Wireless Sensors: How Cost-Effective Are They in Commercial Buildings?

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Introduction

While the proliferation of cellular telephony, wireless computer networking, and wireless personal digital assistants (PDAs) has been phenomenal in the last few years, application of wireless sensing and control to heating, ventilation, and air-conditioning (HVAC) is essentially non-existent. A 1999 expert roundtable of HVAC industry professionals (Ivanovich and Gustavson 1999) unanimously agreed that wireless sensing of indoor conditions would be inevitable for the future because of its cost advantages and flexibility to relocate sensors. However, the building controls industry has not yet seen many wireless devices deployed in the field. Experts agree that the driver for deployment of wireless sensors will be cost advantages and the flexibility to relocate thermostats and sensors as the interior building layout adapts to the changing needs of the tenants and occupants (Ivanovich and Gustavson 1999). While the mobility of wireless sensors is irrefutable, the present cost of wireless technology may still be too high to penetrate this market widely.

For any new technology to penetrate the marketplace, 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 a compelling driver for the impressive inroads of wireless technologies in the communication and computer networking markets, the need for mobility in building control remains limited. This means that wireless technologies must compete predominantly on the basis of cost.

Commercially Available Wireless Technologies

A broad range of wireless data acquisition hardware is commercially available that could be used for sensing conditions in buildings and HVAC systems. Most vendors market generic hardware for use across many industrial and agricultural applications. Wireless computer networking hardware components, which are becoming widely used today, could also be adapted for use in sensor-data collection for buildings. The essential components of a wireless data acquisition system (see Figure 1) include: the sensors themselves; signal conditioners to convert the sensor signal to a sufficiently strong and clean digital signal that will be transmitted; a transmitter for each sensor, for each signal conditioner, or shared by several signal conditioners; repeaters when needed; a receiver; and a connection to a processor where the data are analyzed or processed using control algorithms. Transmitters may be powered by electrical wiring in the building or by battery depending on the availability of electrical connections at the sensor locations. In addition to wireless data acquisition components, wireless systems specifically for building applications are beginning to emerge.

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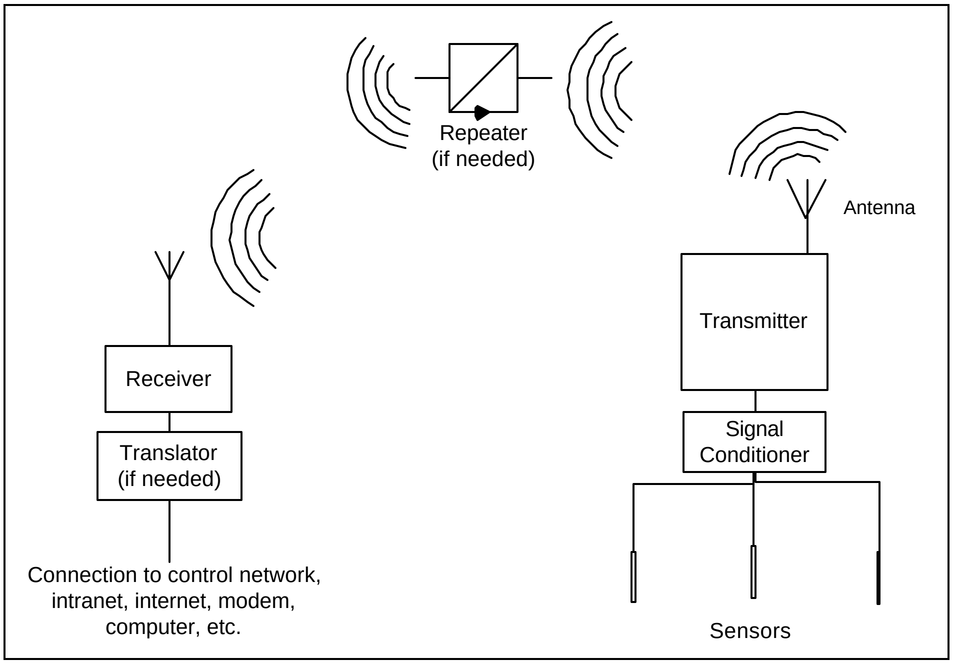

Figure 1. Schematic diagram showing the primary components of a generic wireless radio-frequency data acquisition system.

Table 1 shows the range of hardware costs found in an informal of vendors of wireless data acquisition equipment. Generally, costs are higher for wireless technology that communicates over greater distances and uses more sophisticated signal encoding to ensure successful transmission of signals. Of the components, receivers generally cost the most, but one receiver might serve many transmitters (see, for example, the 30-sensor in-building wireless sensor network that uses only one receiver later in this paper). Maximum transmission distances range from as little as 30 feet to as much as many miles, and in general, interference is overcome and transmission distances extended by the addition of signal repeaters. When manufacturers configure wireless components into application-specific systems, often the costs of the integrated systems are lower than the sum of the costs for the individual components (except for very highly specialized applications).

Table 1. Cost of major components of a radio-frequency wireless data acquisition system in 2002.

Major Wireless Component	Cost
Receivers	$300 to $1995
Transmitters	$68 to $1775
Repeaters	> $250

Two demonstration systems that apply existing radio-frequency wireless technology to building and HVAC monitoring (and ultimately control) are described in the section that follows, along with a comparison of their costs and the costs similar wired systems.

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

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 Pacific Northwest National Laboratory (PNNL). The HVAC system consists of central cooling, boiler, and ventilation system with 100 variable-air-volume (VAV) boxes. The central energy management and control system (EMCS) controls the central plant and the lighting system. A wireless temperature sensor network with 33 temperature transmitters was installed to measure zone-air temperatures. 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 without significantly increasing the energy use by distribution fans.

Figure 2: Demonstration for In-Building Application, Office Building at PNNL Site

Description of the Wireless Temperature Sensor Network

The wireless network consists of commercially-available wireless temperature sensor technology including 33 battery-powered temperature transmitters, 3 repeaters, 1 receiver, and the beta version of the "Translator," a new product for integration of wireless temperature sensors with another vendor's wired building automation network.

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 transmission. The transmitter has an open field range of 2500 feet and is battery-powered with a standard 3-volt $LiMnO_2$ battery with a nominal capacity of 1400 mAh. The manufacturer estimates a battery life of up to 5 years with a 10-min update rate. The transmitter has a battery test procedure with 'low-battery' notification via the wireless network. This feature alerts building staff of the approaching end of the battery life through the EMCS. The repeater is powered by 120 VAC from the wall outlet with a battery backup. There are three repeaters, one installed 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 to the BAS bus.

An engineer performed a radio frequency (RF) field strength survey for the 70,000-ft^2 building, in about 4 hours. The result of the RF survey was the recommendation of three repeaters, one for each floor of the building.

Use of Wireless Sensors for Diagnostics

When Dwight Hughes, building engineer of the PNNL office building, was called because of a heat build-up problem in the cafeteria's kitchen, he knew what to do. He taped a wireless temperature sensor into the corner at the trouble spot, where the heat build-up was noticed, and monitored the temperature trends over a day. He quickly recognized that the original, wired temperature sensor for this zone was too far away from the trouble spot and that it, therefore, did not notice the heat build up. Dwight reprogrammed the EMCS to control for a weighted average of the original wired and the new wireless temperature measurements and, thus, solved the problem.

"The strength of our wireless temperature sensor network shows when we are trying to address some very localized problems in our building. There is nothing more convenient than taking a wireless temperature sensor from one location in our building and taping it with double-side tape somewhere else" says Dwight Hughes, who has embraced the new wireless technology in this building to reduce energy consumption while providing quality indoor work environments.

Rooftop Unit Application—Small Commercial Building Demonstration

The second part of the wireless project focuses on configuring, testing, evaluating and demonstrating wireless technology for use with packaged rooftop HVAC units. A system built from generic commercial components is shown in Figure 3.

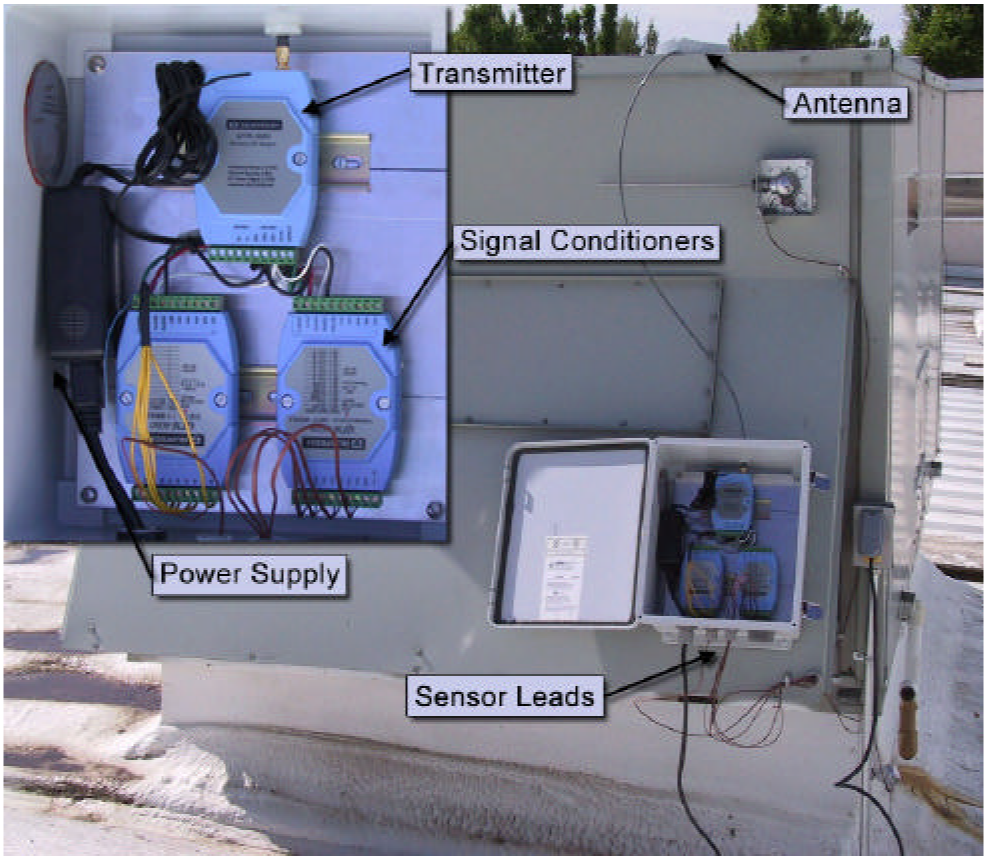

Figure 3: Demonstration of Wireless Rooftop Data Acquisition

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. 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. 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, eliminating the need for batteries.

Cost-Effectiveness: In-Building Temperature Sensor Example

The cumulative wiring distance for all temperature sensors is about 3000 feet, with the majority of wiring being loose in-plenum. Sensor connections are assumed to be 18 AWG cable costing approximately $0.07/ft with a labor cost for installation of $1.53 per linear foot of wiring (RS Means 2001). The cost comparison is shown in Table 2.

Table 2. Cost comparison of wired and wireless sensor systems for 1) a 30-sensor in-building temperature sensor network and 2) monitoring of three packaged rooftop HVAC systems.

Cost Component	Cost			
	In-Building Temperature Sensor Network		Monitoring System for Three Packaged HVAC Units	
	Wired Design	Wireless Design	Wired Design	Wireless Design
Sensors	$1800	$3000[2]	$636	$636
Wiring	$4800[3]	---	$68[4]	---
Communication and signal-conditioning hardware	---	$2475	$1903	$1500 - $5900
Labor	---[5]	$800	$1179[6]	$450
Total cost	$6600	$6275	$3786	$1950 - $7000
Average cost per sensor	$220	$209	$316	$163 - $583

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 $300, assuming a battery cost of $3 per battery and 2 hours (at a rate of $100 per hour) of labor or just under $10 per sensor 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 for the installer mark-up for the wireless system and the wiring cost for the comparable wired-system layout for the demonstration building. The results of this comparison suggest that the wireless system can be a cost-effective solution. In practice, such a wireless system may range from being cost-effective to marginally cost-effective and potentially slightly more expensive than a wired system because of differences in the number of sensors and individual component costs. One of the advantages of the wireless network is that it can be easily extended with additional temperature sensors for the incremental cost of one temperature transmitter. This system can

[2] Temperature sensors each with an integrated transmitter.
[3] Including labor for installation.
[4] Including conduit.
[5] Included in cost of wiring.
[6] Including installation of conduit.

be configured for up to 100 transmitters. Installations with more than 100 temperature sensors require additional receivers and translators.

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, we consider an arbitrary rooftop configuration consisting of three separate units, which would require 100 ft of wiring and conduit for conventional wired networking. 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 particular measurements can be used to detect problems with the air side of the units.

Table 2 shows the system costs for a wired base case and ranges of costs for wireless systems configured from commercially available components. 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 wireless systems that cost is eliminated, but there is the cost of the transmitters and receivers. In addition, laying the conduit and wire generally requires more labor.

The results show that low-cost wireless data collection has cost advantages over wired data collection. High-cost wireless solutions are not cost competitive with wired data collection. These results apply, however, only to the particular configuration chosen. The results illustrate that the cost of the specific wireless system selected is critical for economic application of wireless data acquisition given today's prices.

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

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.

The cost of the <u>wired</u> system depends primarily on two key factors: 1) the degree of difficulty to route the wires and to meet code requirements prescribing shielding and wire support and 2) the distance. In general, the installation of wiring in new construction is less difficult because of the relatively easy accessibility to routing channels.

The key drivers for the cost of <u>wireless</u> systems are the signal attenuation and signal to noise ratio for the transmission. In general, the higher the attenuation in a building is, the more repeaters that are required. We estimated the cost for integrating wireless sensor systems into a wired building automation system (or DDC system) at $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 length of 3000 ft for the wiring. For the retrofit example, we establish a wiring

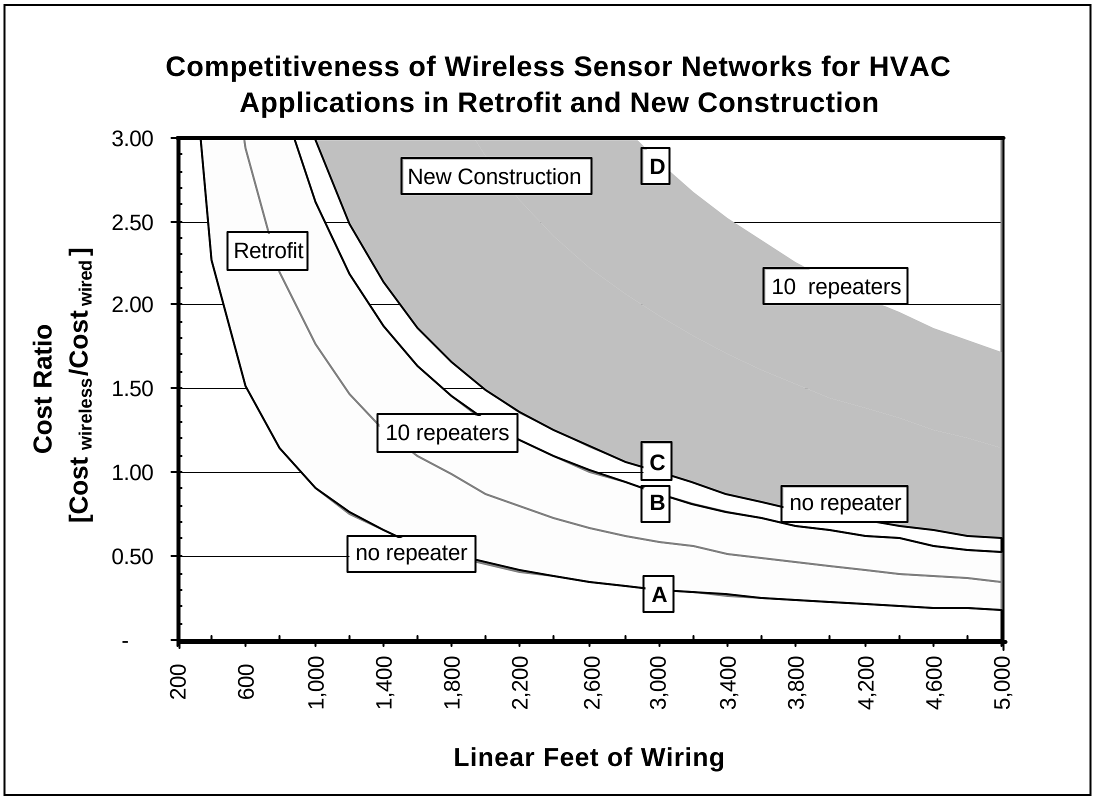

Figure 4: Competitiveness of Wireless Sensors and Data Acquisition Systems Compared to Wired Systems. Point A (cost ratio=0.3) represents the cost competitiveness of a wireless system in a retrofit case with no repeater necessary. Point B (cost ratio=0.9) represents the cost for a building with high attenuation characteristics, requiring 10 repeaters. Points C (cost ratio=1.0) and D (cost ratio=2.9) represent the corresponding cost for new construction.

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. For the wired system, we assume 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 for a retrofit with no repeater necessary. Point B (cost ratio=0.9) represents the cost for a building with high attenuation characteristics, requiring 10 repeaters. Corresponding costs for new construction are represented by points C (cost ratio=1.0) and point D (cost ratio=2.9).

While this cost-effectiveness analysis is simplified, it illustrates the sensitivity to key drivers for wireless technologies in HVAC applications. It indicates that the early adopters of this technology will implement wireless devices most likely in existing buildings that do not pose difficulty in transmission of the RF signal. Likely applications include rooftop connectivity with line-of-sight transmission and applications in light construction that do not require repeaters. Wireless technologies in new construction are not yet commonly competitive. Solely battery-operated wireless sensors currently do not achieve the performance of wired sensors with respect to update frequencies. With lower costs for wireless technology and increased availability of products for interconnecting wireless with wired systems, wireless technologies may become an attractive solution for HVAC control networks coexisting and augmenting wired systems.

Considerations for Using Wireless Sensors for HVAC Applications

This section provides some practical tips for buildings owners and facility managers who are contemplating adopting wireless technologies for their buildings. We provide some general tips and advice along with some specific recommendations for rooftop and in-building applications.

General

- Wireless product offerings are available currently, and new products are emerging. Search the world wide web (e.g., for wireless sensors, wireless HVAC, wireless control) to see what is out there.
- Costs vary broadly, and specific component or system choices can greatly affect whether the wireless alternative is cost competitive with a wired system.
- There are few wireless systems that currently provide products for integrating wireless sensor networks with commonly-used HVAC direct digital controls (DDC) and building automation systems (BASs), but some are beginning to emerge. Ask your controls vendor about wireless technology; some offer it directly.
- Cost of wireless technology is likely to come down with more market penetration. We are expecting greater price reductions in wireless technology than what is common in the rest of the DDC industry.

In-Building Applications

- Consider investing in a wireless network that covers the entire building. Once you have a wireless network, the incremental cost of additional sensors is only the cost of the sensor and very little set-up cost.
- Integration into existing DDC systems is a must if you want to use sensor data for controls in your DDC system. Find out what data items are transported from the wireless into the wired system. For instance, for battery-powered transmitters, are low-battery indications reported to the wired system and integrated into the alarm features of the existing DDC system? Particularly if you have hundreds of battery-powered sensor nodes, low-battery alarming is important for maintainability of the wireless sensors.
- Inquire about extendability of the wireless network. As your building undergoes internal changes, you may need to add a repeater to cover newly constructed space. Similarly you may want to extend your wireless network to cover outside parking lots adjacent to buildings. Wireless technologies should be easily extendable by adding additional repeaters and sensors with minimal setup.
- Consider using wireless data collection first for applications where the cost of wired data collection is very high. This is likely in existing buildings, where you are retrofitting and construction would make installation of wiring expensive (e.g., it requires running wiring in conduits on the surface of walls or opening up existing walls).
- Storage buildings that do not have their own BASs but that you would like to monitor are candidates for wirelessly connecting to the BAS in a nearby building or at least monitoring in the control of a nearby building.

- Batteries in battery-powered transmitters need to be replaced periodically. Battery life may be 5 to 10 years, depending on the frequency of transmission. Although low in some cases, this cost should not be neglected in evaluating wireless sensing as an alternative to wired.
- Sensors mounted using Velcro or double-sided tape that are placed in occupied spaces could be moved by occupants without the knowledge of the building engineer. The authors have not encountered this problem in their work, but this is a distinct possibility. Where this is a concern, more permanent mounting techniques should be considered.

Rooftop Unit Applications

- Determine your objectives before laying out the wireless system. Are you collecting data to monitor performance of the unit, looking for faults in components, or providing control? Select your sensors and components accordingly.
- Select the wireless components carefully to match the needs of your application, the environment in which the system will be installed, and consider component costs.
- Consider future expansion of your wireless networks and make sure that additional rooftop units can be added to the wireless network without redesigning the entire network.
- Ask the vendor, when possible, to conduct a field strength survey to enable you to select optimal positions for antennas and repeaters.
- Find someone experienced in design and installation of similar wireless installations to design the system for your consideration.

Other HVAC Applications of Wireless

- Temporarily-installed sensors can be used to diagnose suspected problems or occupant complaints. If a wireless sensor network is already installed, addition of sensors for this purpose is easy and inexpensive.
- Wireless sensors can be installed temporarily during system and equipment commissioning to provide data potentially at lower cost than wired sensors. After commissioning is complete, these sensors can be removed for re-use at other sites or left in place for use during routine operation and for re-commissioning in the future.
- Temporary addition of a wireless sensor near an existing sensor can be used to check the performance of an existing sensor to determine whether it needs to be re-calibrated or replaced.
- Wireless sensors can be easily removed and updated upon failure or when a better sensor becomes available in the future.
- Additional kinds of sensors can be readily added to a wireless sensor network without the need to run wiring and conduit. For example, wireless CO_2 sensors might be added for retrofit of demand-controlled ventilation.

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 wireless technology. The earliest adoption of wireless technology is expected to occur in retrofit applications, where the technology extends existing wired control networks to places where there are no control-network cables. This includes, for instance, 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 communication. Control applications will likely initially be limited to open-loop control functions, such as turning equipment on or off. Some closed-loop control applications are compatible with current wireless communication; others requiring high update frequencies (e.g., less than a second) pose higher transmission robustness requirements and, therefore, are particularly incompatible with current battery-powered wireless sensing. This presents a challenge for future development. Primary drivers of cost reductions will be optimization of design and manufacturing of RF technology components and further integration of sensing, signal conditioning, and RF-communication modules so they can be mass manufactured at lower cost.

Technological challenges for closed-loop control applications with high update frequency requirements still remain for battery-powered 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 would replace radio broadcasting), it is unlikely that wireless technology will completely replace wired HVAC controls. 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 applications, which in turn will lead to better control and maintenance of systems that will improve the overall energy efficiency of the building stock and provide healthier and more productive workplaces.

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