Wireless Sensors: Technology and Cost-Savings for Commercial Buildings

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ABSTRACT

Two projects underway 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 necessary to establish and maintain highly efficient and effective building operations.

In this paper, the authors present the technical characteristics and costs of off-the-shelf wireless sensor and data-acquisition systems and describe how they can be adapted to commercial buildings. The paper provides a brief overview of wireless communication standards and discusses their appropriateness to HVAC control applications. The authors describe two wireless technology demonstration projects and discuss their cost competitiveness to conventional wired system. The paper provides a general discussion on cost competitiveness of wireless versus wired control networks for retrofit and new construction and concludes with some future prospects for wireless technologies for buildings applications.

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. A 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 and Gustavson 1999). Experts agree that the driving argument for the deployment of wireless sensors will be cost advantages and the flexibility to relocate thermostats and sensors as the interior building 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 compelling driver for the impressive inroads of wireless technologies in the communication and computer LAN markets, the need for mobility in building control applications remains limited. This means that wireless technologies must compete predominantly on the basis of cost.

This paper discusses the cost aspects for the installation of the wireless sensors in two very different retrofit applications that are part of two demonstration projects currently underway at Pacific Northwest National Laboratory (PNNL). These 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 presents a cost comparison between wireless and wired sensor networks and discusses the key drivers for the cost competitiveness of wireless technologies in buildings. The paper concludes with a discussion on future trends of wireless sensing and control applications in buildings.

Before describing the DOE demonstration projects, it is important to understand key technical features and characteristics of relevant wireless technologies that are currently available. Therefore, the paper provides an overview of wireless sensor and control products, followed by a discussion of two demonstration projects.

Existing Commercial Wireless Sensing And Data Acquisition Technology

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. The following sections provide brief descriptions and assessments of applicability for three wireless communication technology classes that are differentiated by their communication modulation and protocols.

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. 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 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 to security of the transmissions. The maximum data rate is 781 kbps. The maximum transmission range for a home environment is 10 meters and for an outside 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. Communication can be extended to more devices by interconnecting 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 latter 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) is a family of standards for wireless local area networks (LANs) operating in the 2.4 GHz frequency band. 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.

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 and about 50 meters indoors.

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 much larger bandwidth and 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 (Fern and Tietsworth 1999). 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; therefore significant cost reductions can be achieved by matching the wireless technology used with the specific application.

Selected Commercially Available Technologies

Table 1 provides representative characteristics and costs for selected wireless data acquisition systems. The selection is based on a preliminary survey of appropriate wireless technologies. It is not an exhaustive survey. For the serial communication products of Table 1, maximum communication distance is a significant cost variable. Products with lower communication ranges are significantly less expensive than those that transmit over several miles (No. 3 and 4). The Bluetooth product listed in Table 1, represents currently available products. The cost target for a Bluetooth radio chip is significantly lower when mass-produced for consumer products.

Table 1. Characteristics of Selected Commercially Available Wireless Technology

No	Freq. Band [MHz]	Com-munication Standard	Maximum Com-munication Distance	Power Source	Point-to-Pont or Point-to-Multi-point	Cost
1	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
2	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: $100 Repeater: $375 Receiver: $450
3	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
4	900	Serial	35 miles line of sight	10.5 to 18.0 VDC	Point-to-multi-point	Transmitter: $1775 Receiver: $1775
5	2,400	Serial	150 ft line of sight	10 to 30 VDC	Point-to-point	Transmitter: $800 Receiver: $800
6	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

FHSS: frequency hopping spread spectrum
DSSS: direct sequence spread spectrum techniques

U.S. DOE Demonstration Projects of Wireless Sensors 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 HVAC system efficiency. The heavy steel-concrete structure is a difficult environment for radio frequency transmission. We chose it to explore the effect 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 will then be communicated wirelessly to an Internet service provider for viewing of the results or alarm notification via email or other notification.

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 in the ceiling throughout the building. 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 zone temperature information and control of the VAV boxes. The long-term goal of PNNL facility management is to network the 100 VAV boxes into the central control infrastructure to improve 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.

Description of the Wireless Temperature Sensor Network

The wireless network consists of a commercially available wireless temperature sensor solution from Inovonics Wireless Corporation. It encompasses 30 temperature transmitters, 3 repeaters, 1 receiver, and a beta version of the "Translator," Inovonics' new product for the integration of their wireless temperature sensors into Johnson Controls N2 networks. The layout of the wireless temperature network is shown in Figure 1.

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 a 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 three repeaters, one installed

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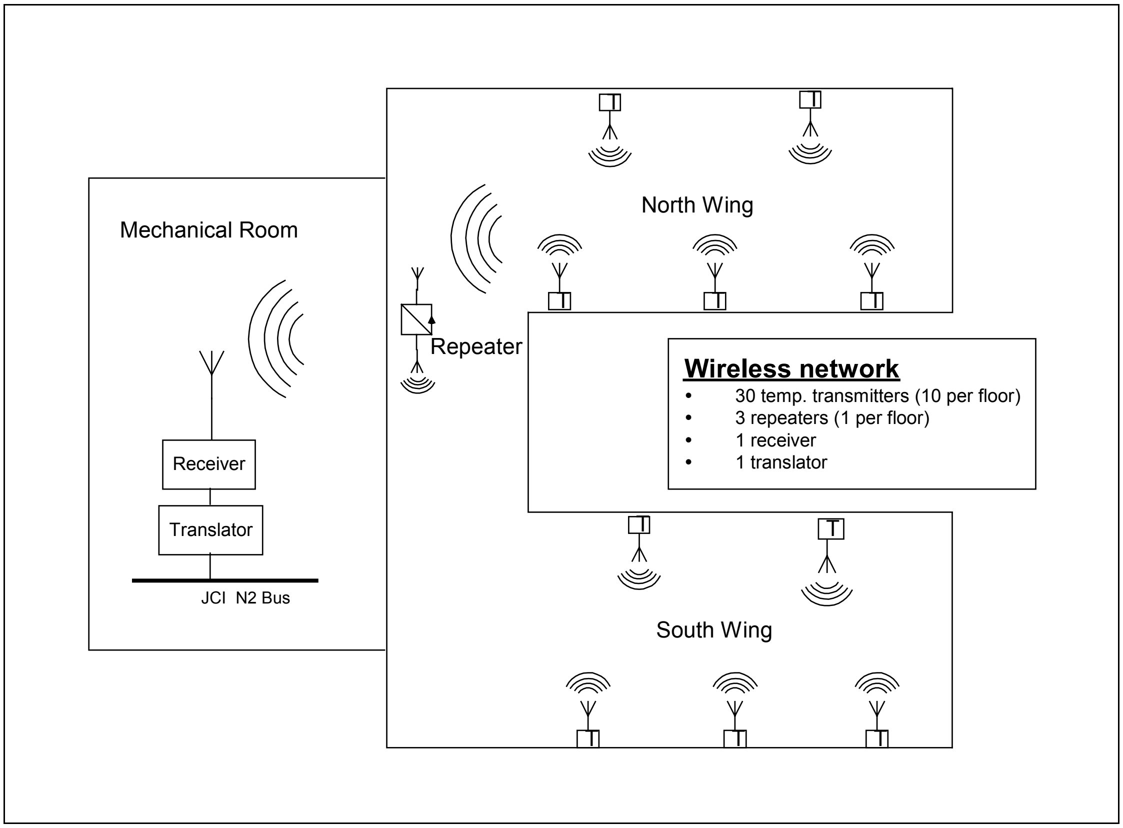
[2] N2 bus is Johnson Controls network protocol.

on each floor. Because the repeater is line powered, the repeater operates at high power and provides up to 4 miles of open field range. The receiver and the translator are installed in the mechanical room. The translator connects the receiver with the N2 bus.

Figure 1. Layout of Wireless Sensor Network: The Building Has Three Identical Floors (Shown Is Only One Floor)



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 received signal strength is sufficient for robust operation 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 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 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.

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 three repeaters, one for each floor of the building (see Figure 1).

Rooftop Unit Application—Small Commercial Building Demonstration

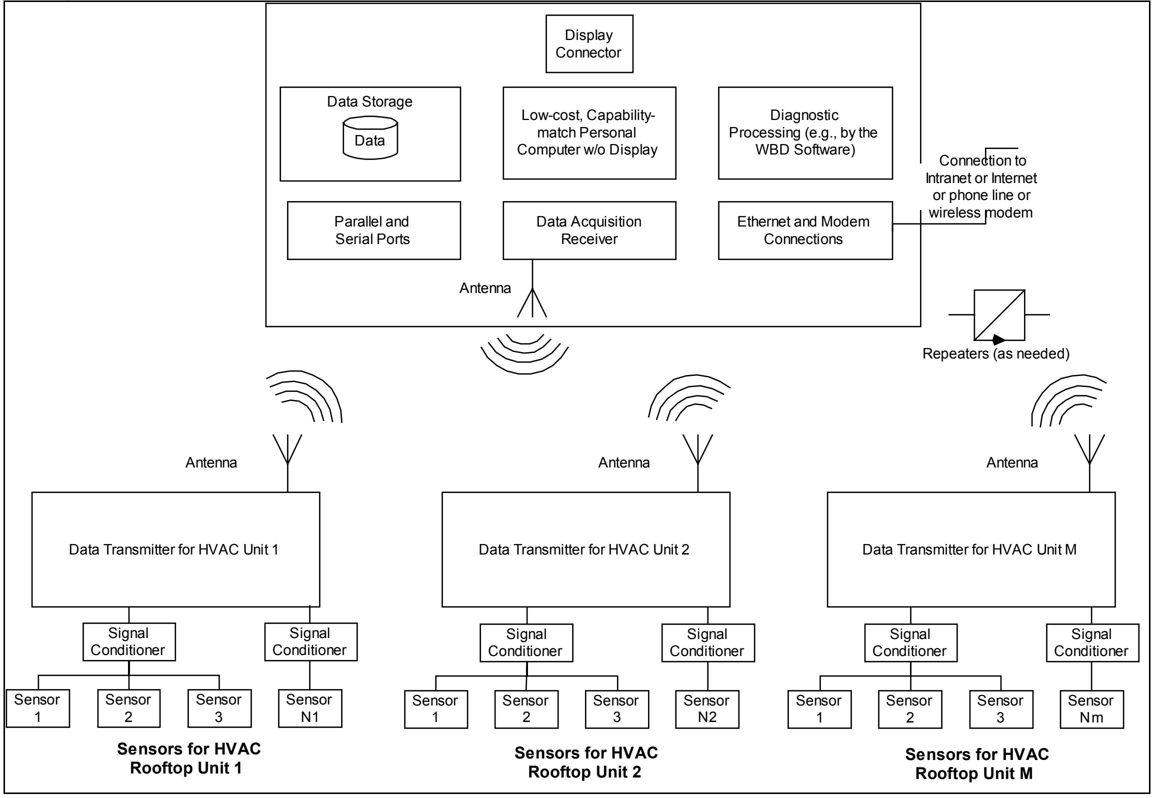
The second part of the DOE wireless project underway at Pacific Northwest National Laboratory focuses on configuring, testing, evaluating and demonstrating wireless technology for use with packaged rooftop HVAC units, commonly used on small- and medium-size commercial buildings. The target application for wireless could system monitoring, diagnostics, and remote control of packaged units. In the initial 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 collect data from packaged 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 (WDAS) for rooftop units is shown schematically in Figure 2. A wireless data acquisition system may serve many individual packaged 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 generally be provided at the packaged unit by tapping into the electrical power supplied for operation of the HVAC unit.

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. 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.

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



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 a 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: 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 wiring being loose in-plenum. Assumed are 18 AWG cable for sensor connections at an approximate 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	$100	$3000
Wiring	3000 ft	$1.6 per lin. ft	$4,800		
Wireless network gear inc. repeater, receiver, translator					$2475
RF surveying	4 hours			$100	$400
Wireless network configuration	4 hours			$100	$400
Total cost			$6,600		$6,275
Cost per sensor			$220		$209

The cost for the wireless system includes an assumed installer mark-up of 50%. For the RF surveying and RF installation we estimated the labor rate of an engineer at $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, the labor cost for battery change-out, expected to occur every 5 years, is not included in Table 2. This activity can be estimated at 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 5% less expensive than a wired solution. It should be noted that the estimates in Table 2 have considerable uncertainties introduced by the assumptions of the installer mark-up for the wireless system and the wiring cost for the layout of the demonstration building. The results of Table 2 suggest that the wireless system can be a cost-effective solution. Due to uncertainties in the cost estimates, the wireless system may range from being cost-effective to marginally cost-effective and potentially slightly more expensive. One of the advantages of the wireless network is that it can be easily extended with additional temperature sensors at an incremental cost of a temperature transmitter, up to 100 transmitters. Installations with more than 100 temperature sensors require additional receivers and translators.

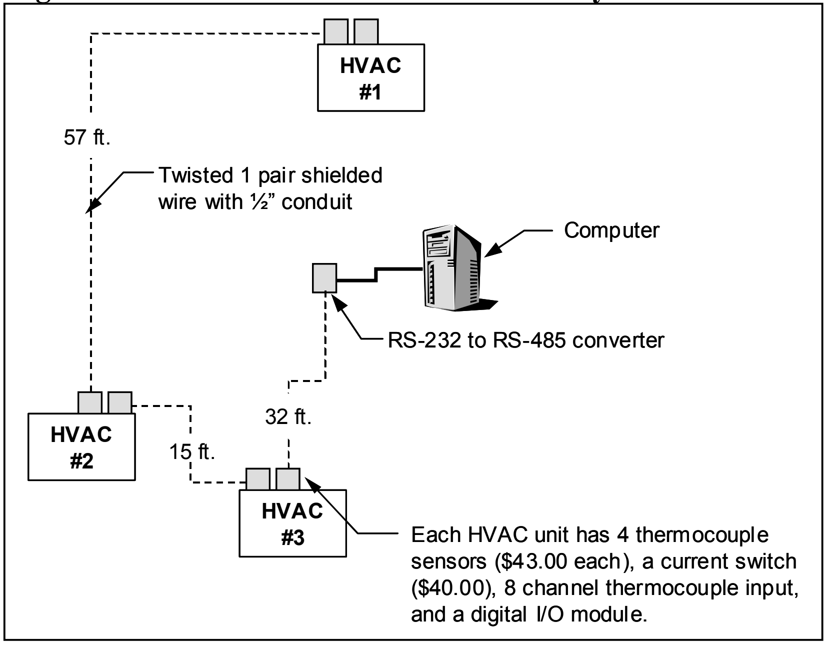
It should also be mentioned that the transmission rates of wired sensors are much higher than those for the wireless sensors. Typically in conventional control networks, zone temperature sensors are polled by the EMCS or a control device every 1 or 2 seconds. The wireless network installed at the PNNL 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 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: Rooftop-Unit Data Acquisition Example

To compare costs of current technology for wired and wireless data acquisition systems for rooftop packaged 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: four temperature sensors (for outside air, return air, mixed air, and supply air) and one 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 low-cost wireless system corresponds to the technology listed as number 1 in Table 1. The high-cost system corresponds to technology listed as number 5. 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.

Figure 3. Baseline Wired Data Collection System



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.

Greater numbers of HVAC units generally will improve the cost-effectiveness of wireless data acquisition because total linear feet of distances from a central point to the HVAC units will generally increase. In all cases, the low-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[1]**		**High-Cost Wireless[2]**	
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**

[1] corresponds to technology number 1 in Table 1

[2] corresponds to technology number 5 in Table 1

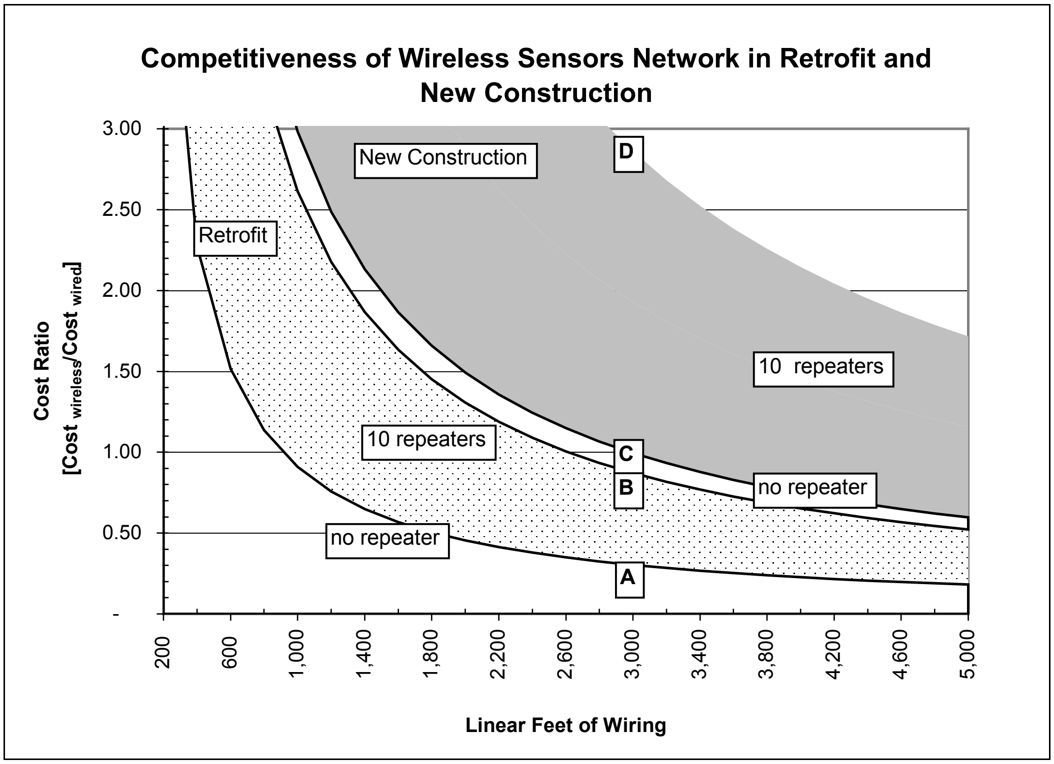
Cost Comparison of Wireless Versus Wired System for Retrofit and New Construction Applications

The cost-effectiveness of wireless sensor systems in buildings with respect to wired systems depends on many factors. We define the cost effectiveness 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 that wireless technology is more cost effective. Of interest is only the cost associated with the transport of a signal from point A to B over a given distance because other components (sensors, controllers, and actuators) are common to both wired and wireless systems. The cost of the wired system depends primarily on two key factors: 1) on the degree of difficulty to route the wires and code requirements prescribing shielding and wire support and 2) on the distance. For simplicity, we neglect the effect of different wire material. In general, the installation of wiring in new construction is less difficult because of 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 that are required. The cost model for the wireless system is used in this analysis corresponds to the second serial wireless technology shown in Table 1. In addition we estimated cost for the integration into a wireless system of $500.

The cost effectiveness ratio ($Cost_{wireless} / Cost_{wired}$) is then a function of distance, installation type (retrofit versus new construction), and number of repeaters. Figure 4 shows this relation. Consider the points 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 for a cost of $0.67 per linear foot. We assumed that wiring conduits already exist and thus, the wiring cost excludes the cost associated with installing conduits. Point A (cost ratio=0.3) represents the cost competitiveness of a wireless system in a retrofit case with no repeater necessary. Point B (cost ratio=0.9) represents the cost for a building with high attenuation characteristics, requiring 10 repeaters. Corresponding for new construction are points C (cost ratio=1.0) and point D (cost ratio=2.9).

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 wireless technologies in HVAC applications. It indicates that the early adopters of this technology will implement wireless devises most likely in existing buildings that do not pose difficulty in transmission of the RF signal. Likely applications are rooftop connectivity with line-of-sight transmission or applications in light construction that do not require repeater devices. Wireless technologies in new construction are not yet commonly competitive. Today's wireless technologies are still expensive. Solely battery-operated wireless sensors currently do not achieve the performance of wired sensors with respect to update frequencies. To gain significant market shares, wireless technology would need to compete in both the retrofit as well as in the new construction markets. With lower cost of wireless technology and available integration products for interconnecting wireless with wired systems, wireless technologies may become an attractive solution for HVAC control networks coexisting and augmenting wired systems.

Future Trends

While the mobility feature in conventional commercial HVAC control applications may remain limited, at least for the short-term, the cost avoidance for wiring will most likely be the key selling point of the wireless technology. The first adoption of wireless technology is expected to occur in retrofit applications where the technology extends existing wired control networks to places where there is are no control networks cables. This includes, for instances, opportunities for one-way or two-way connectivity among packaged rooftop units with line-of-sight transmission, permanent or temporary indoor air monitoring, monitoring of remote equipment (e.g., water pumps, cooling intake valves), and control of outdoor lighting. The first wireless installations are expected to be monitoring applications that are not time critical and require only one-way communications. Control applications will initially be limited to open-loop control function, such as turning equipment on or off. Wireless closed-loop control applications that require higher update frequencies (less than one second) pose higher transmission robustness requirements are therefore, expected to mature later. As wireless technology gains inroads into the HVAC controls markets and sales volumes increase, cost reductions of the technology will follow. Primary driver of the cost reduction will be design and manufacturing optimization of RF technology components and further integration of sensing, signal conditioning and RF communication modules that can be mass manufactured.

Technological challenges for closed-loop control applications with high update frequency requirements still remain for battery-operated devices requiring technological advancements in power management, ultra-low power electronics, and utilization of ambient power sources and power scavenging.

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. Significant reductions in cost for wireless sensing will lead to greater use of sensors in building application, which in turn will lead to better control and maintenance of systems that will improve the overall energy efficiency of the existing building stock and provide healthier and more productive workplaces.

Toward this end, the projects described in this paper will identify technology gaps in order to develop a research, development, and demonstration agenda that will bridge the technology and cost gaps and demonstrate the value of wireless technology in building monitoring, operation and maintenance.

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