How Ambient Intelligence will Improve Habitability and Energy Efficiency in Buildings

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1 Introduction

Buildings are primarily constructed to create indoor environments where their occupants are comfortable, healthy, safe and, not to forget, productive. Inside the building there's a great mixture of systems (HVAC[1], lighting, life safety equipment, the architecture itself and the building's occupants) working together to achieve this purpose. One "problem" is that most buildings are designed and built individually, so that the mixture of systems is different for nearly all buildings. Buildings are usually put directly into operation, rather than spend time and money into testing. Designers and operator rarely have the chance to evaluate systematically how effective and energy efficient their building is producing the desired environment. Once in operation it is very hard for operators to determine how they perform, because there are insufficient channels for collecting physical data and occupant feedback. And buildings usually aren't delivered with an instruction manual. It would be a great help if there were more information available.

In the past two decades, the adoption of computer control systems in commercial buildings has greatly improved the access to and the management of physical data. However, these systems still communicate with only 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. Even in residential buildings, which generally tend to be much simpler, the amount of information is less than optimal – usually all contained within a single thermostat.

In the US 38% of all primary energy is used to condition buildings. This huge energy consumption even exceeds transportation or industry. There have been many approaches to reduce energy consumption of buildings. For example, buildings may be designed to using passive temperature control, natural ventilation, solar control and daylighting to reduce the energy used for HVAC. New air-conditioning systems like underfloor air distribution, displacement ventilation and chilled/heated ceilings

[1] Heating, Ventilating Air Condition

can reduce operating costs. Also replacing old HVAC equipment can be replaced by newer versions, which are generally more energy-efficient.

Here I want to show, how expanding the ambient intelligence in building controls might also reduce energy consumed in building operation. In some cases it would be the fastest and most cost-effective way to obtain a given level of energy saving. In others, expanded intelligence may be necessary to for some of the more efficient new building design techniques to become feasible in practice.

2 Situation today

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, 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. 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. As much as 90% of the cost is in running the wires needed to power the sensors and communicate with them. In some cases the most appropriate sensor position is unavailable to a wired sensor, which must be on one of the building's surfaces. 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. Buildings must be conceived as simplified mechanisms appropriate for this level of control - large indoor spaces are considered as 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, 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%. 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.

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

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. Although buildings are large systems, the small size that is achievable with wireless technology is desirable for buildings because it allows sensors to be embedded in building materials and furnishings without causing aesthetic problems. Today, we are able to develop 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 combined with ambient energy harvesting systems 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 which are able to send data 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 are 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 reduce the need for detailed documentation every time a portion of the building is renovated.

Sensors are essential components in control systems. For thermal comfort, a thermostat sensor should sense how a building occupant feels about the environment. 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.

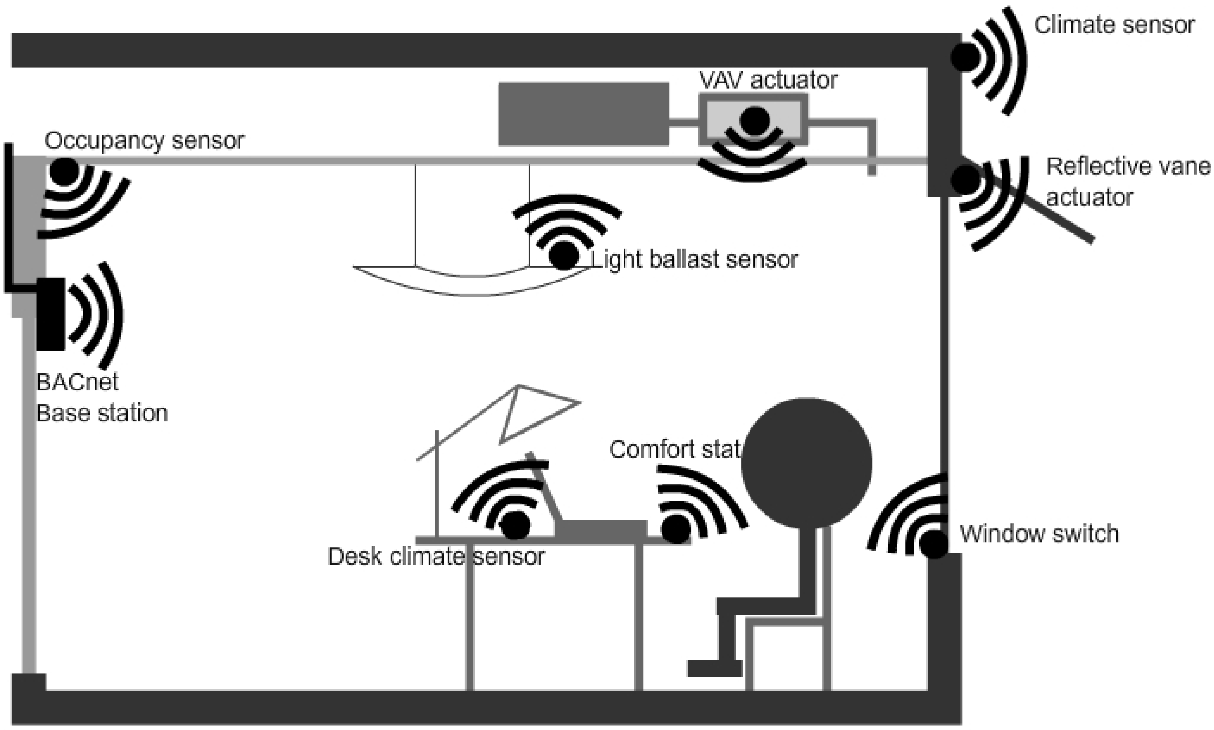

Figure 1– How an office in the near future might look like

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. Going beyond this, occupants 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 on the air movement, thermal radiation, and temperature gradients within the space.

Today wired sensors must often be re-wired and re-located when a space is renovated. Wireless sensor networks could significantly reduce the costs associated with re-wiring because sensors can be freely located and easily moved.

4 BACnet

4.1 History

BACnet is a free of charge data communication protocol developed by the "American Society of Heating, Refrigerating and Air Conditioning Engineers" (ASHRAE). The first version of the standard was published in 1995 after more than 8 years of development.

The question often comes up: why a standard protocol? Among the many reasons is the illogicality of having to have multiple workstations just because a site may have building automation and control equipment from multiple manufacturers in the field. Would anyone tolerate a world where each TV network had its own signal format, each requiring the purchase of a special receiver?

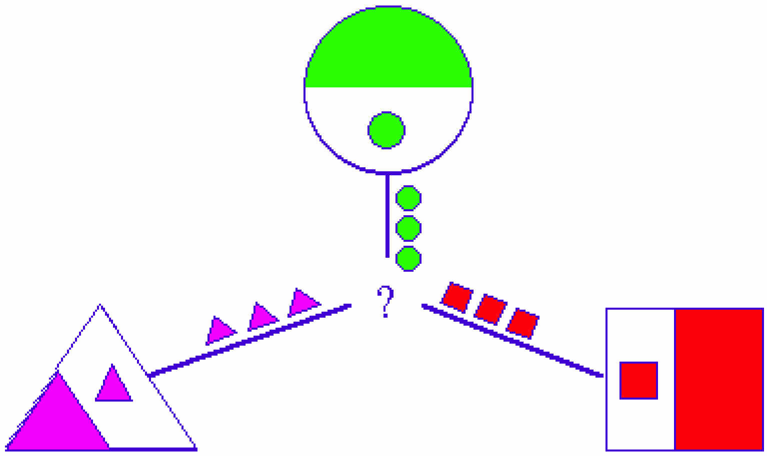

Figure 2 –without a standardized communication. Different vendors = Different communication

Sure, there are ways to interconnect products made by different manufacturers without a standard protocol, but it is not easy. A single front end system can be made which "knows" the proprietary communications technique of each system, effectively bridging their differences in software. This approach requires the cooperation of multiple manufacturers, or reverse engineering. In practice these systems have been very costly to implement and support, as the various systems evolve and change independently.

BACnet was created out of a coproduction of universities and different vendors of building control systems. For a small vendor it was very difficult this time, because they didn't really had a chance against their much greater rivals. At least not without the opportunity to integrate one's own components into an existing building control system. So the idea of developing a standard protocol was born. And after more than 8 years, the first version of BACnet was born.

A key design criterion was that the protocol had to be applicable to all building automation needs. To accomplish this, BACnet specifies most all of the most common functions: analog and binary input, output, and values; control loops; schedules, etc., that clearly applies to almost any kind of monitoring or control application.

One of the positive aspects of the arduous standards development process is that when a standard is finally promulgated, it already has a large measure of industry acceptance because it has been thoroughly reviewed by the industry. As indicated above, BACnet was studied and analyzed exhaustively.

BACnet's "coming out party" was held at the ASHRAE Winter Meeting in Atlanta in January, 1996. Each workstation displayed the same graphics; one was Mac, three were Intel machines. Of the PCs, two were running Windows, one OS/2. Three were on Ethernet, one on ARCNET and so on. Appropriate routers interconnected the various LAN types.

In Europe, BACnet was approved as a European standard within CEN, the Committee for European Standardization, in the year 2003.

4.2 Communication

As a "data communication protocol" BACnet is simply an agreed-upon set of rules that apply to a computer's hardware and software. The rules apply to all aspects of data communication. BACnet is "special" among protocols because its message format was specifically designed to facilitate communication about information related to building automation and control.

The most important thing in the development of BACnet was “Interoperability”. To achieve this goal, BACnet uses both modern and well integrated communication models. The concept is to replace the communication portion of each device with a common, standard set of communication rules - a common "language" - so that each device "looks the same" on the wire. This is accomplished by introducing "objects." An object is simply a collection of information related to a particular function that can be uniquely identified and accessed over a network in a standardized way.

All information in a BACnet system is represented by such data structures. The object concept allows devices to talk about and organize information relating to physical inputs and outputs, as well as non-physical concepts like software or calculations.

Objects may represent single physical “points” or logical groupings of points that perform a specific function. They meet the design requirement of providing each device with a common "network view," i.e., all objects, regardless of the machine in which they reside, look alike. All BACnet objects provide a set of properties which are used to get information from the object, or give information and commands to an object. Although there are thousands of potentially useful object types which might be found in building automation, BACnet defines 23 standard object types in some detail. A BACnet standard object is one whose behavior, in terms of which properties it provides and what they do, is defined in the BACnet standard.

This set of standard objects represents much of the functionality found in typical building automation and controls systems today. BACnet devices are only required to implement the “Device” object, which describes the device itself. Other objects are included as appropriate to the device’s functions.

The second part of the development challenge was to agree on what kinds of messages building automation and control devices might want to send to each other. Because BACnet is based on a "Client-Server" communication model, these messages are called "services" which are carried out by the server on behalf of the client. The message is always sent to a specific recipient and returns, the requested property value in a standard form.

Finally, there had to be decided, which networking technologies should be selected out of the dozens available. The set of technologies (Ethernet, ARCNET, LonTalk etc.) specified in BACnet was chosen because it seemed to span the real-world requirements of building control systems in terms of speed, throughput, cost, familiarity, etc. But BACnet also defines its own transport protocol: “BACnet/IP”. It provides not only the specification for transporting BACnet messages between IP devices but also the framework for embracing other new networking technologies with a minimal impact on existing BACnet technology.

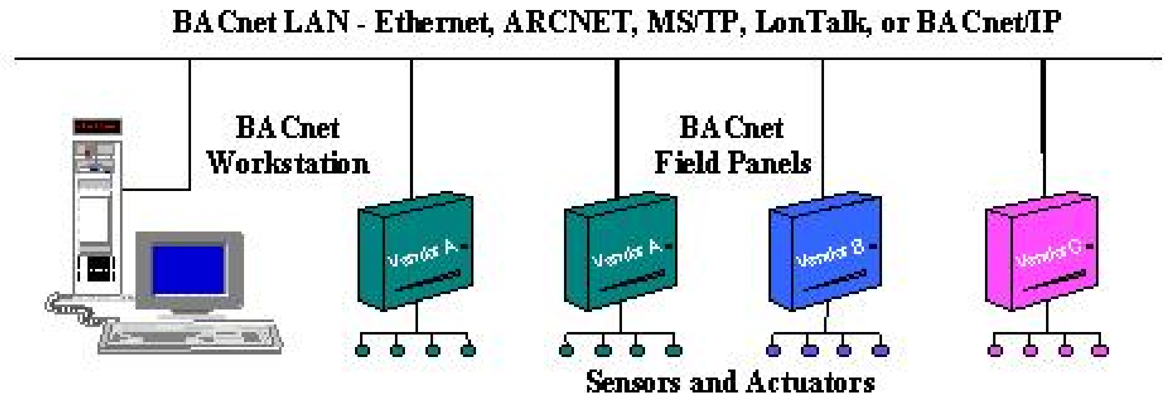

Figure 3 gives an overview over the BACnet communication system

4.2.1 IP-Tunneling

In IP tunneling, Device A on Network 1 addresses a message to Device B on Network 2 using the BACnet network layer protocol (see Figure 4). It sends the message to the router on its local network. The router is called an "Annex H" router because Annex H is the place in the standard where this process is defined. The Annex H router knows how to send IP messages over the Internet (or an "Intranet" based on IP) to its peer device on Network 2. It encapsulates the BACnet message (in a UDP frame) and sends it via IP to the Annex H router on Network 2. Both networks are connected via a standard IP router to the Internet at large.

When the Annex H router on Network 2 receives the IP message from its peer, it removes the encapsulated BACnet message and sends it on to its final destination, Device B.

The only downside to this is that each message shows up twice on each network – once as a pure BACnet message and once as an IP message.

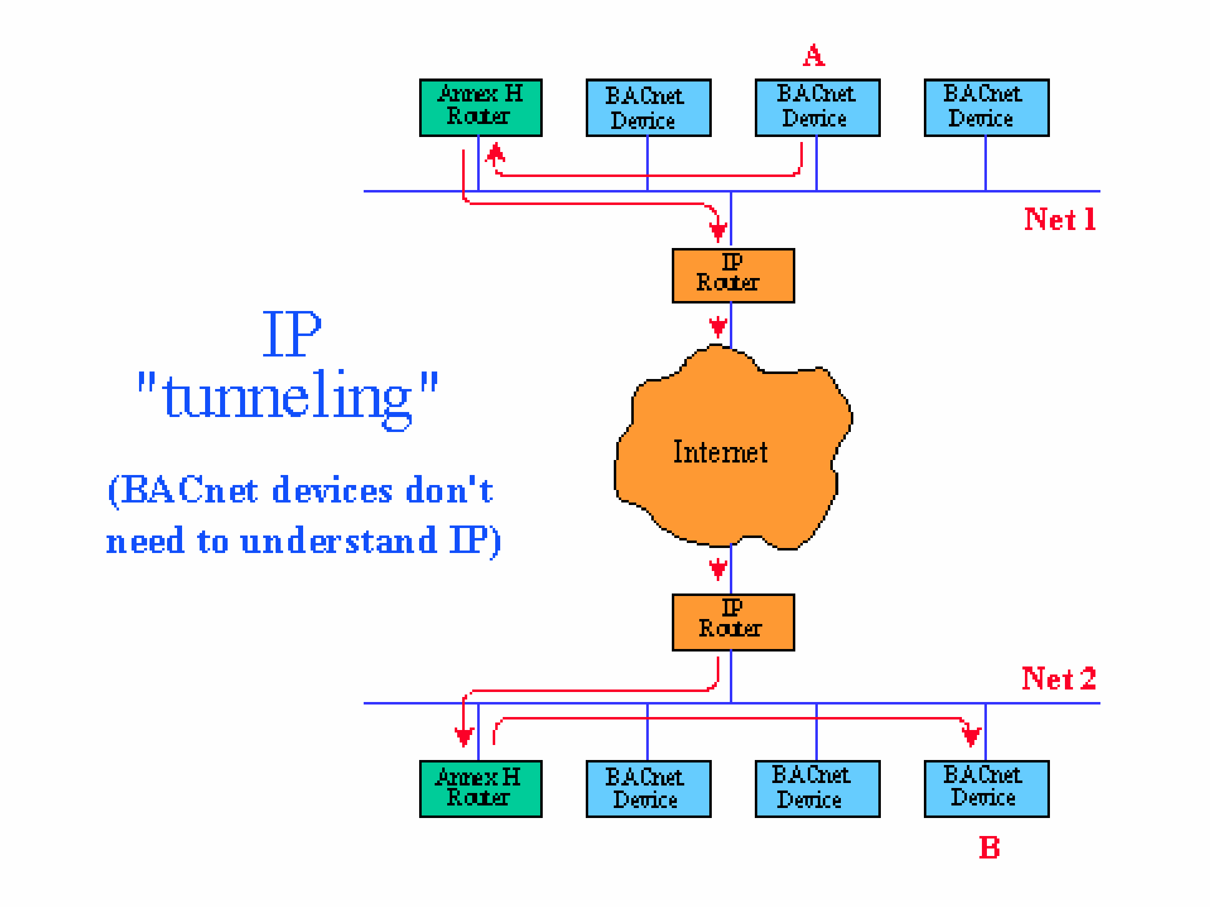

Figure 4 - IP-Tunneling

4.2.2 BACnet/IP

BACnet/IP is a different beast entirely. BACnet/IP devices view the IP internet as if it were a local area network.

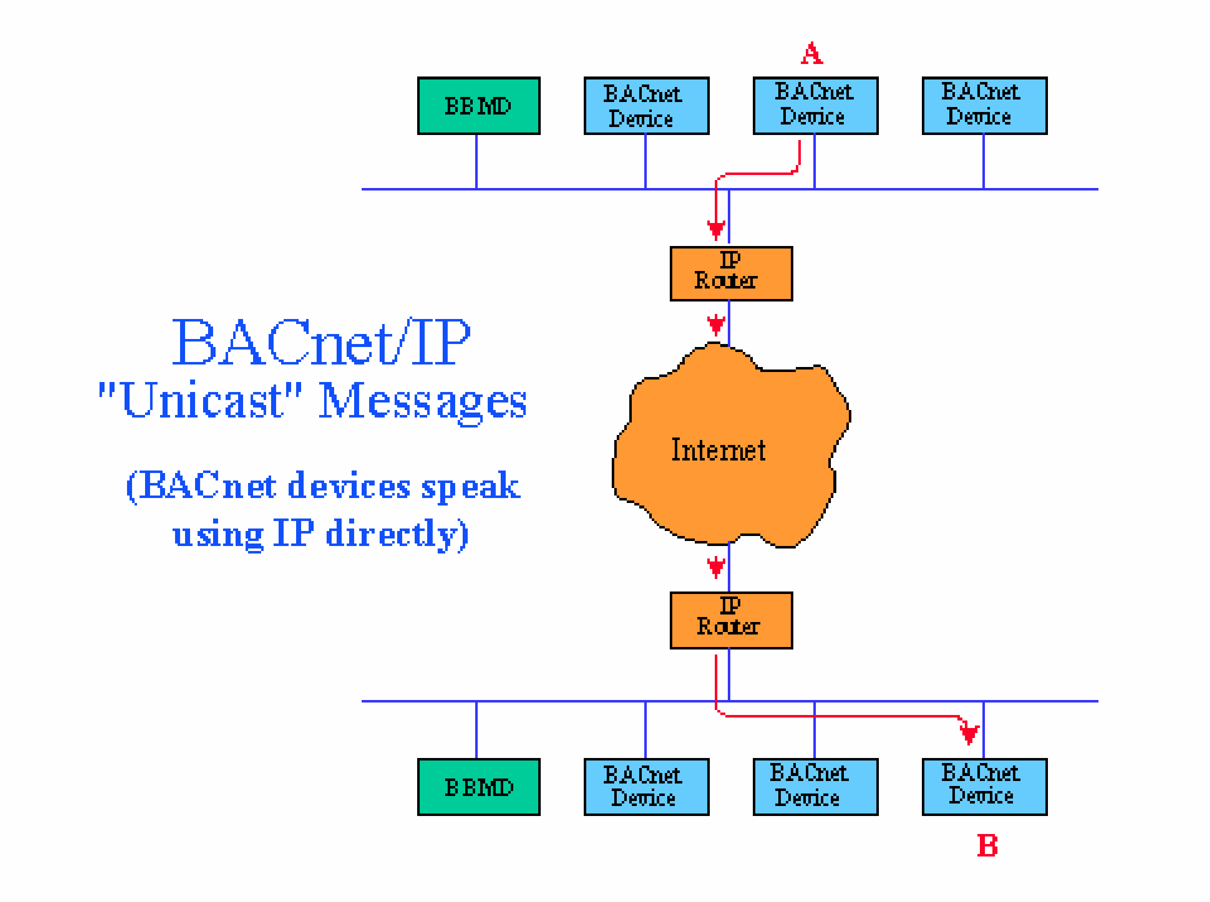

Figure 5 - BACnet/IP

BACnet/IP devices don't need Annex H routers and can talk with each other directly over the Internet. To summarize, BACnet consists of a specification for the BACnet object and services model, a network layer protocol, and a selection of various network transport technologies appropriate for various size and capability systems.

To close the BACnet-part of this paper, a quote from the official BACnet-Homepage:

"BACnet is undoubtedly the worst protocol on the face of the earth - except for all the others!"

5 Applications

5.1 Distributed 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. 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.

The paper (see References (2)) describes a control system that has the sophistication to optimize the cooling of each rack in a data center and to maintain proper thermal conditions for all computers. This system requires:

(1) A distributed sensor network to indicate the local subfloor conditions of the data center.

(2) The ability to vary cooling resources locally (in this case by a moving nozzle that directed cooling supply air at hot spots).

(3) 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 (1), wireless sensor technology makes the addition of a distributed sensor network much more viable and flexible from a client service point of view.

In an experiment, they compared two different setups of cooling systems. One was the “old” approach of ventilating cooled air to the data racks. This system was controlled by a single sensor at the end which measured the temperature of the outcoming air. The second setup was like the one described above and the results were astonishing. The energy consumption was 50% less with the new system and even 70% less when adding a special fan optimization.

5.2 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. 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 the University of Berkley they 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. 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 lights affecting their workspace, greatly increasing the likelihood that lights will be turned off when unneeded.

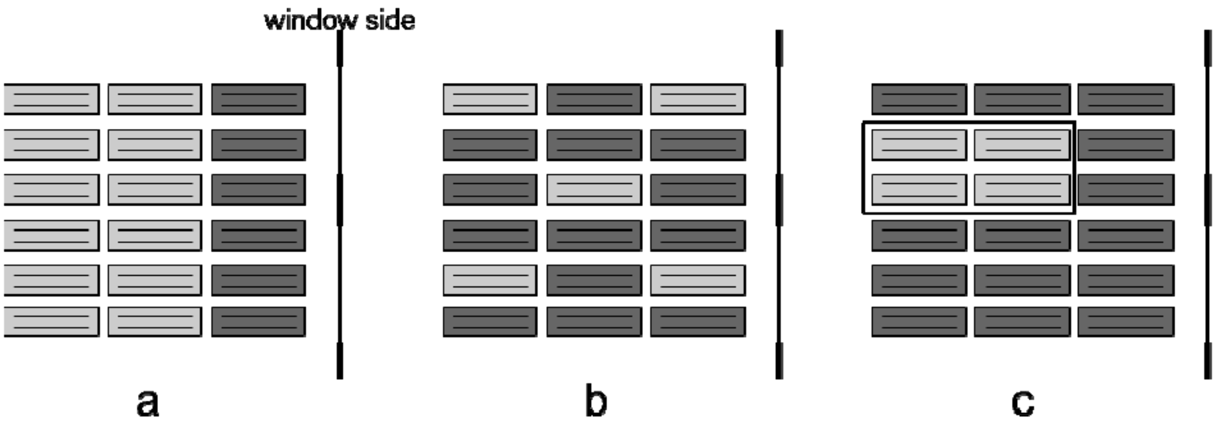

Figure 6 Lights switched in pattern

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. 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. Since lighting is the largest electric end-use in most office buildings, it has significant potential for demand reduction programs.

6 Conclusion

Although sensors are normally seen as devices used for operations, they can have an enormous influence on what is possible in building design. 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 (like AC-cooled air escaping out the window). 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. 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.

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