Smart Energy Management for the Built Environment of Tomorrow

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ABSTRACT

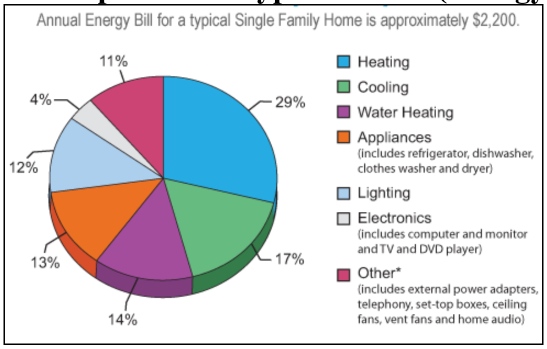
An intelligent home energy management system is proposed that can provide consumers with real-time in-home energy consumption feedback. The system is unique in that it uses SS TDR to locate and identify energy consumption at every node in a buildings electrical system. The proposed technology will also be equipped with a novel multi-function display and feedback schema. Quantitative and qualitative data from a preliminary case study that tested currently available real-time monitors served to inform the system design. In the future, this technology will enable users to know with accuracy the amount of energy their home consumes as well as the location of this consumption. It is hoped that consumers empowered with such knowledge can then make more informed energy use decisions.

Introduction

According to the United States Green Building Council (USGBC), the built environment accounts for 73% of the total electricity consumption, 39% of energy use, 38% of all CO_2 emissions, 40% of raw materials use, 30% of waste output (136 million tons annually), and 13.6% of potable water consumption in the U.S. (USGBC 2008). In terms of electricity, the EIA's short term outlook expects the total U.S. consumption to increase by 1.8% in 2013. At the residential level, the expected increase in consumption is 2.1% (EIA 2012).

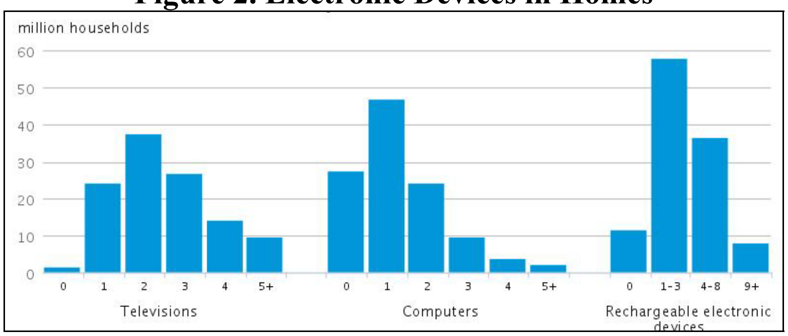
The residential sector, unlike the commercial and industrial sectors, is made up entirely of small, independent energy users such as houses, mobile homes, and multi-unit dwellings. U.S. homes use about one-fifth of the total energy consumed in the nation and about 60% of that is in the form of electricity. The average monthly kilowatt/hour (kWh) consumption in U.S. homes in 2010 was 958 kWhs (EIA 2012). This consumption is driven by the increased number of appliances and electronics in our homes. Figure 1 shows the typical energy consumption by category in a household including lighting, heating, and cooling, that make up 58 percent of the annual energy bill for a typical household (Energy Star 2009). Figure 2 shows the number of electronic devices in U.S. homes (EIA 2009). Research has shown that residential energy consumers waste almost 41% of the primary energy supplied to their homes, on heating/cooling, standby loads and less efficient equipment (Williams & Matthews 2007). The large amount of usage and waste indicates that the residential sector also has significant energy savings potential.

Figure 1. Energy Consumption of a Typical Home (Energy Star 2009)



Source: Energy Star. 2009

Figure 2. Electronic Devices in Homes



Source: EIA. 2009

The future of the residential electricity system will also need to accommodate the demand from plug-in electric vehicles (PEVs). It is the goal of the Obama Administration to invest in advanced technology supporting the introduction of 500,000 plug-in electric vehicles (PEVs) by 2015 (Mallette & Venkataramanan 2010). PEVs represent a new, flexible electricity load and storage, which could play a major role in expanding renewable energy installations. A broad infrastructure plan is being developed to deliver consumer value and satisfaction. This infrastructure includes On-board/Off-board charger, cord and connectors, electric vehicle supply equipment (EVSE)[1], advanced meters, energy storage, home area networks, the smart grid, and distributed generation and storage.

Thus, while the need to save energy is evident and the opportunities for doing so vast, the question that must now be answered is how this difficult task might be accomplished. Using concepts from research on the social dimensions of design, prior literature on smart home energy system prototypes, and an energy monitoring case study, a new energy monitoring system is proposed that better accounts for the complexity of energy usage and thus better meets user needs. This paper details this prototype along with the research that helped inform its creation.

[1] (EVSE): The 2011 National Electrical Code defines EVSE as "the conductors, including the ungrounded, grounded, and equipment grounding conductors and the electric vehicle connectors, attachment plugs, and all other fittings, devices, power outlets, or apparatus installed specifically for the purpose of transmitting energy between the premises wiring and the electric vehicle.

Designing for the Social Dimensions of Energy Consumption

Studies in the US have shown that when presented with feedback information on energy consumption, users save an average of 2-11 % (Ehrhardt-Martinez et al. 2010). However, since the amount and range of such savings is contingent on how well a user responds to the energy information provided by a feedback system, it is important that research on the social dimensions of energy use inform the design of future systems. This calls for a need for research that more closely examines the psychological and socio-cultural factors that dictate how energy is consumed, monitored, and controlled. With this design concept in mind, the authors (in conjunction with the local public power district) conducted a lengthy study to determine how much energy residents could save when equipped with real-time energy monitoring devices already available in the market.

In the January 2008- June 2010 case study, the authors implemented two types of feedback devices configured with three differing feedback schemas into the homes of a group of Omaha, NE electric utility users. All participants self-volunteered for involvement and each participating home received a separate real-time feedback device. The initial phase of the project evaluated 7 different types of devices already available on the market that would best match the study requirements. From this evaluation, the power cost monitior (PCM) and two versions of the Aztech In-Home Display (hereafter referred to as AZ 1 and AZ II) were chosen for inclusion. 50 AZIs were then configured with a feedback schema that displayed fixed time-periods of low, medium, and high usage: A green light bar displayed from 10 pm to 7:59 am, change to yellow from 8 am-1:59 pm and 7 pm-9:59 pm, and to red during the peak-demand period from 2 pm-6:59 pm. 50 AZ II's were configured using a historical consumption feedback schema. As part of this schema, a light bar changed color based on a comparison of the current kWh consumption rate in an individual household with that households average rates from the past three summers. Finally, 50 PCMs were configured with a color changing feedback schema similar to the Aztech device. The main difference between the Aztech devices and the PCM was the aesthetic of the feedback schema. The PCM schema informed users of their current rate of consumption using a spinning wheel that increases in speed as more energy is consumed. Finally, in addition to the 151 participant homes, a control group of 95 homes (pre-selected by the utility) were included for purposes of data comparison. In order to ascertain how users engaged with the devices and where improvements to the device might best be made, surveys were administered halfway through and at the conclusion of the study. The study results revealed that while the majority of users of all the studied device types reported that feedback helped them save energy, the actual calculated savings were statistically insignificant or, as in the case of the Aztech device, did not lead to a reduction in energy savings at all (Alahmad et al. 2009).

As the energy savings reported in the case study are consistent with that of other in-home feedback studies that make use of the same or similar devices in the prior literature, it is clear the current devices on the market are not meeting user needs. By analyzing the survey responses and comparing participants self-reported answers with the actual energy savings achieved, the authors were able to ascertain certain aspects in the design of the feedback systems that could be modified to better meet user needs. The survey results revealed that one area where users felt the design of a system could be improved was the feedback schema provided on the meter display monitor. Determining exactly what makes a feedback schema and display effective has been a focal point in much of the prior literature on feedback system design. Sara Darby (2000) and Corinna Fischer (2008) conclude based on separate reviews of approximately 58 feedback studies that those in which feedback was computerized, highly interactive, specified energy use per appliance, and could be frequently updated gave the highest energy savings (as cited in Froehlich 2009). Although users in the case study reported that the presence of the smart meters made them more aware of their energy use, the technology was unable to inform them how or where to save energy. It is likely that this information gap was one factor that hindered users from taking more decisive actions to reduce energy consumption. The following sections describe how the authors applied the knowledge acquired from this study and others like it to create a prototype for a feedback device that not only informs users of their energy consumption, but, notably, informs them where exactly this energy is being consumed.

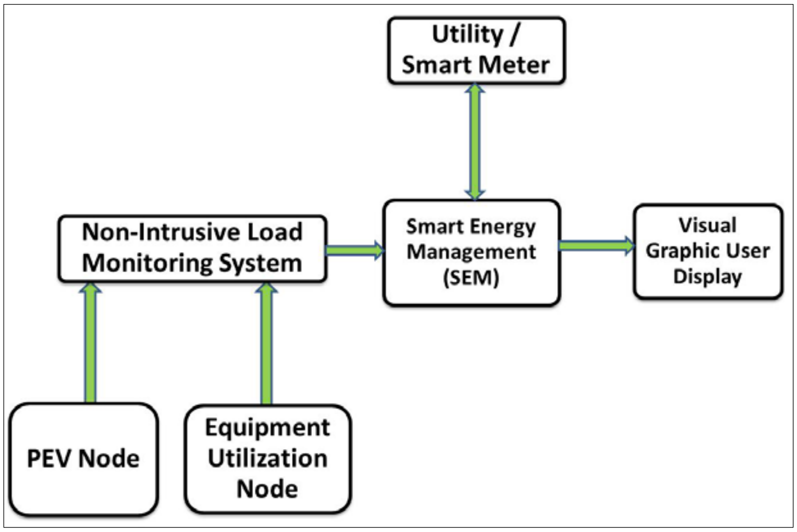
Energy Monitoring in the Smart Home Environment

One area in which the authors plan to test the design of their prototype device is in the smart home environment. Several energy monitoring feedback systems and methods to increase energy use awareness have been proposed in the prior literature for this type of home environment. While these studies propose new energy feedback prototypes for the smart home aimed at increasing user energy awareness, few case studies to the author's knowledge have evaluated energy-feedback prototypes through actual monitoring in different kinds of smart home environments. Recent prototypes built for the smart home environment include those by Marco et al. (2010), Kamilaris & Pitsillides (2011), and Chen & Cook (2011). Finding fault with the rigid proprietary aspects of many smart metering initiatives, Marco et al. (2010) propose combining the web surface interface technologies of Hydra middleware with Plogg wireless plugs and the UbiLense augmented reality technology to enable energy consumers to be more informed of their energy usage. Built specifically for integration in a smart home environment, this prototype will enable the user to use personal smart technologies (such as a smart phone) to identify high energy consuming devices in the home. The authors claim that per-appliance consumption data can be acquired by merely pointing the smart device at a specific energy-consuming device in the home. This data can then be extrapolated to other displays for more detailed analysis and comparison with home-wide consumption data. Kamilaris & Pitsillides (2011) also choose the smart home environment for the implementation of future feedback-technologies. They propose using the internet to synchronize the smart home with the smart grid for improved demand-response management. Chen & Cook (2011) test energy awareness in a smart home environment in a two month feedback study in which non-intrusive load monitoring is used to monitor the energy use patterns of smart home residents. These patterns are then analyzed to create an algorithm that can define a set of "normal" vs. "anamolous" energy use behavioral patterns. It is hoped that such information can help users make better energy management decisions.

Identify and Predict Non-intrusive Electrical Loads

In the creation of their prototype, the authors focused on consumption and conservation at the electrical node, where an electrical node is defined as a point on the electrical wiring system at which electrical current is taken to supply utilization equipment (load). Thus, non-intrusive methods were developed that could identify the location of specific nodes with the ultimate goal of identifying and locating points where energy is consumed while minimizing the number of needed modifications to the hardware of a building's existing electrical circuitry. A block diagram of the proposed addressable power distribution and energy management system is shown in Figure 4. In this figure the PEV is considered as a node where charge/discharge information is monitored, collected, analyzed, and presented to the user in various formats.

Figure 4. Proposed Smart Energy Management System for the Built Environment of Tomorrow



Methodology

A sensor device will be developed and mounted at the panel level for load metering and location identification purposes. Information from this sensor will then be fed into the SEM for further processing using data from the utility/smart meter. The results from the SEM are then sent to the visual display unit. The principles of operation behind the panel level sensor device are explained in the following:

Load Metering

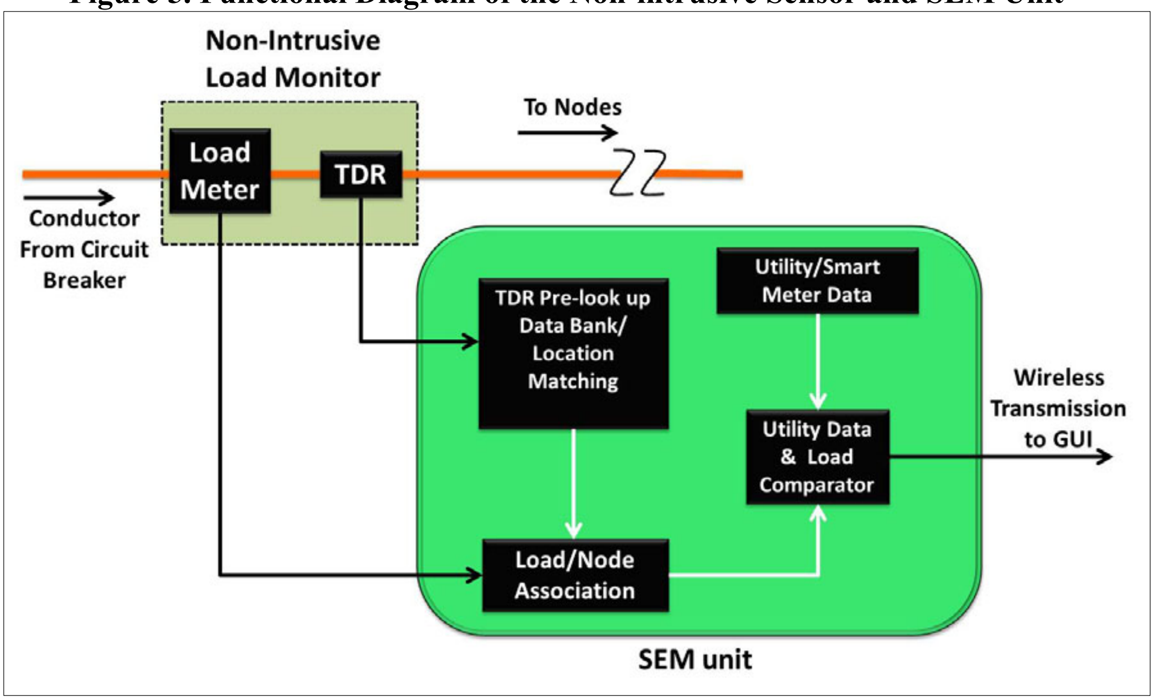
In order to locate load usage from remote locations, real-time power monitoring sensors will be used to acquire energy usage data at the panel level. This data will be sampled every 100 microseconds and sent to a data processing unit incorporated in the SEM system for node location association.

Load Location Identification

In order to identify load points or locations a study of Time Domain Reflectometry (TDR) technologies (Martin & Kabitzsch 2004), Power Line Communication (PLC) (IEEE 2004), (Yu-Ju, Haniph, Richard & Srinivas 2002), and Energy Harvesting (Banting, Fredrick & Mcbee 2010), (Ma, Yang, Sharif, Yi, & Alahmad 2010) with a focus on TDR was conducted. Time Domain Reflectometry (TDR) is based on the reflective property of waveforms on a conducting medium. The principle of TDR is similar to that of radar. A pulse waveform is launched into the conducting medium which in this case comprises the electrical power distribution conductor line, at the source (Banting, Fredrick & Mcbee 2010), (Chung, Nirmal, Cynthia, & John 2009), (Paul, Cynthia, & Paul 2006). The incident wave propagates down the conductor and a reflected waveform is generated upon an impedance change on the line. The reflected wave returns on the line back to the source so that the time delay between the incident and reflected pulses is used to determine the round-trip distance, or twice the distance, to the point of impedance change on the line. The wave propagation along the transmission line depends on the velocity of propagation (VOP) or velocity factor (VF) of the medium, where VF is the speed at which a wave travels through the conductor, relative to the speed of light (Fawwaz, Eric & Umberto 2010). In the event that reflection occurs, one half of the time delay measurement between when the incident and reflected pulses is recorded (AEA 2005) so that product of this time and the cable velocity determines the position where the reflected pulse was generated. No reflection occurs when there is no impedance discontinuity, i.e., when the transmission line is terminated with the characteristic impedance. The shape of the reflected pulse can be analyzed to determine the nature of the complex impedance load at the discontinuity [Howard H 2008], (Aligent Technologies 2006).

The location of the impedance change will be predefined in a lookup table matching the distances of each node from the TDR device in the panel level. The nodes are therefore assigned addresses corresponding to the distances. These addresses combined with metering data and utility rates in the SEM unit are sent to a graphics user interface unit for user monitoring and control. Figure 5 shows the functional diagram of the Non-intrusive monitoring and SEM unit.

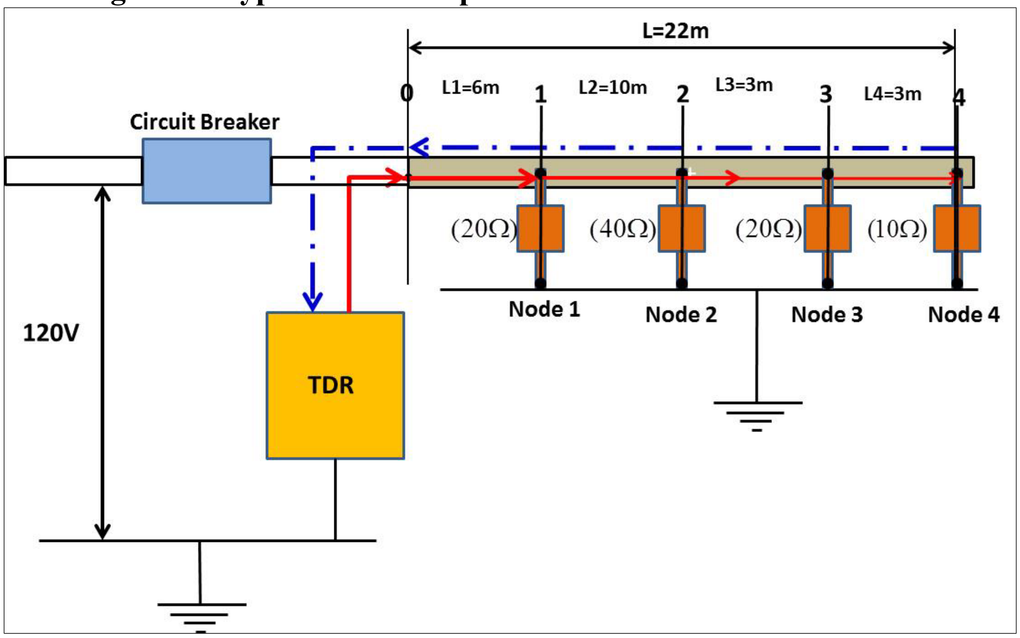
Figure 5. Functional Diagram of the Non-intrusive Sensor and SEM Unit



Preliminary Simulations and Results

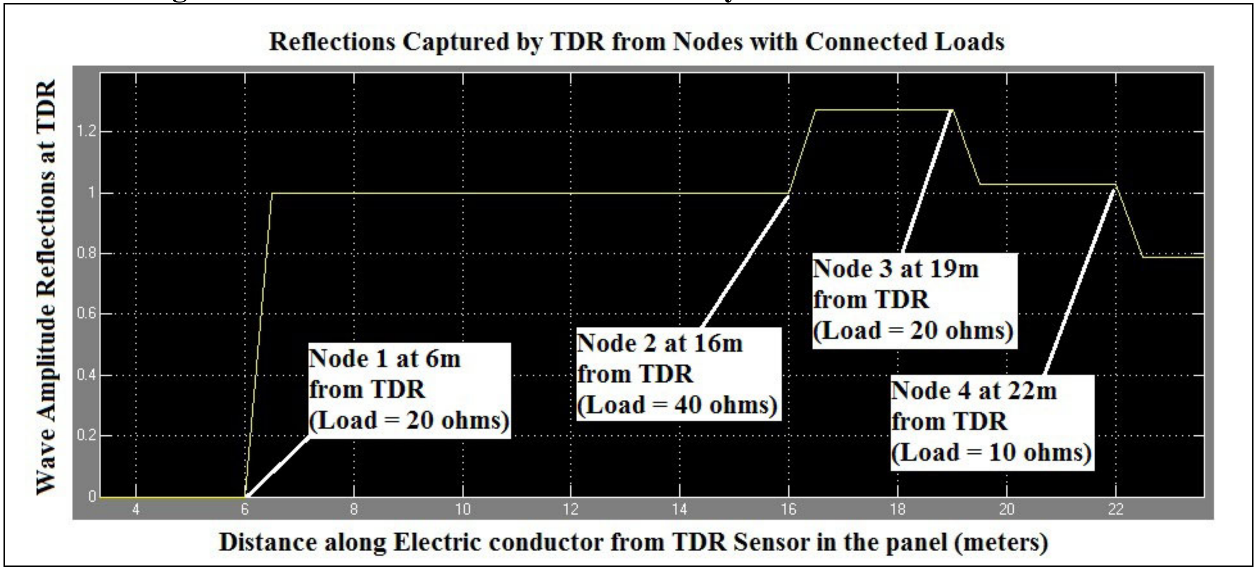
The core challenge of this research is to identify load locations remotely using TDR at the electrical panel level. To demonstrate the feasibility of this concept, MATLab tools are used to simulate a TDR configuration with a current carrying conductor networked with 4 nodes. Figure 6 shows a hypothetical simulation setup for the MATLab simulation.

Figure 6: Hypothetical Setup for MATLab Simulation of TDR.



The configuration setup in figure 6 consist of a TDR connected to a #14 AWG conductor linking 4 power outlets. The current state shows loads connected to all 4 nodes with 20, 40, 20, and 10 ohms, respectively. The MATLab simulation results of the TDR are shown in Figure 7.

Figure 7. Simulated Reflections Detected by TDR from Node Locations



Based on the simulated results shown in Figure 7, TDR captures reflections from node locations with connected loads. The graph shows amplitude reflections of TDR incident wave at respective distances of nodes from the electrical panel. The amplitude of the reflections increase when the change in impedance is increasing from node to node and decrease when there is a reduction. When there is no load or impedance change at the node or along the conductor no reflection occurs. The various node locations with connected loads are shown as reflections on the graph at 6, 16, 19, and 22 meters respectively from the TDR location.

Traditional TDR devices are used on non-live wires. For live wires (current carrying conductors), Spread Spectrum Time Domain Reflectometry (SS TDR) is used. Unlike conventional TDR, SS TDR injects a mixture of pseudo random, or noise (PN) and a sinusoidal waveform signals onto the conductor. The reflected signal is then mixed with a reference signal and fed into a correlator. The correlator output is then further processed to determine the location and nature of the impedance discontinuities (open circuit, short circuit, and intermittent arcs) along the conductor.

Preliminary Demonstration

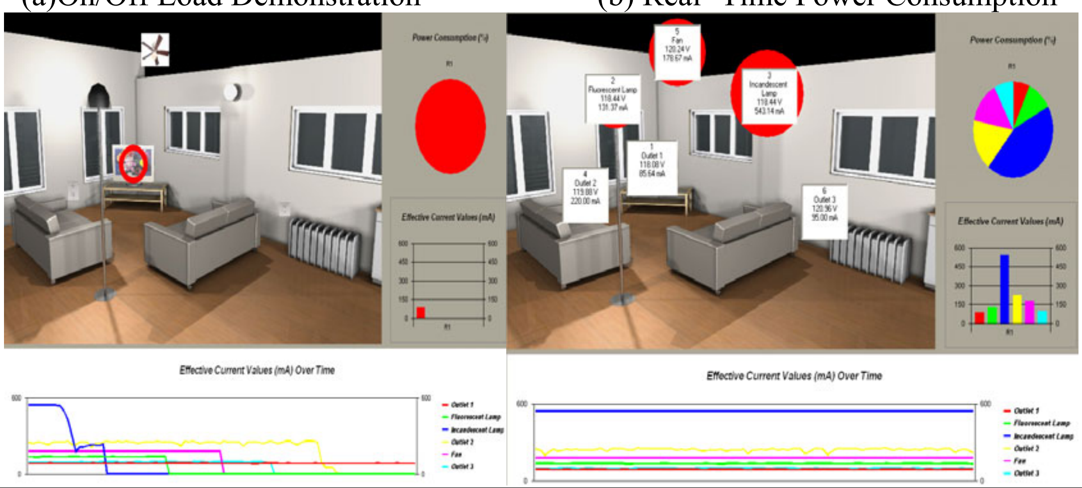
A prototype of the smart energy management system has already been designed and tested. In its current stage it has the ability to collect energy information from every electrical node in a building. Figure 8 is a picture of the system board built to simulate six loads. In order to better illustrate how the physical and virtual aspects of the system work in combination, the output of the board has been integrated with a model of the virtual environment. Created using the Visual Basic software, this virtual environment simulates a room in a house where the system might be implemented. Each load in this room is associated with one of the loads in the prototype board. When power is consumed at a load location, a red circle with a thickness proportional to the power consumption of that load will appear to notify users where to consumption can be reduced in their real-world environment.

Figure 8. The Prototype Board of the Smart Energy Management System (Alahmad et al. 2011)

Figure 9 is a screenshot of the virtual environment. The red circles help users identify locations of energy use and to warn them of possible energy waste.

Figure 9. Physical/Virtual Real-Time Integration (Alahmad et al. 2011)

(a)On/Off Load Demonstration (b) Real- Time Power Consumption



Conclusion

Based on the data acquired from a case study and previous research in energy feedback, it is clear that real-time energy feedback systems on the market are not currently meeting consumer demands. This paper introduced an energy management system for a smart environment that attempts to better meet these needs. The identification methods enabled by the TDR and model technologies of the prototype will reduce the need for hardware additions to the existing electrical circuitry of a building. Preliminary findings from the simulations indicate that a sensor technology can be developed that will upgrade existing electrical systems. This technology is designed to take into account some of the social variables of energy use, is cost-efficient, and can increase building energy efficiency. Thus, it holds promise in helping create for our built environment a more sustainable future.

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