Rapidly Adaptable Plug-load Simulation for Evaluating Energy Curtailment Strategies

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ABSTRACT

In this paper we demonstrate a proof of concept that quickly linking and modifying parameters of a user based simulation driven by real device audit data is possible. Further, we demonstrate an ability to simulate basic functions and behavior of users and their appliances in an office building and have made a solid case for the continuation of this work into a physical deployment. This framework is being developed specifically to help enable a system of distributed intelligent automated demand response (DIADR), as part of a wall plug-level automation system that is powered by user-driven electronic device ecosystems. The audit, powered by an Android application, is capable of populating a data-model with relevant information about plug load usage in a building. This data-driven inventory of devices, along with live meter feeds, can then be used to power a host of applications, such as automated "energy gateway" control of appliances, visualization for use of occupants, and energy-use guidance for individual users. We describe the mobile auditing application, the simulation setup and preliminary results, and how these will be incorporated into a user-driven system capable of power use reduction during times of extreme peak loads.

Introduction and Background

DIADR Project

Gateway control of devices is a new and emerging method of intelligent plug load control, the efficacy of which is currently being researched in residential and commercial environments that have a need to curtail electricity usage. This method of control is being researched as a possible method of enacting demand response strategies. Gateway DR will utilize pricing and energy based rule sets and real time electricity metering to guide actions that are capable of reducing power consumption [Arnold et al, 2012]. The current focus of this paper is a subset of the development for Distributed Intelligent Automated Demand Response (DIADR) – a demand response protocol being designed to as an extension of openADR, the open source Automated Demand Response protocol that enables open source demand response development [McParland, 2011]. The central premise of DIADR is that every single controllable power consuming device is accounted for and integrated into a system capable of providing a range of demand response services. These services may vary from slow, day ahead planning to sub-minute responsiveness in order to balance loads that were previously accounted for with spinning reserves. To accommodate this requirement, new demand response algorithms must be put into place that account for tens of thousand of high granularity control points, with associated telemetry and service requirements [Kiliccote et al, 2011]. Previous monitoring and control have been demonstrated using plug load meters [Xiofan et al, 2009], and some measures of energy management have been demonstrated using distributed systems [Marchiori, 2011]. We aim to deepen the field through the development of DIADR as high reliability, pervasive demand response implementation.

The DIADR project aims to lay out an example of how deep and distributed metering and control can be leveraged to reduce power by 30% during a demand response event. One goal

Figure 1: Typical plug load use on a floor in SDH

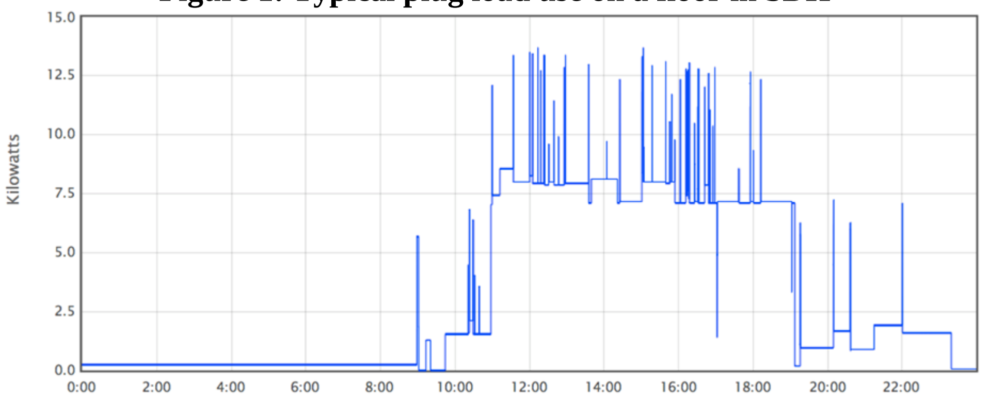
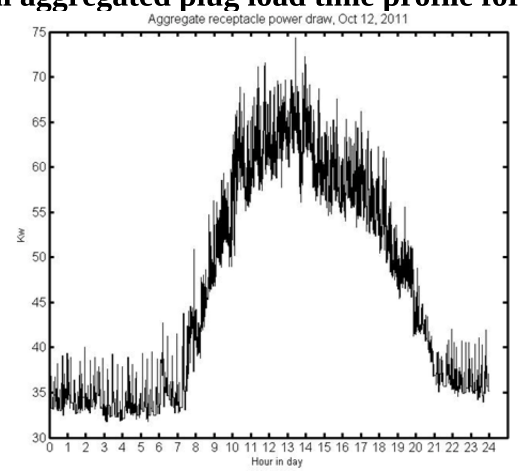


Figure 2: Typical aggregated plug load time profile for all floors of SDH



behind this is to provide a system that allows us to selectively de-activate devices within many efficient buildings instead of turning on many inefficient power plants. Specifically, in this paper, we address the usage of wall-plug loads and their associated behavior within the building through the lenses of auditing and simulation. This will be done through an ability to modulate, monitor, control and aggregate any component of the electrical tree structure of Sutardja Dai Hall (SDH), a 141,000 square ft, mixed use building on the UC Berkeley Campus. In the present paper, we observe the demand response ability of plug loads in SDH. **Error! Reference source not found.** shows the power consumption of one floor of a building over a typical weekday, with spikes caused by singular devices with high power draws. **Error! Reference source not found.** It shows the aggregate power-draw of the entire building's plug loads, indicating a diurnal cycle within the building, as would be expected for occupancy in a mixed-use office building.

Full scale-testing of plug load demand response within any building would be excessively difficult due to the constraints of budget and occupant acceptance. Therefore, in order to justify the need for such wide-ranging testing, we have demonstrated how real plug load data may be loaded into a simulation that can empower us to make intelligent decisions about power use in the building.

Methods

This section will describe the Rapid Auditing Protocol and simulation and their relationship. A description of the visualization can be found in the results section.

The Rapid Auditing Protocol

The Rapid Auditing Protocol (RAP) is an Android based application that allows for easy registration of devices that are plugged into the electrical system of a building. In this context, registration is defined as placing a link to the device into a data-stream such that a monitoring or control framework is aware that it exists. After being registered using our Mobile StreamFS (A streaming file system) (www.is4server.com) application, the device becomes a "resource" in the system – that is, either a current drawing device or a sensor stream publishing data. This information is encoded in a form that is readable as a passable object within our computation system, enabling the movement of the resource between handlers with ease.

Specific information about devices used for RAP includes building location, room number, coordinates within that room, power demand or current draw, make, and model number. From this information, the device is matched to a description within a standardized device taxonomy so that an educated guess may be made as to its behaviors and consumption patterns. The taxonomy we use is the MELS taxonomy described by Nordman et al (2006).

When an auditor starts RAP on their Android device, they are presented with a series of options to choose from, shown in Figure 3. These devices allow the user to build, interact with, and modify the device tree as they see fit. In order to add a room or device to the tree, that item must be assigned a QR code to act a physical identifier – it is the reference key for all instances of that device within the device ecosystem. Figure 4 shows a device and its corresponding QR code below.

Figure 3: RAP appliance edit screen

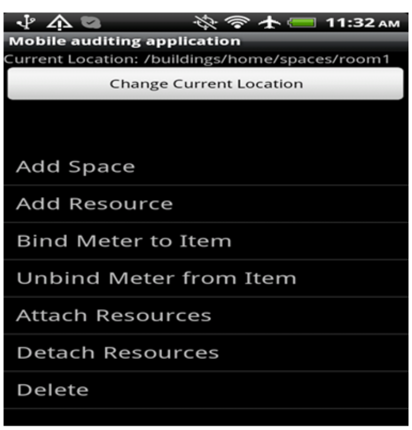


Figure 4: Device with QR code in upper left hand corner

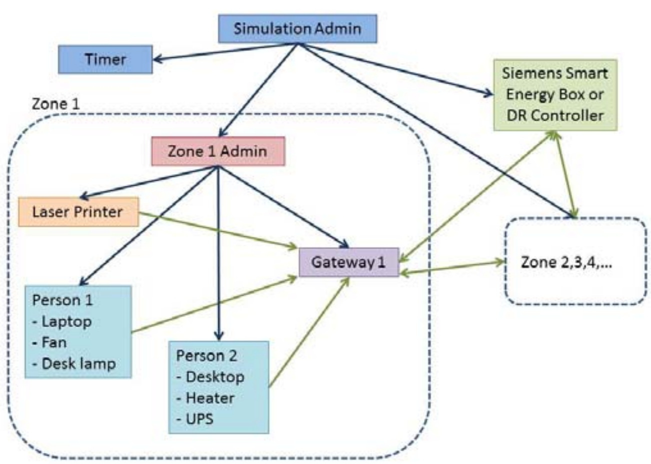
It is from this screen that the auditor selects their interaction with the cyber-physical device ecosystem. Devices can be added in a short amount of time, and from entry to appearance in the database takes less than a minute. Devices may be bound to other devices, as in the case of a metered object, in which case the device being metered will have the meter as a sub-device within the device tree (This can be viewed as parent-child configuration). The metered instances have a subscription to the sensor feed that is attached to the object, in this case a wireless-mesh enabled power meter that monitors single plug consumption. Devices may be unbound from their meter and re-bound to the same or different meter by scanning the QR code on each device in the "Bind meter to Item" menu selection. This allows for devices to be quickly moved around in the case of an updated audit.

Simulation

In order to prepare for full-scale deployment of an actual DIADR system in SDH, a simulation is being utilized to evaluate for possible problems and areas of optimization. While several actual Gateways will be implemented as per project goals, these will only cover a small portion of the total building due to limited available hardware and time. The simulation will give important insight into a single Gateway's strengths and weaknesses and highlight their potential in a building-wide, distributed setting.

To simulate each Gateway's local domain of influence, the building is split up into several zones which are defined by the user. A zone can range from a single office, with one or more occupants, to a group of offices or cubicles. Areas with partial separation such as open area with cubicle dividers in which a source of lighting is shared by several inhabitants can be split any number of ways, a natural choice being by lighting banks or lighting control zones. Each zone contains a single Gateway, one or more people and their personal and shared appliances. The appliances simulated are those commonly found in an office such as laptops, desktops, monitors, fans, heaters, printers (personal and shared), coffee makers, etc. Figure 6 provides a reference to the structure of simulation.

Figure 5: Simulation Structure. Blue arrows represent ownership and control, green arrows represent information



The simulation uses a central clock with a user defined start time, stop time and time step, usually chosen as one minute. At each time step the simulated people update their states based on time and other factors. If their change in state calls for it, the person issues commands and interacts with their appliances. An example is when a person becomes too warm, they will turn on their fan should they have one. The appliances then update their other states that are not directly controlled by their owner, such as a desktop updating its power use to 100W when turned on. Next, the Gateways in each zone poll the local appliances for data. After this happens a data recording scheme is instructed to collect data from all simulated people and appliances within the zone and from the local gateway.

The simulation is written as a standard Java program. The structure of the simulation can be viewed like a tree with bifurcating branches. The main class reads from a configuration containing the simulation parameters for the run. The main class generates multiple Zones with the specified characteristics. Each Zone generates one to several People according to the configuration file. Each person generates the appliances assigned to the by the configuration file. Each Zone also generates a local Gateway, which in turn generates an agent to represent itself using JADE (Java Agent Development framework). Once the necessary objects are set up, the main class starts time stepping until the stop time is reached.

As stated earlier, the simulation is rapidly adaptable in that the input parameters are easily changed and automatically generated from the live audit data. The authors have developed a script which reads RAP data from data-streams to generate the configuration file to be fed into the simulation. This script identifies clusters of appliances, and assigns a person to be their owner. Other appliances, such as printers do not have an owner and so are shared by all people in the zone. The script then generates a file, containing the number of people per zone, their appliances and appliance parameters from RAP data.

The control strategy employed by simulated Gateway, during a DR event, is that of their real world counterparts. Real world users are able to use a web based UI to input their preferences for their appliances. One important preference is called the priority, which is an integer between zero and ten. Appliances with priority of zero are of low importance or have a long lasting battery backup. Higher priority appliances are more important to the user and may not have a battery backup. Using this information, the real and simulated Gateways control lower priority appliances first, increasing the priority to control until the load reduction goal is met or a priority maximum limit is reached.

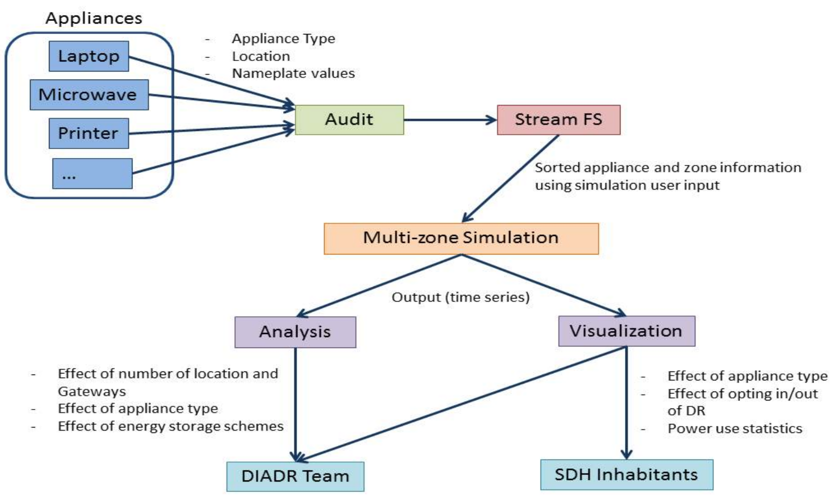
Currently all people in all zones only use simulated desktop computer and monitors. In the real implementation of the Gateway, desktops and monitors are dumb appliances, meaning they lack communication and control capabilities. Therefore they rely on wireless plug load sensors and load switches for these services. They also contain two main power states, on and off. These aspects of the appliances are modeled in the simulation. A person can only turn a desktop and its monitor on and off, and when on the desktops and monitors each draw a constant power. As the Gateway appliance structure and inter-object communication are improved, more appliance types will be added to give a better representation of the office environment. Devices to be added will include smart appliances to be modeled after the devices metered in the audit.

Relationship between RAP, Simulation and Visualization

The three processes in this paper, RAP, simulation and visualization, are joined together by to as an experimental tool. The relationship between the three parts can be seen in **Error!**

Reference source not found.. A user utilizing RAP will audit appliances and devices in the building gathering data about them. This information is sorted and analyzed by the audit and posted to Stream FS. When the simulation is run, it polls Stream FS for appliance and occupant data to use as parameters. The output of the simulation is the fed into various analysis tools such as the visualization described in this paper. The visualization provides feedback to the DIADR project team as well as information to the occupants of SDH.

Figure 6: Depiction of relationship between RAP, the simulation and visualization

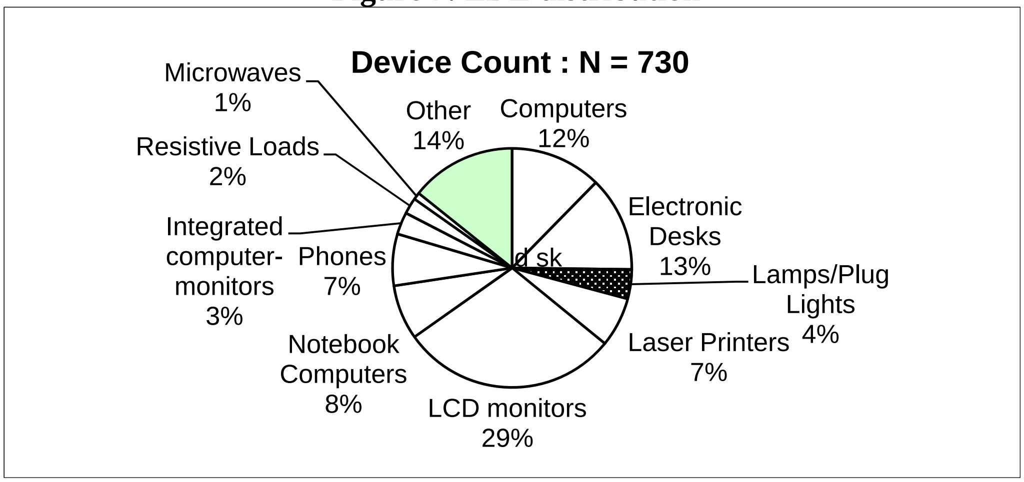


Results

Taxonomy of Devices from RAP

The devices within the building form what we refer to as the "Local device ecosystem" or LDE for short. The LDE is formed from a combination of the pre-defined taxonomy described above, and the observed occurrence of devices within the building. For the simulation described, the LDE is utilized to define the necessary proportion of devices as a function of significant observations of devices from RAP. Minor instances of device occurrence are treated as a bulk group and lumped into an 'other' category. The distribution is shown here in Figure 7.

Figure 7: LDE distribution



Based on the properties of devices in the LDE, devices can be allocated into several behavioral classes that define their contribution to the overall plug load of SDH. Devices fall into the main classes: base load, intermediate and peaking devices (similar in theory to power plants of the same description. Base load devices are those such as computers and phones, which contribute to loads not as a function of their average power draw. This base load is a product of the fact that individual users cannot ascertain that their devices should be shut off at night, and as such, fail to save energy during a time at which doing so would be easy. Intermediate loads, such as LCD monitors, notebook computers, and lamps will be switched to on and off states in a random fashion, yet have a power draw below 200 watts. Informing the occupants of the power use of these devices will help them gain an intuition of their power use when devices are switched on. Peaking devices are those with large power draws (>500W) that go on at random intervals for short periods of time, thus significantly endangering any peak capping that is targeted in the building. Examples of peaking devices include coffee pots, tea-kettles, and laser printers. It should be noted that among these devices, it is not a simple task to defer load, and as such, these devices may be considered randomly distributed peaks in the power signature.

Sample Simulation Results

In its current state, the simulation lacks a proper representation of a complete suite of office appliances. It also lacks a detailed model of inhabitant behavior. The authors are currently developing a probability-based model for simulated people and researching the behavior of appliances. As the simulation does not have complete models for people and all appliance types, this section will described the output of a sample simulation run.

The current simulation version has three building zones incorporated. The first zone (Zone 0) has two people, each with a desktop computer and monitor, and represents an office. The second zone (Zone 1) has five people, each with a desktop computer and monitor, and represents a small workgroup. The third zone (Zone 2) has fifteen people, each with a desktop computer and monitor, and represents an open work area or group of offices. In the figures below A DR event was scheduled into the simulation to start at 1:30 pm and end at 3:30 pm, with the objective of reducing peak power use by a minimum of 18%.

Figure 8: Zone 1 desktop power state over a day. A state of 1 is on, a state of 0 is off

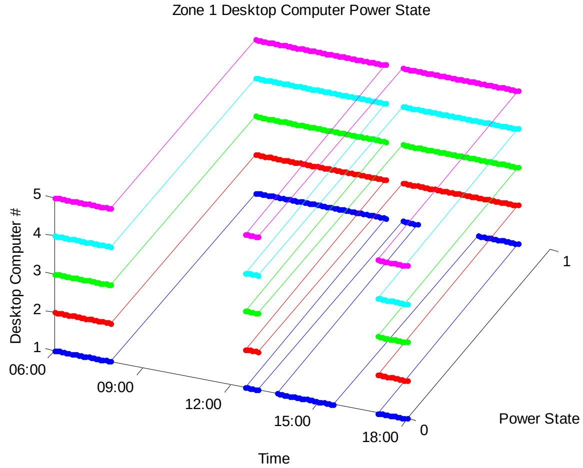


Figure 9: Desktop control state. A state of 1 indicates being under gateway control.

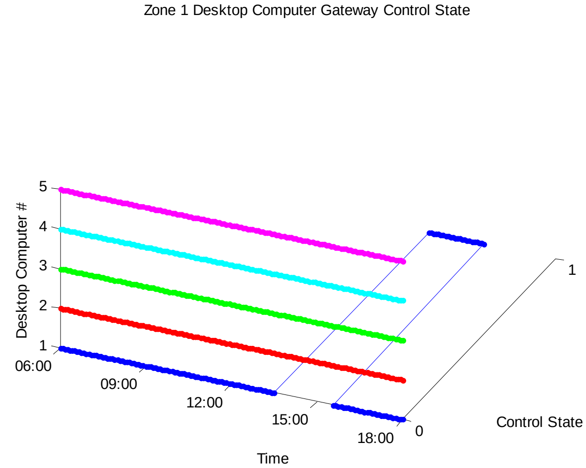


Figure 10: Zone 1 desktop monitor power draw over a work day

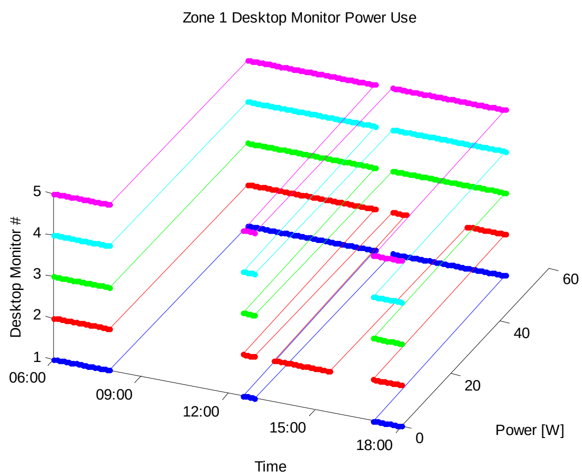
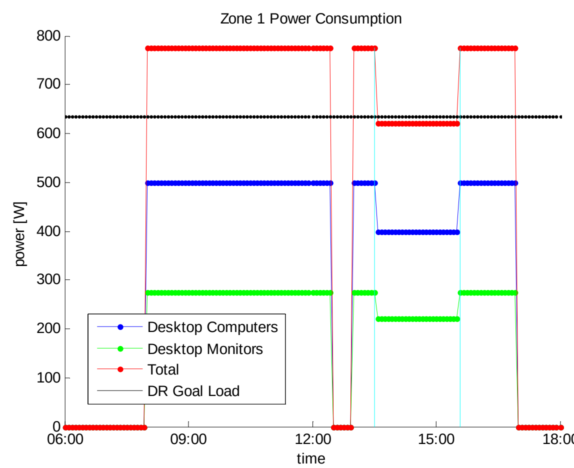


Figure 11: Zone 1 power consumption over a work day with DR event



Error! Reference source not found. shows the power state of the five desktop computers in Zone 1. It can be seen that they all start the day with turned off (a power state of 0), and are turned on at 8:00 am when their owners arrive at work. At 12:30 pm they are turned off while the workers go to lunch and at 1:00 pm are turned back on. At 1:30 p.m. the simulated DR event starts, cueing each zone's Gateway to calculate the total load. With this information, the Gateway calculates it goal load, in this case an 18% reduction from peak. The Gateway then employs its strategy, discussed above, to reach the goal. It can be seen from **Error! Reference source not found.** that Desktop 1 in Zone 1 becomes controlled by its Gateway, and is turned off. As can be seen, Desktop 1 has a low priority and is therefore controlled by the Zone 1

Gateway, shown in **Error! Reference source not found.**, which turns it off for the duration of the event. Figure 10 shows the power consumption of the desktop monitors in Zone 1. It is easily seen that one of the monitors (number 2) is put under Gateway control during the DR event and is turned off. This is due to its user assigning it a low priority. Figure 11 shows the total power use of Zone 1.The power use follows an easily recognizable usage pattern of a simplified work day. The cyan lines mark the start and end of the DR event. As a desktop computer and monitor are under Gateway control and turned off during the event, the total load of each is reduced, as is the total zone load until it meets the load reduction objective. At this point the Gateway enters a passive state until the end of the event, whereupon it releases control, turning the appliances it controlled back on.

Visualization

In an effort to provide timely, relevant and actionable feedback to the users of electrical devices in a participant's zone, a visualization has been developed that is useful for conveying real knowledge of energy usage. As can be seen from the figure below, power usage from individual devices is fed into a diagram of an office in real time. Devices have power draws that are displayed in a heat-map fashion, with white being the greatest, and black being the least, and warm colors indicating the transition. In our design consideration for this portion of the project, attention was paid to specific properties of influential visual graphics. A successful visualization that has potential to reduce power use must have several properties (McKenzie-Mohr, 2011):

- *Timely and Relevant prompts:* Live data has a much more immediate effect on users than data that is old, or feedback on past actions.
- *Spatial familiarity:* The user must be able to feel a connection with the space that they are in, and as such it is best to provide them with a map of their current environment overlaid with power use information.
- *It must be Simple and self-explanatory:* The model will scale the visualization from black to white through a 'hot' spectrum in order to alert the users as to their power usage during the day.

Below in figure 12 is our initial visualization, which will be deployed throughout the building as this work progresses.

Figure 12: visualization of SDH

Preliminary room 464 in

Conclusion

In this paper we demonstrate a proof of concept system that can quickly link and modify parameters of a user base simulation based on real device audit data. Further, we demonstrate an ability to simulate basic functions and behavior of users and their appliances in an office building and have made a solid case for the continuation of this work into a real physical deployment. The visualization has been shown to be able to link the output of the simulation to reality of metered data and enables an advanced user intuition of electrical loads. This will be useful in effective garnering optimal DR strategies as outlined by the simulation.

Future Work

The overall system we have described is in the pre-production stage and as such, is still being refined and re-assessed at every step. The protocol and definition of RAP have been developed over the past year and a half, and thus is at a mature stage. Our current area of focus is on improving the live metering of appliances registered by RAP as well as the infrastructure required to do so efficiently and expediently. The connection between RAP and our streaming data-system and the simulation is also being improved upon. While it is able to locate clusters of appliances and assign a person to be their operator, it does not yet have the capability to adapt and enter the parameters specific to each appliance - drawing from live metering to give more realistic values of power draw. This is being evaluated through a lens of statistical inference of device properties, a useful technique as we move to the phase of our research where we will determine exactly how many meters we need to accurately monitor a building.

Continuous improvement and expansion of the simulation is a key part of this work – appliance models such as laptops, fans, printers, etc. must be included. Accurate modeling of people is also being researched, and we are working to build in real time occupancy sensing in order to inform the probabilities upon which our model is based.

Finally, our visualization will form the key part of the future progress of our work – as this work is refined, live “best options” will be superposed on the metered feedback so that users may determine what the simulation has derived as the optimal power saving option. Appliances will be given individualized application screens so that users may become education and work to save energy on a broader, more informed level.

Acknowledgements

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