

Wireless Demand Response Controls for HVAC Systems

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Synopsis

This paper describes the results of a demand response scoping study designed to develop and test control software and wireless hardware that could enable closed-loop, zone-temperature-based demand response in buildings that have either pneumatic controls or legacy digital controls which cannot be used as part of a demand response automation system. We designed a SOAP client that is compatible with the Demand Response Automation Server (DRAS) being used by the IOUs in California for their CPP program, designed the DR control software, investigated the use of cellular routers for connecting to the DRAS, and tested the wireless DR system with an emulator running a calibrated model of a working building. The results show that the wireless DR system can shed approximately 1.5 Watts per design CFM on the design day in a hot, inland climate in California while keeping temperatures within the limits of ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy.

About the Authors

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Introduction

In California, air-conditioning is one of the largest contributors to peak electrical load. Figure A, taken from Rosenfeld (2004), shows that commercial air-conditioning contributes about half of the difference between the winter baseline load and the summer peak load. On the hottest days of the cooling season, commercial air-conditioning accounts for approximately 15% of the Cal ISO daily peak load.

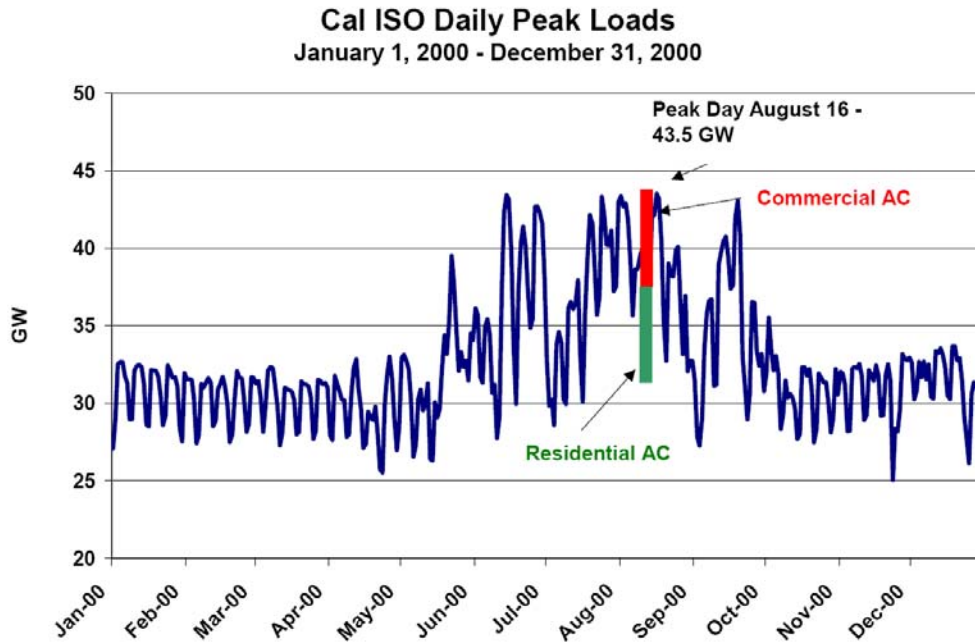


Figure A: Wireless discharge air temperature sensor used for DART demonstration

Recent research on ways to automatically or semi-automatically shed HVAC load on peak summer days has demonstrated that a global zone temperature setup is the preferable way to shed load in response to a DR event [Killicote and Piette, 2005; Piette et al., 2005]. Global zone temperature setup involves raising the cooling setpoint of each and every zone in response to a DR signal, then lowering it to the non-DR level after the DR event has ended. In comparison to other DR control strategies for HVAC, global zone temperature setup has the following advantages: 1) it is a closed-loop strategy, so thermal discomfort can be minimized, and 2) it does not cause system interactions that increase loads on other components or cause system imbalances and discomfort, as do strategies such as raising the supply air temperature (which results in increased fan energy use for VAV systems). A disadvantage of global zone temperature setup is that it can only be implemented with state-of-the-art (SOA) direct digital control (DDC) systems that have zone-level DDC. Most commercial buildings either do not have zone-level DDC or have a DDC system that cannot be programmed for a global zone temperature setup.

In some buildings, internet access for a DR system may be difficult to get. Some information technology (IT) departments will not allow HVAC controls to reside on the organization's data network. Even if the HVAC controls can use the organization's local area network (LAN), most organizations run a firewall between internet and the organization's LAN. The problem is less

acute for a DR client application seeking access to an internet server via web services, but in the event that the HVAC controls cannot use the LAN, it may be necessary to install another means of accessing the internet. A wireless broadband (cellular) connection is one possible solution.

According to the most recent CBECS survey (EIA, 2003) only 24% of the commercial building floor space is served by buildings with an energy management control system (EMCS). Only a fraction of that 24% is capable of implementing global zone temperature setup, either because there is no zone-level DDC, or because the EMCS cannot be programmed to perform a global setup. Retrofitting a building with a SOA EMCS system with zone-level DDC so that a global zone temperature setup can be performed is not cost effective. An SOA EMCS with zone-level DDC typically costs \$4/SF in California [Killicote and Piette, 2005]. Furthermore, the retrofit is disruptive to the building occupants and the business activities in the building. If the owner saves ~0.10/SF/yr from the global zone temperature setup, then the simple payback period is ~40 years, not counting the cost of the business disruption caused by the retrofit.

In a previous PIER-funded research project, Federspiel Controls demonstrated the use of a control system that converted constant air volume (CAV) HVAC systems to VAV using wireless discharge air temperature sensors, such as the one shown in Figure B [Federspiel, 2006]. The demonstration was conducted at the Iowa Energy Center's Energy Resource Station (ERS). The control application is called Discharge Air Regulation Technique (DART). DART can be installed quickly (the system at the ERS was installed in two hours) and at low cost (typical payback period of less than two years), and it provides comparable energy savings to a conventional CAV to VAV retrofit.



Figure B: Wireless discharge air temperature sensor used for DART demonstration.

In a related PIER-funded research project, Federspiel Controls used computer simulations to assess the performance of DART under a variety of operating conditions, including common HVAC system fault conditions [Federspiel, 2007]. The project also

involved the development of an emulator based on the computer simulations. The emulator is a real-time simulation running on a computer with analog input and output cards (data acquisition cards). The emulator is used for hardware in the loop testing of the wireless control hardware and software.

The recent development of wireless sensor network technology offers an opportunity to design a DR control system for existing buildings that either do not have an EMCS or that have a legacy EMCS that cannot be programmed to perform a global temperature setup. Wireless, battery-powered zone temperature sensors can be added to any building at relatively low cost and without disrupting the occupants or the activities in the building. The signals from these sensors are checked by a controller that reduces the HVAC system output and allows the zone temperature readings to rise during a DR event until one or more reach a setpoint that is a function of the DR signal. When the maximum zone temperature reaches the setpoint, the controller regulates the maximum zone temperature by modulating the HVAC system output

until the DR signal changes. Such a system could open up the possibility of getting closed-loop zone-level DR response from the overwhelming majority of buildings that cannot respond to DR signals today.

DART is now one of the control applications of the Federspiel Advanced Control System (FACS™), which is a web-based energy management system that utilizes wireless mesh network technology. FACS hardware includes a Federspiel Supervisory Controller (FSC), a Web-to-Wireless Gateway (WWG), Wireless Sensor Modules (WSMs), and Wireless Control Modules (WCMs). Each FSC has a driver for one or more WWGs, a SQL database, a web server, and one or more control applications such as DART. FACS utilizes the Time Synchronized Mesh Protocol (TSMP™) technology from Dust Networks. TSMP uses time division multiple access (TDMA) combined with frequency hopping. Time division allows for a very low duty cycle, which makes it possible to run all network nodes on AA batteries for years and still have all network nodes be mesh routing nodes. Frequency hopping helps the system avoid interference, and it also improves wireless security. TSMP has additional security features including 128 bit encryption. FACS radios operate in the 902-928 Industrial, Scientific, and Medical (ISM) band, which is unlicensed in North America. The 900 MHz ISM band is better for penetrating building materials than the 2.4 GHz ISM band, and has a longer line-of-sight range for the same radiated power.

To improve the DR value proposition, the DR application would be deployed as a FACS application in conjunction with an energy efficiency application such as DART so that much of the wireless control hardware infrastructure could be reused. This dual EE and DR system design would reduce the incremental cost of DR and should make the DR application cost effective for many commercial operations.

Approach

The approach was divided into the following four technical tasks.

Task 1: DR software development

We wrote communications software so that FACS can communicate with the DRAS [Piette et al., 2007], and we wrote the application software that enables DR capability integrated with other FACS applications. The DRAS is a real-time price server designed by LBNL. It is now being used by the investor-owned utilities (IOUs) in California for their critical peak pricing (CPP) demand response programs.

For the AutoDR client software, we used gSOAP. The gSOAP web services development toolkit is an open-source project that provides an XML to C/C++ language binding to ease the development of SOAP/XML web services in C and C/C++. gSOAP provides a transparent SOAP API through the use of proven compiler technologies that utilize strong typing to map XML schemas to C/C++ definitions. Strong typing provides a greater assurance on content validation of both WSDL schemas and SOAP/XML messages. The gSOAP compiler generates efficient XML serializers for native and user-defined C and C++ data types. More information about gSOAP can be found at <http://gsoap2.sourceforge.net/>. We selected gSOAP because it is open-source software and because it is compatible with C/C++. FACS software is written in C/C++ (as opposed to Java or .NET) because C/C++ results in smaller, faster executables which can be deployed on an embedded computer.

The DRAS API requires that the client request the price at least once every five minutes, but no faster than once every 50 seconds. Once every 60 seconds is recommended. We programmed our client to request the price once every 60 seconds.

The DRAS provides clients with future price change events. Our client doesn't use information about future price changes. This is because our DART application cannot pre-cool. DART only controls the air-handling unit. Attempts to pre-cool (e.g., by lowering the supply air temperature) would be defeated by the terminal controls. The heating would have to be shut off to pre-cool. In a dual-duct system this would have to be done by closing the hot deck.

The DR application software is object-oriented code written in C++. The DR application runs queries against the FACS database, searching for recent values with a "zone temperature" profile associated with the air-handling unit under control. It computes the maximum zone temperature, and provides that value as feedback to a proportional-integral-derivative (PID) control object. The output of the PID object is sent over the air to the control module(s) associated with the AHU under control so that they can change the speed command to the variable frequency drive(s) (VFDs). The application includes feedforward compensation for fast response to sudden DR price changes, and bumpless transfer to and from energy efficiency applications such as DART. The feedforward compensation reduces the fan speed by the ratio of the outdoor air temperature minus the DR setpoint divided by the outdoor air temperature minus the average zone temperature. Bumpless transfer means that the energy efficiency (e.g., DART) output and DR output coincide at the point of switching. The DR application is designed to run as a service in Windows XP.

Task 2: Test cellular routers

In many existing buildings, it is not possible to use the existing LAN/WAN to access a server on the internet. Anticipating this fact, we chose to test the use of routers with embedded cellular connections to the internet. These routers could be deployed in metropolitan areas to provide easy access to the internet independent of the existing communications infrastructure in a building.

We procured and tested two cellular routers. The first is a Linksys WRT54G3G-ST Wireless G router for mobile broadband. This router includes a 4-port switch, a wireless G access point (802.11g), and a standard PC Card slot for a mobile broadband data card. The WRT54G3G-ST has the same features as other Linksys WRT54G routers. We tested the WRT54G3G-ST with a Merlin S720 data card from Novatel Wireless provisioned for the Sprint mobile broadband network. The second router is a Digi ConnectPort WAN provisioned for the Verizon Wireless mobile broadband network. Both of these cellular routers were provisioned with Evolution Data Optimized (EVDO) cellular radios. EVDO is a telecommunications standard for the wireless transmission of data through radio signals, typically for broadband Internet access. EVDO is standardized by 3rd Generation Partnership Project 2 (3GPP2) as part of the CDMA2000 family of standards and has been adopted by many mobile phone service providers around the world – particularly those previously employing CDMA networks, as opposed to GSM networks.

EVDO is significantly faster than the Enhanced Data Rates for GSM Evolution (EDGE) used by GSM networks. It provides access to mobile devices with air interface speeds of up to up to 3.1 Mbit/s (with Rev. A). EVDO provides an IP based network.

We checked that we were able to access the DRAS from a computer located on the private side of the router. We also checked that we could access a web server on the private side of the router from the public side of the router. Additionally, we checked that the router had sufficient bandwidth to run the mesh network commissioning tool from a computer on the public side of the router against a network on the private side of the router.

Task 3: Modify emulator for DR testing

An emulator is a system of software and hardware that enables hardware-in-the-loop testing of control systems. A process (in this case the dynamic thermal behavior of a building) is simulated in real time. A hardware interface between the simulation computer and a control system is provided so that the control system cannot tell that it is not controlling a real building. The emulator produces signals that match sensor signals that the control system expects from a building's sensors, and the emulator accepts commands produced by the control system.

Our emulator runs Matlab code that we call VirtualHVAC, which was developed at Federspiel Controls. This Matlab code can model the transient response of an HVAC system, including transient duct airflows, heat exchanger heat transfer, damper movement, building heat transfer, and local loop controls.

We configured the emulator to model one of the test air-handling units (AHU-B) and associated building mass at the Energy Resource Station (ERS) in Ankeny, Iowa. The ERS is a teaching and testing facility operated by the Iowa Energy Center. The emulator was configured to integrate the differential equations describing the transient heat and mass transfer of the ductwork, mechanical equipment, and building every 10 seconds. We used weather data from California Climate Zone (CCZ) 12, which includes Sacramento and Livermore. When testing the DR application, the emulator was started the previous day. The emulator was started by simulating the 24 hour period prior to starting the emulator three times repeatedly, using the terminal state each of these days as the initial condition for the next day.

We configured the I/O boards to report zone temperatures, discharge air temperatures, outdoor air temperature, fan power, and chiller power. They were also configured to accept voltages corresponding to the supply fan speed and return fan speed.

Task 4: Emulator testing

Figure C shows the components of the emulator testing, which include the emulator (a PC with Matlab software modeling the ERS), the FACS wireless control system (sensor modules, control modules, gateway, and supervisory controller that runs the control application software), and the DRAS. The computer is a standard desktop PC. It has data acquisition cards that accept analog inputs from wireless control modules, and that provide analog outputs to wireless sensor modules. We used the Matlab data acquisition toolbox to interface the Matlab model to the data acquisition cards. The Matlab software integrates a set of differential equations that model the heat and mass transfer of the HVAC system and building. The HVAC and building components that make of the Matlab model of the building were developed by Federspiel Controls for another project. The emulator includes component models for heat exchangers, valves, dampers, ducts, fans, room air, building construction layers, and weather. The Matlab integrator is executed every 10 seconds, and each Matlab integration takes about one second. If FACS makes large control changes, then the integration steps take longer. It is possible, but unlikely, that

integration steps will take longer than the integration period. If that happens, then the dynamic response of the emulator becomes skewed and inaccurate.

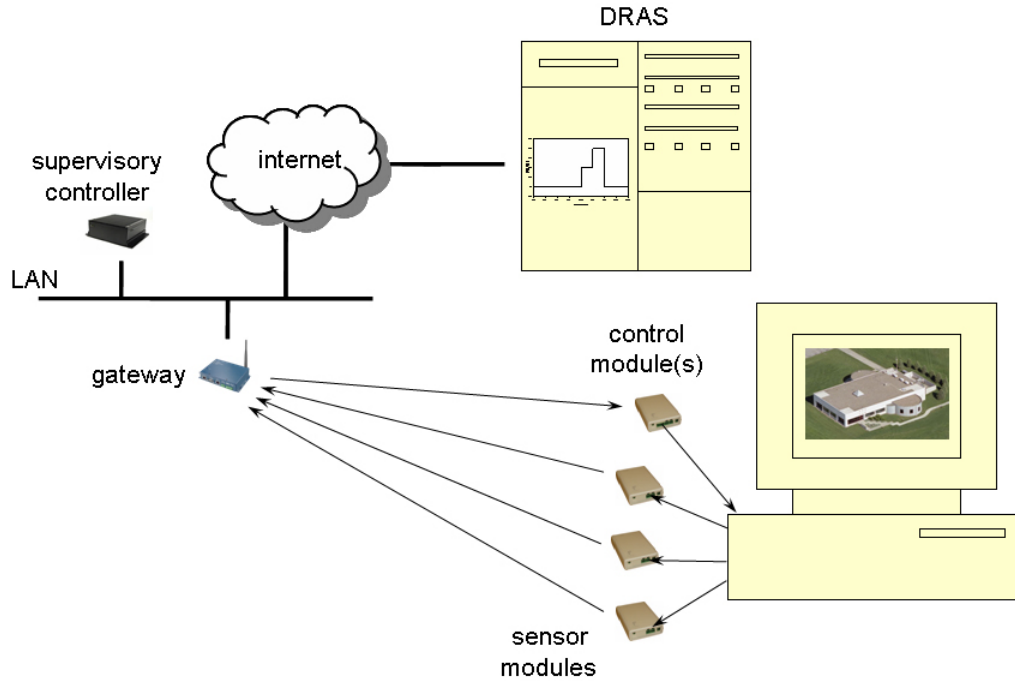


Figure C: Components use for the emulator testing

The DR test was conducted with a critical peak pricing (CPP) signal. The signal represents a price multiplier. Most of the time the signal is 1.0, indicating that no DR event is active. On the event day, the DR signal goes from a value of 1.0 to 3.0 at noon. Between noon and 3pm the DR signal remains at 3.0. At 3pm the DR signal goes from a value of 3.0 to a value of 5.0. Between 3pm and 6pm the DR signal remains at 5.0. At 6pm the DR signal goes from a value of 5.0 to a value of 1.0 and remains at 1.0 for the remainder of the day. Figure D shows the DR signal on the event day.

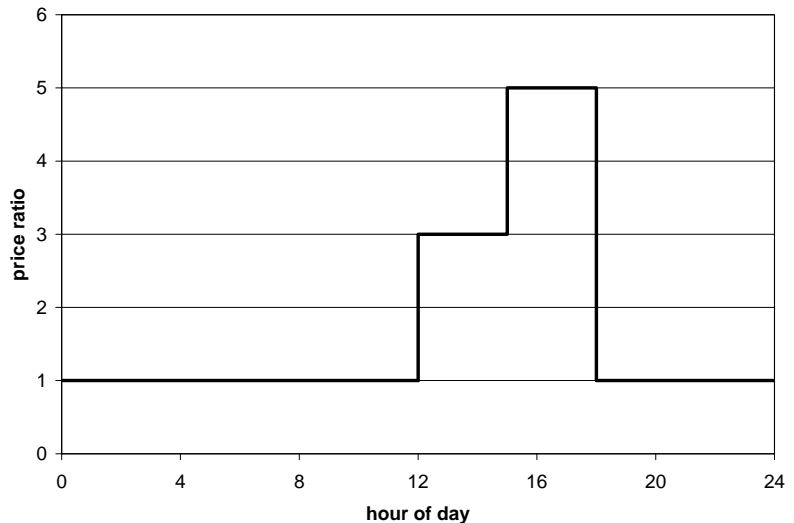


Figure D: Price signal used for emulator tests.

We configured our DR client to poll the DRAS once per minute to get the price signal. We configured the wireless sensor modules connected to the emulator to report their values every 30 seconds. We tested the DR application running in sequence with our DART application. A DART object was instantiated and used to control the fans of AHU-B when the price signal was 1.0. When the price signal became higher than 1.0 the DART object was destroyed (memory freed), and a DR object was instantiated and initialized. The DR object operated the fans until the price signal dropped back to 1.0, at which point a new DART object was instantiated and used to control the fans.

Zone temperature setpoints were 76 degF when the DR price ratio was 3.0, and 79 degF when the DR price ratio was 5.0. When the price ratio was 1.0, the zone temperature setpoint was undefined because the DR object was not instantiated then. Instead a DART object was instantiated when the price ratio was 1.0. Tests were conducted on the design day using California Climate Zone 12 weather data (Livermore) and a price signal that went from 1.0 to 3.0 at noon, from 3.0 to 5.0 at 3pm, and dropped from 5.0 to 1.0 at 6pm. For our purposes, we define the design day as the day in the CCZ 12 weather file with the highest peak dry bulb outdoor air temperature. That day is July 24. The HVAC system was operated 24/7 to demonstrate the thermal recovery period after the DR event ended.

Results

Result 1: Cellular connections are not “always on”

To conserve network bandwidth, the mobile broadband routers are designed to terminate the internet connection if there has been no activity for a period of time. This period can be configured, but has a limit (e.g., one day). If the router closes the connection, then a person or process on the public side can no longer access anything on the private side. For private-side clients polling a public-side server periodically (as was the case for this scoping study), this is not a problem. If the connection is terminated, it will automatically re-connect when a private-side client tries to access the internet. However, if the router were used in a system where the server pushes price changes to subscribed clients (this architecture would reduce network traffic on the server), then it would be necessary for the private-side client to keep the cellular connection active by accessing the public side of the router more frequently than the disconnect period.

Result 2: Wireless DR can provide large load sheds

Figure E shows the total power consumption of the two fans (supply and return) and the chiller power associated with AHU-B on the design day with and without a DR event. We computed the chiller power from the cooling coil heat transfer rate and an assumed chiller efficiency of 1.0 kW/ton (one ton is 12,000 Btu/hr). The system was operated 24/7 for this event and its comparison no-event day to show the thermal recovery. The small difference at the start of the day (shortly after midnight and during the mid-day ramp-up) are caused by differences in the start time of the emulator the prior day; on the no-event day the building has a little more accumulated heat because it was started two hours later the previous day.

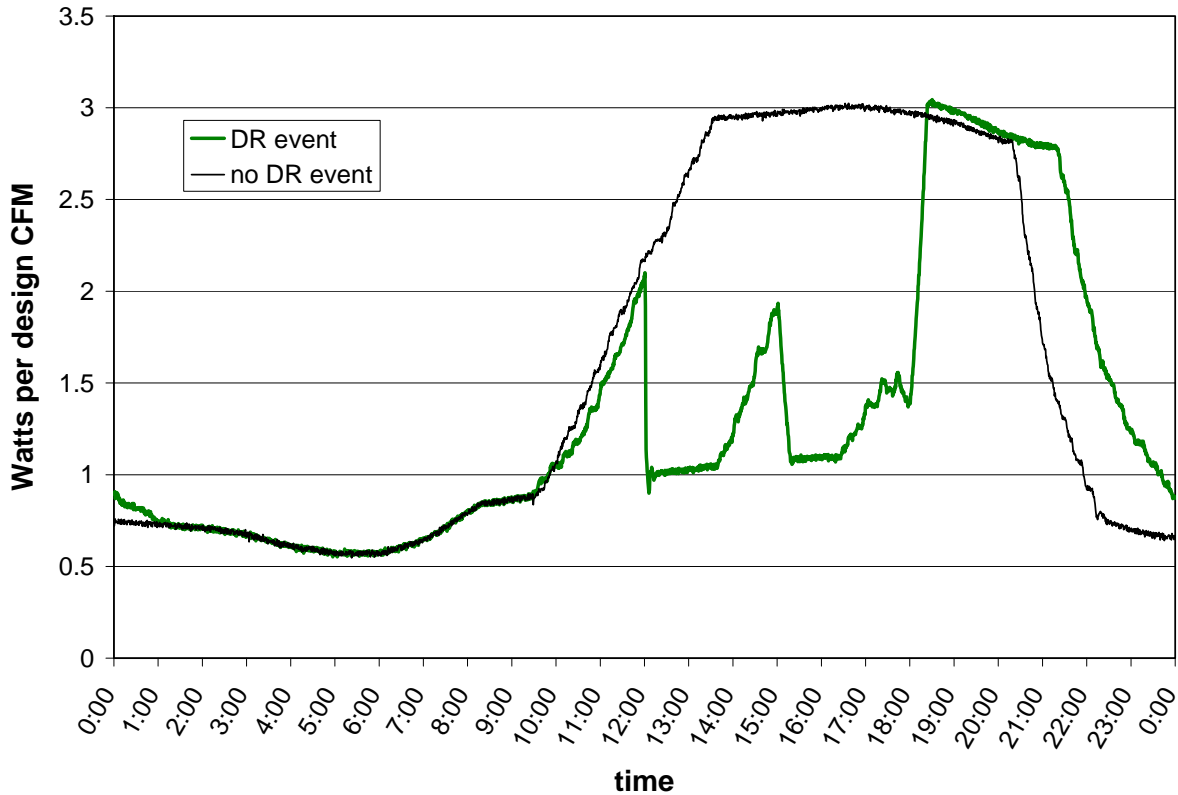


Figure E: Specific HVAC electric power consumption with and without a DR event

Figure F shows the difference between the kW demand on the no-event day and the kW demand on the event day. Under these conditions, the DR application reduces the kW demand by 1.5 W/CFM on average. However, the load shed is not a perfect square wave; the shed load varies from 1.08 W/CFM to 1.9 W/CFM. During the recovery period, the HVAC system fans are running at full speed until after 21:00. This sudden increase in energy consumption at the end of the DR event could cause grid consumption problems. It could be mitigated by limiting the fan speed during the recovery period. In many buildings the fans would shut off at 18:00, in which case the recovery would be avoided by the fan schedule. The magnitude of the area under the curve during the recovery period is significantly less than the area under the curve during the shedding period, demonstrating that the load shedding conserves energy in addition to reducing the demand during the event interval.

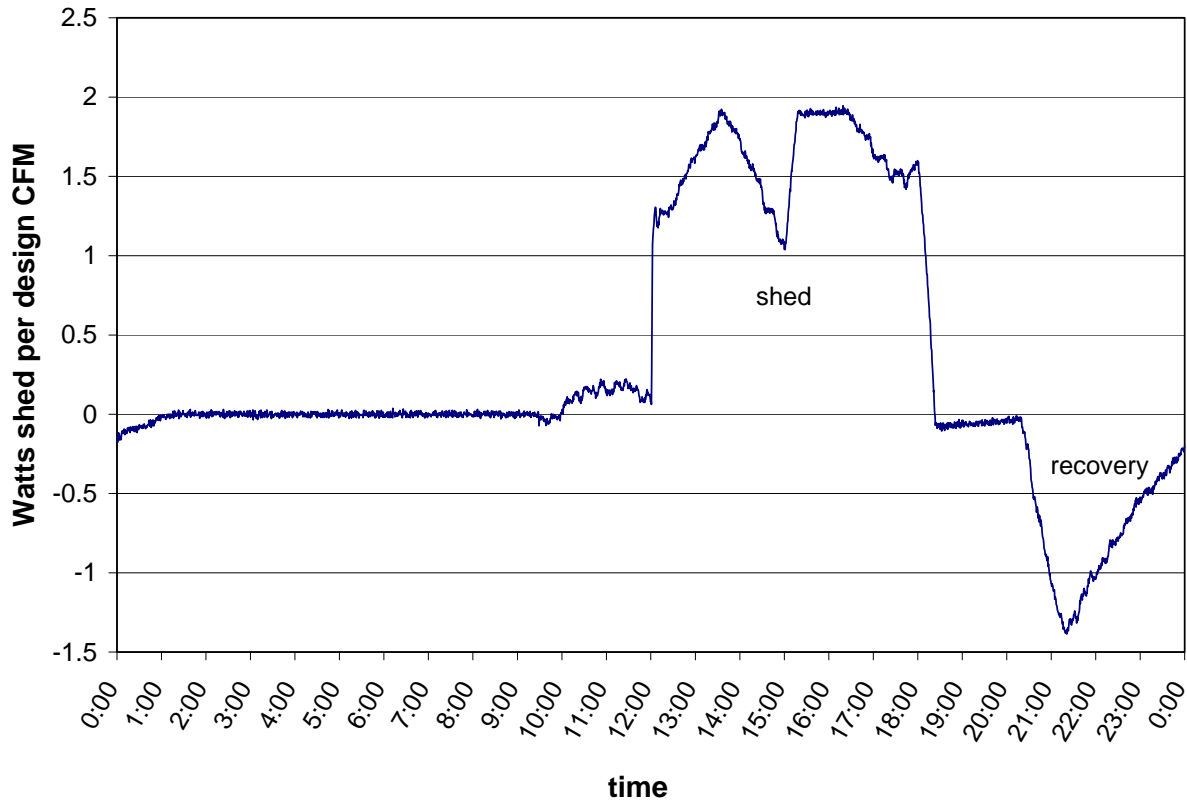


Figure F: Load shed on the DR event day

Result 3: Cost savings of DR is significant

We performed a simple analysis of the financial benefit of wireless DR. We assessed the financial benefit of this load shedding capability with some simple assumptions. We assumed that a customer is on the E-19 rate from PG&E [PG&E, 2007a], and on the E-CPP rate from PG&E [PG&E 2007b]. For this analysis, we compute the economic difference between shedding HVAC load and not shedding HVAC load. This analysis does not consider the economics of the E-CPP tariff itself. Under the assumptions in Table 1, wireless DR capability could save an end user ~\$0.095/SF/yr. In Table 1, row 1 is the average watts per design CFM that we demonstrated could be shed on a design day in Sacramento. Row 2 is the design CFM per square foot; this is typical for hotter, inland climates in California. Row 3 is the number of DR events

Table 1: Assumptions for financial analysis

1	average W/dCFM shed	1.5
2	design CFM/SF	1.5
3	# events/yr	12
4	hrs/event	6
5	kWh shed to kWh recovery ratio	3
6	on-peak \$/kWh	0.14445
7	on-peak credit	0.03167
8	part-peak \$/kWh	0.10576
9	part-peak credit	0.00897
10	moderate price charge, \$/kWh	0.16457
11	high price charge, \$/kWh	0.56128
12	on-peak demand charge, \$/kW	15.02
13	part-peak demand charge, \$/kW	3.57
14	coincidence ratio	0.73
15	\$/SF/yr saved	0.095

Row 2 is the design CFM per square foot; this is typical for hotter, inland climates in California. Row 3 is the number of DR events

per year; this is the maximum allowed by E-CPP. Row 4 is noon to 6pm, which is the entire on-peak period of the E-19 rate. Row 5 is the energy shed during the DR event divided by the extra energy for recovery; the ratio is based on these scoping study results. Rows 6-13 are from the E-19 and E-CPP rate tariffs available from PG&E. Row 14 is the fraction of load shedding (row 1) that decreases the monthly peak demand used for bill calculation; the assumption is that DR events occur on days that would contribute to the peak demand. Row 15 (the result) is energy charges avoided on-peak (E-19 plus E-CPP) minus energy charges incurred during part-peak (for recovery) plus avoided on-peak demand charges (just E-19) minus incurred part-peak demand charges (for recovery).

Battery life for the wireless sensor network is 3-10 years for a pair of AA lithium batteries. Assuming the worst case battery life, 1000 square feet per sensor, 15 minutes labor per battery pack, \$50/hr for labor, and \$2.50 per battery for two batteries, the annual cost of battery maintenance is \$0.006/sf/yr.

Costs for a cellular router range from \$350 to \$850. The service costs \$60/month for a two-year contract. For a 100,000 square foot building, the recurring cost of the cellular connection is just \$0.007/sf/yr.

Conclusions

The study demonstrated a large HVAC load shedding potential for buildings that do not have zone-level DDC using an overlay of wireless mesh network temperature sensors. Factors that will affect the actual load shedding potential are climate, building mass, and HVAC system capacity relative to the design load condition. Most office buildings, college campus buildings containing offices and/or classrooms, or hotels should be good candidates. Poor candidates would include data centers or laboratories, where elevating the indoor temperature – even temporarily – is not acceptable. The site should be available for load shedding of the entire conditioned space so that there is no risk of transferring the shed load to a section of the building that is not shedding load.

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