OPPORTUNITIES TO SAVE ENERGY AND IMPROVE COMFORT BY USING WIRELESS SENSOR NETWORKS IN BUILDINGS

Danni Wang
Graduate Student

Edward Arens
Director

Cliff Federspiel
Research Specialist

Center for Environmental Design Research
390 Wurster Hall, University of California, Berkeley, CA, 94710

ABSTRACT

This paper discusses how intensive information technology can affect future building operation. Recent breakthroughs in wireless sensor network technology will permit 1) highly flexible location of sensors, 2) increased sensing density and variety of sensor types informing more comprehensive control systems, 3) occupants' involvement in control loops, 4) demand responsive electricity management, 5) integration among now-separate building systems, and 6) the adoption of mixed-mode and other new types of air conditioning systems. The paper describes the capabilities of the new sensor networks, assesses how some applications can increase the quality of control and improve energy efficiency, and suggests opportunities for future development.

1 INTRODUCTION

Two-thirds of primary energy use in the US is electrical and about two-thirds of all electric power is used in buildings [Interlaboratory Working Group, 2000]. In commercial buildings, heating, ventilating, and air-conditioning (HVAC) consumes approximately 28% of total energy consumption, followed by interior lighting at 25%. In residential buildings, space heating and cooling have the highest energy consumption at 43%, followed by miscellaneous use at 16%, and water heating at 14%. Reducing energy use in buildings has become a problem of great importance.

There have been many approaches to achieve this objective. For example, buildings may be designed using natural ventilation, solar control, passive temperature control, and daylighting to save energy. Novel air-conditioning systems such as underfloor air distribution, displacement ventilation, and pipe-embedded chilled/heated ceilings may reduce operational costs. In building retrofits, energy efficiency is improved by replacing old equipment with more energy-efficient versions. This paper examines how applying sensor and information technology (IT) to building controls might reduce energy consumed in building operation. In some cases, it could be the fastest and most cost-effective way to obtain a given level of energy saving.

2 PROBLEMS WITH CURRENT BUILDING CONTROLS

The major objectives of a building control system are to minimize energy use and to maintain occupant comfort. The state-of-the-art in building control has greatly advanced in recent years. For example, pneumatic controls are being replaced by digital ones [Moult 2000], and energy management and control systems (EMCS) now are increasingly used to monitor and manage HVAC systems in large commercial buildings. The application format of building controls has been changed, but the control functions are still rudimentary, with on/off, proportional, integral, and derivative (PID) feedback control methods still being dominant. EMCS is usually interfaced through simple trend plots. The intelligence employed in these controls is low.

Occupants' comfort is not directly considered in building operation, although occupant complaints decrease occupants' work productivity and increase maintenance cost millions dollars annually in commercial buildings [Federspiel 2001]. Thermal comfort depends on multiple factors. If one controls a space with a single temperature sensor, the temperature needs to be tightly controlled within a narrow range to avoid potential discomfort caused by other variables such as air movement or radiation that the thermostat cannot detect. Such tight control requires extra energy consumption by the HVAC system.

Controls that could somehow measure and then efficiently condition the comfort of individual occupants has yet been achieved in building operation.

3 WIRELESS SENSOR-NETWORK TECHNOLOGY AS A VEHICLE

Sensors and wireless transceivers can now be manufactured on printed circuit boards measuring one square inch or less. Wireless MEMS and CMOS sensors used for measuring common environmental variables (such as temperature, humidity, light level, and pressure) have become available in the commercial market. They tend to be standalone devices at this stage. But research soon will enable low-power wireless sensor and actuator networks to be used in building control systems [Rabaey et al. 2000]. (see Appendix for details) In the future, building control could become more flexible, interoperable, and sophisticated, using such sensor nets.

However, there are at this stage many technical problems, such as how to optimize the network, locate sensors in the network, scavenge energy to keep the system running on a building timescale (10 years), and integrate it with existing building automation systems. Exploitable solutions that save energy and benefit comfort would be of interest to both the IT and HVAC industries.

4 OPPORTUNITIES CREATED BY WIRELESS SENSOR NETWORK TECHNOLOGY

4.1 FLEXIBLE SENSOR LOCATIONS

Sensors are essential components in control systems. Ideally, a thermostat sensor should sense how a building occupant feels about the environment. It should therefore be placed near the occupant. In closed offices, thermostats are usually mounted close to the door for convenience of wiring. In open plan offices, thermostats have to be mounted on an external wall, an internal wall or on a column. Thermostats mounted on external walls can easily be affected by nearby sunlight or thermal transfer through the wall. In the interior, plumes and jets create local differences between the thermostat and occupant locations.

Remote sensors could misrepresent the room conditions that the occupants experience and produce sensing delays or inaccurate information. Wireless sensors make it much easier to sense variables of interest directly within the occupied zone. Sensors on a desk, within chairs, or on phones or computers could measure air temperature and air motion within the occupant's local microclimate. Sensors at various levels on furniture, partitions, and ceiling tiles could detect vertical stratification in the environment. In some cases, wearable sensors could sense the thermal state and locations of the occupants.

Field studies of occupants in 170 buildings [de Dear 1997] show that they feel comfortable in, and often prefer, a wider range of environmental conditions if they have control over their local conditions. This range could be controlled in ways that are energy efficient if there were sensors providing information

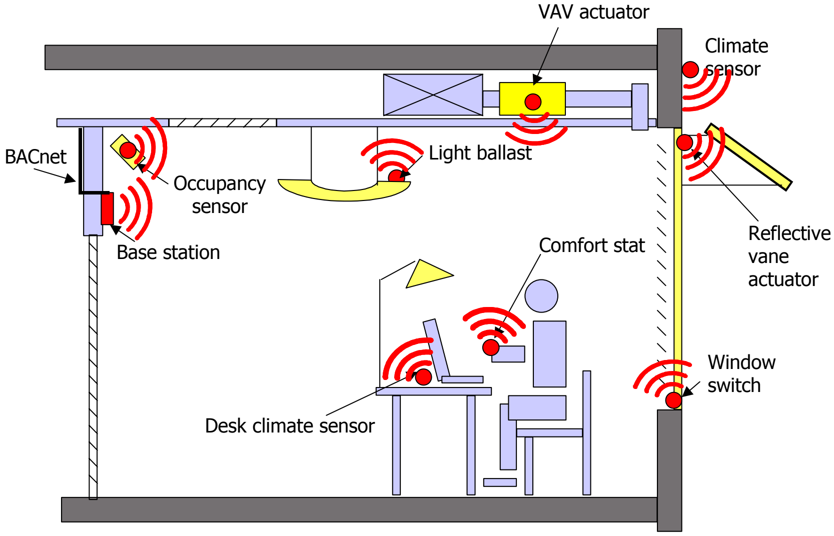


Figure 1 Diagram of multiple sensor usage in occupant space

on the air movement, thermal radiation, and temperature gradients within the space.

4.2 INCREASED SENSING DENSITY

Wiring to sensors is a substantial fraction of the cost of environmental controls. In commercial buildings the wiring for a single sensor averages $200~800 in addition to the cost of the sensor (on the Berkeley campus the wiring cost is $1000). The cost lies mostly in the need to install the wires behind building surfaces, which especially discourages retrofits. Partly because of this cost, commercial buildings tend to use a low density of sensors in the building space. For example, in a variable air volume air conditioning system, it is common to use one sensor or one local control box to control multiple spaces or rooms, while these multiple rooms could be experiencing different load profiles and occupancy patterns and therefore have widely varying temperatures.

The potential energy benefit of increasing sensing resolution in office buildings has been investigated by Lin et al (2002) using computer simulation. They showed that by increasing the number of sensors they could optimize comfort or energy consumption individually, or improve both comfort and energy saving whenever some rooms require heating and others simultaneously require cooling. Wang et al (2002) similarly assessed the effect of adding an additional temperature sensor at foot level, on the energy needed to condition a typical office room when air stratification is present in the space. Their simulation shows that large energy savings could be achieved by using the sensor data to adjust the supply air conditions to keep room stratification near but not exceeding allowable limits.

Ventilation air is known to be wastefully distributed in fully mixed spaces. 10 l/s may be supplied per person; only 0.1 l/s or 1% is actually inhaled [a person doing moderate work consumes 16ml/s oxygen]. Efficiency could be gained by supplying fresh air directly to the occupants' breathing zone. Velocity and temperature sensors near the occupants' head would make it possible for the system to view the air movement around the occupants to achieve a desirable airflow pattern.

Finally, efficiency could be increased by much more extensive use of occupancy sensors in buildings. Shutting down lights and certain HVAC equipment when no one is present could achieve large reductions in energy use.

4.3 OCCUPANTS' INVOLVEMENT IN CONTROL LOOPS

We view occupants as a useful resource to control the environment. By providing occupants with information that allows them to play a more active role in the environmental controls in their buildings they will be more satisfied, and arguably more productive, than is possible today [Wyon 1997]. They can also save energy expense: 3M corporate headquarters in Minnesota uses their public address system two or three times per year to control demand during peak price periods. They broadcast a message asking workers to close fume hoods, shut off lab equipment not in use, shut off lights, shut off office equipment not needed, close blinds, etc. The net result of one such recent use was that the building's electrical demand dropped from 15 MW to 13 MW in 15 minutes, and then to 11 MW over 2 hours.

Wireless sensor network technology makes occupant involvement more feasible. For example, wireless actuators could make it possible for occupants to exercise control over the building systems. With wireless light switches, occupants could operate overhead lights without leaving their desks. Programmable switches and ballasts could give occupants more flexibility to adjust ambient light levels according to their preferences.

A two-way communication infrastructure could be constructed to manage large commercial buildings. For the buildings with wideband communication infrastructure, it would be easy to provide occupants access to facility management through an intranet. They could then report problems and track facility management's response more conveniently. Such an advanced facility management could also allow occupants to receive messages. For example, an occupant in a perimeter zone might receive messages that ask him to close the blinds at a certain time to reduce use of peak-rate electric power.

It would be desirable to design devices that provide critical information to the occupants. Such devices could be wireless motes that only receive price signals. For example, in residential buildings, a lighting mote could be red when the electricity price is high, yellow when medium, green when low. It could also flash these colors to indicate an upcoming price. Thus informed, occupants could decide how to operate their appliances, such as to postpone washing clothes when the red light is on or flashing, or to precool the house with the air conditioner when high

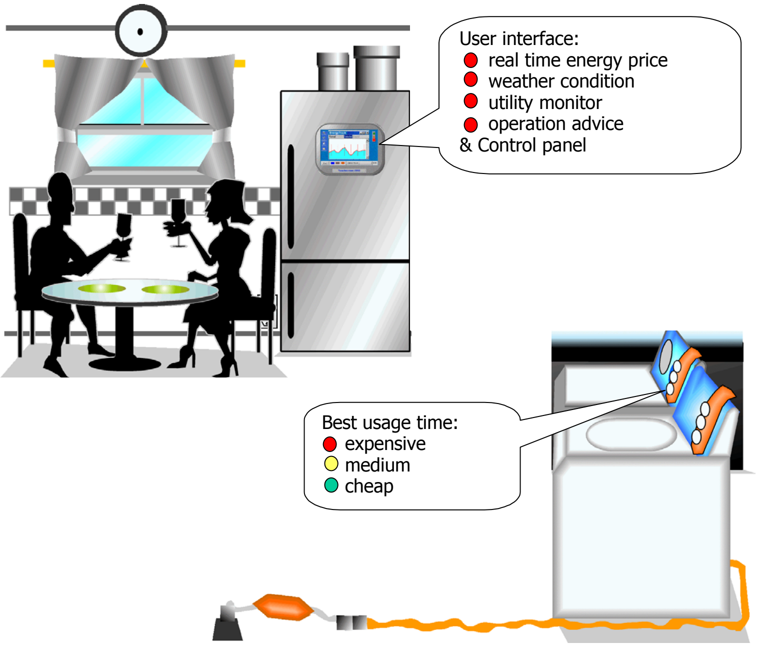


Figure 2 Involving residential occupants in electricity use decisions

prices are foreseen. Some of this could be automated but ideally the occupants should have access to the system's control strategy, and also to be able to override it at any given time.

4.4 DEMAND-RESPONSIVE ELECTRICITY MANAGEMENT

In California, demand-responsive electricity management is being proposed to solve the problem of energy demand and supply. It is intended to increase the efficiency and improve the control of the electricity-supply infrastructure in urban or regional levels. For instance, hourly pricing gives the users the option to reduce their usage during expensive periods and increase their usage during inexpensive periods; thus demand response in a connected market reduces load levels at high retail prices, and reduces pressure in the wholesale power market, allowing prices to fall. In the long term, energy generation resources could also be managed and utilized more efficiently.

To enable the full power of this technology requires a fully integrated network that combines distributed metering and smart energy-consuming appliances with global cost-setting mechanisms [Hirst 2002]. The electric consumption meters should be capable of receiving real-time electricity tariffs and initiating responses within the house that reduce overall energy cost. They must be flexible enough to respond to changing pricing plans and billing intervals, and to signal the consumer's intentions and usage to the utility. They should also be capable of acting as a platform to support other sensors and actuators, and have a user interface that is clear and intuitive to typical residential users. UC Berkeley is developing such a system for residences based entirely on wireless communications [dr.me.berkeley.edu].

4.5 INTEGRATION AMONG DIFFERENT BUILDING SYSTEMS

Seamless interoperability has been the goal of building automation systems for many years. While progress has been made (emergence of the BACnet protocol and LonWarks technology…), there are still many problems. For example, the design of building envelopes requires that daylighting, solar heat gain control, ventilation, and space conditioning are integrated. Different types of sensing (solar radiation, daylighting, temperature, CO_2 concentration, window position, access, etc.), and different types of control (HVAC set-points, angles of reflective vanes, blind movement, window switches, etc.) need extensive communication between different systems and devices. This is rarely the case at present.

Sensor networks provide a solution to the above dilemma by providing signal processing, decision-making algorithms, and self-organization. They would enable building owners and operators to integrate the necessary control components and systems from different manufacturers and from different industries to minimize energy and maintenance costs in a life-cycle-cost analysis.

4.6 ENCOURAGE THE ADOPTION OF NEW AIR CONDITIONING SYSTEMS

It has become routine to rely on centralized air conditioning to create the interior environment in building. In many less-developed parts of the world, air conditioning has become a synonym for "modernization." But there are energy and environmental consequences to this mechanical approach, and occupants who inhabit those artificial environments often suffer health symptoms and comfort effects such as the sense of stuffiness.

Recently more and more buildings are designed with operable windows, double facades, and hybrid/mixed-mode ventilation systems with the intent of providing healthy air and decreased energy consumption. The integration of such systems with traditional HVAC is difficult because of the added complexity of communication between the various building and mechanical components.

Consider a mixed-mode building as an example. The mixed-mode provides building ventilation and/or cooling services using a combination of natural and mechanical systems. Typically the natural ventilation system consists of operable windows, either manually or automatically controlled, while the mechanical system includes fans, ducts and refrigeration equipment. If properly designed and operated, mixed-mode cooling can reduce HVAC energy consumption compared with conventional sealed air-conditioned buildings; and improves occupant comfort and indoor air quality. With window switches and temperature sensors in/near the window, the air movement in/out of the window could be determined and used for control the "desired" direction of airflow.

It is not hard to image that such new systems could become an ideal testbed for wireless network technology. Such new technology would also encourage the entry of new air conditioning devices and systems into the market.

5 CONCLUSION

This paper discusses how wireless sensor network technology can affect future building operation. Highly flexible location of sensors and increased sensing density, as well as increased variety of sensor types would make imminent improvements in the energy efficiency and building occupants well-being. However, affordable low price of the technology is necessary to penetrate the HVAC market. Dust (motes manufacturer) expects to sell motes for $50-100 each now. But as the market grows, high volume requirement always results a much lower manufacture price.

The technology would make the following changes in the near future: to include building occupants in control loops, to achieve demand responsive electricity management in residential buildings, to integrate now-separate building mechanical, electrical, security, and fire/safety systems in commercial buildings. Challenges for researchers and design practitioners are to develop exploitable applications.

In the long term, the interaction between technology and applications would encourage the adoption of mixed-mode system and entry of other new types of air conditioning systems. The social scale impacts on the energy resources, environmental conservation, and industrial economy are unclear now.

6 REFERENCES

de Dear, R. "Developing an Adaptive Model of Thermal Comfort and Preference", ASHRAE Report 884, Conducted: September 1995 - March 1997. Sponsored by: TC 2.1, Physiology and Human Environment.

Federspiel, C. C., 2001, Chapter 56, "Estimating the Frequency and Cost of Responding to Building Complaints," Indoor Air Quality Handbook, Eds. J. Spengler, J. M. Samet, and J. F. McCarthy, McGraw-Hill.

Hirst, E., "Barriers to Price-Responsive Demand in Wholesale Electricity Market", June 2002, Prepared for Edison Electric Institute, Washington, DC.

Interlaboratory Working Group. 2000. "Scenarios for a Clean Energy Future (Oak Ridge, TN; Oak Ridge National Laboratory and Berkeley, CA; Lawrence Berkeley National Laboratory)"; ORNL/CON-476 and LBNL-44029, November, Chapter 4.

Lin, C., Federspiel, C., and Auslander, D., "Multiple Sensors with Single HVAC System Control", International Conference for Enhanced

Building Operations, Oct, 16-17, 2002. Richardson, Texas.

Moult, R. (2000). "Fundamentals of DDC." ASHRAE Journal November.

Rabaey, J. et al., "PicoRadio Supports Ad Hoc Ultra-Low Power Wireless Networking", IEEE computer, Vol.33, No. 7, pp.42-48, July 2000.

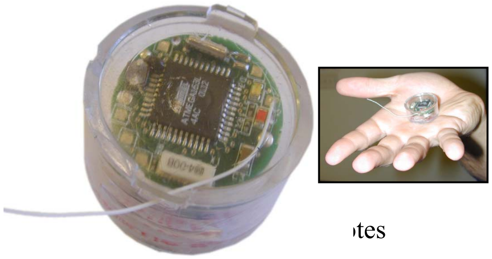
Wang, D., Arens, E., Webster, T., Shi, M., "How the Number and Placement of Sensors Controlling Room Air Distribution Systems Affect Energy Use and Comfort", International Conference for Enhanced Building Operations, Oct, 16-17, 2002. Richardson, Texas.

Wyon, D. "Individual Control at Each Workplace for Health, Comfort and Productivity", Creating the Productive Workplace Conference, Oct 1997, London .

APPENDIX

MICROSENSOR MOTES

Researchers at Berkeley Sensor and Actuator Center (BSAC) have developed an open-source hardware and software platform that combines sensing, communications, and computing into a very small package at low cost. The MICA motes are the second-generation wireless modules that contains light and temperature sensors and now uses a fraction of a watt of power and consists of commercial components a square inch in size.



tes

SOFTWARE AND TINY OS

TinyOS is an open source operation system. It is an efficient and modular embedded software platform for the motes. It runs the hardware and network, making sensor measurements, routing measurement data, and controlling power dissipation. TinyDB is the database built on top of TinyOS.

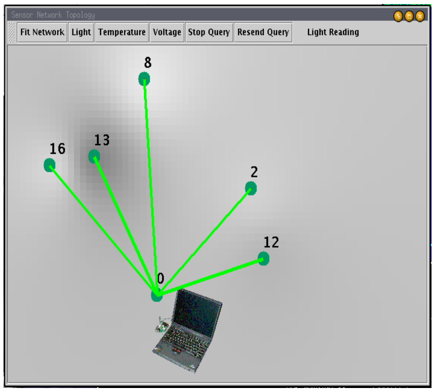


Figure 2. Screenshot of TinyDB interface for light measurements

PICORADIO AND SENSOR NETWORKS

Researchers at Berkeley Wireless Research Center (BWRC) are developing the technologies for the realization of ultra-low energy wireless sensor networks. The PicoRadio and sensor network support low (but variable)-rate data transmission, while ensuring energy-consumption levels that are close to the theoretical limits.

APPLICATIONS

The general application fields of wireless sensor network include:

- Physical security for military operations
- Environmental data collection
- Seismic monitoring
- Industrial automation
- Smart homes and intelligent buildings

For more information, see:
http://www.bwrc.eecs.berkeley.edu
http://www.bsac.berkeley.edu