Title
An Architecture for Integrated Commercial Building Demand Response

Permalink
https://escholarship.org/uc/item/8fh50034

ISBN
9781479913039

Authors
Sankur, Michael
Arnold, Daniel
Auslander, David

Publication Date
2013

DOI
10.1109/pesmg.2013.6672800

Peer reviewed

An Architecture for Integrated Commercial Building Demand Response

Michael Sankur, Daniel Arnold, David Auslander
Department of Mechanical Engineering
University of California, Berkeley
Berkeley, California 94720
http://i4energy.org/index.php/projects/affiliate-projects/6-sutardja-dai-hall/
http://mechatronics.berkeley.edu/gateway.htm
msankur@berkeley.edu, dbarnold@berkeley.edu, dma@me.berkeley.edu

***Abstract*—Enthusiasm for commercial demand response (DR) has inspired research efforts to create new building electric load control frameworks. In this paper we introduce a software architecture for an integrated building control system, the Central Load Shed Coordinator (CLSC). The CLSC provides functional control over three building systems which are large power consumers: lighting, HVAC, and plug loads. The system acts upon external demand response signals to meet load-shed criteria, while minimizing occupant inconvenience. In this paper, we present the purpose and relevant characteristics of this architecture. In addition, we discuss its deployment in a UC Berkeley building and present results from preliminary testing.**

***Index Terms*—Commercial Demand Response, Distributed Plug Load Control, Energy Information Gateway, Energy Management System**

I. INTRODUCTION

Commercial demand response is gaining popularity as a way for building managers to prevent high costs and fees associated with peak energy costs, and for utilities to satisfy growing energy demand with existing infrastructure [1]. There has been significant research into the impact and implications of demand response in both residential and commercial buildings. In [2], the authors present a central building load control scheme for a variety of appliances, and discuss the differences in appliance control with regard to an appliance's innate control capability or lack of. An experiment in which the architecture is used to demonstrate the effectiveness of different DR strategies is also discussed. In [3], the authors present a centralized energy management system for automated demand response. They investigate the viability of wireless communication hardware. In [4], the authors discuss the motivation for, and development of, a framework for coordination of multiple local plug load controllers. A small deployment of this framework in a commercial space is examined. While noteworthy, these efforts do not adress problems associated with employing several diverse load-shed resources.

Most modern commercial buildings contain a building energy management system (BEMS), capable of controlling lighting and HVAC systems, that can be leveraged to curtail total building load during critical demand periods. In the current commercial demand response context, where most likely a building manager would choose how to reduce building load, choosing between two or three available, yet different, resources may be a tough decision. It may also be difficult to continuously monitor building-wide lighting and HVAC systems to detect problems and occupant overrides over control actions. Additionally, while a load-shed goal may be met, doing so may adversely impact occupant (dis)comfort and productivity throughout the building. Thus, automated load control technologies are being researched to address these problems.

Once such technology, often referred to a gateway, a home and/or commercial energy management system, enable distributed plug loads to become a viable load-shed resource at the building level. One specific gateway is under development, in the UC Berkeley Mechanical Engineering Department, as a reference design and is referred to as the Energy Information Gateway, or EIG. The EIG is a software program that facilitates energy related communication and control for connected components in a residential or commercial environment [5]. Multiple EIGs require a mechanism to coordinate their actionable resources at the whole-building level in order to meet an overall load reduction goal [4]. The EIG has

This work was sponsored by the US Department of Energy (DOE) through a joint project between UC Berkeley and Siemens Corporate Research (SCR) entitled Distributed Intelligent Automated Demand Response (DIADR). Work on the EIG was mainly sponsored by the California Energy Commission (CEC) Public Interest Energy Research (PIER) program and the California Institute for Energy and the Environment (CIEE).

been deployed in small numbers to manage connected office plug loads in a large mixed-used building on the UC Berkeley campus, Sutardja Dai Hall (SDH), as part of a DOE funded project. The Distributed Intelligent Automated Demand Response (DIADR) project has the ambitious goal of curtailing total SDH building load by 30% from peak consumption through lighting, HVAC, and plug load control [6]. For these reasons, a software architecture for a central building controller, called the Central Load Shed Coordinator (CLSC), was developed.

The purpose of the CLSC is to provide a centralized mechanism for control of the three large consumers of building electricity: lighting, HVAC and plug loads. Lighting and HVAC systems can be viewed as central resources from a control standpoint, as they are usually monitored and controlled from a single entity such as a BEMS. However, plug loads are viewed as a distributed resource, which are monitored and controlled via multiple EIGs coordinated by the CLSC. While commercial demand response has mainly been focused on lighting and HVAC systems, the use of the CLSC in conjunction with EIGS implements the untapped resource of plug loads. In doing so, we show that several load-shed resources can be employed separately or in tandem to meet a power savings goal with minimal inconvenience imposed on building occupants. The following sections will discuss the design and function of the CLSC, its modular software architecture, system deployment, and field tests.

II. OVERVIEW

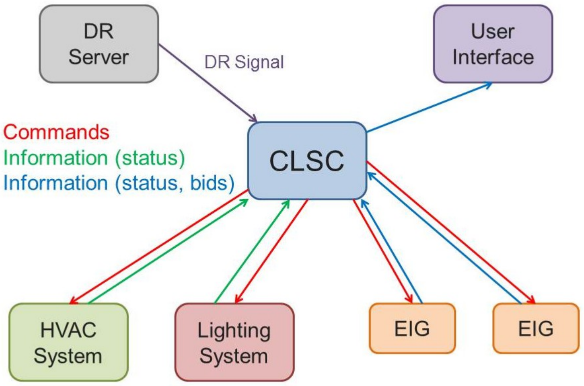

Fig. 1: CLSC architecture within a commercial building.

The CLSC is designed as a program that facilitates coordinated control over building lighting, HVAC, and plug loads. As shown in Fig. 1, the CLSC has the ability to poll DR servers for event information, and can display pertinent building information to a building manager via a user interface. The CLSC is also an energy related information aggregator, quite similar to an EIG as described in [5]. An EIG communicates with, and gathers data from, connected plug loads in its domain; whereas the CLSC gathers data on lighting and HVAC systems, as well as pertinent plug load information from EIGs. The CLSC communicates with, and controls, lighting and HVAC systems. The CLSC also communicates with EIGs to allow the participation of their plug loads in the load-shed process.

In order to generalize actuation resources across the three systems, a measure of power and occupant inconvenience is needed so actuation of different resources can be compared. Terminology relevant to this process is now discussed.

A **strategy** refers to what control actions, and at what times, a system (lighting, HVAC or plug loads) will actuate. A strategy has one or more steps (control actions at times relative to the onset), and a time validity window for when it can be used. For example, a lighting strategy may turn off all hallway lights on all floors at its onset and dim all office lights on the fifth floor after 30 minutes.

A **bid** is a time profile of power savings with an associated metric of inconvenience (occupant discomfort and/or loss of productivity). Every strategy has an associated bid, which is calculated in the context of the strategy being activated at a certain time. For example, a two hour lighting strategy activated at noon may reduce power by 20 kW for its duration, with a low level of inconvenience, and a three hour HVAC strategy activated at 1 p.m. on a hot day may save 100 kW with a much higher level of inconvenience.

A **plan** is a group of strategies and the time(s) they are to be activated. For example, a plan may consist of enacting an hour long lighting strategy at 2 p.m., and a three hour HVAC strategy starting at noon.

Due to the diverse nature of the load-shed resources, and given communication hardware requirements, the CLSC is sectioned into four modules (see Fig. 2): Core Module (CM), Lighting Module (LM), HVAC Module (HM), and Gateway Module (GM). The CLSC encompasses a two-tier design, where the CM acts as the information coordinator for the LM, HM and GM. The CLSC is designed so that a lower level module may be replaced or modified to accommodate for different communication standards, without the need to redefine intra-module interaction. The process in which the CLSC operates for a single DR event is as follows:

- The CM polls for, and receives a DR signal
- The CM parses the signal, sends it to each module,

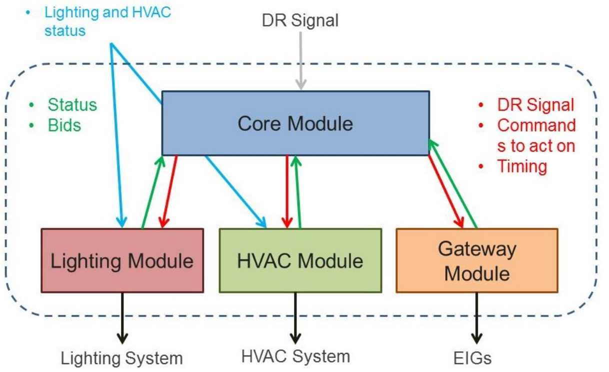

Fig. 2: CLSC software architecture, with the dashed line representing the boundary.

and the GM relays the signal to EIGs

- The LM, HM and EIGs, with knowledge of a priori defined strategies, calculate associated bids
- The CM collects all bids and a plan is selected either by the user or optimization program
- The CM schedules strategy execution for lighting and HVAC and relays plan to EIGs
- The CM queries each module for pertinent system information

The CLSC can repeat the aforementioned process for multiple non-overlapping DR events. The flow of the DR signal, bids, system information and instructions between modules is highlighted in Fig. 2 The software architecture of the controller will now be discussed along with the specifics of its interaction with the three load-shed resources.

III. SOFTWARE ARCHITECTURE

A. Core Module

The CLSC core module acts as the architecture administrator. The CM handles DR event timing, and contains scheduling logic for strategy execution and system monitoring. The CM polls openADR [7] compliant DR servers, and when a valid DR signal is received, the CM interprets the signal for its own timing and relays it to the three other modules. Once a plan is chosen, the CM instructs the GM to relay the plan to the EIGs. The CM schedules execution of strategies for lighting and HVAC, instructing the LM and HM to perform a step of a strategy at the appropriate time.

B. Lighting Module and HVAC Module

The lighting module (LM) is the communication bridge between the CLSC and a building lighting system. The LM has knowledge of user defined lighting strategies. When prompted by the CM calculates associated bids for each strategy, which are returned to the CM when requested. The LM contains methods to send commands to a lighting system for control. It also contains methods, that are called by the CM, to query for system information. The HVAC module (HM) parallels the LM in function, but for the HVAC system. The separation of functionality into two modules is to accommodate for differences in lighting and HVAC system communication. Furthermore, lighting and HVAC are likely to have different types of strategies. Lighting is usually actuated with binary control (on/off), and HVAC systems contain multiple control parameters for temperature, flow rates, operation mode, etc.

C. Gateway Module

The Gateway Module enables communication between the CLSC and EIGs in SDH. The paradigm in which this architecture is designed is for the EIGs to aggregate data from, and control, plug loads within their domain (the reader is invited to read the highly relevant papers [4], [5]). The GM utilizes existing infrastructure, such as WiFi, LAN, or Zigbee, to host a network for CLSC-EIG communication. The GM disseminates the DR signal to the EIGs. EIGs read user defined strategies for their connected plug loads and create associated bids. The bids are passed up to the CM through the GM. When a plan is selected, the relevant information is sent to the EIGs through the GM. The GM contains methods to poll EIGs for overall and plug load status.

D. Optimization Program

As mentioned earlier in this paper, a plan is chosen based on strategies and bids from the three modules. Every strategy has an associated bid, which is calculated from the strategy and models of power saving and inconvenience. The term inconvenience is a measure of the negative effects of actuation of a load-shed resource. Inconvenience can be loss of productivity in man-hours or dollars, or a measure of occupant discomfort, such as the square sum of occupant preferred temperature to actual temperature. Models for power saving and inconvenience are user defined and the architecture is designed for ease of modification and replacement. While a building manager can choose a plan based off the bids, the CLSC is designed to be able to utilize a modular optimization program.

The optimization program takes in bids and associated strategy timing parameters as its input. The program objective is to minimize total inconvenience while meeting a power reduction constraint (the load-shed goal) over a period of time. It returns a course of action (plan) for a user defined cost function and set of constraints. The architecture is also designed for ease of modification of the optimization program parameters. When the optimization program is used, the CLSC is fully automated in the sense that it only requires a user to initiate the program.

E. *User Interface*

Though the CLSC is designed as an autonomous architecture, it is still important to provide pertinent information to a building manager and/or occupants. Furthermore, the building manager needs to retain supervisory control over the architecture and its control decisions. For safety reasons, he or she must be able to interrupt CLSC operation, assume control of the a system, and return the systems to their defaults, should the need arise. To this end, the CLSC incorporates a simple user interface (UI). The UI displays relevant information such as total building load, DR event parameters and plan/strategy information. It also allows a user to interrupt operation and restore system defaults.

IV. ARCHITECTURE DEPLOYMENT, TESTING AND RESULTS

The CLSC is currently deployed as part of a automated DR system in SDH. The adaptation to the building's communication and control media is shown in Fig. 3. The LM and HM communicate with a BACnet, an interface to the SDH BEMS, server over LAN [8]. The LM and HM periodically poll sMAP (simple MAnipulation and Actuation Profile), a repository of energy related information, for information on the lighting and HVAC systems [9]. The GM utilizes JADE (Java Agent DEvelopment framework) to create a network for communication with EIGs. JADE is a FIPA compliant agent-based framework [10]. A comprehensive discussion of how JADE is used for communication between EIGs and a central administrator can be found in [4].

The CLSC has undergone several tests to determine its efficacy in load-shedding for a hypothetical DR event. During tests, the CLSC controlled both lighting and HVAC in SDH, and networked with a handful of EIGs for plug load control. The CLSC is run on a desktop computer in SDH. Tests involve several EIGs within an office, connected to a variety of plug loads. The small number of EIGs and connected plug loads means that plug loads are a negligible portion of potential load-shed, but these tests have proven the ability of the CLSC to coordinate multiple EIGs with building wide lighting and HVAC. Several custom strategies for each resource are designed by the authors a priori to each test, representing a range of load-shedding options.

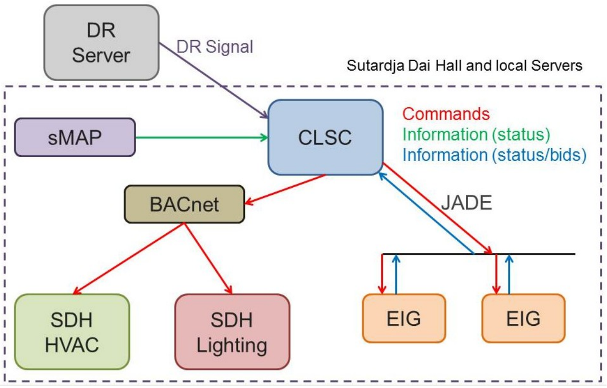

Fig. 3: CLSC deployment in DIADR project DR system in SDH.

Once such test was performed on October 1, 2012, with a hypothetical DR event from 2 p.m. to 6 p.m. The LM and HM and EIGS contained knowledge of a few strategies for their respective systems. Upon request of the CM, these bids were presented to the optimization program which selected a plan consisting of a lighting strategy from 2 p.m. to 4 p.m., and an HVAC strategy from 10 a.m. to 6 p.m.

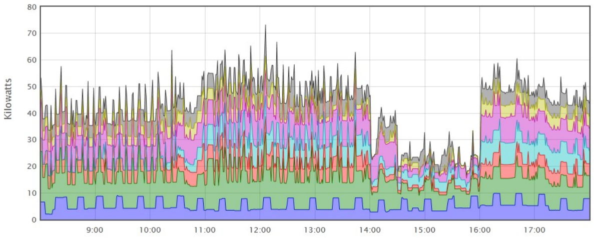

Fig. 4: Lighting power consumption for Thursday October 1, 2012. The total floor lighting power consumption for floors 1 to 7 of SDH are stacked bottom to top. The square wave like pattern on the first floor is from water heaters, and the spikes from the second floor are cafeteria refrigerators.

Fig. 4 displays the total lighting power for each floor in SDH. During normal midday operation, the total building lighting power is between 45 and 55 kW with the exception of large power spikes. It can be seen, at 2 p.m., immediately after the start of the DR event, the total lighting load drops significantly, only to rise shortly thereafter. This immediate rise is surmised to be in part from occupants turning their local lights back on. The CLSC, through querying sMAP, learned of lighting zones which were on after the initial command was issued. It then reissued as appropriate commands to switch the lighting zones off. After the initial rise, the total lighting power drops again and settles at roughly 25 kW. This is an approximately 50% drop in total lighting power from before the event.

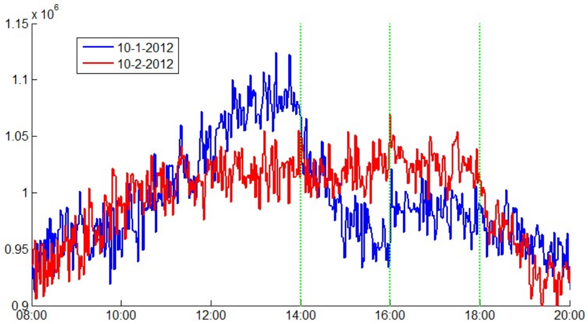

Fig. 5: Total SDH electricity load for two hot days. The green dashed lines represent, from left to right, start of DR event at 2 p.m., CLSC relinquishing lighting control at 4 p.m., and end of DR event at 6 p.m.

Fig. 5 shows the total building power from the test day of October 1 (blue), and the next day October (red), which is used as a baseline (normal operation) due to the very similar weather. The second strategy used in this test was an HVAC precooling, wherein the entire building would be set to cool to 70° F from 10 a.m. to 2 p.m., at which time the building would be set to cooling mode with a set point of 76° until 6 p.m. Essentially this strategy cools the building when energy is cheap, and only cools when necessary when electricity is expensive. This time-shift of building load is easily seen seen in Fig. 5, where the total load for the test day is higher than normal until the start of the event and lower until then end of the event. When both the lighting and HVAC strategy are activated the maximum shed is roughly 70 kW around 3:30 p.m. When only the HVAC strategy is active the load-shed is roughly 50 kW. These promising results demonstrate the effectiveness of the CLSC as a load-shed coordinator between the three resource of lighting, HVAC and plug loads. The ability to generalize actuation of these systems, and choose how to meet a load-shed while minimizing a measure of the negative effects of doing so, is clearly evidenced.

V. SUMMARY AND FUTURE WORK

In this paper an architecture for a central building energy and load-shed scheduler is introduced. Similar efforts to this architecture are presented and the purpose and background of the architecture are given. An overview of the architecture is presented, highlighting on a bidding process to generalize across multiple load-shed resources. The software architecture, its tiered design and execution process is discussed. An overview of how the architecture can utilize an optimization program is also given.

The adaptation of the CLSC for use in a UC Berkeley campus building is shown. Testing of the CLSC with hypothetical DR events is discussed and results presented. The CLSC was able to reduce lighting load by roughly 25 kW, and total building load by 70 kW. Testing also demonstrated the ability to generalize load-shed actions across different systems.

The CLSC is a central component of the automated DR system for SDH, as it actuates the load shedding of both central and distributed loads. Further efforts on the CLSC will concentrate on improving models for power savings and inconvenience computation. Another key area for future efforts is the closed-loop control algorithm for load reduction, in which the CM may choose to rehost the bidding process. Finally, it is envisioned that the lighting and HVAC modules will be given intelligence to create a unique set of strategies for a DR event using the event parameters.

VI. ACKNOWLEDGMENTS

We would like to thank Therese Peffer, Domenico Caramagno, Andrew Krioukov, Jay Taneja, Tyler Jones and Jason Trager for their invaluable help and support in this endeavor.

REFERENCES

[1] National Action Plan for Energy Efficiency (2010). *Coordination of Energy Efficiency and Demand Reponse*. Prepared by Charles Goldman(Lawrence Berkeley National Laboratory), Michael Reid (E Source), Roger Levy, and Alison Silverstein. <www.epa.gov/eeactionplan>

[2] M. LeMay, R. Nelli, G. Gross and C. Gunyer, “An Integrated Architecture for Demand Response Communications and Control”, in Proc. *Proceedings of the 41st Hawaii International Conference on System Sciences*, Waikoloa, Hi, 2008.

[3] M. Pipattanasomporn, M. Kuzlu and S. Rahman, “Demand Response Implementation in a Home Area Network: A Conceptual Hardware Architecture”, in *Proceedings of the 2012 IEEE Power and Energy Society Conference on Innovative Smart Grid Technologies*, Washington, DC. 2012.

[4] D. Arnold, M. Sankur and D. Auslander, *An Architecture for Enabling Distributed Plug Load Control for Commercial Building Demand Response* unpublished, accepted for publication at *IEEE Innovative Smart Grid Technology Conference*, Washington, DC, 2013

[5] D. Arnold, M. Sankur and D. Auslander, “An Energy Information Gateway for use in Residential and Commercial Environments”, in *Proceedings of the IEEE Power and Energy Society General Body Meeting*, San Diego, CA, 2012

[6] T. Peffer, et.al., *Deep Demand Response: The Case Study of the CITRIS Building at the University of California-Berkeley*, unpublished, presented at the *ACEEE Summer Study on Energy Efficient Buildings*, Monterrey, CA, 2012

[7] (2012 October) openADR website. [Online]. Available: http://www.openadr.org/

[8] (2012 September) BACnet website. [Online]. Available: http://www.bacnet.org/

[9] (2012 August) UC Berkeley EECS sMAP website. [Online]. Available: http://code.google.com/p/smap-data/

[10] (2012 September) JADE White Paper. [Online]. Available: http://jade.tilab.com/papers/2003/WhitePaperJADEEXP.pdf