrical outlet. Architecture-wise, it contains: *a) A data capturing and processing module*, which collects and calculates real-time electrical consumption data, such as voltage, current, apparent power, real power, and power factor from appliances; *b) A control module*, which is simply an electronic relay circuit that provides the capability to switch a selected appliance ON/OFF, depending on the command sent by the HEM unit; and *c) A communication module*, which is responsible for providing communication paths between a load controller and the HEM unit. This is to allow the collected electrical consumption data from a load controller to be sent to the HEM unit; commands from the HEM unit to be received by a load controller; and response signals from a load controller to be sent to the HEM unit.

A commercial off-the-shelf load controller product is selected for the proposed HEM demonstration. This product is capable of controlling power-intensive loads (up to 276 V).

### D. Communications Within the HEM System

In any HEM systems, two types of communication modules are needed. One is integrated with the HEM unit (as discussed in Section II-B); and the other is built-in in each load controller (as discussed in Section II-C). The type of communication modules selected will impact the overall system's data communication rate, range, cost, and its residual power consumption. Under a typical home area network/smart-device platform, one or a combination of the following communication technologies may be deployed: Wi-Fi (802.11/n), Bluetooth (802.15.1), ZigBee (802.15.4), and Power Line Carrier (PLC). According to the evaluation study of various communication technologies [15], we select ZigBee to demonstrate the proposed HEM system. This is because ZigBee is a low-cost, low-power consumption option, and does not require an extensive new infrastructure.

## III. The Embedded HEM Algorithm

For this HEM hardware demonstration as presented here, we used the previously published DR algorithm [5] that is designed to allow a homeowner to operate his/her appliances when needed as long as the total household consumption remains below the specified limit during a DR event. At the same time, it takes into account load priority and customer comfort preference for power-intensive appliances. Here, we provide only the brief description of this DR algorithm. Please refer to [5] for the detailed DR algorithm description, and the extensive set of case studies to showcase the effectiveness of the proposed algorithm.

In this demonstration, we assume that a utility's DR event signal sent to a home comprises the demand limit amount (kW) and the duration of a DR event (hours). The demand limit specifies the maximum electric power consumption that is allowed by a house for the entire DR event duration. The embedded HEM algorithm considers that controllable loads in a house are of four types: water heater (WH), air conditioner (AC), clothes dryer, and electric vehicle (EV).

*Step 1:* The HEM load management algorithm starts by gathering system information: 1) the demand limit in *kW* and its duration; 2) appliance power consumption in *kW*; 3) room, ambient and hot water temperatures in °F; and 4) load priorities and customer preference settings. See Section V-A for a detailed description on priority and preference settings.

*Step 2:* The HEM algorithm then checks for both demand limit and comfort level violations. For the demand limit violation, the HEM algorithm checks if the total household consumption exceeds the specified demand limit level. For the comfort level violations, for example the HEM algorithm checks: a) for WH, if the hot water temperature falls outside the preset threshold; b) for AC, if the room temperature falls outside the preset threshold; c) for a clothes dryer, if the clothes dryer can finish its job before the specified completion time; and d) for EV, if the EV can be fully charged before the specified charging completion time.

*Step 3:* If there is any comfort level violation, the HEM unit decides on the status of each appliance based on the requested

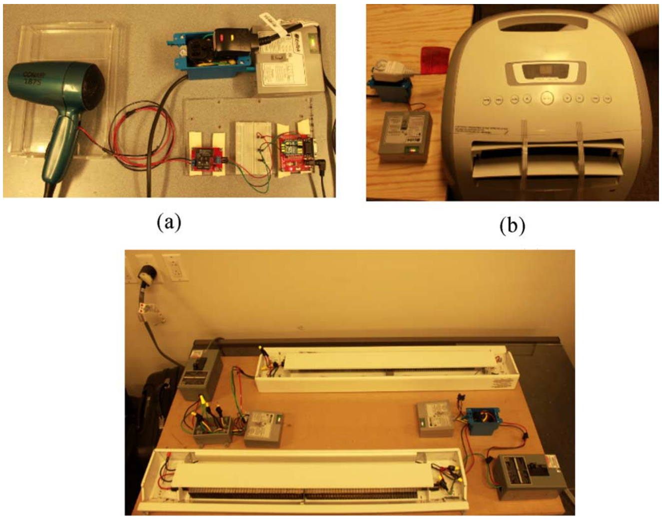


Fig. 2. HEM system installation: (a) a load controller connected to a hair dryer w/ the added relay circuit to allow turning OFF its heating coils; (b) a portable AC unit connected to a load controller; and (c) two sets of a load controller, each connected to an electric baseboard heater.

demand limit level. With the demand limit violation, the HEM unit sends command signal(s) to turn OFF selected appliances according to their priority, as necessary. With any comfort level violations, selected appliances will be turned ON in order to keep their comfort levels within their pre-specified ranges. In this case, the HEM unit will go through a decision-making process to ensure that the total household power consumption-with additional appliances turning ON—will not exceed the demand limit.

## IV. The Demonstration of the HEM System

### A. The Overall System Setup

The HEM system installation in our laboratory environment is shown in Fig. 2 with four commercial load controllers and four actual loads: a hair dryer, a portable air conditioning unit, and two electric baseboard heaters.

As discussed earlier, our DR algorithm focuses on controlling power-intensive loads, which are a water heater (WH), an AC unit, a clothes dryer, and an electric vehicle (EV). Due to limitations in using an actual WH, a clothes dryer and an EV in our laboratory environment, selected appliances are used that have similar operating characteristics as follows:

a) A hair dryer is used to represent the clothes dryer. Both loads have a motor load and heating coils. Instead of completely shutting OFF the clothes dryer, we have designed the DR algorithm to turn OFF its heating coils during a DR event if required, while the motor part is still in operation. This approach will allow the clothes dryer to resume its operation after the DR event ends. For our experiment, as shown in Fig. 2(a), the hair dryer's electrical circuit is modified by inserting a relay circuit to allow switching OFF the hair dryer's heating coils. This will allow turning OFF the hair dryer's heating coils, while the hair dryer motor keeps on running during a simulated DR event.

TABLE I
Electrical Power Ratings and Measurements of the Actual Loads Used in the Experiment

| Data Type | Hair Dryer Motor | Hair Dryer Motor & Heating Coils | Portable AC | Baseboard Heater 1 | Baseboard Heater 2 |
|---|---|---|---|---|---|
| **Electrical ratings:** | | | | | |
| W<br>V | 1.875kW @<br>110-125V | | 560W @<br>115V | 750W @<br>240V | 750W @<br>240V |
| **Measurements:** | | | | | |
| V | 121.3 | 119.1 | 120.5 | 213.9 | 213.2 |
| A | 1.5 | 7.3 | 5.3 | 2.8 | 2.8 |
| VA | 182 | 869 | 639 | 599 | 597 |
| W | 181 | 867 | 600 | 598 | 596 |
| PF | 0.997 | 0.997 | 0.940 | 0.999 | 0.999 |

b) Two electric baseboard heaters are used to represent the water heater and EV loads. Electric baseboards consume relatively constant power during their operation, which is quite similar to that of the water heater and EV loads.

The power ratings, together with the electrical measurement data, of all four loads used in this experiment are summarized in Table I. Note that the power consumption of the hair dryer is lower than its rating because the low heat setting is used in the experiment.

### B. The HEM Graphical User Interface (GUI)

The HEM GUI is developed in a visual C++ development environment, i.e., C++ Builder. It is embedded in the laptop computer, and consists of the HEM algorithm described in [5]. The HEM GUI provides a dashboard for a homeowner to monitor appliance status, appliance power consumption, total household power consumption, the requested demand limit, as well as room, ambient, and hot water temperatures. The dashboard is configured to update these parameters in 1-min intervals. A homeowner can also change his/her load priority and preference settings from the HEM screen.

### C. The Load Controller

Four identical load controllers are used in this demonstration. These are general-purpose load controllers for DR and sub-metering applications suitable for controlling 85-276 $V_{AC}$ loads. The selected load controller includes a microcontroller unit (MCU) with an analog front end that can measure voltage, current and provide power factor, real and apparent power in real-time. It also has a built-in ZigBee communication module and a 30 A power relay for switching ON/OFF its connected load.

### D. The HEM Communication Module

Fig. 3 illustrates two identical ZigBee modules in our HEM system: a) the ZigBee module in the HEM unit; and b) the ZigBee module in each load controller.

Table II shows an example of a response frame from a load controller when the HEM unit requests its electrical power consumption data.

The "Received Data" (0x0A510C90083F001C024F024E03E703) contains voltage, current, power factor, real, and

(a) (b)

Fig. 3. ZigBee modules in: (a) the HEM unit; and (b) the load controller.

TABLE II
AN EXAMPLE FORMATTED RESPONSE FRAME

| Frame Part (Byte) | Hex Data |
|---|---|
| Start delimiter (1) | 0x7E |
| Length bytes (2-3) | 0x001B |
| Frame type (4) | 0x90 |
| 64-bit Destination Add.(5-12) | 0x0013A200407A6303 |
| 16-bit Destination Network Add. (13-14) | 0x0884 |
| Receive Options (15) | 0x41 |
| Received Data (16-30) | 0x0A510C90083F001C024F024 E03E703 |
| Checksum (31) | 0xE5 |

TABLE III
HOUSE PARAMETER ASSUMPTIONS

| Parameter | Value | Unit |
|---|---|---|
| House size | 2000+500 basement | *sqft* |
| $A_{floor}$, $A_{ceiling}$, $A_{wall}$, $A_{window}$ | 2000, 2000, 2600, 520 | *sqft* |
| $R_{ceiling}$, $R_{wall}$, $R_{window}$ | 49, 13, 2 | *ft²*°F/(Btu/h)* |
| Number of people | 3 | people |

apparent power data. The electrical data in the message body of the "Received Data" can be interpreted as

- Voltage (V) : 083F = 211.1 V
- Current (A) : 001C = 2.8 A
- Apparent power (VA) : 024F = 591 VA
- Real power (W) : 024E = 590 W
- Power factor (PF) : 03E7 = 0.999

Per the load controller's specifications, the voltage and current data in Hex are to be divided by 10; the apparent and real power data is simply a conversion from Hex to Decimal; and the power factor data in Hex are to be divided by 1000.

## V. HEM SYSTEM DEMONSTRATION CASE STUDIES

In this section, we present the hardware demonstration to showcase the ability of the proposed HEM system to perform load control during a DR event. For the selected case studies, electrical measurements of voltage, current, real and reactive power as well as power factor of loads that are controlled in this demonstration are presented.

### A. Case Study Assumptions

*Assumption 1: House Parameters:* The hypothetical house which is an average U.S. single-family home size of 2500 sqft [16] is used as a basis for this case study. The house parameters are presented in Table III, including the total house size in $ft^2$; areas of wall, ceiling, and window of the house in $ft^2 (A_{\text{wall}}, A_{\text{ceiling}}$ and $A_{\text{window}})$; the heat resistance of the wall, ceiling and window in $ft^2 *^\circ F/(Btu/h)(R_{\text{wall}}, R_{\text{ceiling}}$ and $R_{\text{window}})$; and number of people living in the house.

*Assumption 2: Representation of Household Controllable Loads by Actual Loads in the Laboratory Environment:* Controllable loads in this house are a water heater, an AC unit, a clothes dryer, and an EV (Chevy Volt) [17]. In our laboratory set up, we represent a clothes dryer by a hair dryer; use a real AC unit; represent a WH by an electric baseboard heater; and represent an EV by another electric baseboard heater. See Table IV for the load size comparison.

TABLE IV
LOAD SIZE ASSUMPTIONS VS. ACTUAL LOADS USED IN THE DEMONSTRATION AND SCALE FACTORS

| Household Controllable Loads (kW) | | Actual Loads used in the Demonstration (kW) | | Scale Factors |
|---|---|---|---|---|
| Clothes dryer | 4.0kW | Hair dryer | 0.87kW | 4.6 |
| - Motor | 0.3kW | - Motor | 0.18kW | 1.7 |
| - Heating coils | 3.7kW | - Heating coils | 0.69kW | - |
| Air conditioner | 2.3kW | Portable AC | 0.60kW | 3.8 |
| Water heater | 4.5kW | Baseboard heater#1 | 0.59kW | 7.6 |
| Electric vehicle | 3.3kW | Baseboard heater#2 | 0.59kW | 5.6 |

TABLE V
LOAD PRIORITY AND PREFERENCE SETTINGS

| | Load | | | |
|---|---|---|---|---|
| | Water Heater | AC | Clothes Dryer | Electric Vehicle (EV) |
| Priority setting | 1 | 2 | 3 | 4 |
| Preference setting | 110-120°$F$ | 76°$F$ (±2°$F$) | - Min ON/Max OFF: 30 min - Finish by 24:00 | - Min ON: 30 min - Fully charged by 08:00 |

To demonstrate the household DR action using the proposed HEM system, HEM's load controllers measure the electrical data (V, I, W, VA, PF) of the hair dryer, the AC, and two electric baseboard heaters in real time. Then, the scale factors as shown in Table IV are used to scale up these measurements so that they represent the electrical consumption of four controllable loads in the hypothetical house. The HEM then determines the total household consumption (kW) by adding these scaled-up measurements, together with the assumed critical load data from the RELOAD database [18]. Also, we assume that: a) the AC cooling capacity is 34 000 *BTU*; b) the WH tank size is 80 gallons; c) the clothes dryer needs 60 min to complete its clothes drying job; and d) the EV needs 90 min to fully charge its battery.

*Assumption 3: Load Priority & Comfort Level Settings:* In this case study, the load priority assumptions are that the WH has higher priority than AC; the AC has higher priority than the clothes dryer; and the clothes dryer has higher priority than EV. See Table V.

The comfort level setting assumptions are as follows: the hot water temperature should be between 110–120 °F; and the room temp should be between 74–78 °F. For the clothes dryer, the heating coils' minimum ON time limit is specified at 30 min; the heating coil OFF time limit is set at 30 min to prevent excessive heat loss; and it must finish its drying job by midnight. For the EV, the minimum EV charging time of 30 min is specified before the EV charging status can be on hold; and it must be fully charged by 08:00 in the morning. These preference settings are allowed to be violated if operation of any appliance of higher priority is required to maintain a specific preference setting.

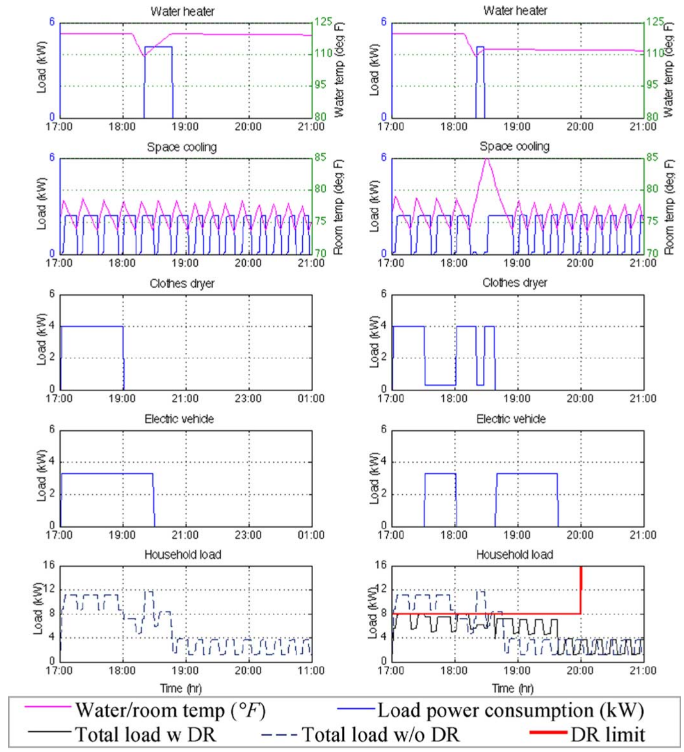
*Assumption 4: Demand Limit:* To evaluate the operation of the HEM algorithm, an 8 kW demand limit level is imposed on this hypothetical house between 17:00 and 20:00. The demonstrated HEM system monitors household consumption and performs load control to keep the total consumption below the specified 8 kW limit during this DR event.

*Assumption 5: Appliance Status Representation and Their Operation:* For the clothes dryer, the purpose of this demonstration is to simulate the 4.0 kW clothes dryer operation (modeled by a hair dryer) in this hypothetical house and use the HEM to control the status of the heating coils of the hair dryer in our laboratory environment. In this demonstration, the ON/OFF status of the clothes dryer's heating coils is represented by that of the hair dryer's heating coils. We assume that the clothes dryer's heating coils will be turned OFF when it gets controlled while the motor part keeps on running; and that any interruption during the clothes dryer's operation will result in prolonging its drying job equal to the interruption time.

For the AC, we use the actual portable AC unit in our experiment and use the HEM to control the status of the AC according to the simulated room temperature to match the operation of the 2.3 kW AC in a hypothetical house. We use the relationship presented in [19] to quantify indoor temperature of our hypothetical house, which is a function of the size of the AC unit, house parameters, outdoor temperatures, and heat gains from outside and number of people living in the house. The portable AC unit will be turned OFF when the room temperature falls below the preset threshold, i.e., 74 °F; and ON when the room temperature exceeds the preset threshold, i.e., 78 °F. Also, the AC unit can be turned OFF by the HEM during the DR event if necessary as long as the room temperature is within the preset comfort range, i.e., 74–78 °F.

For the WH, we simulate the 4.5 kW WH operation in the hypothetical house using an electric baseboard heater in our laboratory. The ON/OFF status of the WH is represented by that of the electric baseboard heater#1. The baseboard heater will be turned OFF when the water temperature exceeds the preset threshold, i.e., 120 °F; and ON when the water temperature falls below 110 °F. Also, the baseboard heater can be turned OFF by the HEM during the DR event if necessary as long as the water temperature is within the preset comfort range. We use the relationship presented in [19] to quantify the change in water temperature of our hypothetical house. This is a function of water heater tank size, inlet water temperature, hot water flow rate (gallons per minute), rating of the water heater, heat resistance of the tank, and surface area of the tank.

For the EV, we simulate the 3.3 kW EV operation in the hypothetical house and use the HEM to control the status of the electric baseboard heater#2. In this case, the ON/OFF status of the EV is represented by that of the baseboard heater. We assume that the EV charging status will be on hold if it gets controlled during a DR event; and any interruption during the EV charging will result in prolonging the EV charging completion time equivalent to the interruption time. Note that, although varying EV charge rates may be possible in future scenarios, the DR strategy used in this paper considers a fixed EV charging rate because this is the only charge profile available in the market today.




(a) (b)

Fig. 4. Demand response demonstration for a hypotheritical 2500 sqft home with all four appliances. Power consumption of all loads shown are derived by multiplying the measured power consumption of the actual loads by the scale factors presented in Table IV.

## B. Operation of the HEM Algorithm

As presented in our previously published paper [5], the proposed DR algorithm performed satisfactorily under different scenarios with different appliance ownerships and demand limit levels. As the objective of this paper is to demonstrate the HEM hardware system and its operating performance, we focus on the following two scenarios: Scenario 1-there is no demand limit; and Scenario 2—the demand limit is 8kW between 17:00–20:00.

*Scenario 1: Base Case Scenario:* As shown in Fig. 4(a), in the base case scenario with no demand limit, at 17:00 the homeowner operates the clothes dryer and plugs in his Chevy Volt. There is one intensive hot water draw event between 18:10–18:20, which makes the water temperature drop below the preset threshold at 110 °F. The WH then operates to bring the water temperature back to 120 °F. The AC unit cycles ON and OFF to maintain the room temperature within the preset comfort level, i.e., 74–78 °F. As shown in Fig. 4(a), the total power consumption of this house increases to about 11kW (AC 2.3 kW+ clothes dryer 4 kW+EV 3.3 kW+critical loads) between 17:00 and 18:00; and closed to 12 kW (WH 4.5 kW+AC 2.3 kW+EV 3.3 kW+ critical loads) between 18:20 and 18:30. The critical load power consumption (not shown in Fig. 4) varies every hour with an average value of 1.37 kW during the DR event period.

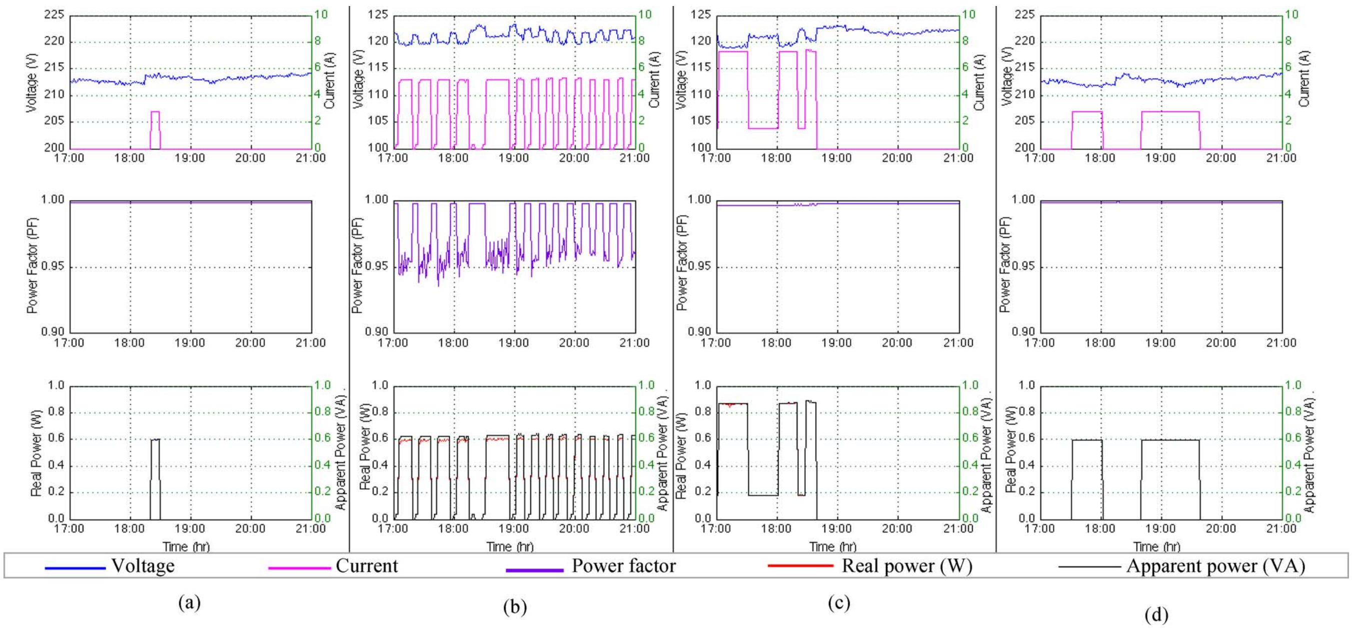



Fig. 5. Voltage, current, power factor, real and apparent power data of the actual loads under study in Scenario 2. (a) V, I, PF, W, VA of the electric baseboard heater#1 (represent WH). (b) V, I, PF, W, VA of the portable AC unit (represent AC). (c) V, I, PF, W, VA of the hair dryer (represent clothes dryer). (d) V, I, PF, W, VA of the electric baseboard heater#2 (represent EV).

*Scenario 2: 8 kW Demand Limit:* As shown in Fig. 4(b), with the 8 kW demand limit, the load shifting/compensation period occurs between 17:00–19:40. This is because, during this period, the AC unit (2.3 kW) can only operate together with either the clothes dryer (4 kW) or the EV (3.3 kW) and the critical loads; and only the WH (4.5 kW) can operate with the critical loads to keep the total household consumption below the 8 kW limit. When the water temperature drops below 110 °F at around 18:20, the WH operates to bring the water temperature back to 112 °F before it gives the AC priority to operate due to the room temperature violation at around 18:28. Once the AC operates, room temperature decreases. Turning off the WH also triggers clothes dryer operation as the clothes dryer has higher priority than the EV. Note that in our DR algorithm, the EV is allowed to partially charge as soon as it is plugged. This is regardless of the EV's priority as long as the total household demand limit is not violated. This will allow the homeowner to have the privilege to use the car earlier if needed.

The overall HEM algorithm results in a 40-min delay of clothes dryer operation time and 70-min delay of the EV charging completion time. The actual voltage, current, power factor, real, and reactive power of the four loads provided by the load controllers are presented in Fig. 5 for this scenario (Scenario 2), and are summarized in Table VI.

As shown, the portable AC used in this experiment consumes low current (i.e., roughly 0.3 A) during the first 2–3 min of its operation. Then, the AC current reaches 5.2–5.3 A until it is turned OFF. Both electric baseboard heaters consume roughly 2.8 A during their operation. The hair dryer consumes 1.5 A with the motor-only mode and 7.2–7.4 A when the heating coils are ON. While the PF of the baseboard heaters and the hair dryer remains close to 1, that of the AC reduces during its operation. This results in noticeable differences between the measured real and apparent power of the portable AC as shown in Fig. 5(b).

TABLE VI
VOLTAGE (V), CURRENT (A), POWER FACTOR (PF), REAL (W), AND APPARENT POWER (VA) MEASUREMENTS OF FOUR ACTUAL LOADS

| | Baseboard heater#1 (represent WH) | Portable air conditioning (represent AC) | Hair dryer (represent clothes dryer) | Baseboard heater #2 (represent EV) |
|---|---|---|---|---|
| V | 211.9-214.1 | 119.2-123.3 | 118.9-123.2 | 211.5-214.2 |
| A | 2.8 | 0.3-5.3 | 1.5 (M); 7.2-7.4 (M+H) | 2.8 |
| PF | 0.999 | 0.936-0.998 | 0.997-0.998 | 0.999 |
| W | 0.597-0.599 | 0.562-0.618 | 0.181-0.891 | 0.592-0.596 |
| VA | 0.597-0.599 | 0.599-0.644 | 0.182-0.894 | 0.592-0.597 |

Note: M = hair dryer's motor; H = hair dryer's heating coils.

*HEM Demonstration Observations:* This DR experiment showcases that the proposed HEM system is able to measure the electrical power consumption from all four loads, and correctly perform necessary control actions to switch ON/OFF selected loads during a DR event. As the total household consumption is kept at or below the 8 kW demand limit at all times during the DR event, we can conclude that the proposed HEM algorithm is capable of managing the appliance ON/OFF status to meet the DR limit request, taking into account customer's load priority and preference settings.

### C. Total Communication Time Delay Between the HEM Unit and Load Controllers

The total communication time delay between the HEM unit (transmitter) and its associated appliance controllers (receiver) is measured using a software time-stamp [20]. It is determined by combining the communication time of the forward path (i.e., from the HEM unit to load controllers) and that of the backward path (i.e., from load controllers to the HEM unit).

The average total communication time delays of 60-sample sets are measured for two distances at 1 meter and 10 meters

TABLE VII
TOTAL COMMUNICATION TIME DELAYS

| Device | Total communication time delays between the HEM unit and the load controllers | |
|---|---|---|
| | @ 1 meter | @ 10 meters |
| Load controller | 240 milliseconds | 265 milliseconds |

between the HEM unit and the load controllers. These average round-trip time delays are presented in Table VII.

These results indicate that the total communication time delay between the HEM unit and load controllers is in millisecond scale with ZigBee as the selected communication technology; and that a longer communication distance leads to a slight increase in the overall communication time delay. Note that the measurement results are experimental, and can change under different environments.

The HEM operation is multiplexed. In other words, it has to transmit and receive a signal back from one appliance before it can ping the second appliance. The time required to complete one cycle is the sum of all transmit-receive signals for all appliances under control. This determines the frequency of measurements. Thus when there are more appliances to be monitored, the frequency of monitoring goes down. Therefore, the communication time delay between an HEM unit and a load controller is one of the most important factors in determining the number of appliances that can be connected to an HEM unit and its appropriate data sampling intervals.

## D. Analysis of Residual Power Consumption

The deployment of the HEM system that runs 24 hours a day for 365 days a year will add to the annual electricity consumption due to the HEM's residual power needs. For this reason, we analyze the energy consumption of the demonstrated HEM unit and load controllers used in this experiment. Their estimated consumptions are shown in Table VIII, and explained in more details below.

*HEM Unit's Residual Power Consumption:* The Toshiba Portege M700 notebook—which runs GUI software applications including the DR algorithm and the monitoring interface—is used to perform data monitoring and decision-making functions of the proposed HEM system. Its power consumption is roughly 21.9 watts when the monitor is on, and it consumes roughly 15.8 watts when the monitor is in sleep mode. With the assumption that for HEM operation the monitor is looked at (turned on) five times a day (for one minute each), annual energy consumption of the HEM unit is estimated at 139 kWh per year. Note that this experiment disregards the electrical consumption when the notebook's fan operates or the battery is being charged.

*Load Controller's Residual Power Consumption:* Without a relay operation to perform DR control, the load controller continuously draws approximately 1.4 watts when there is no data transmission to the HEM unit. With the data transmission, this power draw increases slightly to 1.7 watts. Our laboratory experiment also indicates that the experimental transmission peak current remains high for approximately 5 seconds for each 1-min data transmission interval. Therefore, for the monitoring purpose (i.e., no relay operation), the estimated annual energy

TABLE VIII
POWER/ENERGY CONSUMPTIONS OF SYSTEM MODULES

| HEM component | Device | Approx. Power Consumption | Operating Duration | Annual energy consumption (kWh/yr) |
|---|---|---|---|---|
| HEM unit | - Notebook - ZigBee Coordinator (data transmission at 1-min intervals) | 21.9 watts (laptop monitor in active mode) | HEM operates 24/7 w/ the laptop monitor in an active mode for 1 minute each day | 139 kWh |
| | | 15.8 watts (laptop monitor in sleep mode) | | |
| Load controller | - Data capturing and processing module - ZigBee communication module - Control module (i.e. NC power relay - status: close) | 1.4 watts (No data transmission) | At all time, except during transmitting / receiving data | 12.5 kWh |
| | | 1.7 watts (w/ data transmission) | Approx. 5 seconds for each 1-min interval | |
| | - NC power relay (status: open) | 1.3 watts | Depend on appliances' schedule | N/A |

consumption of the load controller used in this experiment is at 12.5 kWh per year at 1-min data transmission intervals.

The relay's power consumption is also measured and is estimated at 1.3 watts when the relay operates. The relay in the selected load controller is a standard normally closed (NC) power relay with a 30 A rating. The relay remains closed at all times, and will be open with a command signal from the HEM unit to turn OFF the selected appliance. For example, as shown in Fig. 4(b) when the total EV charging is deferred for 70 min, this implies that approximately 1.3 watts will be continuously added to the load controller's power consumption during the entire 70 min of EV deferral. Annual energy consumption for the relay was not included in Table VIII because this will depend on how the EV charging would work for the whole year. It is obvious that this added power consumption can be significant if the load controller is used to control low power consumption appliances, such as lights and fans.

*The Overall HEM System's Power Consumption:* The overall energy consumption is estimated at 189 kWh per year for the proposed HEM system with four load controllers. Total system energy consumption could be reduced by selecting lower power consumption products for the HEM unit. For example, instead of using a laptop computer, any home energy display that is ZigBee-enabled (such as an LCD display panel on a kitchen wall) can be used.

# VI. CONCLUSION

In this paper, the demonstration of the proposed HEM system based on ZigBee is presented for residential DR applications, along with the analysis of the communication time delay and the evaluation of the overall HEM system's residual power consumption. The objective of this demonstration is to evaluate the

HEM operation performance, in particular how each load performs when being controlled by the HEM unit. Electrical measurements of the four loads under study are presented, including voltage, current, real power, apparent power and power factor.

The HEM hardware demonstration comprises a laptop computer that runs GUI software with the embedded HEM algorithm, four identical commercial off-the-shelf load controllers and four loads. This demonstration indicates that the proposed HEM system can monitor and control actual loads according to the designed DR algorithm. The measured electrical measurements of the loads confirm that the system performed satisfactorily during the entire experiment. The average communication time delay between the HEM unit and load controllers is in millisecond scale and increases slightly with communication distances. The residual energy of the proposed HEM system is estimated at 189 kWh per year.

It is expected that this paper will provide an insight into the overall HEM system operation, in particular providing a detailed look at the implementation of an HEM system for automated residential DR applications. The real-world implementation of the proposed system will benefit electric power distribution companies by helping to avoid distribution transformer overloads with the presence of new power-intensive loads, like electric vehicles.

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