Wireless Sensors: Technology and Cost-Savings for Commercial Buildings

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ABSTRACT

Two projects under way for the U.S. Department of Energy Office of Building Technology, State and Community Programs, aim to adapt, test and demonstrate wireless sensors and data acquisition for heating, ventilating, and air-conditioning (HVAC) in commercial buildings. One project focuses on built-up systems in medium to large buildings; the second on applications for rooftop units in small- to medium-size facilities.

Beyond mobility, which is the driver for many wireless applications, the key promise of wireless technology in building operation is to reduce the cost of installing data acquisition and control systems by eliminating the wires. Installation of wiring can represent 20% to 80% of the cost of a sensor point in an HVAC system. The availability of low-cost wireless sensor systems could not only reduce sensor costs overall, but also lead to increased use of sensors. While not the only answer, deploying more sensors is a key factor in achieving the improved monitoring and control necessary to establish and maintain highly efficient and effective building operations.

In this paper, the authors characterize the physical performance and costs of off-the-shelf wireless sensor and data-acquisition systems and describe how they can be adapted to commercial buildings. The discussion includes wireless serial communication, standards for its use, and some of the highly publicized emerging wireless networking technologies, Bluetooth and IEEE 802.11b. The authors also discuss the limitations of today's technology and how wireless technology might be improved to reduce costs and enhance the performance of commercial-building systems.

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 common practice. An 1999 expert roundtable of HVAC industry professionals unanimously agreed that the wireless sensing of indoor conditions will be inevitable promoting more localized and personalized control of indoor climates (Ivanovich M, Gustavson D., 1999). Experts agree that the driving argument for the deployment of wireless sensors will be cost advantages and the flexibility to re-locating thermostats and sensors as the interior layout adapts to the organizational changes of the tenants and occupants that require ever changing space requirements. While the mobility of wireless sensors is irrefutable, the cost of the wireless technology at the current time may still be too high to penetrate the market more widely.

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For any new technology to penetrate the market place it either must be significantly less expensive than the existing technology or it must have additional features that provide a competitive advantage and justify the same cost as the technology to be replaced. While mobility is the key and compelling reason for the impressive inroads wireless communication and computer LAN technologies has experienced over the last few years, the need for mobility in buildings control applications remains limited. This means that wireless technologies must compete predominantly on the basis of cost.

This paper will discuss the cost aspects for the installation of the wireless sensors in two very different retrofit applications. These two applications were selected to explore the competitiveness of wireless sensors in a range of typical applications in which wireless technology may successfully compete. The paper will provide a general overview of currently available wireless sensor and control products applicable for buildings controls applications, followed by a discussion of two wireless demonstration projects currently underway at Pacific Northwest National Laboratory (PNNL). It will conclude with some general cost-effectiveness discussion of wireless technologies for building's applications and how wireless technology might be improved to enhance the performance of commercial-building systems.

Existing Commercial Wireless Sensing And Data Acquisition Technology

The major components of a wireless data acquisition system include: sensors, signal conditioners, transmitters, repeaters (which are optional), at least one receiver, a computer if processing is planned, and connections for external communications for communicating information to users (e.g., building operators).

Wireless communication can be accomplished using any of a number of different communication schemes and protocols. Selection of these for data acquisition for HVAC monitoring, diagnostics, and control, today and for the foreseeable future, is likely to be driven primarily by cost. Some of the protocols that have received significant attention in the popular and technical-news press in the last year or two include Bluetooth and IEEE 802.11b. They may not be the most cost effective choices for sensor-data acquisition at this time. Brief descriptions and assessments of applicability follow.

Bluetooth

Bluetooth (Official Bluetooth Website 2002; Bhagwat 2001; Bluetooth SIG Inc. 2001) is a royalty-free technology specification for short-range wireless communication among devices meeting the specification. It defines a wireless radio frequency communication interface and associated sets of communication protocols and application profiles. It uses the 2.4-GHz industrial, scientific, and medical (ISM) radio band, which is available for license-free use worldwide (FCC, Part 15, 1998). In the U.S. and most other countries, this band extends from 2400 MHz to 2483.5 MHz. The Bluetooth specification defines 79 channels spaced 1 MHz apart in this band. The protocol uses a frequency-hopping spread spectrum technique, where the radio hops through the 79 channels in a pseudo-random sequence at a rate of 1600 hops per second. This provides excellent immunity to interference and contributes some to security of the transmissions. Gaussian frequency shift keying (GFSK) modulation is used to provide a link speed of 1 Mbps. This ultimately provides a maximum data rate of 781 kbps. The maximum transmission range for a home-like environment is 10 meters and for a clear environment can reach 30 meters.

Bluetooth devices can form small ad hoc nets known as piconets. A piconet consists of up to eight Bluetooth devices, one master and a maximum of seven slaves. Communication can be extended to other units by formation of scatternets, which consist of interconnected piconets.

The intended purpose of Bluetooth is to provide a universal standard for connecting a broad set of wireless devices. Bluetooth includes definitions for a set of application-level profiles for 13 applications, which are necessary to implement user functions. These include among others cordless telephone, LAN access, FAX, and serial-cable emulation. The later is likely to serve building sensor data acquisition in the near-term. The Bluetooth radio is intended to be a low-cost device, which will become even lower cost when deployed in billions of units (which is projected over the next 5 years).

IEEE 802.11b

The IEEE 802.11 (IEEE, 1997), also known as WiFi, is a family of standards for wireless local area networks (LANs) operating in the 2.4 GHz frequency band. Connection rates of 1 and 2 Mbps are provided using either frequency hopping spread spectrum (FHSS) or direct sequence spread spectrum (DSSS) techniques. The standard is compatible with IEEE 802.3-2002, which is the specification defining Ethernet LANs.

Standard IEEE 802.11b (IEEE 1999) is an extension to 802.11 covering wireless LANs transmitting at up to 11 Mbps in the 2.4 GHz band. The 802.11b extension requires use of DSSS to achieve this higher data throughput. DSSS adds a pseudo-random numerical (PN) sequence to each information bit before transmission. The signal is then modulated onto a carrier frequency using a technique called complimentary code keying (CCK). The result is a spread spectrum signal with reduced peak power but unchanged total power. The receiver of the DSSS signal includes a bank of matched filter correlators that remove the PN sequence and recover the original signal. The standard also specifies methods for providing multiple access, including collision avoidance, security, power management, and roaming.

IEEE 802.11b devices may connect in ad hoc networks (i.e., networks requiring no base station) or in infrastructure mode with a fixed access point, which connects to a stationary LAN. Roaming is provided between multiple access points. LAN connections are available in some hotels, airports, restaurants, and other locations. Devices using 802.11b have a maximum range of about 500 meters outdoors at a data rate of 1 Mbps. Maximum ranges at higher data rates are more typically 100 meters outdoors or and about 50 meters indoors. The 802.11b standard only addresses the physical and datalink (lowest two) layers of the International Organization for Standardization (ISO) Open Systems Integration Seven-Layer Model. As a result, any LAN application, network operating system, or network protocol (including TCP/IP) can run on an 802.11b wireless network.

The data rates provided by 802.11b far exceed the requirements of most building data collection needs. As a result, 802.11b-based devices have greater electrical power consumption than required for wireless data acquisition. Unless the cost of wireless LAN systems becomes competitive with alternative wireless communication, they are unlikely to see use for this purpose.

Wireless Serial Communication

Wireless data acquisition for industrial and agricultural applications is currently provided primarily with serial communication. Communication is at much lower bandwidth than wireless LAN systems, but is generally sufficient for data collection from most sensors. Data rates range up to 115.3 kbps, although most wireless serial units operate at 19.2 kbps and lower. A number of different license-free bands are used (some having greater limitations than others), including 300 MHz, 433 MHz, 900 MHz, and 2.4 GHz. Maximum transmission distances vary from about 100 feet to many miles. Modulation techniques include FHSS, DSSS, pulse position modulation, and others (Fern and Tietsworth 2001). Generally, lower bandwidth and less sophisticated modulation schemes are used to lower costs when compatible with the installation environment and data transfer needs. In many cases, a sensor may need to be polled only once every several minutes, with each transmission requiring only a few bits; so significant cost reductions can be achieved by matching the wireless technology used with the specific application. Table 1 provides representative characteristics and costs for wireless data acquisition systems.

Table 1: Characteristics of Selected Commercially Available Wireless Technology

Frequency Band [MHz]	Communication Method/Standard	Maximum Communication Distance	Power Source	Point-to-Pont or Point-to-Multi-point	Cost
433	Not known	Approximately 200 ft.	Transmitter: 24 VAC Receiver: DC power supply connected to 120 VAC	Point-to-multi-point	Transmitters: $300 Receiver: $600
900	Serial FHSS	2500 ft open field	Transmitter: 2/3 A size $LiMnO_2$ (for example Duracell DL123A) Receiver: 24 VAC	Point-to-multi-point	Transmitter with air temperature sensor $68 Repeater $250 Receiver $300
900	Serial DSSS	15 miles line of sight	11-25 VDC	Point-to-point and point-to-multi-point	Transmitter: $1428 Point-to-point bridge $995 Point-to-multi-point $1995
900	Serial	35 miles line of sight	10.5 to 18.0 VDC	Point-to-multi-point	Transmitter $1775 Receiver $1775
2,400	Serial	150 ft line of sight	10 to 30 VDC	Point-to-point	Transmitter $800 Receiver $800
2,400	Bluetooth	30 ft to 320 ft	5 VDC Transmitter: 5 VDC: 4 AA alkaline batteries	Point-to-multipoint	Bluetooth enable wireless monitoring unit: $1,795 PCMCIA Bluetooth radio card: $395

U.S. DOE Demonstration Projects of Wireless Sensor in Buildings

To investigate the performance and cost of wireless sensor and control technologies in buildings, PNNL is conducting two demonstration projects. The first project focuses on a wireless temperature sensor network in a 70,000 ft^2 office building with a heavy steel-concrete structure and a central plant HVAC system. A total of 30 zone temperature sensors are networked and integrated into the existing Johnson Controls HVAC and lighting control network. The temperature data provide input for a chilled-water reset algorithm designed for the reduction of peak demand and overall electric energy. This demonstration is typical for an in-building retrofit application to enhance zone temperature control for improved thermal comfort and overall HCAC system efficiency. The heavy steel-concrete structure is a difficult environment for radio frequency transmission. We chose it to explore the affect of high attenuation on the performance and cost of wireless technology.

The second project focuses on small commercial buildings with rooftop units. The wireless technology communicates system conditions from individual packaged units to a central station located on the roof for overall HVAC system diagnostics. The results of the diagnostics are then communicated wirelessly to an Internet service provider for viewing of the results or alarm notification via email or other notification means.

In-Building Central Plant Retrofit Application

The demonstration building is a heavy steel-concrete office building with a total floor area of about 70,000 ft^2 distributed over three floors. It is located on the campus of PNNL. The HVAC system consists of a central cooling, boiler, and ventilation system with 100 variable-air-volume (VAV) boxes distributed throughout the building in the ceiling. The central energy management and control system (EMCS) controls the central plant and the lighting system. Zone temperature control is performed by means of stand-alone and non-programmable thermostats controlling individual VAV boxes. The centralized control system lacks any zone temperature information. Neither exist control capabilities of the VAV boxes from the central control system. The long-term goal of the PNNL facility management is to network the 100 VAV boxes into the central control infrastructure and to enable improved controllability of the indoor environment. As an intermediate step toward this end, a wireless temperature sensor network with 30 temperature transmitters was installed to provide zone air temperature information to the EMCS. The wireless temperature sensor network consists of a series of Inovonics wireless products including a beta version of an integration module that interfaces to a Johnson Controls N2 network bus[2]. The zone air temperatures are then used as input for a chilled-water reset algorithm designed to improve the energy efficiency of the centrifugal chiller under part-load conditions and reduce the building's peak demand. The layout of the wireless temperature network is shown in Figure 1.

Description of the Wireless Temperature Sensor Network

The wireless network consists of a commercially available wireless temperature sensor solution from Inovonics Wireless Corporation. The wireless network consists of 30 temperature transmitters, 3 repeaters, 1 receiver, and a beta version of the "Translator", Inovonics new product for the wireless temperature sensor integration into Johnson Controls N2 networks.

[2] N2 bus is Johnson Controls network standard. It has been adopted as an standard.

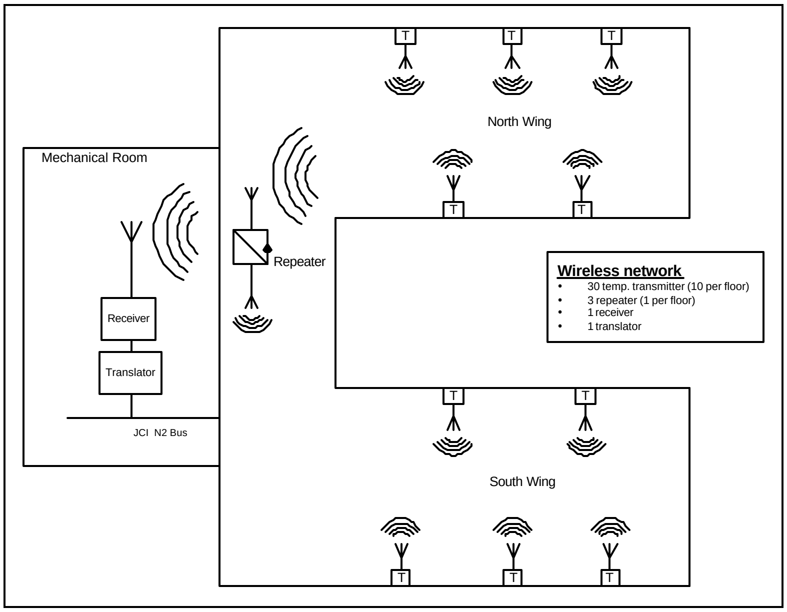

Figure 1: Layout of Wireless Sensor Network. The building has 3 identical floors. Shown is only one floor.

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. The transmitter has an open field range of 2500 feet and is battery-powered with standard 123 size 3-volt $LiMnO_2$ battery with a nominal capacity of 1400 mAh. The battery life depends on the rate of transmission that can be specified in the transmitter. The manufacturer estimates the battery life up to 5 years with a 10-min update rate. The transmitter has a battery test procedure with a 'low-battery' notification via the wireless network. This feature will alert the facility operator through the EMCS that the useful life of the battery in a specific transmitter is approaching its end.

The repeater is powered by the 120 VAC from the wall outlet with a battery backup. There are 3 repeaters, one installed on each floor. The open field range is 4 miles. The receiver and the translator are installed in the mechanical room. The translator connects the receiver with the N2 bus.

Design And Installation Considerations Of The Wireless Network

Installation of the wireless network requires a radio frequency (RF) survey for the placement of the repeaters to ensure that the receiving signal strength is sufficient for robust operations of the wireless network. The RF surveying is an essential engineering task in the design of the wireless network topology. Care must be given to the RF survey or the wireless system may lack robustness in the transmission. The signal attenuation in metal-rich indoor environments caused by metal bookshelves, filing cabinets, or structural elements such as metal studs or bundles of electric or communication wiring placed in the walls can pose a significant challenge to achieving a robust wireless communication. Background RF noise emitted from microwave ovens and other sources can also impair the transmission such that the receiver cannot distinguish noise from the real signal. There is no practical substitute for

RF surveying a building because each building is unique with respect to its RF attenuation characteristics.

Attempts have been made to simulate the RF attenuation characteristics in buildings. Simulation programs exist that utilize the building's structural information to predict transmission ranges inside the buildings (WVCOMM 2002). This simulation tool assists in the preliminary design of the repeater placement; however, it cannot fully substitute a thorough survey. For practical purposes and as long as buildings are accessible for RF surveying, there is relatively little use of a prior simulation analysis.

For the 70,000 ft^2 PNNL building, an engineer performed the RF survey in about 4 hours. This provided sufficient time for investigating several scenarios, whereby the metal bookshelves were placed in the direct pathway between transmitter and receiver. The result of the RF survey was a recommendation of 3 repeaters for each floor of the buildings (see Figure 1).

Rooftop Unit Application—Small Commercial Building Demonstration

The second part of the DOE wireless project underway at Pacific Northwest National Laboratory focuses on configuring, testing, evaluating and demonstrating wireless technology for use with package rooftop HVAC units, commonly used on small- and medium-size commercial buildings. In the initially phase of this project, commercially-available wireless technology has been characterized, and selected systems showing the greatest potential for cost-effective and technically-successful application configured for testing.

Application of wireless RF technology to collection of data from package rooftop HVAC units relaxes some of the demands imposed by in-building applications of wireless communication. Equipment can be physically located so direct lines of sight are preserved and obstructions minimized. By simply positioning antennas sufficiently above the roof, all transmitting antennas can "see" their corresponding receiving antenna. If this is not possible and reliable communication cannot be established, repeaters can be used to extend communication distances and improve the reliability of communication. As a consequence, lower transmission power can be used, greater sources of interference can be tolerated, and communication protocols with less sophisticated means for ensuring reliable data transmission can be used. As a result, system and component costs are likely to be lower for rooftop wireless data acquisition than for in-building systems.

A representative wireless data acquisition system for rooftop units is shown schematically in Figure 2. A wireless data acquisition system (WDAS) may serve many individual package HVAC units. Equipment on the HVAC unit includes: 1) sensors, 2) signal conditioners for the sensor signals, 3) at least one transmitter, and 4) an antenna for each transmitter. Sensors are selected based on the data needs for planned monitoring, diagnostics, or control. For example, diagnostic monitoring of outdoor-air control and economizing might be performed using measurements of outdoor-air, return-air, and mixed-air temperatures plus a signal indicating the on/off status of the unit's supply fan (see, for example, Brambley et al. 1998; Katipamula et al. 1999). Several sensors might be matched with one signal conditioner or several signal conditioners with one transmitter to minimize hardware costs. Connections between the sensors and signal conditioning hardware within the HVAC unit are likely to be wired because equipment costs today are too high to permit cost-effective RF transmission from each individual sensor. In the future, transmitters may be packaged as part of individual sensors, but such equipment is not available commercially today. Electrical power for the data collection equipment can be provided at the packaged unit by tapping into the electrical power supplied for operation of the HVAC unit or by using batteries. Batteries, however, have the disadvantage of finite life and, therefore, require replacement periodically.

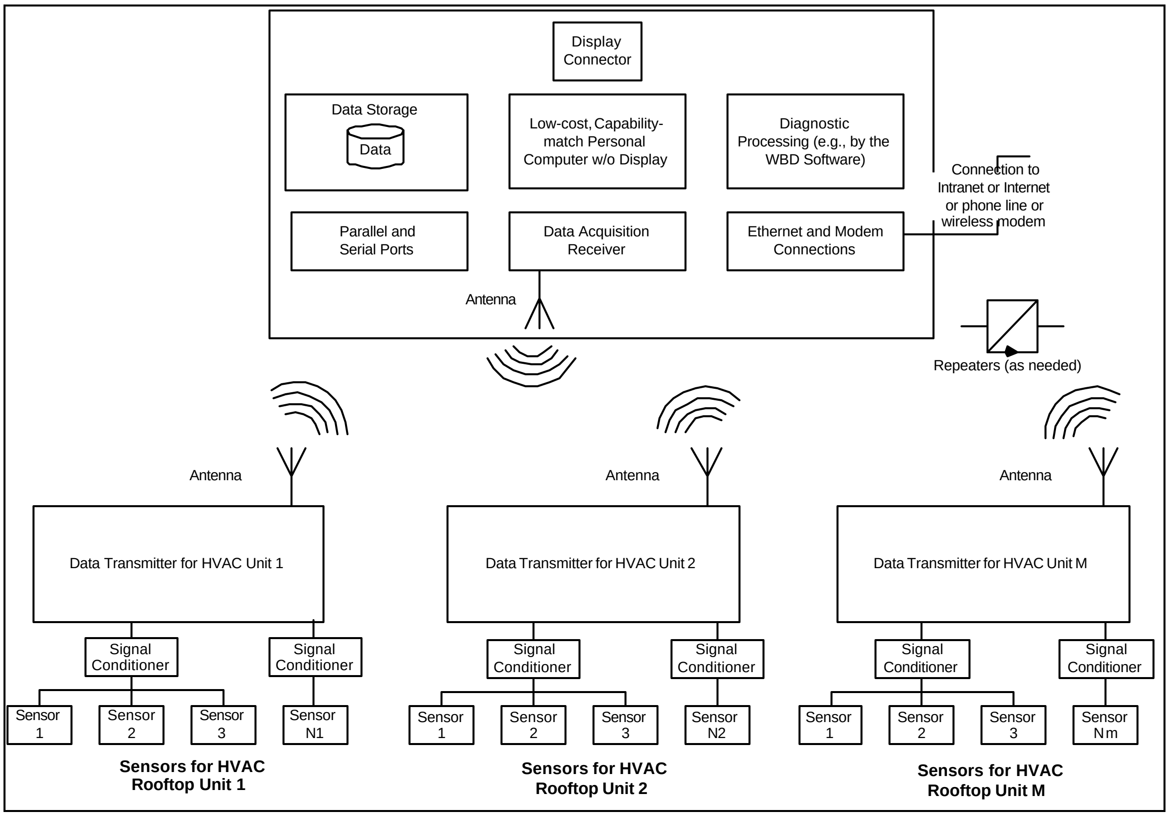

Figure 2: Schematic Diagram of a Representative Wireless Data Acquisition System for Packaged HVAC Units.

Receiving and data processing equipment can be located at a central location (e.g., on the rooftop). The antenna for the receiver is located with as direct a line of sight to the transmitting antennas as possible. The receiver must be compatible with the transmitting units, using the same frequency and communication protocols. Data is transferred from the receiver to a computer for processing via a suitable communication protocol. This might be RS-232 serial, RS-485, USB, Ethernet, or other protocol. The selection depends on the capabilities of the receiver unit and the computer and can be selected to minimize the cost of the components. This equipment must be located near a source of power, which is usually available on commercial-building rooftops.

The computer can be co-located with the receiving unit or located separately in the building. When located on a rooftop, no monitor is required. A handheld device, laptop computer, or a ruggedized LCD monitor can be used temporarily as an user interface during installation and maintenance. Data storage (disk space), processing (CPU), and communication capabilities (motherboard and ancillary boards) should be selected to meet the specific needs of data processing software installed on this computer. Results of processing (e.g., diagnostic results in text, tables, or graphics) can be made available in the building or at remote locations using a connection to an intranet or the Internet via direct wired, wireless-LAN, wireless-Internet, or dial-up connections. The DOE demonstration project currently uses a wired LAN connection for communication to staff located in the building. Plans call for use of a combination of wired LAN, wireless LAN, and wireless Internet connection for communication locally and remotely later in the project.

Wireless data collection systems of this general architecture have been configured and are being tested, first in a laboratory, then in field applications. Target buildings include a small leased office building occupied by PNNL in Washington State and a commercial office building and two fast-food restaurants in northern California.

Cost-Effectiveness Estimation: In-Building Temperature Sensor Example

For the cost comparison, we considered a wired system design with in-plenum wiring. The cumulative wiring distances for all temperature sensors are about 3000 feet with the majority of loose in-plenum wiring. Assumed are 18 AWG cable for sensor connections at an approximately cost of $0.07/ft and a labor cost of $1.53 per linear foot of wiring (RS Means 2001). The cost comparison is shown in Table 2 below.

Table 2: Cost comparison Between Wired and Wireless Designs for In-building Temperatures Sensors

	Qty	Wired Design		Wireless Design	
		Cost per Unit	Total Cost	Cost per Unit	Total Cost
Temperature sensor	30	$60	$1,800	$70	$2,100
Wiring	3000ft	$1.6 per lin. ft	$4,800		
Wireless network gear inc. repeater, receiver, translator					$1,650
RF surveying	4 hours			$100	$400
Wireless network configuration	4 hours			$100	$400
Total cost			$6,600		$4,550
Cost per sensor			$220		$152

For the RF surveying and RF installation we estimated the labor rate of an engineer at an hourly rate of $100 per hour. Omitted in the cost comparison are the costs for the sensor configuration in the Johnson Controls network, which are assumed to be similar, if not equal for both the wired and the wireless designs. For simplicity reasons, the labor for battery change-out, expected to occur every 5 years, are not included in Table 2. This activity can be estimated to cost about $200 assuming a battery cost of $3 per battery and 2 hours of labor for replacing 30 batteries.

The wireless system for this in-building temperature sensor application is about 30% less expensive than a wired solution. Given the layout of the PNNL building, the majority of the cost for the wired temperature sensor solution (72%) is attributed to the wiring. This is a typical percentage for retrofit measures of the wired control networks. For older buildings with asbestos ceilings, for instance, the estimated cost for wiring could be higher.

The wireless temperature sensors are attached to the wall using Velcro, which provides ultimate flexibility to relocate them as the interior layout changes. This flexibility may be reduced when sensors need to be theft-protected by installing them in theft-protected housings. With three repeater stations throughout the building, the wireless network accommodates many more additional sensors only limited by the number of addresses in the receiver. Thus, the incremental cost for any temperature sensor network extension for this specific building is only the cost of the temperature transmitter and the cost for adding one more address to the receiver.

It should also be mentioned that the transmission rates of wired sensors are much higher than those for the wireless sensors. Typical in conventional control networks, zone temperature sensors are polled by the EMCS or a control devices every 1 or 2 seconds. The wireless network installed at the PNNL building updates its temperature every 10 minutes. The user can define the update rate of the temperature transmitter. The penalty of a higher update rate is a higher power consumption and, hence, a reduced life-time of the battery. Thus, battery-operated wireless sensors are not suitable for closed-loop control circuits as employed in the economizer or air-handler control loops. The typical polling rate of in these closed-loop applications is less than 1 second. For zone temperature control, however, the time constant for temperature changes is generally 30 minutes or longer. A 10 minute update frequency is therefore, sufficient and acceptable.

Cost-effectiveness Estimation: Rooftop-Unit Data Acquisition Example

To compare costs of current technology for wired and wireless data acquisition systems for rooftop package HVAC units, consider the situation shown in Figure 3. Three rooftop units separated by the indicated distances are shown. For each unit, four sensors are installed: 4 temperature sensors (for 1) outside air, 2) return air, 3) mixed air, and supply air) for and 1 indicator of the on/off status of the supply fan. These measurements are sufficient to perform diagnostics (or even control) of outside-air control and air-side economizing based on dry-bulb temperature. Other sensors might be installed for other purposes and increase the total cost of the system but not make a difference in communication costs between wired and wireless systems.

Table 3 shows the system costs for a wired base case and two wireless systems configured from commercially-available components—low and high cost. The key cost differences between the wired system and the wireless systems are attributable to the communication components. For the wired case, cable and conduit must be installed to each HVAC unit. For the wireless case, the cable and conduit are replaced with RF transmitters and receivers. The results show that low-cost wireless data collection has cost advantages over wired data collection. The high-cost wireless solution is not cost competitive with wired data collection. These results apply, however, only to the configuration shown in Figure 3. Shorter cable runs increase the cost advantage for wired data collection. Conversely, longer cable runs (greater distances from the data collection point to the HVAC units) increase the cost advantage for wireless systems, up to the point where one or more repeaters are required.

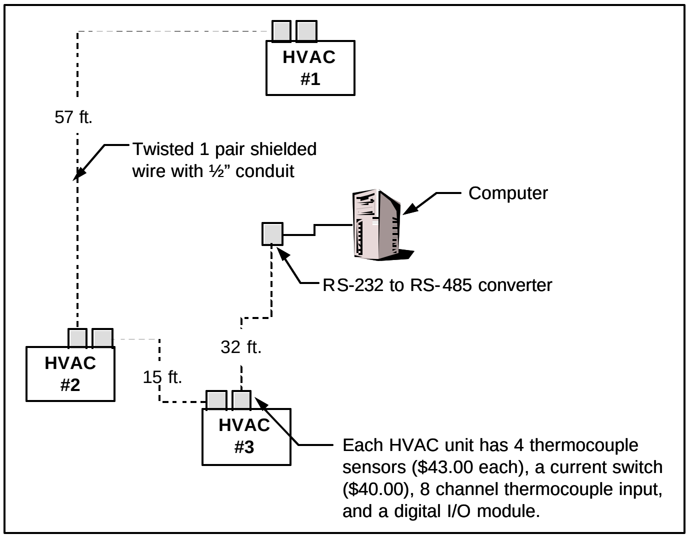

Figure 3: Baseline Wired Data Collection System

Greater numbers of HVAC units generally will increase the cost-effectiveness of wired data acquisition because distances to the units will generally decrease on average. In all cases, the lower cost wireless solutions have a cost advantage. The Pacific Northwest National Laboratory is testing wireless systems to determine the limits on technical performance in typical rooftop environments; results of performance testing will be presented in future publications.

Table 3: Results of Cost Analysis for Rooftop Units

	Wired System		**Low-Cost Wireless**		**High-Cost Wireless**	
Description	**Quantity**	**Cost**	**Quantity**	**Cost**	**Quantity**	**Cost**
Thermocouple Sensors	12	$516			12	$516
Current Switch	3	$120			3	$120
RS-232 Converter	1	$799				
Thermocouple Signal Conditioner ($239 each)	3	$717				
Digital I/O module ($129 each)	3	$387				$387
Twister pair wiring	104 ft	$13				
½" Conduit	104 ft	$55				
Labor for installing sensors (3 hr per unit)	9 hrs	$450	9 hrs	$450	9 hrs	$450
Labor for installing wire and conduit (at $7 per ft)	104 ft	$729				
R.F. transmitting units with sensors and signal conditioners			3	$900		
R.F. receiver unit			1	$600		
2.4 GHz wireless radio modem ($800 each)					6	$4800
Thermocouple input transmitter ($239 each)						$717
Total Cost		**$3785**		**$1950**		**$7000**

Cost-effectiveness Discussion for Retrofit and New Construction

The cost-effectiveness of wireless sensor systems in buildings with respect to wired systems depends on many factors. We define the cost effectiveness by as the ratio of capital cost for a wireless system over the capital cost of a wired system ($Cost_{wireless}/Cost_{wired}$). A ratio of less than unity indicates cost-effectiveness of wireless technology. Of interest is only the cost associated with the transport of a signal from point A to B over a given distance. The cost of the wired system depends primarily on two key factors: 1) on the degree of difficultness to route the control wires and code requirements prescribing shielding and wire support and 2) on the distance measured in linear feet. For simplicity reasons, we neglect the effect of different wire material. In general, the wiring in new construction is less difficult because the relatively easy accessibility to routing channels. As a consequence, we assume the wiring cost to be lower for new construction than when performed as a retrofit measure.

The key drivers for the cost of wireless systems are the signal attenuation and signal to noise ratio for the transmission. In general, we find that the higher the attenuation in a building the more repeaters are required. Figure 4 shows the relations of the cost ratio with respect to the two different implementation environments (retrofit versus new construction) and the dependency on the distance for the wiring. Consider the loci A, B, C, and D in Figure 4 representing different cost ratios at a constant distance of 3000 ft for the wiring. For the retrofit example, we establish a wiring cost of $6,600 assuming a cost per linear foot of $2.2 including wires. For new construction, we assumed a reduced wiring cost because of easier access in the amount of $2,010 assuming a cost of $0.67 per linear foot. Locus A (cost ratio=0.26) represents the cost competitiveness of a wireless system in a retrofit case with no repeater necessary. Locus B (cost ratio=0.71) represents the cost for building with high attenuation characteristics requiring 10 repeaters. The corresponding loci for the new construction are locus C (cost ratio=0.85) and locus D (cost ratio=2.34).

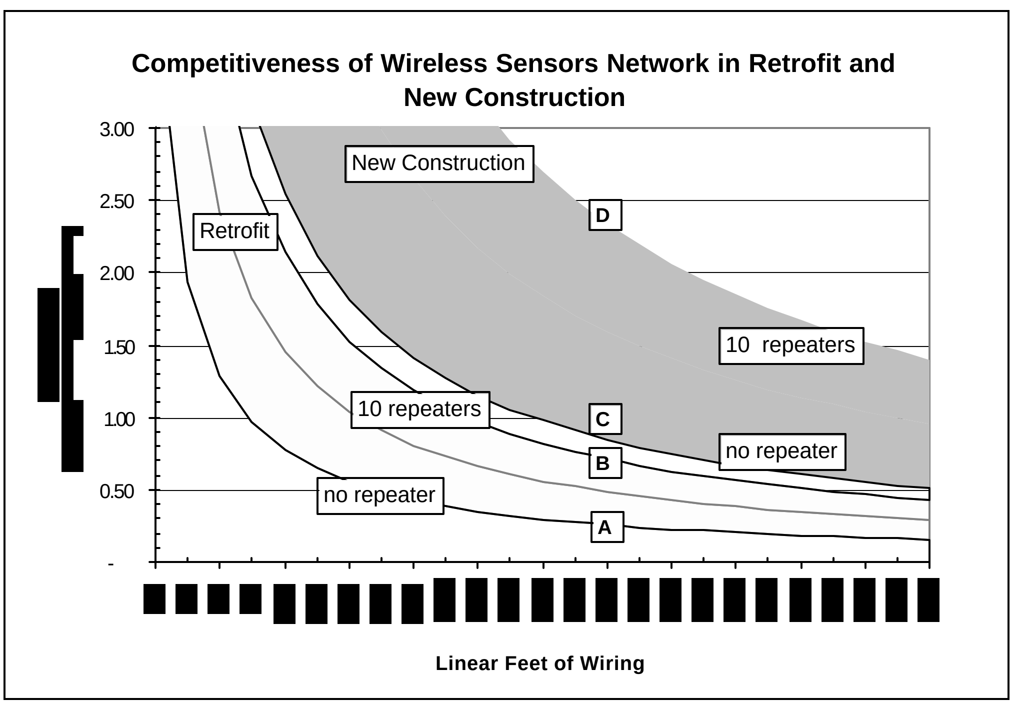

Figure 4: Competitiveness of Wireless Sensors and Data Acquisition Systems Compared to Wired Systems

While the cost-effectiveness analysis is simplified it illustrates the sensitivity of the key drivers for the cost effectiveness of wireless technologies in HVAC applications. It indicates that the earlier adopters of this technology will implement wireless devises most likely in existing buildings that do not pose difficulty on transmission of the RF signal. Likely applications are rooftop connectivity with light of sight transmission or applications in light constructions. Wireless technologies in new construction are not yet commonly competitive. Today's wireless technologies are still too expensive or do not achieve the performance of wired sensors with respect to update frequencies. To compete solely in the retrofit markets may not provide the needed market pull necessary for larger market penetration. It is the new construction market, where large volumes of controls and sensor technologies are purchased. Cost targets for competing in this market segment may need to be attained for larger inroads of wireless technology.

Future Directions

To completely utilize the advantages of wireless technology any wires to the HVAC control device need to be avoided include power supply cables. To achieve this today's wireless technology needs to mature in two directions to provide comparable performance to conventional wired HVAC control components: 1) aggressive use of power management strategies of wireless devices, use of ultra-low power consuming electronic circuitry, and utilization of ambient power sources and power scavenging and 2) seamless integration into conventional DDC control networks. Only if the performance of wireless devices approaches that of today's wired control components at competitive cost, will we see more penetration of the wireless technology. While the mobility feature in conventional commercial HVAC control applications may remain limited, the cost avoidance for wiring and its competitive cost will most likely be the key selling point of the wireless technology.

As with the advent of television, when many feared that it will replace radio broadcasting, so it is unlikely that wireless technology will replace the entire wired HVAC controls market. A more likely scenario is that it will complement the conventional wired controls technology where it makes economic sense. We envision that the first niche markets will be retrofit applications where the technology extends existing wired control networks in places where there is no electricity supply or over long distances at hard-to-reach places. It is hoped that the implementation of emerging wireless HVAC control technologies will ultimately result in better monitored and controlled HVAC systems that will improve the overall energy efficiency of the existing building stock and provide healthier and more productive workplaces.

Toward this end, the U.S. Department of Energy is funding technology demonstration projects to quantify the cost and performance characteristics of commercially available wireless technologies. From these activities, technology gaps can be analyzed in order to develop a research, development, and demonstration agenda that will be directed to bridge the technology gaps and to demonstrate its usefulness.

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