ARE WIRELESS SENSORS AND CONTROLS READY FOR THE BUILDING AUTOMATION INDUSTRY?
SELECTED CASE STUDIES AND TECHNOLOGY DEVELOPMENT ACTIVITIES

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ABSTRACT

The rapid maturity of everyday wireless technologies has a tremendous impact on our ability to collect information from the physical world. There are tremendous opportunities for using wireless radio-frequency technologies in sensors and controls for building operation. The key promise of wireless technology in building operation is to reduce the cost of installing data acquisition and control systems. Installation costs typically represent 20% to 80% of the cost of a wired sensor and control point in a heating, ventilation, and air-conditioning (HVAC) system – reducing or eliminating the cost of installation of wiring has a dramatic effect on the overall installed system cost.

This paper discusses the question of whether or not today's wireless sensors are ready for building controls and energy efficiency monitoring applications. The paper starts with a general description of wireless technologies that are likely to be used for building controls applications. It then provides a detailed discussion on a recent demonstration project in a Federal Government facility, in which wireless temperature sensors were installed and integrated into a Johnson Controls Metasys building automation system. Described are the technology used, cost and labor to install the wireless devices and the overall operational benefits. To provide further experiences of wireless technologies commercially available today, we provide an overview of a large deployment effort of wireless sensors by Pacific Northwest National Laboratory (PNNL) facility staff across a large research campus. To shed light on future application of wireless technology, the paper then discusses the development of a wireless diagnostics technology that is specific for use in packaged HVAC systems. The paper concludes with a look at the possible future of wireless technology and its potential opportunities to improve building operations.

INTRODUCTION

While long promised as an emerging technology for the building automation industry, wireless applications in HVAC controls are still in their infant stage at best and are not commonly used in practice. A 1999 expert roundtable of HVAC industry professionals unanimously agreed that the wireless sensing of indoor conditions is inevitable, promoting more localized and personalized control of indoor climates [Ivanovich and Gustavson, 1999]. Experts agree that the driving argument for deployment of wireless sensors will be cost advantages and the flexibility to relocate thermostats and sensors as the interior building layout adapts to organizational changes of the tenants. While the mobility of wireless sensors is irrefutable, the cost of the wireless technology at the current time may still be too high for the technology to penetrate the market very widely. This may soon change. According to a 2004 market assessment of wireless sensor networks, the cost of the radio frequency (RF) modules of sensors were projected to drop to $4 per unit by 2010 [Chi and Hatler, 2004]. While these costs reflect only one portion of a wireless sensor, the cost of the sensor itself is also expected to decrease with technology advancements. For instance, digital integrated humidity and temperature sensors produced in large quantities are currently commercially available for less than $3 per sensor probe[1]. The general trend in sensor technology development toward solid state devices is likely to produce low-cost sensors for the mass markets.

To date, however, end-users are caught between enthusiasm for the benefits that wireless sensing and control can provide, the skepticism that the technology will operate reliably compared to the wired solution, and the fact that relatively few wireless products are

[1] Quote by SenSolution, Newberry Park, CA. February 2004.

commercially available. While the advancements of wireless local area networks (LAN) have paved the road for market adoption of wireless technology, they also have made end-users aware of the inherent reliability challenges of wireless transmission in buildings and facilities. With the increasing awareness of cyber-space vulnerabilities of modern facility and building automation, additional protection requirements are being imposed on wireless networking technology, which runs counter to the general attempt to simplify technology to reduce cost. Many of these challenges are currently being addressed by technology vendors and standards committees to provide technology solutions with the necessary technical performance that the market demands.

At a recent ASHRAE Forum at the Winter 2006 Meeting in Chicago, about 40 building professionals from the controls, building management and research communities discussed experiences with wireless sensors, potential applications and requirements of wireless sensor technology, and the roles wireless sensing may or could play for building automation and facility management[2]. While almost all of the attendees indicated experiences with wireless LANs either at the workplace or at home, less than 10% of the attendees indicated any experiences with wireless sensors for building operation. The main reason for this low adoption rate is that very few commercial products are available and that prices are still high. Despite the significant attention to low-cost wireless sensors technologies in the general and professional media, the technology is still in its infancy. While the concept of ubiquitous sensing for building applications may be an ultimate end-goal, it is expected that the commercial building sector will adopt this new technology incrementally for those applications where wireless technology is clearly cost-competitive first.

The following section provides a general overview of wireless technologies and network standards by describing some of the most commonly used technologies and their suitability for building controls applications. The paper then provides a detailed discussion on a recent demonstration project, in which wireless temperature sensors were installed and integrated into a Johnson Controls Metasys building automation system (BAS) in a Federal Government facility. Described are the technology used, cost and level of effort to install the wireless devices and the overall operational benefits. To provide further examples of the use of wireless technologies commercially available today, we provide an overview of a large deployment effort of wireless sensors by facility staff across the PNNL research campus. To shed light on future applications of wireless technology, the paper then discusses the development of a wireless diagnostics technology that is specific for use in packaged HVAC systems. The paper concludes with a look at opportunities for using wireless technology to improve building operations in the future.

[2] No official written records for Forums are published by ASHRAE. This is based on notes taken in the Forum.

OVERVIEW OF WIRELESS TECHNOLOGY

There are a large number of wireless network technologies on the market today, and “wireless networks” as a technology span from cellular phone networks to wireless temperature sensors. This perhaps confusing array of wireless technology choices is, on the whole, not fully developed nor targeted for building automation applications, where ease of installation is a top priority, and the functionality of many of the existing and emerging wireless standards is not well matched to the needs of building automation.

In building automation applications, power consumption is of critical importance. “Peel-and-stick” temperature sensors can only be realized with very low-power wireless devices and networks; 3- to 5-year battery lifetime is a minimum. Although power is generally available in commercial buildings, it is often not provided at the precise location for the sensor placement. Thus, for many wireless sensors, battery-powered operation is necessary to keep the installed cost low (by avoiding the need to run power connections to the sensors). Figure 1 shows the power consumption and the data rate for several wireless communications standards. The IEEE 802.11a, b, and g standards (also referred to as “WiFi” {Wireless Fidelity}), which were developed for mobile computing applications, are at the high end of data rate and mid-range of power consumption.

While these standards have proven very popular for mobile web browsing, they are not suitable for most building automation applications because of their high power consumption, limitations on the number of devices in a network, and the cost and complexity of the radio chipsets. Furthermore, they provide much higher data rates than necessary for many of the connections (e.g., between sensors and processors) in building control systems.

Bluetooth – another wireless communications standard – was developed for personal area networks (PANs) – and has proven popular for wireless headsets for cordless phones [Bluetooth, 2001]. The data rate and power consumption of Bluetooth radios are both less than WiFi, which puts them closer to the needs of building automation applications, but the battery life of a Bluetooth-enabled temperature sensor is still only in the range of weeks to months – not the 3- to 5-year minimum requirement for building applications. The number of devices in a Bluetooth network is also severely limited, making the technology applicable for only the smallest in-building deployments.

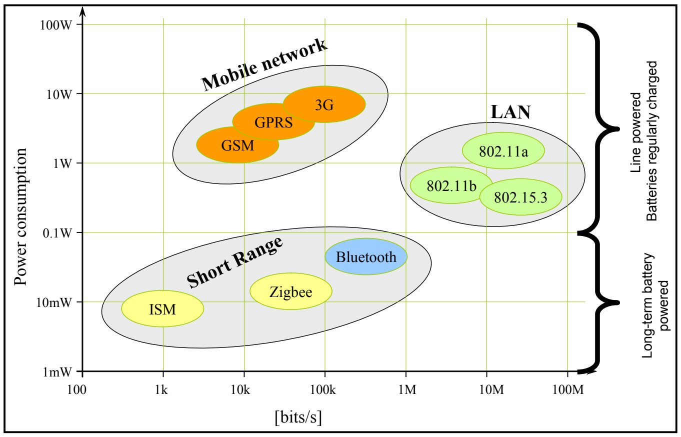

FIGURE 1: WIRELESS DEVICE AND NETWORKING STANDARDS

The IEEE 802.15.4 standard, which was approved in 2003, is designed specifically for low data-rate, low-power consumption applications including building automation, and also devices ranging from toys, wireless keyboards and mice to industrial monitoring and control [IEEE 802.15.4, 2003]. For battery-powered devices, this technology is built to specifically address applications where a trickle of data is coming back from sensors and sent out to actuators. The communication distance of the 802.15.4 radio devices is in the range of 100 to 300 feet inside typical buildings, which, when coupled with an effective network architecture, provides excellent functionality for most building automation applications.

The industry group ZigBee Alliance developed a specification (called ZigBee) that is built upon the physical radio specification of the IEEE 802.15.4 Standard [Kinney, 2003]. ZigBee adds logical network, security, and application software for use with the 802.15.4 standard and was created to address the market need for a cost-effective, standards-based, wireless networking solution that supports low data rates, low-power consumption, security, and reliability. ZigBee defines both the conventional star as well as the innovative meshed network topologies, a variety of data security features, and interoperable application profiles [ZigBee, 2004].

There are also non-standardized radios operating with proprietary communication protocols. They offer further improved power consumption with optimized features for building automation applications. These radios often are classified as ISM (industrial, scientific, medical) radios referring to their original industrial, scientific, and medical application areas and the frequency bands devoted to them. The existence of these radio devices, however, is not sufficient by itself for implementation of low-power reliable wireless networks. The network architecture – defining how wireless devices communicate with each other, how networks are installed and managed, and how the overall network reliability is ensured – is critical to the overall fulfillment of the promise of modern wireless networks for building automation.

The next three sections provide information on actual installations of wireless sensing used in building operation.

WIRELESS TECHNOLOGY DEMONSTRATION

This section describes in detail a wireless sensor demonstration project that was performed by PNNL in collaboration with the Environmental Protection Agency (EPA) in 2005.

The demonstration facility was EPA's National Health and Environmental Effects Research Laboratory in Duluth, MN. Installed were 37 wireless temperature sensors as part of a Department of Energy, Federal Energy Management Program (FEMP) technology demonstration. The facility's total floor area is about 90,500 ft^2, with research laboratories, office space and a conference center. The wireless sensor technology demonstration was limited to the office space within the main building.

The objective of the demonstration was to showcase the technology so that the experiences with the technology and benefits of the project may be replicated throughout the Federal sector. In 2005, EPA installed a network of 37 wireless temperature sensors and integrated it into the existing Johnson Controls Metasys BAS.

The result of this demonstration program was that EPA recognized that wireless sensor technology can be a cost effective, easily deployable and flexible retrofit solution for achieving operational improvements, including diagnostics capabilities and zone comfort-condition monitoring. As a result, EPA is considering including wireless sensor technology for HVAC facility controls and management system as part of their architectural and engineering (A&E) design guideline revisions[3] in 2006.

[3] At the time of writing this paper, EPA was in the process of revising the A&E guidelines for anticipated release in 2006, according to EPA's National Energy Manager.

Description of the Wireless Technology

The wireless temperature sensor technology demonstrated was made by Inovonics Wireless Corporation[4]. Inovonics products were chosen because of prior familiarities with the technology. The technology encompasses temperature transmitters, repeaters, usually one receiver, and one integration module (called a translator), which connects the wireless temperature sensors to a Johnson Controls network [Johnson Controls, 1996].

The operating frequency of the wireless network is 902 to 928 MHz, which requires no license per FCC Part 15 Certification (FCC Part 15, 1998). The technology employs spread spectrum frequency hopping techniques to enhance the robustness and reliability of the transmission [Weisman, 2002].

The transmitter has an open field range of 2500 feet and is battery-powered with a standard model 123, 3-Volt, $LiMnO_2$ battery with a nominal capacity of 1400 mAh. The battery life depends on the rate of transmission, which can be specified in the transmitter (e.g., once per minute, five minutes, 15 minutes, etc.). The manufacturer estimates the battery life at up to 5 years with a 10-min update (transmission) rate. The transmitter has a battery test procedure with a 'low-battery' notification via the wireless network. This feature alerts the facility operator through the BAS that the useful life of the battery in a specific transmitter is approaching its end. The temperature sensor uses a 10 kΩ thermistor. The operating range is between -13 to 140 degrees Fahrenheit with accuracy of ±0.3 degrees Fahrenheit[5].

The repeater is powered by 120-Volt AC from the wall outlet, with a battery backup (see Figure 2). The repeater operates at higher output power than the transmitters and, thus, extends the range to 4 miles in open field. The repeater receives transmitter signals and amplifies each received signal before re-transmitting it. No setup is required for the repeater, other than connecting the power adapter and the backup battery to the respective terminals in the repeater.

The receiver is powered by the translator. The receiver communicates all recognized temperature signals to the translator via an RS 232 serial link. Signals that are not recognized to be compatible with the temperature sensor product line are suppressed in the receiver.

The translator is physically connected to the receiver and the Johnson Controls N2 control network bus via a three-wire RS 485 cable. The primary function of the translator is to convert the received temperature signals to the Johnson Controls Metasys system N2 protocol. To be recognized by the Metasys system on the N2 bus, the translator emulates N2 devices. Up to 100 N2 devices can be represented by each translator. For wireless networks with more than 100 temperature sensors, an additional translator, including a receiver, is necessary. The translator requires a brief setup that registers the available temperature transmitters on the wireless network and allows the operator to assign specific names to each temperature sensor. Each temperature sensor must be registered in the translator for Metasys to recognize the temperature sensor. The configuration of the translator is performed using Inovonics' ComfortWave™ software, supplied with the translator [Inovonics, 2003]. ComfortWave™ runs on a MicroSoft (MS) Windows computer and connects to the translator via an RS 232 port temporarily during this configuration process. The translator is powered by a 24-Volt AC power supply, which is generally available at a N2 bus control panel. The translator provides 12-Volt DC power to the receiver.

Figure 2 illustrates the wireless temperature sensor network integrated into the Johnson Controls wired Metasys system.

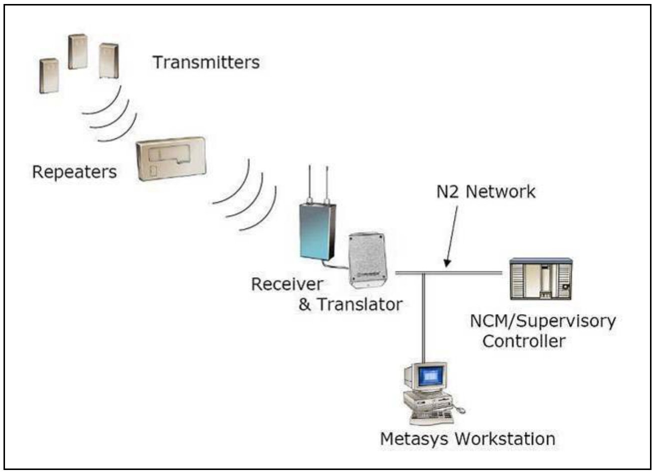

FIGURE 2: WIRELESS TEMPERATURE SENSOR NETWORK INTEGRATION INTO JOHNSON CONTROLS METASYS

Wireless Temperature Network Installation

A total of 37 wireless temperature transmitters, 3 repeaters, 1 receiver, and 1 translator were installed and integrated into the BAS at the EPA facility. The 37 temperature sensors were installed in individual offices

[4] More information can be found at http://www.inovonics.com.

[5] Derived from the device accuracy performance characteristics obtained from Inovonics.

and hallways of the two-story Main building. The floor of the building is made of reinforced steel-concrete construction, which is generally more difficult to penetrate by RF signals than wooden floor construction. The receiver and translator were installed in the core section of the first floor in direct proximity to a Johnson Controls network control module (NCM) for the air-handling unit. Two repeaters were placed at the second floor toward the end of the East/West hallway to amplify the signals from all 2nd floor transmitters so the repeated signal would reach the receiver on the first floor. Because the receiver was in close proximity to metal piping and metal equipment in the core area on floor 1, a third repeater was installed in the center of the first floor core area to assure sufficient signal strength to the receiver. Figure 3 and Figure 4 depict the locations of the temperature sensors within the floor space of the Main building.

The transmitters were attached to the walls using double sided tape, except for the four transmitters, which were placed inside fan coil units to measure supply air temperatures. Placing a wireless transmitter inside the metal casing of a fan coil unit significantly reduces the transmission range by shielding the RF signal. However, no degradation of the wireless transmission was noted. All 37 transmitters and 3 repeaters were registered in the translator using a laptop with the ComfortWave™ software. The Johnson Controls contractor installed the receiver and translator onto the housing of the NCM controller panel. The contractor configured Metasys such that the wireless temperature sensors were recognized and logged in the Metasys system.

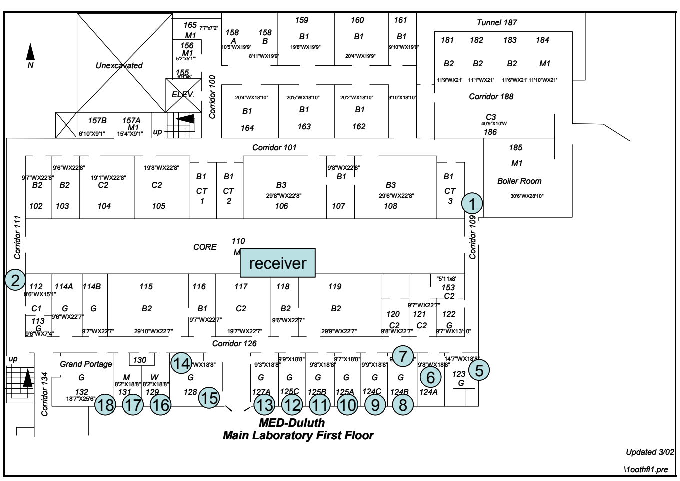

FIGURE 3: DETAILED FLOOR SPACE OF FIRST FLOOR OF MAIN BUILDING

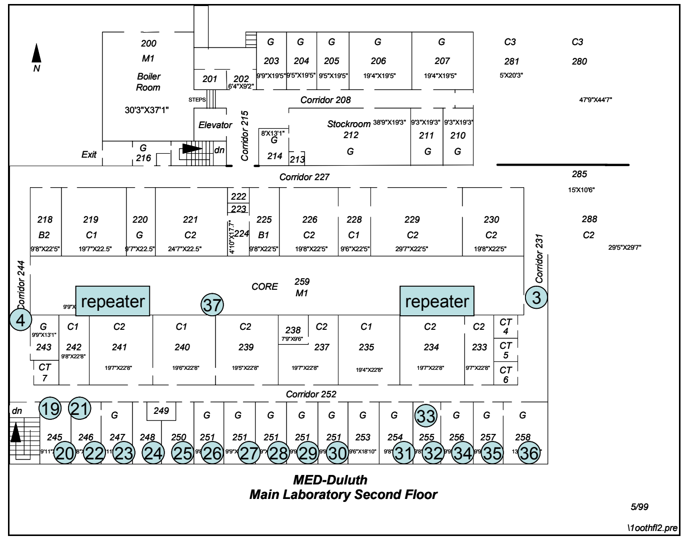

FIGURE 4: DETAILED FLOOR SPACE OF SECOND FLOOR OF MAIN BUILDING

Setup and Configuration of Wireless Sensor Network

In total 37 temperature sensors, 3 repeaters, and 1 receiver and translator were setup, configured in Metasys, and tested in 1 day. Staff familiar with the wireless technology performed the wireless network setup, which consists of:

- Developing a list of locations of wireless sensors. This list is necessary for labeling the transmitter when registered in the translator and when configured in Metasys.
- RF survey of the facility. The results of the survey determine the needs and best location for repeaters. Inovonics provides a survey kit with user-friendly instructions. Unless facility staff plan to install Inovonics wireless products themselves, a control vendor will perform the RF survey. The RF survey kit consists of a field strength meter and a transmitter that transmits continuously. The RF survey transmitter is placed at the most distant location from the receiver for a prospective wireless temperature sensor. As one walks away from the transmitter, which continuously sends out signals, toward the receiver, the field strength of the received RF signals decreases. The field strength meter indicates when the range limit is reached, at which point a repeater should be placed. The RF survey was performed in about 30 minutes for the placement of 37 transmitters.

- Setup of the wireless network including the registration of transmitters in the translator using Inovonics' setup software.

In total, the wireless network setup took between 4 and 5 hours to install, setup, configure and test all 40 transmitting devices (37 transmitters and 3 repeaters).

Johnson Controls contractors installed the receiver and translator and performed the configuration of 37 temperature sensors in the BAS, which became new network devices on the BAS network. The contractor also established trend logs for all 37 new temperature sensors and tested the communication of all 37 wireless temperature sensors. The contractor started his work after the wireless sensor network installation and setup was completed, and completed the activity in about 3 hours.

In this particular demonstration installation, Pacific Northwest National Laboratory (PNNL) provided the wireless technology expertise and performed the setup of wireless sensor network, such that the controls vendor did not need to have any knowledge or familiarity with the Inovonics system. When connected to the BAS network, the Inovonics translator was recognized as a set of N2 devices with characteristics similar to wired analog network devices. The controls vendor did not have any problems recognizing and configuring the wireless temperature sensors; the process was very smooth.

The following table summarizes the labor elements of the wireless sensor network installation.

TABLE 1. SUMMARY OF THE LABOR FOR WIRELESS TEMPERATURE SENSOR NETWORK INSTALLATION

No	Setup element	Time estimate
1	Develop list of locations for temperature sensor placements	30 minutes
2	RF survey	30 minutes
3	Registration of all transmitting devices	2 hours
4	Placement of transmitters and repeaters	1-2 hours
Labor for wireless sensor network setup		**4-5 hours**
5	Installation of receiver and translator into NCM panel	1 hours
6	Configuration of BAS to recognize wireless temperature sensors	1 hours
7	Setup of trend logging in BAS	1 hour.
Labor for integration into existing controls network		**3 hours**
Labor for entire installation		**7-8 hours**

Operational Reliability of Wireless Sensors

Measurements from the 37 wireless temperature sensors were logged in BAS over a period of about 7 months (March through September 2005). During this period, no problems with the measurements or the wireless communication were detected. We did find nine instances during the entire 7-month monitoring period where the logged data set had missing or unavailable data for one 30-minute trending period. We determined this to be attributable to the BAS trending procedure and not caused by the wireless sensor network because of the consistency pattern of the missing data.

The wireless sensor network has worked very reliably beyond the monitoring period, which ended in mid-September 2005.

Operational Improvements: Diagnostics Capabilities

On the first day of testing, EPA staff recognized that one of the existing wired temperature sensors located at the first floor east hallway was out of calibration or faulty. This problem was recognized by a notable temperature difference between the readings of the wireless and wired sensors that were only 1 foot apart. EPA staff verified the zone air temperature with a hand-held device and determined that the existing wired temperature sensor was out of calibration by about 7 degrees Fahrenheit. EPA replaced the thermistor of the wired temperature sensor. Both sensors were then in agreement. This example is indicative of diagnostics potential for other existing temperature sensors that may lead to energy savings.

Because of the ease of placing and removing a wireless temperature sensor, EPA staff configured one spare temperature sensor as a diagnostics sensor to be used for short-term temperature verifications by temporarily placing it at a point where a temperature needed to be verified.

Control Improvements

While it was not possible to directly attribute energy savings to installation of the wireless temperature sensor network at the demonstration site, the added wireless temperature sensors led indirectly to energy efficiency improvements in the facility. EPA performed repair and retrofit work that eliminated concurrent heating and cooling in fan coil units located in several offices. The solution of this energy wasting problem led to additional discussions of what else could be done with the repaired fan coil units and the wireless temperature sensors. EPA staff felt sufficiently confident to increase the zone set point temperatures because, with a wireless temperature sensor in every office, they had the ability to monitor the zone air temperature and watch for excessive temperatures. EPA initially reset the zone temperatures by 2-degrees Fahrenheit and made this change permanent after a few days of testing. No complaints were received as a consequence of this change.

The ability to observe zone temperatures office-by-office was noted as a key motivator for exploring creative reset strategies, which in turn may lead to improved energy efficiency. Because air temperatures are available at a high spatial resolution, facility staff are more comfortable experimenting with new control strategies, such as more aggressive night-setback or delayed morning startup.

Cost of Wireless Temperature Installation

The cost for the wireless sensor network, including installation and integration into the BAS was estimated to be $3,858, with an average cost of $104 per sensor. See Table 2 for more details on the cost. The hardware cost listed below is representative of wholesale prices. Retail prices for hardware are approximately 1.8 to 2.0 time the hardware costs in Table 2. Therefore, using a factor of 1.8, the total retail cost is estimated as approximately $7,036, or $190 per sensor.

TABLE 2. SETUP COST FOR THE WIRELESS TEMPERATURE SENSOR NETWORK

	Cost per unit	Qty.	Total
Hardware			
Temperature sensors	$50 ea	37	$1,850
Repeater	$235 ea	3	$705
Receiver	$200 ea	1	$200
Translator	$423 ea	1	$423
Total hardware cost			**$3,178**
Labor			
RF surveying (labor)	$80 /hr	0.5	$40
Wireless sensor setup and placement (labor)	$80 /hr	4.5	$360
Integration by control vendor (labor)	$80 /hr	3.5	$280
Total labor cost			**$680**
Total cost estimate			**$3,858**
Cost per sensor			**$104**

Although a cost estimate for a wired temperature sensor alternative was not developed, some qualitative comparison between wired versus wireless technology can be made. Labor costs for installation of the wired technology are replaced by the cost of the innovative wireless technology. While the wireless sensor hardware may be more expensive compared to a standard wired sensor, the cost of labor associated with running wires usually dwarfs the hardware cost of the wireless technology. The fact that 37 temperature sensors were installed and tested in 1 day (with approximately 8 hours of labor) is unlikely to be matched by a wired retrofit sensor solution. Other wireless temperature sensor demonstration activities compared wired to wireless sensor solutions and concluded that the wireless sensor technology, with as few as 33 sensors, was the lowest cost solution [Kintner-Meyer and Conant, 2004]. As the number of sensors for any given installation increases, the per-sensor cost decreases because no further network infrastructure costs are incurred. This suggests that wireless installations with many sensors tend to be more cost effective than a wire solution.

It should also be mentioned that this project was a retrofit installation. For new construction with easy assess to cable conduits, wireless sensor technologies may not have a cost advantage. The real cost advantage of wireless is in retrofit applications, where the labor cost component is large.

EPA's Experiences

EPA staff was very engaged in all phases of this demonstration project and demonstrated an interest in exploring other wireless sensor technology for other sites and other building applications. EPA identified an additional application of the wireless technology. The application involved monitoring of water temperatures in small water tanks, in which EPA performs scientific experiments. EPA expressed interest in expanding the wireless sensor network with additional sensors that measure the water temperature in the water tanks and to use the alarm notification features of the BAS to monitor the water temperatures.

One of the major outcomes from this demonstration project is EPA plans to incorporate wireless sensors for HVAC control in the EPA architectural guidelines. The new guidelines are expected to be released in the summer of 2006.

LARGE WIRELESS SENSOR DEPLOYMENT AT PNNL CAMPUS

PNNL facility staff was first introduced to wireless sensor technology as part of a U.S. DOE demonstration project in 2002 [Kintner-Meyer et al., 2002], [Kintner-Meyer and Brambley, 2002], [Kintner-Meyer and Conant, 2004]. Because of their involvement, they quickly familiarized themselves with all aspects of the technology including setup and configuration, and learned to appreciate the easy installation and integration into their existing Johnson Controls Metasys building automation system. Equipped with this knowledge, PNNL facility staff purchased and installed additional wireless technology and explored a variety of applications to improve facility operation. A key motivating factor was to improve the energy efficiency at the PNNL site. Almost all of the wireless products were purchased from Inovonics Wireless Corporation with a few exceptions of less than 10 wireless devices that included a contact closure switch and occupancy sensors from a local vendor. The Inovonics products are the same as used in the EPA demonstration project.

To date a total of about 750 wireless temperature sensors are deployed and integrated into the Johnson Controls Metasys system in over 16 buildings and other structures on the PNNL campus. Most applications were indoors, measuring zone air temperatures for climate control. A few applications deal with water- and air-temperature monitoring in laboratory experiments. Researchers recognized that the wireless temperature sensor solution used for climate control is equally applicable for monitoring water tank temperatures and even air temperatures in freezers. Researchers added wireless temperature sensors for their experiment and then utilized the existing wireless sensor network and the BAS for data acquisition, data logging, and alarm handling and notification. In a few cases, researchers utilized the same wireless temperature sensor technology for monitoring water temperatures in ponds of some life science experiments. This sensor was sealed in a weather-proof housing with thermistor leads fed through the housing and submerged under the pond's water surface.

In another application, facility staff used the wireless sensor for stack discharge air temperature monitoring purposes. The temperature transmitters communicated over quite an astonishing distance of 400 to 500 yards (line of sight) to a repeater, which then amplifies the signal to reach a receiver inside the building. Because of the dispersed stack locations across a large area and the unavailability of communication cables at each stack, this particular wireless application resulted in a very cost-effective solution. Alternative approaches requiring communication wires for data logging over a network, or standalone data logging solutions would have been much more expensive.

The wireless temperature sensors were employed for one or more of the following purposes:

- Monitoring of water or air temperatures to comply with code requirements or for diagnostic purposes.
- Establishing improved zone conditions. In several applications, additional wireless temperature sensors were installed in those offices that did not have a temperature sensor or thermostat. The VAV controller input for that zone was then modified to using an arithmetic average of all of the office room temperatures, rather than one measurement at one thermostat.
- Enhancing the air supply temperature control from a fixed set point to a range between 55 and 75 degrees Fahrenheit based on the average zone temperatures. For the cooling season, a linear relationship was established that increases the supply air temperature with decreasing zone temperatures. This control enhancement was performed for laboratory space with no return air, in which all air is exhausted into the environment. The averaged zone air temperatures provide a good feedback signal to indicate if the cooling load is met.
- Implementing night setback. This strategy changed the formerly 24/7 operation to a nightly setback, in which either the zone air set point temperature is reset or the entire air handling unit is turned off. The reset stays in effect as long as none of the individual wireless air temperatures installed the offices indicates too low or too hot a temperature (using thresholds of 78 degrees for the cooling season, and 63 degrees for the heating season). Previously, without sufficient information on every room air temperature, operations staff did not attempt to implement night setback, because of the risk that occasionally a few researchers who stayed late in their offices to perform experiments might complain about uncomfortable space conditions.

PNNL facility staff also installed a wireless contact closure switch to turn off the air-handling unit whenever a large garage door opens. The contact closure switch was installed at several garage doors that provided access for material delivery to the machine shop. This control strategy was designed to prevent the air conditioner from operating when hot outdoor air infiltrates the machine shop during openings of these large doors.

In addition, several low-cost wireless occupancy sensors were installed in the machine shop to turn off a 25-hp air-compressor motor when no one is present in the machine shop. This strategy enabled PNNL facility staff to prevent useless air-compressor operation over the weekend, holidays and nights to overcome the standby losses.

PNNL facility staff estimate the cost for the wireless temperature sensor network. Estimates varied between $70 and $140 per temperature measurement. Comparable costs for a wired system were estimated to range between $500 and $1000 per measurement depending on the complication of the retrofit application. With these encouraging experiences, PNNL facility staff continue to explore further opportunities for wireless sensor and controls devices. While so far almost all of the wireless sensors are temperature sensors from one vendor, PNNL facility staff sees several other energy savings opportunities utilizing other wireless sensors and control devices. These include the following.

HVAC controls and diagnostics

- Low-cost wireless on/off control device for controlling lighting and electrical motors in remote locations.
- Wireless power meter for 3-phase and single-phase (120 VAC) applications. Power meters could be easily retrofitted on large and small equipment and even appliances for performance monitoring and sub-billing.
- Mobile wireless energy-audit kit with commonly used sensors (power meters, temperature, humidity, and pressure sensors) used for energy audits and commissioning.

Lighting control and monitoring

- In open-space office buildings, retrofit lighting controls for individual and localized control from each occupant's desk.
- Retrofit reconfigurable lighting systems with individually addressable dimmable ballasts.
- Retrofit light sensors at the work space to turn off lighting fixtures in zones that are well lit by daylight.
- Monitor emergency lighting ballasts to avoid manual inspection. Integrate monitoring into centralized automation system for data logging.

WIRELESS TECHNOLOGY FOR PERFORMANCE MONITORING OF PACKAGED HVAC SYSTEMS

This section describes a technology under development for the U.S. DOE that will provide automated monitoring and diagnostics specifically for packaged HVAC systems, using low-cost wireless sensor devices for data collection. This project is led by NorthWrite Inc.[6].

Packaged HVAC systems are commonly used on small commercial buildings (<50,000 ft^2) and mid-sized commercial buildings of 2 stories or less. They are some of the most neglected building systems, in the best of cases receiving semi-annual inspections by service technicians. Problems commonly found with packaged systems include (but are not limited to): incorrectly operating economizers, refrigerant charges that are low or high, unnecessary 24 hour per day operation (or other schedule problems), and dirty or clogged filters and coils. Often these problems are unknown to building owners and operations staff.

The system currently under development aims to help remedy these problems by increasing awareness of them as they occur, isolating them so service can be targeted, and providing information for building owners and managers as well as service contractors. This information can be used to assess the impacts of problems and decide whether service to correct them can be delayed or should be taken immediately. Often operating cost impacts of problems, the cost of correction, and the potential for further equipment damage are the primary drivers for these decisions. This automated wireless monitoring and diagnostic system focuses on detecting such problems and providing information essential for maintenance decision making.

For each HVAC unit, the monitoring and diagnostic (M&D) system continuously monitors operation, detects faults with unit operation and diagnoses the faults detected. Key aspects monitored by the M&D system include overall energy use and power consumption, air-side subsystem performance, refrigerant loop performance, and controls problems such as incorrect operation schedules and set points. The system also detects faulty sensors, which prevent accurate detection and diagnosis of other faults.

Use of the system requires no special software on the computers of users. The system collects sensed data from HVAC units, processes it with automated diagnostic software, and makes the resulting performance indicators and diagnostic information available to owners, operators, and service providers over the world wide web (the web). Access to the information by an individual user requires only a computer with an Internet connection, a web browser (such as Internet Explorer or Mozilla Firefox), and a subscription to the service. The monitoring and diagnostic hardware and software also must be installed on the HVAC equipment to be monitored.

System Description

The M&D system, shown in Figure 5, is based on wireless data acquisition and communication technologies. At the building, short-range wireless mesh networking technology is used to collect sensed data from the HVAC units. These data are sent wirelessly to a central wireless master control module located on the rooftop or inside the building, where they are pre-processed. The resulting pre-processed or aggregated data are then sent via long-range wireless cell-based

[6] Other team members include Pacific Northwest National Laboratory, SensorIQ Inc., Texas A&M University Energy Systems Laboratory, and the Trane Company.

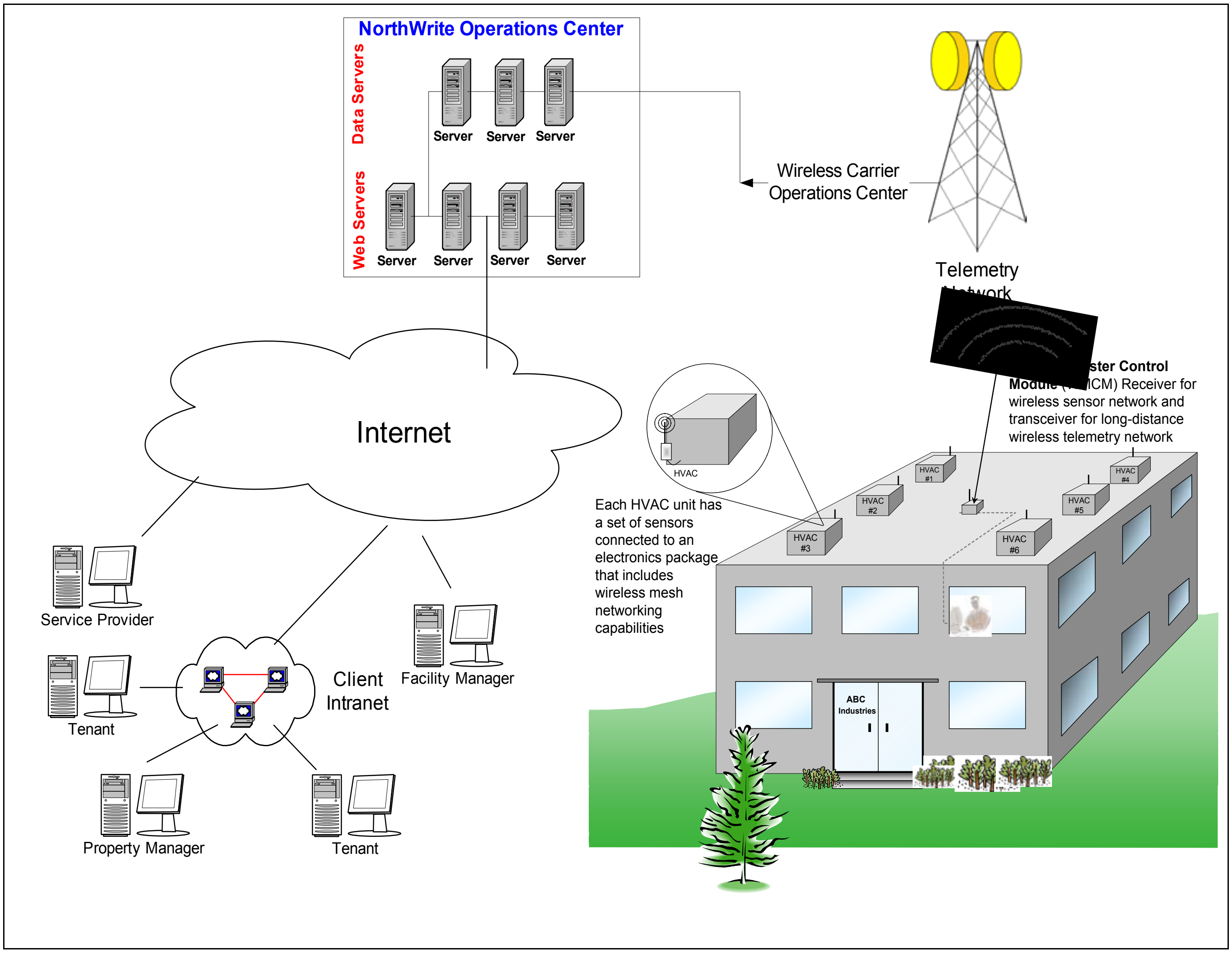

FIGURE 5: WIRELESS HVAC MONITORING AND DIAGNOSTIC SYSTEM

technology to a network operations center (NOC), where full diagnostic processing takes place. Results of the diagnostic processing are then made available on web pages for authorized users for each site to access. All data are secured and only available to properly authorized users.

Each HVAC unit is outfitted with a set of up to 17 sensors (the exact number depending on the type of HVAC system) to monitor key operation parameters. The sensors measure various temperatures, humidities, the on/off status of key components of the unit, and electric power uses in the unit. The sensors themselves are connected by wires inside the HVAC unit to wireless nodes located on the unit. Each node can accommodate up to eight sensors, so that full monitoring of an HVAC unit might require as many as three nodes. Wire leads from the sensors to the nodes may range from 1 foot to several feet in length, the exact length depending on the size of the unit, the location of the node, and the distribution of measurement points on the unit.[7] These measured data, along with fixed data characterizing the unit and its application, which are entered once during installation of the system, provide the basis for the diagnostics generated during processing at the NOC. The data are sent from the wireless nodes to the master control module at various sampling periods ranging from once per minute to once every 15 minutes, the frequency depending on the specific parameter measured.

[7] Wire leads are used inside the units between the sensors and the wireless nodes because wireless data communication costs are not yet sufficiently low to justify a wireless radio for each individual sensor.

Generally, there will be one master control module per building (or a small number for very large buildings). Results of the diagnostics are generated in the NOC and published as a webpage. The results are displayed hourly in a matrix that consists of 24 rows and 7 columns. Each column represents a day with the 24 rows in the column representing the 24 hours in the day (see Figure 6). Color coding of each cell is used to indicate the presence or absence of faults during the corresponding hour. Red indicates a fault was detected, white indicates no fault was found during the hour, and gray indicates that no diagnosis is available, usually because the unit did not operate during the hour, or the diagnosis was incomplete. Incomplete diagnoses usually result because conditions were such that differences between some of the temperatures were not measurable (e.g., when indoor and outdoor temperatures are nearly equal).

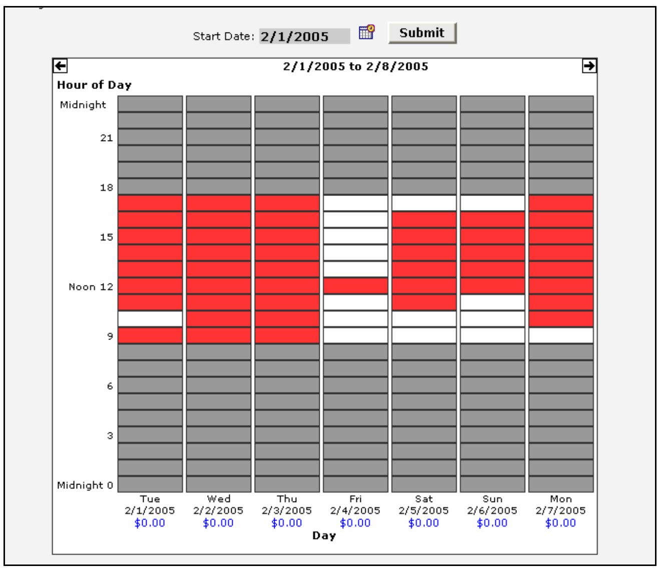

FIGURE 6: EXAMPLE MAIN DISPLAY FOR DIAGNOSTIC RESULTS FOR ONE AIR HANDLING UNIT.

Further detailed diagnostic information is available to the user for fault conditions. The user can obtain this information by clicking on a cell for which a fault is indicated. The information provided includes the kinds of faults found, the energy and cost impacts of each fault, and some suggested actions to remedy or further investigate the faults as a step in correction.

Benefits

The wireless M&D system provides continuous monitoring of the condition and performance of rooftop packaged HVAC equipment, something that is not done today. It provides a basis for condition-based maintenance of these units, which will improve the condition and operating performance of the average rooftop unit found today on commercial buildings. Benefits will include:

- Energy savings
- Savings on energy expenditures
- Better control of indoor comfort
- Improved indoor air quality
- Longer equipment lives
- Lower total O&M costs for the units (in the long run[8])

More information on the cost effectiveness of wireless monitoring of packaged HVAC equipment and use of the web for condition monitoring can be found in [Katipamula and Brambley, 2004] and [Brambley et al., 2005], respectively.

WIRELESS SENSING AND CONTROL FOR LIGHTING

Lighting represents a somewhat unique application opportunity for wireless technology. Each room in a commercial building usually has several lighting fixtures (luminaires). Even small offices often have a couple luminaires. Individual luminaire control could be added so that a central controller or handheld control device could be used to turn individual luminaires or banks of luminaires on or off, providing greater spatial control of illumination and potentially saving significant energy by reducing unused lighting. Condition monitoring could also be added to these units to measure indicators of performance and remaining life such as accumulated usage hours on the current lamps and the temperature in the luminaire. Addressable wireless controls on each luminaire would provide the basis for such capabilities.

Because so many luminaires are distributed throughout commercial buildings, often separated by relatively short distances of a few feet to maybe 20 feet for nearest neighbor luminaires, the required communication distances for a mesh network, in which each radio serves as both a transmitter of data and a repeater for all signals it receives from other nodes, are relatively short. This is an ideal application for a mesh network. Because of the location of luminaires throughout buildings, once wireless mesh network is established for lighting, other sensors for measurements such as space temperature, humidity, occupancy, and other purposes, could be readily added to the network. Communication for these sensors, which are generally spaced apart by distances much greater than the

[8] Deferred maintenance on poorly maintained units could cause initial increases in costs for maintenance and repair.

distances between adjacent luminaires, would then benefit by using the radios on the luminaires to communicate their signals. In essence the mesh network for lighting would establish a wireless environment to which other sensors could be added anywhere in the building at a very low incremental cost of just the added wireless sensor.

Wireless lighting controls are under development by industry, universities and government laboratories [Teasdale et al., 2005].

TRENDS AND FUTURE OUTLOOK ON WIRELESS TECHNOLOGY FOR BUILDING APPLICATIONS

The steadily growing number of technology companies offering products and services for monitoring and control applications in various market sectors fuel the expectation that the sub-$10 wireless sensor is likely to be available in the near future. When we reach that point of technological advancement, the cost of the battery may then be the single largest cost item of a wireless module. Even the battery may be replaceable by ambient power scavenging devices that obviate the need for a battery as a power source. A self-powered sensor device creates fundamentally new measurement applications, unthinkable with battery-powered technology. For instance, sensors can be fully embedded in building materials, such as structural members or wall components. They can measure properties in the host material that currently cannot be accessed by external measurement probes. In the energy efficiency domain, new diagnostic methods could be envisioned that will use embedded sensors for early diagnostics to prevent equipment failure and degradation of energy efficiency. Higher sensor densities in the conditioned space will enable and support more localized and personalized control opportunities of the work and living environments of our commercial buildings.

Researchers are exploring different ambient sources for the extraction of electric power [DeSteese et al. 2004]. Mechanical vibration emanating from rotary energy conversion equipment, such internal combustion engines, pumps, and fans can be converted into electric power by induction driving a magnetic element inside a coil. Alternatively, piezo-electric materials generate an electric potential when mechanically strained. Current research and technology development focuses on maximizing the energy extraction of mechanical energy by adaptive techniques that sense and adjust to a given vibration frequency and amplitude to maximize the power extraction. Thermo-electrical power generators utilize the Compton Effect, commonly used in thermocouple probes for temperature measurements. A few degrees Celsius of a temperature differential can, in cleverly designed probes, generate power in the micro Watt range. Small power generation from all ambient power devices is then stored typically in a capacitor to operate the wireless sensor at selected intervals.

Recent news releases about prototypes of ambient energy scavenging devices that generate sufficient electric power to operate a wireless sensor give rise to anticipate and hope that these revolutionary technologies will soon be commercially available [FerroSolution, 2003].

With an optimistic outlook on cost projections of wireless sensors and revolutionary self-powering devices, what are the likely impacts and opportunities of this technology for the building sector in general, and for energy efficiency improvement opportunities in buildings in particular? While the scenario of ubiquitous sensing by miniaturizing sensors to the size of paint pigments that can be painted on a wall may be in the realm of science fiction, there are real opportunities for low-cost wireless sensor devices that can be realized today with commercially available technologies.

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