HOW AMBIENT INTELLIGENCE WILL IMPROVE HABITABILITY AND ENERGY EFFICIENCY IN BUILDINGS

Edward Arens
Clifford C. Federspiel
Danni Wang
Charlie Huizenga

Center for the Built Environment
University of California, Berkeley, CA 94720

Ambient intelligence has the potential to profoundly affect future building operations. Recent breakthroughs in wireless sensor network technology will permit 1) highly flexible location of sensors and actuators, 2) increased numbers and types of sensors informing more highly distributed 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 that require more sensor information to operate efficiently. This chapter describes the issues with current building automation technology, assesses how some applications of wireless sensor technology can increase the quality of control and improve energy efficiency, and suggests opportunities for future development.

1 INTRODUCTION

Buildings are primarily constructed to produce indoor environments in which their occupants are comfortable, healthy, safe, and productive. A complex mixture of systems (heating, ventilating, air-conditioning (HVAC), lighting, life safety equipment, the architecture itself, and the building's occupants) is used to achieve this purpose. Since buildings tend to be designed and built individually, the mixture of systems is virtually unique for each building. Most buildings are essentially prototype designs, but rather than being used for testing, they are put directly into operation. Designers and operators rarely have the chance to evaluate systematically how *effectively* their buildings produce desirable environments, or how *energy-efficiently* they do so. There is a great shortage of such information throughout buildings' lives—they are delivered to the operators without instructions, and once in operation, operators often cannot determine how they perform because there are insufficient channels for collecting physical data and occupant feedback. As a result, they tend to be operated in rather ad-hoc ways—often whatever works to cause the least complaints. It would help if more information were available.

In the past two decades, the adoption of computer control systems in commercial buildings has greatly improved the access to and management of physical data. However, these systems still communicate with relatively few sensors and actuators, so their information is not detailed or reliable enough to truly operate the building effectively or efficiently. In addition, few of them integrate HVAC with related but independently marketed systems like lighting, security, fire, or occupant information. Residential buildings tend to be intrinsically much simpler than commercial ones, but even here the amount of sensing and the information provided to systems and to occupants is less than optimal—usually all contained within a single thermostat.

Arens, E., C.C. Federspiel, D. Wang, and C. Huizenga, 2005. "How Ambient Intelligence Will Improve Habitability and Energy Efficiency in Buildings." Published in the book *Ambient Intelligence*, eds. W. Weber, J.M Rabay and E. Aarts, Springer, March. pp.63-80. with kind permission of Springer Science and Business Media

In the US, 38% of all primary energy is used to condition buildings, divided evenly between commercial and residential buildings. This is the largest single energy use sector, exceeding transportation and industry. 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%. The Department of Energy (DOE, 2000) estimates that in both building types, roughly half the total energy use could be economically avoided. Reducing energy use in buildings is both important and feasible.

There have been many approaches to achieve this objective. For example, buildings may be designed using passive temperature control, natural ventilation, solar control, and daylighting to reduce the energy used for HVAC and electric lighting. New air-conditioning systems such as underfloor air distribution, displacement ventilation, and chilled/heated ceilings can reduce operational costs. Old HVAC equipment, lighting, and windows can be replaced by newer versions which are generally more energy-efficient.

This chapter discusses how expanding the *ambient intelligence in building controls* might also 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. In others, expanded intelligence may be necessary for some of the more efficient new building design techniques to become feasible in practice.

Increased ambient intelligence should also help produce more habitable indoor environments. In commercial buildings, our surveys consistently show thermal complaints (too hot and too cold) are the highest sources of dissatisfaction, with air quality, acoustics and lighting also high. The percentage of occupants voting dissatisfied typically exceeds 20%. For manufactured objects, this level of dissatisfaction would be totally unacceptable, but for current buildings it is clearly very hard to do better. We will argue that in order to do better, occupants need to be informed about and involved in the control of their indoor environment.

2 CURRENT BUILDING CONTROLS: PROBLEMS AND NEEDS

Ideally, building control systems maintain occupant comfort at a low energy cost. The state-of-the-art in building control has greatly advanced in recent years. In commercial buildings digital controls are replacing pneumatic controls [Moult 2000], and energy management and control systems (EMCS) now are increasingly used to monitor and manage the HVAC systems in large commercial buildings. Some of these are web-enabled and most allow for remote monitoring and control. However, while the communication and hardware technology of building controls has changed, the control functions are still rudimentary, with very little use of supervisory control or embedded intelligence. The sensing is far more complete on the HVAC machinery than in the building and its interior spaces. Lighting control technology still consists primarily of switching large banks of fixtures based on a time clock. The intelligence employed in these controls is low because with limited numbers of sensors and actuators one cannot practically do much more.

Sensors and actuators have historically been so expensive that keeping their numbers minimal has been taken for granted. The cost of installing a single sensor or unit controller in a commercial building can be as high as $1000. As much as 90% of that cost is in running the wires needed to power the sensors and communicate with them. Installing wire usually requires making openings in walls and ceilings and then having to refinish them. In some cases the most appropriate sensor position (say on an office worker's desk or chair) is unavailable to a wired sensor, which must be on one of the building's surfaces. So compromises are made such that the sensor is positioned where it is most convenient and inexpensive.

This leads to a situation where buildings are "sensory starved". The building is run on a small amount of sensor data whose accuracy cannot be cross-checked, and whose measurement locations may not represent the environments that the occupants actually experience. Because such sensory shortcomings are taken for granted by designers, the whole approach to building design is essentially distorted. Buildings must be conceived as simplified mechanisms appropriate for this level of control—large indoor spaces are considered as a single nodes, mechanical systems are designed to mix the air in such spaces uniformly even when this imposes an energy and air-quality penalty, and lights are arrayed in uniform banks even when the need for light varies across the space.

Occupant complaints decrease occupants' work productivity and increase maintenance cost by millions of dollars annually. For example, Federspiel (1998) reported that the most common action taken in response to thermal sensation (hot/cold) complaints is to adjust a control system setting, and that automating these actions could reduce HVAC maintenance costs by 20%. Additional sensors would make it easier to determine when problems reported by occupants can be resolved automatically, and when it is necessary to dispatch maintenance personnel to solve the problem. In addition, thermal comfort depends on multiple factors besides temperature. If a space is controlled 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. If the environment were more completely sensed, it could be possible to tune it to provide comfort and ventilation as efficiently as possible.

Occupants' comfort is now never considered directly in building operation. Controls that could obtain information about the comfort of individual occupants have been proposed (Federspiel and Asada, 1994), but have not yet been put into use in buildings. Occupancy and predetermined preferences could be identified by sensors in the chair, as is now done in some automobiles. A person's thermal state could also be predicted from measured skin temperatures sensed through contact or remotely by infrared radiation. None of these things is readily possible if sensors must be mounted on building surfaces, such as walls or ceilings. The workstation furniture is the closest to, indeed in contact with, the occupants. But the difficulty of making hard-wired connections to furniture systems makes such placement traditionally impossible.

The heating and cooling of relatively small local body parts like the hands, feet, or face have a disproportionately strong effect on comfort and satisfaction. If these could be comfortably conditioned with a relatively tiny energy input, the overall ambient space temperature could be allowed to float in a relatively wide range, generating great energy savings. Workstation furniture within a building provides promising sites for occupant sensing and comfort control, perhaps using a parallel local HVAC system allowing individual control independent of the central building HVAC system. The localized actuation of heating and cooling panels and jets within the furniture would probably be best controlled by wireless means, as with a television remote.

3 WIRELESS SENSOR-NETWORKS: AN ENABLING TECHNOLOGY

There are at least four attributes of emerging wireless sensor network technology that could be significant for building applications: small size, low power, and self-organization. These attributes will enable a number of new applications that will improve habitability and improve energy efficiency.

Although buildings are large systems, the small size that is achievable with MEMS technology is desirable for buildings because it allows sensors to be embedded in building materials and furnishings without causing aesthetic problems. For example, Hill (2003) describes the development of a single-chip wireless sensor node of just five square millimeters. Small size is also expected to help reduce the per-unit cost of wireless sensors.

In the past, the need for wired power was one of the key attributes of wireless sensor technology that prevented its widespread use in buildings. Low-power radios such as those described by Rabaey et al. (2000) combined with ambient energy harvesting systems such as those described by Roundy et al. (2003) and firmware designed to conserve energy stored in batteries or capacitors will allow wireless sensors to operate without wired power for years. This will enable the placement of sensors in locations that have been desirable but impractical in the past. It will also enable mobile sensors.

Self-organizing embedded software will allow large networks to configure themselves so that the labor associated with system installation, operation, and maintenance will be lower than it is today. It will enable data from mobile sensors to get where it needs to go.

There are a number of emerging techniques for automatically determining the location of sensors. This is very important even with today's wired sensors. In today's buildings, the CAD drawings that should describe the location of sensors is often inaccurate either because the building was not constructed exactly as planned or because it has been renovated without adequate documentation. Sensors that can self-locate will make it much easier to maintain buildings, and will reduced the need for detailed documentation every time a portion of the building is renovated. In addition, where sensors are embedded within office partitions or furnishings, continued locationing would help operators keep track of the network as office cubicles are moved or relocated.

4 OPPORTUNITIES FOR IMPROVEMENTS

From the building's perspective, here are some of the opportunities enabled by wireless sensor networks.

A) IMPROVED SENSOR LOCATIONS

Sensors are essential components in control systems. For thermal comfort, a thermostat sensor should sense how a building occupant feels about the environment. The thermostat should therefore be placed near the occupant. However, thermostats in closed offices 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, air circulation patterns cause local differences between the thermostat and occupant locations. Poorly located sensors therefore misrepresent the room conditions that the occupants experience and produce sensing delays or inaccurate information.

Wireless sensors can make it much easier to sense variables of interest directly within the occupied zone. Sensors on a desk, within chairs, on phones, or computer keyboard or mouse 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 addition, the increased sensor densities that we envision will allow measurement errors and sensor faults to be more easily spotted and corrected than is possible at present.

Figure 1 shows sensors and actuators that might be found in an office in the near future. Sensors on walls, windows, lights and blinds, furniture, exterior, HVAC system, even *on* the occupant (a temperature-sensing ring, or a voting device) might prove useful. The sensor information is ported via the open-source building-automation protocol BACnet to the building's energy management system from a base station functioning as a gateway. At the room scale, some of the control and actuation could take place within the room itself. The comfortstat (a kind of remote controller) could control the lights or the variable-air-volume (VAV) diffuser in the ceiling.

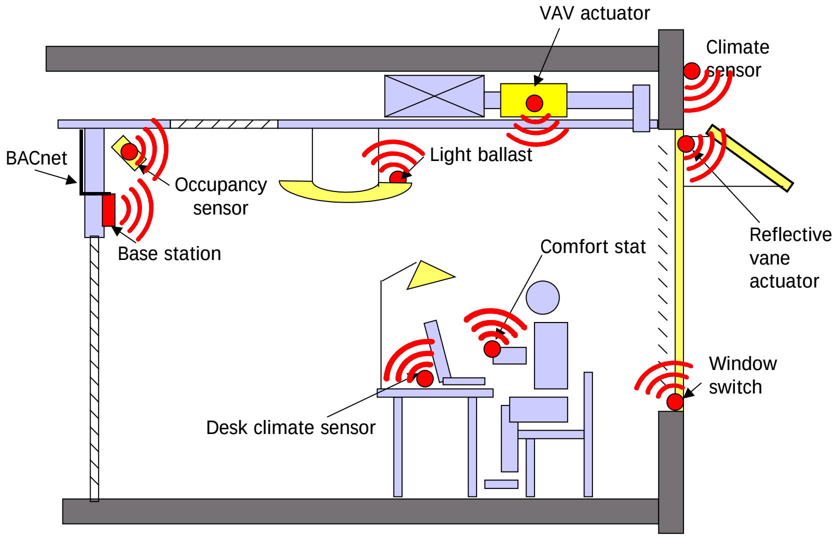

Figure 1: Diagram showing the use of sensor networks indoors

Going beyond this, occupants feel comfortable in, and often prefer, a wider range of environmental conditions if they have *control* over their local conditions [de Dear 2001]. This range could be controlled in ways that are energy efficient if there were sensors providing information on the air movement, thermal radiation, and temperature gradients within the space.

In both tenant-occupied and owner-occupied commercial buildings, churn (renovations resulting from organizational changes) is a significant operating cost. Today wired sensors must often be re-wired and re-located when a space is renovated. According to IFMA (1997), the average move in the government costs $1340 (per person). If new walls, new or additional wiring, new telecommunications systems, or other construction is needed to complete the move, the average cost in a government setting is $3640. Wireless sensor networks could significantly reduce the churn costs associated with re-wiring because sensors can be freely located and easily moved.

B) MORE SENSOR TYPES

MEMS technology makes it possible to add sensing modalities to a sensor node without significantly increasing the cost. Sensors that would be useful for building applications include light spectrum (in three bands to differentiate daylight, sunlight, and artificial light), sound spectrum (to differentiate noise sources and control masking systems), averaging air velocity sensors across a deep column of air, carbon dioxide concentration, and perhaps a pollutant or tracer-gas-specific concentration sensor.

C) OCCUPANTS' INVOLVEMENT IN CONTROL LOOPS

Networks of physical sensors and actuators will make it possible for occupants to become more involved in controlling their local space. This is a good thing. 'Smart buildings' controlled without occupant intelligence or involvement are often highly unpopular. Occupant control helps satisfy occupants by widening their comfort zone, so that such buildings do not need to be as rigorously conditioned as buildings with totally automated control. The 'adaptive model' quantifies this widening effect [de Dear 2001]. It is currently being incorporated in ASHRAE Standard 55, one of the two major standards for indoor thermal environmental control. [ASHRAE, 2004].

In operation, occupants could operate the room's overhead lights without leaving their desks. Programmable switches and ballasts could give occupants more flexibility to adjust ambient light levels according to their preferences. Similarly, the VAV damper positions could be independently overridden while the central control system is informed of the action via BACnet.

At a broader level than just providing individual controllers, we view occupants as a useful resource to control the environment. By providing occupants with information that allows them to play a more effective role in the environmental control of 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. This type of information could take place continuously in a less obtrusive way.

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 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.

5 APPLICATIONS

A) HVAC: OPTIMIZING ENERGY AND COMFORT IN MULTIPLE ROOMS:

In a air conditioning system in commercial buildings, it is common to use one sensor 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 simulations. They showed that by increasing the number of sensors they could simultaneously reduce discomfort and energy consumption. Table 1 shows the results compared to the standard case where a set of rooms on a perimeter exposure of a building is controlled by a single sensor. In the multi-sensor case, each room has a sensor. A strategy optimized for comfort reduced energy consumption by four percent and reduced the predicted percent dissatisfied (PPD, a measure of the fraction of people who are uncomfortable) by 9.5%. A strategy optimized for energy consumption reduced energy use by 17.3% while still reducing PPD by 5.7%. Even simple, ad-hoc strategies worked well. Controlling the average temperature reduced energy consumption by 7.1% and reduced PPD by 9.1% while controlling the average of the highest and lowest temperature reduced the two metrics by 7.1% and 6.5% respectively. For the case of controlling the average, the authors could show that the improvements arise when one or more rooms requires cooling while one or more other rooms in the same zone requires heating at the same time.

Table 1: Predicted percent reductions in energy and discomfort from increasing sensing density

	cooling	heating	total	PPD
comfort opt	2.1	7.3	4.0	9.5
energy opt	8.3	32.9	17.3	5.7
average	3.5	13.4	7.1	9.1
span	2.8	14.6	7.1	6.5

B) HVAC: OPTIMIZING ENERGY AND COMFORT WITHIN A SINGLE ROOM:

Wang et al (2002) studied the energy needed to condition an office room with air stratification present in the space, and quantified the effects of adding temperature sensors at foot level to the traditional sensors at chest height—a scenario that would be readily accomplished with a net of wireless temperature sensors. The stratification was produced by air supplied from an underfloor plenum, a relatively new technology with a number of attractive features. The additional foot-level sensors enable a more sophisticated variable-temperature-and-volume (VTV) system for controlling the air supply than could be possible with a conventional single thermostat. The traditional single-thermostat systems use variable-air-volume (VAV) and constant-air-volume (CAV). The three systems were compared.

The two-sensor (VTV) system used the least energy among three cases with savings of 8% compared with the VAV system, and 24% when compared with the CAV system. The major energy difference came from fan energy consumption: the VTV consumed 14% less fan energy than that of VAV and 37% less than that of CAV. All three of these systems had the same average temperature in the occupied zone, and all three had vertical temperature gradients within acceptable limits.

A similar situation occurs when controlling indoor air quality. Ventilation air is 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.

C) HVAC: FAULT TOLERANCE, FAULT DETECTION AND DIAGNOSIS:

It is often difficult to quantify the benefit of fault detection and diagnosis capabilities in building control systems because not enough is understood about the frequency and severity of even the most common faults. This fact combined with the high cost of wired sensors and the relatively low cost of energy makes it uncommon to have redundancy that would be useful for fault-tolerant control, fault detection, or diagnostics.
Braun and Li (2003) reported that 75% of the labor spent on preventative maintenance could have been avoided by using existing fault detection and diagnosis technology. Furthermore, the energy performance of 15 of the 21 units (70%) they inspected were negatively impacted by faults, causing the efficiencies to be reduced by 20-30%.

We expect that the energy benefits of increasing sensor density will create sensor redundancies that can be exploited for fault tolerance, fault detection, and diagnosis. For example, the study by Lin et al. (2002)

involved adding more space temperature sensors and changing the control software to reduce energy consumption and thermal discomfort. In such a system, a failure of a single space temperature sensor would not necessarily cause the control system to fail because it could revert to an alternative strategy that made use of the available, properly functioning sensors.

D) DISTRIBUTED CONTROL OF DATA CENTERS:

With the advent of increased power densities in today's computer chips and the explosion of demand for centralized computing services, data centers have grown hotter and larger, respectively. The power densities per unit area have risen in recent years from $500W/m^2$ to $3000W/m^2$ [Patel, 2003]. These energy rates yield computer racks that each dissipate 10-15 kW [Sharma et al., 2002]. Therefore, a cooling control system that could modestly increase cooling efficiency could save a significant amount of money and justify the equipment costs required for such a system.

Boucher (2004) describes a control system that has the sophistication to optimize the cooling of each rack in a data center, to maintain proper thermal conditions for all computers. This system requires:

(i) A distributed sensor network to indicate the local subfloor conditions of the data center.
(ii) The ability to vary cooling resources locally (in this case by a moving nozzle that directed cooling supply air at hot spots, like a fire hose).
(iii) Knowledge of how local cooling variation affects the overall conditions of the data center.

Using these three things, a "smart" dynamic cooling controller was developed and implemented to automatically optimize the computer room air conditioner (CRAC) settings with respect to minimum energy usage. To achieve (i), wireless sensor technology makes the addition of a distributed sensor network much more viable and flexible from a client service point of view.

Table 2 shows the energy performance achieved by the smart dynamic cooling controller implemented in the data center shown in Figure 2. The experiment was conducted by isolating the section of the data center in the upper right region of the figure and using false compute loads in the two rows of racks. The compute load was 52kW. The two CRAC units were controlled in parallel.

Table 2: Energy performance of data center cooling controls.

Configuration	Fan Speed, %	Supply Temperature, °C	Power Consumption, kW
Return temperature control (base case)	95	13.8	45.8
Rack inlet control (uses sensor network)	95	20.4	31.2
Rack inlet control with fan optimization	45	20.0	13.5

The table illustrates that simply by replacing the single sensor at the return point with a sensor network at the rack inlet locations the power consumption could be reduced by almost 50% from the base case. Explicitly regulating the rack inlet conditions enabled us to use a fan optimization strategy that reduced energy consumption by 70% from the base case.

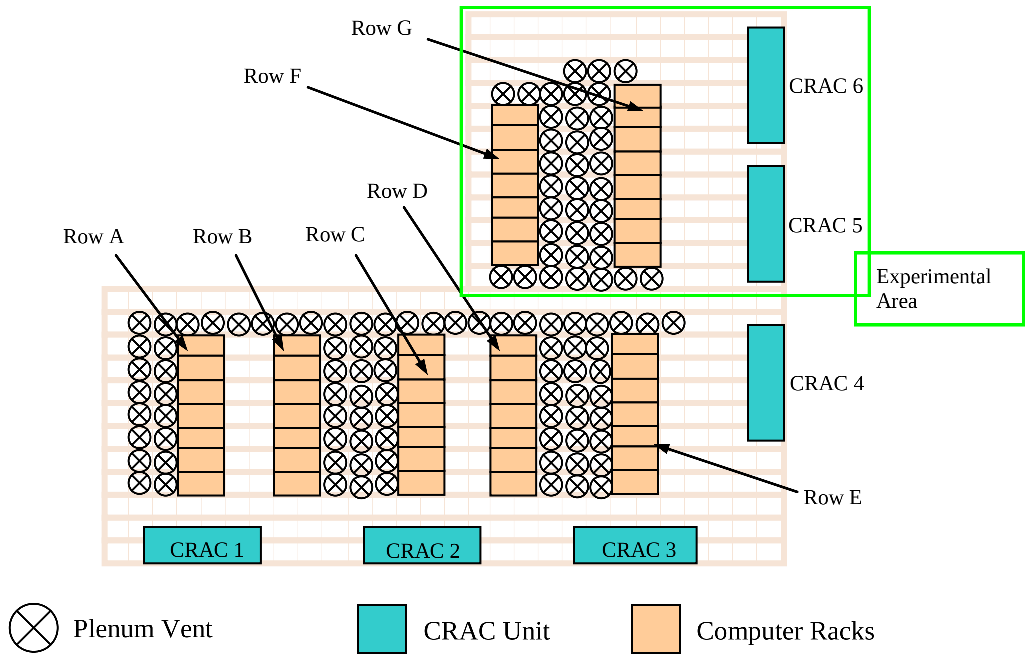

Figure 2: Schematic diagram of data center used for experiments.

E) LIGHTING CONTROL:

Lighting in commercial buildings uses almost the same energy as HVAC (28% of total energy use and over 50% of electricity consumption). Like HVAC controls, lighting controls are also ‘starved’ for sensors (daylight, occupancy) and actuation (too few switches, unnecessary lights often on when few would suffice). Wireless sensors and actuators would permit programmable switches for each occupant, switching and dimming in response to daylight sensors, occupancy sensors, or commands from occupants. At UCB we are developing a system of wireless sensors, wireless switches, and wireless controls that can be easily integrated with existing wired systems. This system promises to greatly increase energy efficiency while simultaneously improving controllability and lighting quality for occupants.

Wireless lighting control networks can provide control at the fixture or ballast level, as illustrated in Figure 3. Ballast level control can be implemented using stand-alone relay devices that switch power to the ballast or by ballasts with integrated wireless capability (currently under development). Ballast-level control provides greatly enhanced flexibility for the occupants and can lead to significant energy savings. With traditional wired switches, occupants in open plan offices usually have limited control over ambient lighting. One switch normally controls lights for many different workspaces and “ownership” of the switch is unclear. As a result, occupants leave lights on unnecessarily. A programmable wireless network enables individuals to control only the lights affecting their workspace, greatly increasing the likelihood that lights will be turned off when unneeded.

Light level sensors can be integrated into the network to take advantage of available daylight. In the most advanced systems, dimming ballasts can be used to maintain the desired light levels. Even without dimming ballasts, fixtures with standard ballasts can be turned off in areas that have adequate daylight. Many fixtures provide bi-level control by using two ballasts and provide an intermediate level of electric light in response to daylight levels. Motion sensors can be added to the network to turn lights on or off as needed in response to occupancy.

Wireless networks have great potential to lower lighting electric demand in response to requests from the electric utility. A fraction of fixtures can be designated as non-critical and can turn off in response to a broadcast request. Since lighting is the largest electric end-use in most office buildings, it has significant potential for demand reduction programs.

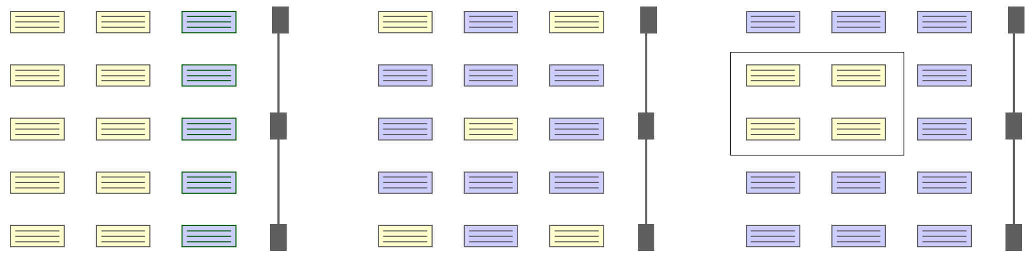

Figure 3. Wireless lighting network control allows many control patterns for a given set of light fixtures. Shown here in plan view (a) perimeter daylight control where fixtures near the windows are turned off when sufficient daylight is available, (b) a demand reduction control scheme where 2/3 of the lights are turned off to shed load (this could also function as an emergency lighting scheme, and (c) lights for an individual workspace are on while adjoining workspaces lights are off.

UC Berkeley's prototype wireless lighting control system can easily be applied as a retrofit in existing buildings. As shown in Figure 4, the system includes relays, light sensors, motion sensors and control switches that communicate via a wireless network.

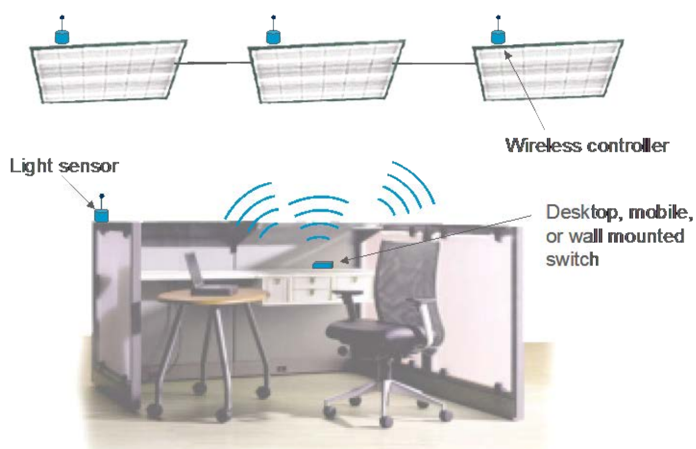

Figure 4: Arrangement of wireless control hardware

F DEMAND-RESPONSIVE ELECTRICITY MANAGEMENT

Wireless technology provides an important opportunity in residential and small-commercial buildings as well. Such buildings typically do not have the complex environmental systems and central control of large commercial buildings. Wireless networks of sensors and controllers could enable residential-scale systems of considerable sophistication that are now only possible in commercial buildings.

In California and other states, 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 aggregate, this allows energy generation resources to be managed more efficiently.

For demand response to be implemented in practice, a network combining distributed time-sensitive metering and smart energy-consuming appliances with cost-setting mechanisms is needed [Hirst 2002]. Figure 5 illustrates some of the components of a residential demand-response system. Within each house, the electricity meters should be capable of receiving real-time electricity tariffs and automatically initiating responses that reduce overall energy cost, while being responsive to the occupants' preferences. They must be flexible enough to respond to changing pricing plans and billing intervals, and to signal the consumer's usage to the utility. The meters 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. Finally, to be widely adopted, they must be more inexpensive to purchase and install than current solutions. For this, the sensors/actuators must be combined on one or two chips with wireless communications and power scavenging. Federspiel et al. (2004) describe some of the design concepts for such a wireless demand-response system.

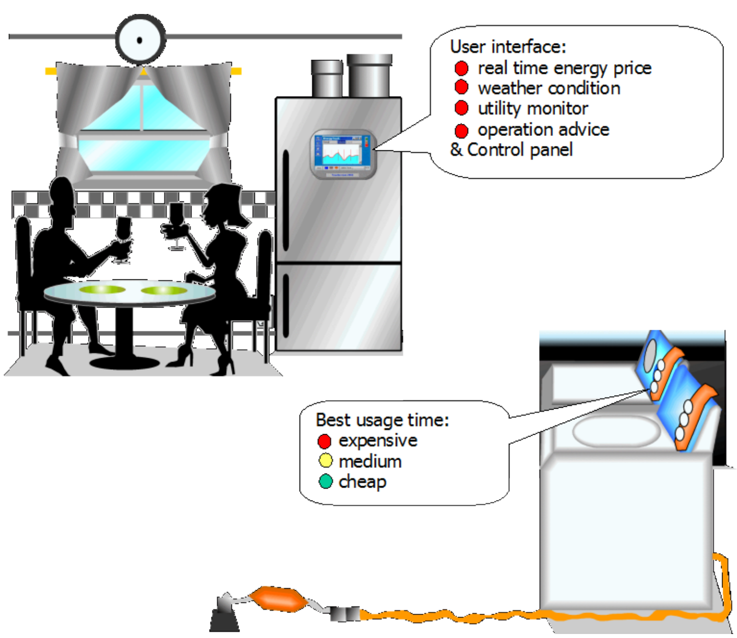

Figure 5: Involving residential occupants in electricity use decisions

6 INTEGRATION OF SYSTEMS

Wireless ambient intelligence may also help solve an environmental control problem that is unrelated to wiring: the general lack of integration among the different environmental control functions. Figure 6 shows how many of the control functions in buildings might be integrated. In commercial buildings, the environmental controls include the following:

- Heating, ventilating, and air conditioning (HVAC) systems control thermal conditions and air quality through mechanical heating, cooling, and ventilation equipment. In some cases, primarily overseas, such systems are interlinked with building envelope components, such as operable windows.
- Interior lighting is controlled by electric lighting systems and, in some buildings, by automated daylighting and solar controls.
- Acoustical systems mask, dampen, or eliminate unwanted sound.
- Fire safety systems detect combustion and activate fire suppression, smoke control, and evacuation systems.
- Energy management systems are used in conjunction with some of the above systems to improve their efficiency; these typically sense both environmental and system state variables.
- Security, lighting, HVAC, and energy management systems all may monitor human occupancy through thermal, chemical, and acoustic means.

The controls associated with any one of these functions rarely respond to the operation of one of the other functions. For example, temperature controls do not respond pro-actively to the operation of lighting or automated window-shading devices. This is because distinct systems are dedicated to each of these functions. Consequently, it is difficult and expensive for the temperature control system to get information about the operation of lights or windows, and vice-versa. This problem could be solved if the sensory information used for each function were derived from the same source.

Ambient intelligence will involve multiple sensing modalities being embedded in a single sensing node. This will ensure that the sensory information for each of the functions described above is readily available for use by any control application. Ambient intelligence will also involve developing control algorithms designed to take advantage of a data-rich system. These algorithms will result in functionally integrated environmental controls.

Arens, E., C.C. Federspiel, D. Wang, and C. Huizenga, 2005. “How Ambient Intelligence Will Improve Habitability and Energy Efficiency in Buildings.” Published in the book *Ambient Intelligence*, eds. W. Weber, J.M Rabay and E. Aarts, Springer, March. pp.63-80. with kind permission of Springer Science and Business Media

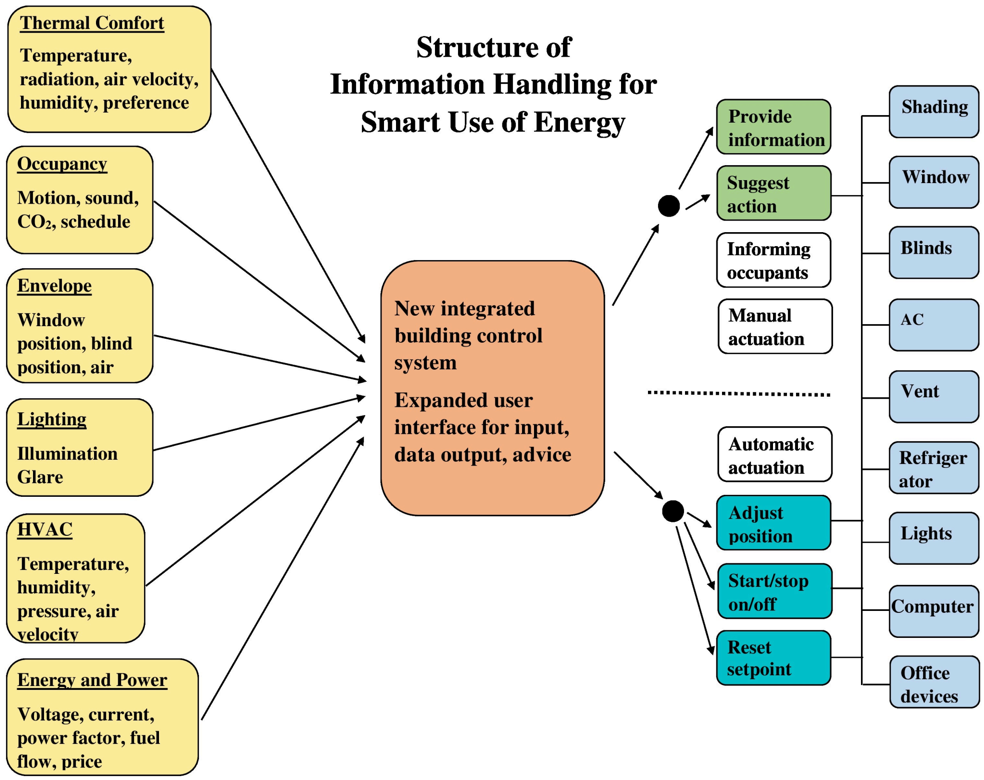

Figure 6: Structure for an integrated wireless building control system

7 ENCOURAGING MORE ADVANCED BUILDING DESIGN

Although sensors are normally seen as devices used for operations, they can have an enormous influence on what is possible in building design. We see opportunities for wireless sensor networks to enable new more efficient architectural and HVAC design concepts that until now have not been accepted for a variety of reasons.

It has become routine in the US and elsewhere to rely on mechanical air conditioning to create the interior environment in buildings. In many less-developed parts of the world, air conditioning has become a synonym for "modernization", and their buildings follow western models which may be inappropriate for their economic context. In both developed and developing parts of the world, there are energy and environmental consequences to this mechanical approach, and occupants who inhabit the artificially controlled environments may suffer health symptoms and comfort dissatisfaction. It would be desirable to design buildings that were climate-adaptable, which could take advantage of natural climate whenever possible without degraded energy or environmental performance.

Recent buildings designed with operable windows, dynamic lighting and solar control, and hybrid/mixed-mode ventilation systems, have the potential to provide higher levels of occupant satisfaction, direct natural ventilation, and decreased AC energy use. When uncoordinated, such systems could waste energy (e.g., AC-cooled air escaping out the window, or unwanted humidity leaking in). With window sensors and temperature sensors in/near the window, the air movement in/out of the window can be determined and used to control for the "desired" direction of airflow.

The success of such new building systems may depend on wireless network technology, and the higher level of ambient intelligence it enables. Wired sensors for window-position, temperature, humidity, sunlight, and airflow have typically been too expensive to install at the sensor density needed. With continuous monitoring of enough of the important variables, such systems could be operated efficiently and lessons about their performance understood by both their operators and by designers of future advanced building systems.

8 CONCLUSION

This paper discusses how wireless sensor network technology may affect future building design and operation.

Flexible location of sensors and increased sensing density, as well as increased variety of sensor types, can make significant improvements to building energy efficiency and the well-being of their occupants.

The technology will make the following changes in the near future: to include building occupants in control loops via information and distributed interfaces, 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 wireless technology and applications would encourage the adoption of sophisticated climate-adapting building designs, new types of air conditioning systems that provide individual control at the workstation level, and sophisticated energy-cost and comfort-management for small residential-scale buildings.

9 REFERENCES

American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 2004. “ANSI/ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy”. Atlanta.

Boucher, T., 2004, “Self-Optimizing Cooling Control for Data Centers,” MS Thesis, Department of Mechanical Engineering, UC Berkeley.

Braun, J. and H. Li, 2003, “Fault Detection and Diagnostics for Rooftop Air Conditioners,” Attachment 1, California Energy Commission report 500-03-096.

de Dear, R.J. and Brager, G.S. 2001, “The Adaptive Model of Thermal Comfort and Energy Conservation in the Built Environment”, International Journal of Biometeorology, Vol. 45, No. 2, 100-108.

DOE. 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.

Federspiel, C. C. and Asada, H. 1994, “User-Adaptable Comfort Control for HVAC Systems,” *Journal of Dynamic Systems, Measurement and Control*, 116(3), 474-486.

Federspiel, C. C., 1998, “Statistical Analysis of Thermal Sensation Complaints,” ASHRAE Transactions, 104(1), 912-923.

Federspiel, C. C., E. Arens, T. Peffer, and D. M. Auslander, 2004 “Design Concepts for Residential Demand Response Systems,” submitted to *2004 ACEEE Summer Study on Energy Efficiency in Buildings*.

Hill, J. L., 2003, *System Architecture for Wireless Sensor Networks*, Ph.D. dissertation, UC Berkeley.

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

IFMA, 1997, *Benchmarks III* , Research Report #18, International Facility Management Association, Houston, Texas.

Lin, C., C. C. Federspiel, and D. M. Auslander, 2002, “Multi-Sensor Single-Actuator Control of HVAC Systems,” *International Conference for Enhanced Building Operations*, Austin, TX, October 14-18, 2002.

Moult, R., 2000, “Fundamentals of DDC.” ASHRAE Journal. November.

Patel, C. D., 2003, “A vision of energy aware computing – from chips to data centers”, *The International Symposium on Micro-Mechanical Engineering*, ISMME2003-K15, December.

Rabaey, J. M., M. J. Ammer, J. L. da Silva, D. Patel, and S. Roundy, 2000, “PicoRadio supports ad hoc ultra-low power wireless networking,” *IEEE Computer*, 33(7), 42-48.

Roundy, S., P. K. Wright, and J. Rabaey, 2003, “A study of low level vibrations as a power source for wireless sensor nodes,” *Computer Communications*, 26(11), 1131-1144.

Sharma, R. K., C.E. Bash, C.D. Patel, 2002, “Dimensionless parameters for evaluation of thermal design and performance of large-scale data centers”, *American Institute of Aeronautics and Astronautics*, AIAA-2002-3091.

Wang, D., Arens, E., Webster, T., Shi, M., 2002, “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. 1997, “Individual Control at Each Workplace for Health, Comfort and Productivity”, Creating the Productive Workplace Conference, October, London .

Arens, E., C.C. Federspiel, D. Wang, and C. Huizenga, 2005. “How Ambient Intelligence Will Improve Habitability and Energy Efficiency in Buildings.” Published in the book *Ambient Intelligence*, eds. W. Weber, J.M Rabay and E. Aarts, Springer, March. pp.63-80. with kind permission of Springer Science and Business Media