Wireless Sensor Applications for Building Operation and Management

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Abstract

The emerging technology of wireless sensing shows promise for changing the way sensors are used in buildings. Lower cost, easier to install, sensing devices that require no connections by wires will potentially usher in an age in which ubiquitous sensors will provide the data required to cost-effectively operate, manage, and maintain commercial buildings at peak performance. This chapter provides an introduction to wireless sensing technology, its potential applications in buildings, three practical examples of tests in real buildings, estimates of impacts on energy consumption, discussions of costs and practical issues in implementation, and some ideas on applications likely in the near future.

Introduction

Wireless communication has been with us since the invention of the radio by Marconi around 1895. We have benefited from the broadcast of information for purposes of informing and entertaining. Radio technology has also enabled point-to-point communication, for example, for emergency response by police and fire protection, dispatch of various service providers, military communications, communication to remote parts of the world, and even communication into space.

We commonly think of communication between people by voice when thinking of radio frequency (RF) communication technology but need to look no further than a television set to realize that other forms of information, such as video, can also be transmitted. In fact, RF technology can be used to transfer data in a wide variety of forms between machines and people and even among machines without human intervention. This more generic wireless RF transfer of data and its application to operating and maintaining buildings is the focus of this chapter.

Wireless communication of data via WiFi (or IEEE 802.11 standards) is now routine in many homes, offices and even airports.[1,2] Rather than ripping walls open or fishing networking cable through them to install computer networks in existing homes and commercial buildings, many users opt to use wireless technology. These standards use license-free frequency bands and relatively low power to provide connections up to several hundred feet (although additional parts of IEEE 802.11 are currently under development for much longer ranges of up to 20 miles and higher data transfer rates). These standards are generally for relatively high bandwidth so that large files can be transported over reasonable time periods.

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In contrast to the data rates required for general computer networking and communication, most sensor data collection can get by with much slower rates with as little as a few bits every second, every minute, 10 minutes, or even less frequently. Sensing generally imposes (or loosens) other constraints as well. For example, if the value of a single sensor point is low, its total installed cost must be very low as well. Furthermore, if power for sensing and communication is not conveniently available where sensor measurements are needed, an on-board power source may be needed. In general, we'd like to put sensors in place and then forget about them, so they should have long lives and require little attention. If a sensor requires frequent maintenance, the cost for its use increases rapidly, so power sources, like batteries, with lives of 10 years or more would be ideal. These requirements for sensors and sensor networks are leading to the evolution of wireless sensor network technology and standards that provide specifically for convenient, widespread use of large numbers of sensors from which data are collected wirelessly.

The ideal wireless sensor would have very low installed cost, which would require that its hardware cost be very low and that it be installed quickly and easily using limited labor. One concept calls for wireless sensors that you "peel, stick and forget." The radio frequency identification (RFID) tag industry debatably has reached a cost as low as about $0.20 per tag and seeks to reach $0.05 per tag with a production of 30 billion tags per year for inventory tracking purposes. [3] Wireless sensors for active property measurements like those suitable for use in building operations still cost on average two to four orders of magnitude more than this.

To achieve easy and low-cost installation, wireless sensor networks, which provide the means for moving data from the collection points to where it can be used, will probably need to be **self-configuring**. This means that the sensors would assign themselves identifications, recognize their neighboring sensors, and establish communication paths to places where their data are used (e.g., on a personal workstation or a receiver connected to a building automation system). A self-configuring wireless sensor network would only require placing the sensors where the measurements need to be made and possibly providing a connection to a user interface or computer network.

To reduce the cost of maintenance, the sensors and sensor network would need to be **self-maintaining** and **self-healing**. For example, if a metal cabinet were moved into the communication path between two sensors, blocking communication between them, the network would automatically reroute the signal by another path with no human intervention. In addition, the sensors would need to maintain their own calibration reliably over their lifetimes (be **self-calibrating**), actively ensuring that they are within calibration periodically. These capabilities are critical to ensuring low cost and reliable sensor networks. If each sensor has to be maintained by technicians periodically during its life, the cost will be too high to justify its use in all but the most critical and high-value applications. To increase sensor use, lower life-cycle costs are essential.

Some wireless sensors may have access to hardwired power, but for many applications the sensor and its radio must be **self-powered**, using a battery that lasts for many years or harvesting power from the ambient environment. [4] In 2004, some manufacturers of wireless sensors claim battery lives as long as 7 years for some applications. Wireless sensors that use environmental vibrations as a source of power have also been developed for a limited set of applications, [5] but most ambient power harvesting schemes are still under development. Complementary developments are underway for a wide range of applications that reduce the power requirements of electronic circuits. Examples for sensor networks include: intelligent management of on-board power use by sensor radios to limit power requirements (and battery drainage), using sleep modes, transmitting only as frequently as absolutely required, and minimizing message size. Power requirements are also tied directly to the distance over which signals must be transmitted. By decreasing this distance and using multiple hops to span a long distance, power can be conserved. The mesh networking schemes described later in this chapter have the potential to significantly reduce the power requirements for wireless sensors.

These are some of the capabilities of the ideal wireless sensor. In the sections that follow, an introduction to wireless sensor technology is provided, potential applications for wireless sensors in buildings are described, potential benefits are discussed, a few real-world cases are presented, and the current state of wireless sensing and likely future developments are described. Three primary concerns are frequently raised in discussion of wireless sensing for building operation: cost, reliability, and security. This chapter addresses each of these, providing references for the reader interested in more detail. Some practical guidance for using wireless sensors in buildings today is also provided.

Why use wireless sensing in buildings?

The cost of wiring for sensors and controls varies widely from about 20% to as much as 80% of the cost of a sensor or control point. The precise costs depend on the specific circumstances, e.g., whether the installation is in new construction or is a retrofit in an existing building, the type of construction, and the length of the wiring run. For situations where wiring costs are high, eliminating the wires may produce significant cost reductions.

Too often today operators are not able to effectively monitor the condition of the vast array of equipment in a large commercial building. Field studies and retro-commissioning of commercial buildings show that dirty filters, clogged coils, inoperable dampers, and incorrectly-implemented controls are all too common. [6, 7] Pressures to reduce operation and maintenance costs only exacerbate this problem. The problem can be even worse in small commercial buildings, which frequently don't even have an operator on site. Keeping apprised of the condition of equipment and systems in these buildings is nearly impossible for an offsite operator. If an equipment problem does not directly affect the occupants of a building (and this is quite common when the systems compensate by running harder and using more energy), it will usually continue undetected and uncorrected until conditions deteriorate and the occupants complain. This is often long after the problem started wasting energy and costing the bill payers money. Annual or semi-annual service visits by maintenance technicians, often catch only the most obvious problems. Incorrectly-implemented controls can go undetected for years unless major retro-commissioning of the building is undertaken.

More sensors to monitor the condition of equipment and systems, as well as conditions in the building, are needed along with software tools that automatically sort through data as it arrives and alert building operations and maintenance staff (or service providers) to problems. Building owners, however, often cite the need to keep costs down as the reason for not installing these sensors. By doing this, they are trading lower initial costs for higher expenditures on energy and lost revenue from tenant churn caused by poor environmental conditions in the building. This might be addressed by education and more evidence of the net value of good operation and maintenance over the building ownership lifecycle, but lowering the cost of collecting data and obtaining useful results from it may be a more direct approach. This chapter focuses on the data collection issue by presenting information on wireless sensing; the need for tools that automatically process the data is a companion problem that is just as critical, but that is the subject of Chapter 18 in this book.

Better sensing in commercial buildings would lead to greater awareness of the condition of buildings and their systems. Operation and maintenance (O&M) staff would have the information to recognize degradation and faults in building equipment and systems and prioritize problems based on cost and other impacts. Today, most building staffs do not have this information. With it, the most costly and impactful problems could be identified, even those that are not usually recognized today.

The benefits of more data and tools that provide useful information from that data would be: lower energy and operating costs, longer-equipment lives, and better, more consistent conditions provided to building occupants. The value of these should all well exceed the cost of collecting and processing the information. With new, lower cost means such as wireless sensing for gathering data, first costs should also decrease making the financial decision to make this investment easier for building owners.

There are also some advantages directly attributable to the unique characteristics of wireless sensing beyond lower cost. Wireless sensors having their own power sources are mobile. Such a sensor can be readily moved from one location to another to investigate a problem. If a particular office, for example, were chronically reported as too hot, a wireless air-temperature sensor might be moved to that office or an additional one added to the wireless sensor network for that office to verify that the temperature was indeed unacceptably hot, then used to verify whether the corrective actions were successful. New sensors could be added to equipment for similar purposes without installing additional wiring. For example, if a pump motor were thought to be intermittently running hot, a wireless sensor might be installed on it to monitor its temperature and verify the need for repairs. If not wired, these sensors could be placed temporarily and then used at different locations as needed; no wiring costs would be necessary. One of the benefits of a wireless sensor network is that once it is in place in the building, sensors can be added or moved easily without installing new cables. As a result, wireless sensors have unique value for diagnostics.

Wireless Sensor Networks

Primary components

Each wireless radio frequency (RF) sensor requires three critical components to sense a condition and communicate it to a point at which it can be used (whether by a human or directly by another machine): 1) a **sensor** that responds to a condition and converts it to a signal (usually electrical) that can be related to the value of the condition sensed, 2) a **radio transmitter** that transmits the signal, and 3) a **radio receiver** that receives the RF signal and converts it to a form (e.g., protocol) that can be recognized by another communication system, another device, or computer hardware/software. This is the simplest communication configuration for wireless sensing (see Figure 1).

At the sensor the device usually consists of signal processes circuitry as well as the sensor probe itself. This circuitry may transform the signal with filtering, analog to digital conversion, or amplification. The transmitter, in addition to modulating and sending a signal, may encode it using a protocol shared with the receiver. At the receiver, electronic circuits will perform similar operations, such as filtering, amplification, digital to analog conversion, embedding in another communication protocol (e.g. Ethernet or RS-232 serial), and transmission as output.

Many wireless networks replace the transmitter and receiver with radio transceivers (which have combined transmitting and receiving abilities). This permits 2-way communication so that the radio at the receiving point can send requests for data transmissions (poll the sensor transmitter) and send messages acknowledging receipt of both data and messages transmitted from the sensor's radio. The sensor's transceiver can receive requests and acknowledgements from the transceiver at the receiving point, as well as send the sensor data. In addition to these functions, both radios formulate packets of data that precede and follow the main data or messages sent that are specified as part of the protocol the radios use for communication purposes.

All of these components require electric power to operate and, therefore, a power supply, which is usually either wired power or a battery. The power supply then converts the source power to the form (e.g., direct current, DC) and voltage required by the device. Battery operated devices generally have sophisticated power management schemes implemented to conserve the battery's energy by powering the electronics down between transmissions. Another source of power for distributed devices under development is power-scavenging technology, which can extend battery lifetime or even fully substitute for a battery. Power-scavenging devices convert ambient energy forms such as vibrations, light, kinetic energy inflows, and temperature differentials into electric energy.

Networks of sensor nodes (the combination of a radio, other electronic circuitry, and the sensor) can be formed from the basic principle illustrated in Figure 1, but many sensor nodes transmit data to points of reception. Wireless sensor networks can have tens, hundreds, even thousands of nodes in the network, providing measurements from different kinds of sensors that might be located at many different positions. For example, a wireless network might measure many temperatures, humidities, and pressures throughout many HVAC systems, the electric power use of all major equipment, as well as the temperature and occupancy of rooms throughout a building, all reported to one receiver that sends the data to a computer for processing or display.

Network Topology

Wireless sensor networks have different requirements than computer networks and, thus, different network topologies and communication protocols have evolved for them. The simplest is the **point-to-point topology** (see Figure 2) in which two nodes communicate directly with each other. The **point-to-multipoint** or **star topology** is an extension of the point-to-point configuration in which many nodes communicate with a central receiving or gateway node. In the star and point-to-point network topologies, sensor nodes might have pure transmitters, which provide one-way communication only, or transceivers, which enable two-way communication and verification of the receipt of messages. Gateways provide a means to convert and pass data between one protocol and another (e.g., from a wireless sensor network protocol to the wired Ethernet protocol).

The communication range of the point-to-point and star topologies is limited by the maximum communication range between the sensor node at which the measured data originate and the receiver (or gateway) node. This range can be extended by using repeaters, which receive transmissions from sensor nodes and then re-transmit them, usually at higher power than the original transmissions from the sensor nodes. By employing repeaters, several “stars” can communicate data to one central gateway node, thus expanding the coverage of star networks.

In the **mesh network topology** each sensor node includes a transceiver that can communicate directly with any other node within its communication range. These networks connect many devices to many other devices, thus, forming a mesh of nodes in which signals are transmitted between distant points via multiple hops. This approach decreases the distance over which each node must communicate and reduces the power use of each node substantially, making them more compatible with on-board power sources such as batteries. In addition to these basic topologies, hybrid network structures can be formed using a combination of the basic topologies. For example, a mesh network of star networks or star network of mesh networks could be used (see Figure 3).

Point-to-Point: In a point-to-point network configuration each single device (or sensor node) connects wirelessly to a receiver or gateway. An example would be a remote control for a TV, a garage door opener, or a wireless PLC (programmable logic controller) to turn on/off a remote pump or light. The communication can be kept simple with identification schemes that are either set up in the hardware with dip switches or by software during the initial configuration. Point-to-point wireless architectures apply a simple master/slave communication protocol whereby the master station issues a command for a single dedicated slave.

Star Networks: The star network is an extension to the point-to-point configuration. One central node broadcasts to many end nodes in the network (i.e. point to multipoint).

Alternatively, the communication can originate from the end nodes, communicating to one single central point (i.e. multipoint to point). The latter is a typical architecture for currently available in-home and building security products. Remote sensors on doors and windows, when triggered, communicate to one central station, which then issues an alarm and performs other pre-programmed procedures such as dialing the police or fire department. A star topology can be used in building operation for monitoring zone-air temperatures with wireless sensors as described in References 8, 9 and 10.

The star network is a simple network topology to support many sensors. Before standard integrated-circuit (IC) manufacturing technologies were capable of making high performance RF chipsets, the only cost-effective wireless network was the star network because the sensor nodes often had only transmitters and not transceivers.

This topology provides only one communication path for each sensor node, so there is no redundancy in the network. As a result, each link in the network infrastructure is a single point of failure. Ensuring a reliable communication path for each sensor is critical, and a thorough RF site survey must be performed to determine the need and locations for repeaters to carry each sensor signal reliably to the receiver. Sufficient resilience should be built into the design of star networks so that reliable communications of all sensors can be maintained even if the interior layout of the building changes. Simply repositioning a bookcase into the path of a weak signal could add enough signal attenuation to stop communication between a sensor and the receiver.

Mesh Networks: With the significantly reduced cost of microprocessors and memory over the last decade, additional computational power at the device level can now be used to operate a more complex network that simplifies both the installation and commissioning of a sensor network while maximizing reliability. Mesh networks – where each device in the network acts both as a repeater and a sensor node – can achieve the long communication range of a star network with repeaters while also providing increased total network reliability through redundant communication paths. The nodes in a mesh network automatically determine which nearby neighbors can communicate effectively and route data through the network accordingly, changing the routing dynamically as conditions change. Having multiple links in a network provides built-in redundancy so data can be effectively routed around blocked links. This means that there are few single points of failure in the system, so the overall network is extremely reliable even if individual wireless links are not. Mesh networks also pass data from one node to another in the network, making the placement of additional sensors or controllers in the network akin to building out additional infrastructure. As additional devices are placed in a mesh network, the number of communication paths increases, thereby improving network reliability.

The most-used nodes in any sensor network use the most energy. So if the routing is static, even in a mesh network (when the “best” communication routes don’t change with time), the energy demands will vary among nodes with those used most expending the most energy. For battery-powered nodes, this demand can rapidly drain the battery. Network protocols are being developed that are “energy aware.” To help maximize network performance time, these protocols even account for energy use along each potential communication path and check the remaining charge of batteries along the paths in selecting the preferred route. [11, 12] This approach, however, works best where node density is high throughout the area covered by a network. In situations where node density is not high (as during initial adoption of wireless monitoring in buildings or other cases where sensor node deployment may be sparse), a single critical node or a small number of nodes that provide the path for all communication will be subject to excess power use and lower battery life (see Figure 4).

A disadvantage of mesh networking could be the use of the wireless data channels for network management and maintenance, which not only takes up part of the available radio bandwidth, but also uses power and drains batteries. For low-data-rate applications in facility monitoring and control as well as many other sensing applications, this limitation is likely manageable. The protocols under development for wireless sensor networks seek a balance between these factors. [11, 12, 13] Sophisticated network routing schemes, however, impose an overhead on hardware and firmware potentially adding a premium to the overall cost, but advances in electronics manufacturing should minimize the impact of this factor. Mesh sensor networking technology is in a nascent stage with early products just beginning to enter the building automation and monitoring market.

Frequency bands

To minimize interference and provide adequately for the many uses of radio frequency communication, frequency bands are allocated internationally and by most countries. The International Telecommunication Union (ITU) is the organization within which governments coordinate global telecommunication networks and services. The United States is a member of the ITU through the Federal Communications Commission (FCC). The ITU maintains a Table of Frequency Allocation that specifies regionally and by country the allocations of radio spectrum. [14] The ISM (industrial, scientific, medical) bands provide frequencies for license-free radio communications given a set of power output constraints. The ISM frequencies and common applications are shown in Table 1.

Consumer products ranging from cordless telephones to wireless local area networks use the 2.4 GHz band. The trend for selecting higher frequencies is primarily driven by the need for higher data rates. As can be seen in Table 1, the bandwidth is greater at higher frequencies. Bandwidth is defined as the width of a particular frequency band. For instance, the 900 MHz band has a bandwidth of 26 MHz (928 MHz – 902 MHz, see Table 1). Data rates and bandwidth of a frequency band are related. According to Nyquist, the maximum data rate in bits per second (bps) that can be achieved in a noiseless transmission system of bandwidth B is $2B$. [15]Using the Nyquist theorem for the example of a bandwidth of 26 MHz, we would obtain a theoretical data rate limit of 52 Mbs. In practical applications where we encounter signal noise, the signal-to-noise ratio limits the actually achievable data rate to a value less than that determined by the Nyquist theorem. [16]

For wireless local area networks (LANs) higher bandwidth provides higher data rates, a generally desirable feature. Wireless sensor networks, on the contrary, are generally low-data-rate applications sending, for instance, a temperature measurement every 5 minutes. Hence, higher frequencies provide no bandwidth benefit for sensor network applications. In fact, higher frequency signals attenuate more rapidly in passing through media, thus shortening the range of the RF transmission as signals penetrate materials, e.g., in walls and furnishings. [17] To maximize transmission range, a low transmission frequency technology should be selected (see the discussion on signal attenuation in the section Designing and Installing a Wireless System Today: Practical Considerations).

Communication Protocols

There are a large number of wireless technologies on the market today, and "wireless networks" as a technology span applications from cellular phone networks to wireless temperature sensors. In building automation applications where line power is not available, power consumption is of critical importance. For example, battery-powered "peel-and-stick" temperature sensors will only be practical if they and their network use power at a very low rate. In general, a 3- to 5-year battery lifetime is believed to be a reasonable minimum. Although power is generally available in commercial buildings, it is often not conveniently available at the precise location at which a sensor is needed. Thus, for many wireless sensors, some kind of onboard power, such as a battery is necessary to keep the installed cost low. To maximize battery life, communication protocols for wireless sensor networks must minimize energy use.

Beyond power requirements, communication range is important. A radio that has a maximum line-of-sight range of 500 feet outdoors may be limited to 100 feet or even less indoors, the range depending on a number of factors including the radio's frequency, the materials used in construction of the building, and the layout of walls and spaces. Communication protocols for sensor networks installed indoors, therefore, must provide adequate communication ranges in less than ideal indoor environments.

Table 2 provides a summary of power consumption, data rate, and communication range for several wireless communication standards. The IEEE 802.11b and g standards (also referred to as "WiFi" for Wireless Fidelity), which were developed for mobile computing applications, are at the high end of data rate and have moderately high power consumption and moderate range. While these standards have proven very popular for wireless home and office networking and mobile web browsing, they are not suitable for most building sensor applications because of their high power consumption. Furthermore, in the long run, 802.11b and g are likely to see quite limited use for sensor networking because of their limits on the number of devices in a network and the cost and complexity of their radio chipsets, compared to simpler, ultimately lower cost, wireless sensor networking standards.

Bluetooth, another wireless communications standard, was developed for personal area networks (PANs) and has proven popular for wireless headsets, printers, and other computer peripherals. [18] The data rate and power consumption of Bluetooth radios are both lower than for WiFi, which puts them closer to the needs of the building automation applications, but the battery life of a Bluetooth-enabled temperature sensor is still only in the range of weeks to months, not the 3 to 5-years minimum requirement for building applications, and the communication range is limited to about 30 feet (100 feet in an extended form of Bluetooth). The number of devices in a Bluetooth network is also severely limited, making the technology applicable for only the smallest in-building deployments.

The IEEE 802.15.4 standard [19, 20] for the hardware layers together with the Zigbee standard [21] for the software layers provides a new standards-based solution for wireless sensor networks. IEEE 802.15.4, which was approved in 2003, is designed specifically for low data-rate, low power consumption applications including building automation as well as devices ranging from toys, wireless keyboards and mouses to industrial monitoring and control [19, 20]. For battery-powered devices, this technology is built to specifically address applications where a “trickle” of data is coming back from sensors or being sent out to actuators. The standard defines star and meshed network topologies, as well as a “hybrid” known as a cluster-tree network. The communication range of 802.15.4 radio devices is 100 to 300 feet for typical buildings, which, when coupled with an effective network architecture, should provide excellent functionality for typical building automation applications.

The industry group ZigBee Alliance developed the ZigBee specification that is built upon the physical radio specification of the IEEE 802.15.4 Standard [21]. ZigBee adds logical network, security, application interfaces, and application layers on top the IEEE 802.15.4 standard. It was created to address the market need for a cost-effective, standards-based wireless networking solution that supports low data rates, low power consumption, security, and reliability. ZigBee uses both star and meshed network topologies, and provides a variety of data security features and interoperable application profiles.

Non-standardized radios operating with proprietary communication protocols make up the majority of today’s commercially available wireless sensors. They usually offer improved power consumption with optimized features for building automation applications. These radios operate in the unlicensed ISM frequency bands and offer a range of advanced features which depend on their target applications.

Technical Issues in Buildings

The primary issues of applying wireless sensor technologies in buildings are associated with 1) interference caused by signals from other radio transmitters (such as wireless LANs) and microwave ovens that leak electromagnetic energy, 2) attenuation as the RF signal travels from the transmitter through walls, furnishings, and even air to reach the receiver, and 3) security.

Interference generally stems from electromagnetic noise originating from other wireless devices or random thermal noise that may impact or overshadow a sensor signal. Spread spectrum techniques are used to increase immunity to interference from a single-frequency source by spreading the signal over a defined spectrum. Spread spectrum techniques utilize the available bandwidth such that many transmitters can operate in a common frequency band without interfering with one another. Spread spectrum, however, is not guaranteed to be completely immune to interference, particularly if the frequency band is heavily loaded, say with hundreds of wireless devices sending messages. Early technology demonstration projects with 30 to 100 wireless sensors in buildings have not revealed any problems with crosstalk or loss of data in the transmission; however, it remains unclear whether reliable communications can be maintained as the frequency band becomes crowded with hundreds or thousands of wireless devices. Experiences with the technology over time will reveal how wireless technology will perform under these conditions.

Signal attenuation is a weakening of the RF signal. It is a function of distance and the properties of the material through which the signal travels. Signal attenuation can be compensated by using repeaters that receive signals, amplify them, and then retransmit them to increase the transmission range.

With steadily increasing threats from hackers to the networking infrastructure, the **security** needs of modern facility automation systems have grown. The vulnerability of wireless networks is of particular concern because no direct "hard" physical link is required to connect. Data encryption techniques have been successfully applied to wireless LAN systems to combat intrusion and provide security. These techniques encode data in a format that is not readable except by someone with the "key" to decode the data. Encryption, however, requires additional computational power on each wireless device, which runs counter to the general attempt to simplify technology in order to reduce cost. These challenges are currently being addressed by researchers, technology vendors and standards committees to provide technology solutions with the necessary technical performance that the market demands.

Costs

Costs of commercially available sensor network components in 2004 are shown in Table 3. Excluded from the table are single point-to-single point systems based on RF modems. The table shows that costs vary widely, and as with many technologies, costs are expected to decrease with time.

According to a recent market assessment of the wireless sensor networks, the cost of the radio frequency (RF) modules for sensors is projected to drop below $12 per unit in 2005 and to $4 per unit by 2010. [22] While these costs reflect only one portion of a wireless sensor device, the cost of the sensor element itself is also expected to decrease with technology advancements. For instance, digital integrated humidity and temperature sensors at high volumes are currently commercially available for less then $3 per sensor probe[2]. The general trend toward greater use of solid state technology in sensors is likely to lead to lower cost sensors for mass markets.

To date, end users are caught between the enthusiastic reports of the benefits that wireless sensing and control can provide and skepticism regarding whether the technology will operate reliably compared to the wired solution. While advancements in wireless local area networks (LAN) have paved the road for wireless technology market adoption, it

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

also has made end users aware of the inherent reliability challenges of wireless transmission in buildings and facilities.

Types of Wireless Sensing Applications for Buildings

Applications of wireless sensing in buildings can be placed into two broad categories that significantly affect requirements on the underlying wireless technology and its performance: 1) applications for which at least some (and often most) of the devices must be self-powered (e.g., with an on-board battery) and 2) applications for which line power is available for each device. In this section, we describe experiences in field testing both types of applications. The first (Building Condition Monitoring) is illustrated with wireless sensors used to measure the air temperature in buildings at a much higher resolution than possible with the wired thermostats usually installed. In the second (Equipment Condition Monitoring), data for continually monitoring the performance of rooftop packaged HVAC units is collected using a wireless sensor data acquisition system.

Building Condition Monitoring

As discussed above, eliminating the need for wiring makes wireless sensor technology particularly appealing and well suited for monitoring space and equipment conditions in buildings of all sizes. Without the wires though, some additional care must be exercised in engineering and installing the wireless network to ensure sufficient robustness of communication.

Starting in 2002, Pacific Northwest National Laboratory (PNNL) conducted some of the first demonstrations to assess the performance of commercially available wireless sensor technology in real buildings and to compare the cost of the wireless solution with that of a conventional wired system. The first demonstration building was an office building with 70,000 square feet of open office floor space on three floors and a mechanical room in the basement. The building is a heavy steel-concrete structure constructed in the early 1960s. The second demonstration building represents a more modern and structurally lighter building style with individual offices totaling 200,000 square feet of floor space in a laboratory building completed in 1997.

Demonstration 1: In-Building Central Plant Retrofit Application

The building is located in Richland, Washington. The HVAC system consists of a central chiller, boiler, and air distribution system with 100 variable-air-volume (VAV) boxes with reheat distributed in the ceiling throughout the building. A central energy management and control system (EMCS) controls the central plant and the lighting system. Zone temperature control is provided by means of stand-alone and non-programmable thermostats controlling individual VAV boxes. The centralized control system receives no zone temperature information and cannot control 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, a wireless temperature sensor network with 30 temperature sensors was installed to provide zone air temperature information to the EMCS. The wireless sensor network consists of a series of Inovonics wireless products including an integration module that interfaces the sensor network to a Johnson Controls N2 network bus[3]. 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 Wireless Temperature Sensor Network: The wireless network consists of a commercially available wireless temperature sensor system from Inovonics Wireless Corporation. It encompasses 30 temperature transmitters, 3 repeaters, 1 receiver, and an integration module to interface the sensor network to a Johnson Controls EMCS N2 network. The layout of the wireless temperature network is shown in Figure 5.

The operating frequency of the wireless network is 902 to 928 MHz, which requires no license per FCC Part 15 Certification [23]. 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, which can be specified in the transmitter. The manufacturer estimates a battery life of up to 5 years with a 10-minute time between transmissions. The transmitter has an automatic 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 repeaters are powered from ordinary 120 volts alternating current (VAC) wall outlets and have a battery backup. Three repeaters were installed, one on each floor. Because the repeaters are 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 in the basement. The translator connects the receiver with the Johnson EMCS system.

Design and Installation Considerations: Installation of the wireless network requires a radio frequency (RF) survey to determine the proper locations for the repeaters to ensure that the received signal strength is sufficient for robust operation of the wireless network. RF surveying is an essential engineering task in the design of the wireless network topology. 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 cordless phones 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 square foot test building, an engineer performed the RF survey in about 4 hours while instructing others in survey procedures. This provided sufficient time for investigating several scenarios, whereby metal bookshelves were placed in the direct

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[3] N2 bus is the Johnson Controls network protocol.

pathway between transmitters and a receiver. The result of the RF survey was a recommendation for three repeaters, one for each floor of the building (see Figure 5). An experienced surveyor should be able to perform this survey in about 2 hours, if not running special tests or instructing others.

The cost for the wireless system, including installation, was approximately $4000. See Table 4 for more details on the cost.

Operational benefits: Operational improvements resulted from use of the wireless temperature sensor network. The wireless sensors enabled facility staff to respond to ‘hot’ and ‘cold’ complaints much more effectively. Because sensors can be easily moved and new ones readily introduced into the network, a spare sensor can be easily taped directly into a localized problem area for monitoring air temperature over a few hours or days. The much higher spatial resolution provided by the 30 zone air-temperature sensors enabled facility staff to identify individual VAV boxes that were causing uneven supply air. These malfunctioning boxes spread the range of air temperatures through the building. After repairing the faulty VAV boxes, the facility staff was able to raise the supply-air temperature by 2°F, alleviating the need for overcooling some zones in order to deliver enough cooling capacity through the faulty VAV boxes. Repair of VAV boxes improved the thermal comfort of occupants and eliminated the occasional use of space heaters during the early morning hours in both summer and winter months.

Energy efficiency benefits: The energy savings resulted directly from repairing several VAV box controllers, resetting the supply air temperature by 2°F during cooling periods, and reducing the use of small space heaters by occupants who were previously uncomfortably cool at times. In addition, a chilled-water reset strategy was implemented based on an average value of the 30 zone air temperatures. This allowed the chilled water set point to be reset between 45 and 55°F, the value depending upon the zone air temperature. Formerly, the chilled water temperature was fixed at 45°F. The average zone air temperature was used as an indicator for meeting the cooling loads. As a result the average coefficient of performance (COP) increased by about 7% due to the higher chilled water temperatures. The fan power for any given cooling load increased some but not nearly enough to offset the savings. The net result was an estimated cost savings of about $3500 over the cooling season (May through September). Additional energy savings were achieved by avoiding the use of space heaters and resetting the supply air temperature for a total estimated annual cost savings of about $6000. Based on the costs and estimated savings, the simple payback period for this wireless system was about 7 months.

Demonstration 2: Laboratory/Office Building

The second building, opened for occupancy in 1997, houses laboratories and offices. The gross floor space is about 200,000 square feet with three protruding office wings of about 49,000 square feet each. Only the office area was used for the demonstration. Each office wing has a separate air-handling unit and a variable-air-volume (VAV) ventilation system. Each VAV box supplies air to two offices controlled by a thermostat located in one of the two offices. The construction of the office area consists of metal studs with gypsum wall. The offices contain metal book shelves, and at a minimum, two computers with large screen monitors. The office space is relatively metal-rich, posing a challenge for wireless transmission from the sensors to the receivers.

Facility staff explored night setback options for the ventilation of the office space that would turn off the air-handling unit during the night hours after 6 p.m. The decision to implement such a strategy was suspended out of concern that those offices without a thermostat might be occupied during late hours and if so, that the air temperature in those offices could exceed the thermal comfort limits. Because of this concern, the ventilation system operated on a 7-day per week, 24-hour per day schedule. It was believed that if each office were equipped with one zone temperature sensor, the night setback could be implemented and then overridden if the zone temperature exceeded an upper threshold of 78^{o}F. A cursory cost estimate from a controls vendor for installing wired temperature sensors in the offices without thermostats yielded an installed cost per sensor of about $500, which exceeded acceptable costs.

After the initial positive experiences with wireless sensors in the other building, facility staff re-examined the viability of the ventilation night setback using a wireless solution and implemented wireless temperature sensors in early 2004. The same wireless temperature sensor network technology as deployed in Building 1 was used. Familiarity with the technology and experience gained from the first wireless demonstration greatly reduced the level of effort for a RF survey of the building and the wireless network setup.

The wireless temperature sensor network: Each office not previously equipped received a wireless temperature sensor. Forty wireless temperature sensors were deployed in each of the three office wings of Building 2, bringing the total to 120 sensors (see Figure 6). The temperature signals were read by three receivers, each located where the office wing meets the main hallway and connected via an integrator to the Johnson Controls network control module. The wireless network consisted of a total of 120 sensors, three receivers and three integrators. Facility staff tested the need for repeaters and found that with the use of one receiver for each wing, the communication was sufficiently robust. An alternative wireless network design was considered that would use one receiver in the middle wing and repeaters in each of the side wings to assure communication from the most distant transmitters in the exterior wings to the receiver. The integrator has a limit of 100 transmitters. Since this alternative used only one integrator, it could not support enough sensors for all the offices, and it therefore was rejected.

The temperature sensors are programmed to transmit a temperature measurement every 10 minutes. A sensor will transmit early when a temperature change is sensed that exceeds a pre-set limit. This is to enable detection of rapid temperature changes as quickly as possible.

Installation and setup of wireless network: The installation costs for the wireless sensor network were minimal. They included a 2-hour RF survey, an initial setup of the integrator device to specify the number and ID numbers of the sensors, and the physical connection of the integrator and the Johnson Controls network control module. Configuration of the integrators was done in stages (each wing at a time) and the total time for setup of all 120 sensors was conservatively estimated afterward to be 8 hours. The integrator installation involves physically connecting the 24 VAC power supply provided in the Johnson Control network module and connecting the Johnson Controls N2 bus to the integrator using a 3-wire shielded cable. A short 4-wire cable connects the integrator and the receiver providing power supply and communication between the two devices. This work was performed by an instrument technician. The sensors were then attached to the office walls using double-sided tape.

Table 4 presents the cost components for the two demonstration buildings. The capital costs for the hardware represent the costs to PNNL and are representative of costs for a wholesaler. List prices would commonly be 75% to 100% higher than those shown.

Energy savings: The supervisory control program was augmented to schedule night setback starting at 6 p.m. and suspending it if an office zone temperature exceeded a threshold temperature of 78°F during the cooling season or dropped below 55°F during the heating season, instead of maintaining the temperature continuously at a set point of 72°F. Initial estimates concluded that energy savings are largely attributable to the shut down of the supply and return fans and, to a lesser degree, to reduced thermal loss during the night as the temperature is allowed to float (rise in the cooling season and drop in the heating season). Trend-logs of run time using the new night setback strategy were used to estimate the electric energy savings. Preliminary estimates suggest that the night setback will achieve savings of approximately $5,000 annually. Verification of the savings is planned after one full year of night setback operation is completed. We attribute the cost savings to the wireless sensors because they enabled implementation of the ventilation night setback, something the facility operations staff was unwilling to do without the additional information provided by these sensors. Based on these energy savings, the wireless sensor system (which had an installed cost $9390) has a simple payback period of less than 2 years (22.5 months).

Other impacts: Building operators also implemented a temperature averaging scheme for controlling the distribution system VAV boxes based on the average of the office temperatures in the zone served by each box. Although no energy savings resulted from this change, the building operators report that the number of occupant complaints about temperature has decreased significantly, saving building staff time and enabling them to devote that time to other improvements in operation.

Discussion on Costs for Demonstration Projects

Cost for the sensor and controls technology is a critical factor for the viability of any retrofit project or even in new construction. The wireless sensor solution was slightly more cost effective compared to an equivalent wired solution for Building 1. [9] For Building 2, the wireless sensor cost ($78/sensor) was significantly less than the estimated cost for the wired sensor retrofit (~$500/sensor). These examples tend to show that wireless sensor networks can compete with wired sensing on the basis of cost for retrofit projects. In both demonstration buildings, the wireless network infrastructure is sufficient to accommodate many more sensors at the cost of sensors alone. No additional infrastructure (repeaters, receivers, or translators) is needed to accommodate additional sensors. This enables facility staff to add sensors at the cost of the sensor itself plus a minimal setup time (a few minutes) for configuring the integrator.

Figure 7 shows cost curves for both demonstration buildings as a function of number of sensors installed. These curves are nearly identical. For 30 sensors, for example, the difference in cost is $22/sensor ($160-$138), and for 120 sensors, the difference is $6/sensor ($78-$72). This suggests that the cost of the wireless system per sensor might be nearly independent of the building itself but highly dependent on the number of sensors installed. The curves are actually dependent on the costs of the wireless components. The two curves shown are for the same brand and models of hardware. Average costs per sensor for systems built from components with substantially different costs will lie on other curves. Unless signal attenuation differs so significantly among buildings that it affects the number of sensors that can be served by each repeater or receiver, the curves for different buildings using the same wireless components should lie very close to one another. This observation proves useful in simplifying estimation of costs for wireless sensor systems.

The second insight from Figure 7 is that at high quantities of the sensors, the system cost on a per-sensor basis asymptotically approaches the cost of a sensor (in this case, $50/sensor). Therefore, for densely deployed sensors (high numbers of sensors per unit of building area), further cost reductions for wireless sensor networks must come from reducing the cost of the sensor modules (sensors plus transmitting radio) rather than decreasing the cost of infrastructure components--the receiver, repeaters and translators. In the short-term, however, while wireless sensing technology is just beginning to be deployed, sensor densities are likely to be relatively low, and as a result, all components will have a significant impact on cost. Users should realize, though, that once a wireless sensor network is installed in a building, additional sensors generally can be added to the network in the area covered by the network at the incremental cost of the additional sensors. The more uses the building staff can find for the wireless sensor network, the more cost-effective its installation becomes.

Wireless Monitoring of Equipment Conditions

Heating, ventilating, and air-conditioning equipment is often run until it completely fails (“hard” faults), for example from a failed compressor, failed condenser fan, failed supply fan, or significant loss of refrigerant. Upon complete failure, the owner, operator, or building occupant calls a service company to repair the unit. Complete failure, though, is often preventable. Avoiding failures by properly maintaining the equipment would reduce repair costs, increase operating efficiency, extend equipment life, and ensure comfortable conditions, but this would require awareness of equipment condition and when the equipment needs servicing. Furthermore, several studies have noted that building systems operate under degraded conditions caused by insufficient refrigerant charge, broken dampers, stuck dampers, mis-calibrated and failed sensors, improperly implemented controls (e.g., incorrect schedules), electrical problems, and clogged heat exchangers [6, 24 – 29]. Many of these faults do not result in occupant discomfort because the system compensates by working harder (and expending more energy), and therefore, these faults are not reported nor are they corrected. Some of the faults require a service technician to correct, but many can be fixed with minor adjustments to controls or schedules; these faults are referred to as "soft" faults in this Chapter.

With increasing pressure to reduce operation and maintenance (O&M) costs and with the reduced number of operations staff in today's facilities, regular visual inspection by staff is out of the question. For small buildings without on-site operators, this was never a possibility. Service contracts providing scheduled but infrequent inspection and servicing alone are not likely the solution to this problem. Without a lower cost solution, package units are likely to continue to be maintained poorly and operated inefficiently.

Automated continuous condition monitoring provides a potential solution, but its cost is generally perceived as too high. Even installation of adequate sensors alone is usually viewed as too costly. Studies have shown, however, that automated monitoring and diagnostics implemented with wireless sensing and data acquisition can provide a cost effective solution [6, 8, 30]. In this section, we describe a wireless system for monitoring the condition and performance of packaged air conditioners and heat pumps, which are widely used on small commercial buildings.

Wireless System for Automated Fault Detection and Diagnostics

Functionally, packaged rooftop units can be divided into two primary systems: 1) air side and 2) refrigerant side. The air-side system consists of the indoor fan, the air side of the indoor coil, and the ventilation damper system (including its use for air-side economizing), while the refrigerant-side components include the compressor, the refrigerant side of indoor and outdoor heat exchangers, the condenser fan, the expansion valve, and the reversing valve (for heat pumps).

The choice of the fault detection and diagnostic (FDD) approach depends on the type of faults to be identified and the sensor measurements available. Many researchers have developed FDD algorithms to detect and diagnose faults in air-conditioning equipment. In this chapter we do not discuss the details of the diagnostic approaches, which can be found in other references [e.g., 31, 32, 33, 34] but instead describe the measurements needed, the faults that can be detected, and the system for collecting and processing the data. This system, which can be applied to both the air side and the refrigerant side of a heat pump, is shown in Figure 8.

The minimum set of information required for monitoring the state of the air-side system with temperature-based economizer controls or no economizing includes: 1) outdoor-air dry-bulb temperature, 2) return-air dry-bulb temperature, 3) mixed-air dry-bulb temperature, 4) outdoor-air damper-position signal, 5) supply-fan status, and 6) heating/cooling mode. To identify whether the system is actually in heating or cooling mode, the status of the compressor (and the reversing valve for heat pumps) is required. If these measurements are available, economizer operations and ventilation requirements can be monitored and evaluated to verify their correct performance. If an enthalpy-based economizer control is used, then the outdoor-air relative humidity (or dew-point temperature) and return-air relative humidity (if differential enthalpy controls are used) are required in addition to the 6 measurements needed to monitor the performance of systems with temperature-based economizer controls. If supply-air temperature is also measured, additional faults relating to control of supply-air temperature can be detected and diagnosed. Details of the approach for detecting and diagnosing air-side faults are given in References 32 and 33.

The faults that can be detected on the air side can be grouped into four categories: 1) inadequate ventilation, 2) energy waste, 3) temperature sensor and other miscellaneous problems including control problems, and 4) missing or out-of-range inputs. For more details on the faults that can be detected on the air-side, see References 6 and 32.

The minimum set of measurements required to monitor refrigerant-side performance include: 1) outdoor-air dry-bulb temperature, 2) liquid-line temperature (refrigerant temperature as it leaves the condenser), 3) liquid line pressure (as it leaves the condenser), 4) suction line temperature (refrigerant temperature at the compressor inlet), and 5) suction line pressure (refrigerant pressure at the compressor inlet). In addition to the five measured quantities, several derived quantities are used in monitoring the refrigerant-side performance: 1) liquid sub-cooling, which is estimated as a difference between the condensing temperature (calculated from liquid pressure and refrigerant properties) and the measured liquid line temperature, 2) the superheat, which is the difference between the evaporating temperature (calculated from the suction pressure and refrigerant properties) and the measured suction temperature, and 3) condensing temperature over ambient, which is the difference between the condensing temperature and the outdoor-air dry-bulb temperature.

The refrigerant-side faults that can be detected with these five measurements (two pressures and three temperatures) include: 1) evaporator (indoor coil) heat transfer problems, 2) compressor valve leakage (compressor fault), 3) condenser (outdoor coil) heat transfer problems, 4) improper supply-fan speed, 5) expansion device fault, 6) improper charge (too little or too much refrigerant), and 7) non-condensable substances in the refrigerant, such as air in the system. Details of diagnostics for the refrigerant side can be found in References 29 and 34.

Additional measurements that improve diagnostic capability and also increase the number of faults that can be detected include: 1) supply-air dry-bulb temperature, 2) mixed-air dry-bulb temperature, 3) mixed-air relative humidity (or dew point), 4) surface temperature of the condenser, 5) surface temperature of the evaporator, and 6) compressor power consumption. These measurements enable refinement of the diagnostics provided by the minimum set of sensors. In addition, cooling/heating capacity and efficiency degradation can be computed and tracked with these additional measurements. Although having pressure measurements makes diagnosis of the faults more reliable, pressure sensors are expensive compared to temperature and humidity sensors. The pressure sensors can be replaced with surface temperature sensors at the evaporator and condenser [31], and the temperature measurements can then be used as indicators of saturation temperature in the evaporator and condenser. Although the use of temperatures to estimate superheat and subcooling may lead to some error, their use will reduce the system cost and should still provide adequate diagnostics.

A wireless system providing data collection and diagnostics for only the air side of package HVAC units had a total installed cost per sensor of approximately half that of a wired system providing the same capabilities ($78 per point compared to $147 - $193 per point for the wired system). [30] This wireless system uses one radio on each packaged unit, sending measurements from 4 thermocouples and a current switch used to measure the on/off status of the supply fan of the unit. Six units are monitored using one receiver unit, distributing its cost over the 30 sensors it serves. Power is tapped off the power supply for the packaged HVAC unit, so no batteries are used. Both the cost and benefits of a wireless condition monitoring system depend on several parameters, such as number of roof top units to be monitored, the size of the units, the size of building, the local climate, and potential savings from use of the monitoring and diagnostic tool. For a typical application on an 18,000 square foot 2-story building with six 7.5 ton units, the simple payback will be less than 3 years for most U.S. climates (assuming energy savings of 15% are achieved through better operation and maintenance) [30]. Paybacks will be shorter for larger units in more severe climates and longer for smaller units or units in milder climates.

Deploying Wireless Condition Monitoring

There are several ways to deploy wireless condition monitoring: 1) centralized data collection and processing at each building, 2) distributed or on-demand diagnostics and 3) centralized data collection and processing at a remote server – an application service provider model.

Method 1: The first approach is a conventional approach where all data from wireless monitors are collected by a wireless receiver that is directly connected to a computer. The data are continuously or periodically processed using automated software and results provided to the user through a simple and user-friendly graphical user interface. The authors have tested a prototype wireless monitoring and diagnostic system described in the previous section using this approach. Although the prototype system was capable of monitoring both the air- and refrigerant-side performance, only air-side diagnostics were tested. In this approach, data from packaged roof top units are automatically obtained at a user-specified sub-hourly frequency and averaged to create hourly values that are stored in a database. As new hourly values become available in the database, the diagnostic module automatically processes the data and produces diagnostic results that are also placed in the database. The user can then open the user interface at any time to see the latest diagnostic results, and can also browse historical results.

Method 2: Detailed diagnosis often requires historical data to isolate the primary cause of a fault or performance degradation; however, some faults can be detected with instantaneous or short-term measurements. The second deployment uses wireless data collected while servicing units along with simple rules-of-thumb to determine the condition of equipment. For example, data from rooftop packaged units might be accessed wirelessly by a technician visiting the site using a Personal Digital Assistant (PDA) with compatible wireless communication capabilities. This method can be effective in identifying incorrect refrigerant charge, blocked heat exchangers, and blocked refrigerant lines. The technician could get a report on each unit without even opening the units. Time at the site could then be devoted mostly to the units with faults or degraded performance. The authors have not yet demonstrated this approach, but a wired system with these sorts of diagnostic capabilities is available commercially. [35] The wired system requires physically connecting to previously installed sensors on each unit or connecting the instrument's sensors before use. Once the sensor system has been installed, the wireless approach is likely to save time and enable service technicians to identify units requiring the most attention immediately upon arriving at a site, improving the quality of service while decreasing cost.

Method 3: The third approach is similar to the first approach but all data are collected and sent to a central server possibly hosted by a third party – an application service provider (ASP). Ideally, the data are received at a central location at each building or site and then transferred to the central server. The transfer of data can be by phone line (wired or wireless) or through an existing wide area network (wired or wireless). The ASP provides access to software and data via subscriptions. For payment of a monthly subscription fee, users obtain access to software on the world wide web using nothing more than a web browser to access it. The software needs to be installed on only one computer, the web server, rather than on the individual work station of every user. To provide reliability, usually the software is installed by the ASP on several redundant servers to provide backup in case a computer fails. Many users are then able to access a small number of installed copies of the software. User files are also maintained on the ASP's servers and backed up in a similar manner. The wireless monitoring equipment can be purchased by the owner or can be leased from the ASP for a subscription fee. This type of approach is still in its infancy. The authors will soon be testing this delivery approach.

The three approaches may also be combined to provide information on equipment condition more flexibly. For example, once the wireless sensing and data acquisition infrastructure is installed on the equipment at a building, it can be connected for remote monitoring by building operations staff/management or at a service provider's office and also be accessed by service technicians when they visit the site. Availability of information on equipment condition and performance would provide the basis for a conditioned-based maintenance program that would help ensure that equipment gets serviced and repaired when needed rather than more frequently than needed or less frequently (which is all too common, especially for package equipment).

Long-Distance Data Transmission

So far, this chapter has focused on short-range wireless data acquisition at a building for monitoring indoor conditions and equipment conditions and performance. Although not widely used yet, wireless communications have also proven effective in transmitting data between individual building sites and central monitoring systems. Deployment of this model by an ASP was discussed briefly in the preceding section. Central monitoring using wireless communication of data, however, can be implemented by any organization having geographically distributed facilities and the willingness to maintain the computer infrastructure necessary to implement and maintain such as system. This requires appropriate security and backup to ensure the system meets the necessary performance and reliability demands.

An example system is shown in Figure 9. Data collected from electric meters and sensors on equipment are transmitted by a wireless pager network to the operations center of a wireless carrier. Data are then sent through the Internet to the operations center of the ASP providing the service. There, the data are stored securely in databases and processed by the tools provided by the ASP. Customers can then securely access the processed results from their buildings from any computer with a web browser. The monitoring equipment for collecting and transmitting the data is provided by the ASP.

Designing and Installing a Wireless System Today: Practical Considerations

Laying out a wireless network indoors is probably as much art as it is science. Every building is unique, if not in its construction and floor plan, at least in the type and layout of its furnishings. Predicting wireless signal strength throughout a building would require characterizing the structure, its layout, and the furnishings and equipment in it and using that information to model RF signal propagation. No tools are available today for accurately doing this. Furthermore, when space use changes or furnishings are moved or change over time, radio signals encounter new obstacles in new positions. Despite these difficulties, there are several practical considerations for the design of a wireless network that are helpful for generating bills of materials and budget estimates and laying out wireless sensing networks.

Determining the Receiver Location

The decision with perhaps the most impact on the design of a wireless sensor network for in-building monitoring is determining the number and locations of the receivers. A stand-alone wireless network (not connected to a wired control network) may have some flexibility in choosing the location of the receiver. The best location from a communications perspective is one that is open and provides the best line-of-sight pathways between the most wireless sensors and the receiver. Convenient connection to a computer where data will be processed and viewed is another important consideration. These factors must be balanced. If the design requires integration of the wireless sensor network with an existing building automation system (BAS) infrastructure, then receivers must be located near points of connection to the BAS. Locations are constrained somewhat in this case, but there are typically still many options. Frequently, a convenient integration point is a control panel that provides easy access to the communication cables as well as electricity to power the receiver and integration devices. In commercial buildings, the BAS network wires are often laid in cabling conduits (open or closed) above the ceiling panel and are relatively easily accessible. Often the lack of electric power in the ceiling space, however, renders this location less convenient than a control panel.

Signal Attenuation and Range of Transmitters

Estimating the range of the transmitting devices is important from a cost point of view. If the transmission range from a transmitting device to the ultimate end-node cannot be accomplished with a single transmission path, additional hardware is required for signal amplification adding to the total cost of the installation. The discussion below is designed to provide a general overview of this topic that may lead to generating some rough estimates of how many repeater or amplification devices an installation may need. It does not replace a thorough RF survey of a facility to determine the exact number and locations of receivers, repeaters, or intermediate nodes necessary to assure robust communication.

The range of a transmitter depends on the three key variables: 1) attenuation because of distance between wireless devices, 2) attenuation caused by the signals traveling through construction material along the signal pathways, and 3) overall electromagnetic noise levels in the facility.

The attenuation of the signal strength due to distance between the transmitter and receiver (free path loss) is governed by the relation of the electromagnetic energy per unit area of the transmitter to the distance of the receiving surface (see Figure 10). The energy per unit area at a distance d from the transmitter decreases proportionately to $1/d^2$. Therefore, for every doubling of the distance d, the energy density or signal strength received decreases to one-fourth of its previous strength. This relationship accounts only for the dispersion of the signal across a larger area with distance from the source. In practice, other factors affect the strength of the signal received, even for an unobstructed path, including absorption by moisture in the air, absorption by the ground, partial signal cancellation by waves reflected by the ground, and other reflections. In general, this causes the signal strength at a distance d from the transmitter to decrease in practice in proportion to $1/d^m$, where $2 < m < 4$. [11]

The following example illustrates signal attenuation with distance from the transmitter in free air for a 900 MHz transmitter. This example shows how simple relations can be used to obtain an estimate of potential transmission range.

For this example, assume that the signal strength of a small transmitter has been measured to be 100 mW/cm^2 at a distance of 5 cm from the transmitter's antenna. The transmission path efficiency or transmission loss is customarily expressed in decibels, a logarithmic measure of a power ratio. It is defined as

$$\mathrm{dB} = 10 \log_{10} (p_1/p_0),$$

where p_1 is the power density in W/cm^2 and p_0 is a reference power density (i.e., the power density at a reference point) in W/cm^2.

We choose the power density measured at 5 cm distance from the transmitter's antenna as the reference power density p_0. Table 5 shows the attenuation of the emitted signal as a function of distance from the transmitter for a signal traveling through air only. For every doubling of the distance, the signal strength decreases by 6 dB or, stated alternatively, the attenuation increases by 6 dB.

Further, assume that the ambient noise is measured to be -75 dB. For a signal to be detectable above the surrounding noise level, the strength of the signal should be at least 10 dB above the noise level (i.e., signal margin of 10 dB or greater is recommended) [36]. Using the results of Table 5, we can determine the transmission range of the wireless system in our example that meets the 10 dB signal margin requirements to be 80 meters, since -75 dB +10 dB = -65 dB, which is less than -64 dB at 80 meters.

Next, we extend this example to consider attenuation inside buildings. Suppose that the receiver is placed in a mechanical room of a building and that the signal from the furthest transmitter must go through two brick walls and two layers of drywall. Using signal attenuation estimates from Table 6, the combined attenuation of the brick and drywall is 14.6 dB [2 x 0.3 (for the ½” drywall) + 2 x 7 (for 10.5” brick wall) = 14.6], for practical purposes say 15 dB. Adding the material-related attenuation of 15 dB to the -65 dB signal strength requirement yields -50 dB as the new indoor signal strength requirement for the free air transmission segment. Using Table 5, we conclude that the transmission range is between 10 and 20 meters, only 1/8 to 1/4 of the range in open air. This example illustrates how significantly radio signals can be attenuated indoors compared to outdoors simply by the structure itself. Furniture further adds to attenuation and complicates prediction of the signal strength as a function of location in buildings. Therefore, to characterize indoor environments with respect to RF signal propagation, empirical surveying is recommended.

RF Surveying

The purpose of an RF facility survey is to determine the actual attenuation of RF signal strength throughout the facility. This information, together with knowledge of the locations at which sensors will be positioned, is used to lay out the wireless network. The layout will include the number of repeaters and receivers in the network and their locations. For instance, for a multi-story facility there may be good reasons for placing one receiver on each floor, provided the data are needed only on each floor (e.g., one user per floor for that floor) or there is another means to communicate the data between floors (such as a BAS connection on each floor). If the data are needed at a computer located on a specific floor (such as a control room in the basement), a repeater might be used on each floor to transmit signals to the location of a central receiver located close to where the data are needed. If communication between receivers on different floors is not sufficient, there may be opportunities to route signals inside an elevator shaft, stair case, or on the exterior of the building. The most cost-effective solution is in most cases determined by the difference in cost between repeaters and receivers and the cost of interfacing the receivers to pre-existing wired networks. The layout with the lowest total cost that provides sufficient (reliable) communication is generally optimal.

Most vendors of wireless sensor networks offer RF survey kits that are specific for the vendors’ technologies. These kits consist of a transmitter and a receiver. The transmitter is often a modified sensor transmitter that is programmed to transmit at frequent time intervals. The receiver generally is connected to (or part of) an indicator of signal strength, together making a wireless signal-strength meter. These meters may simply give an indication whether the signal strength is adequate or provide numerical values of signal strength and background noise levels from which the adequacy of signal strength can be determined.

Before the RF facility survey is performed, potential receiver and sensor locations need to be known. The survey is then performed by placing the transmitter in anticipated locations for the receivers, then moving the signal-strength meter to locations where sensors will be positioned and taking measurements. By taking measurements throughout the facility, the limits of transmission range where the signal can no longer be detected (or is not of sufficient strength) can be identified. Repeaters will then need to be located in the layout within the transmission range to extend the range further.

The RF surveying is generally done by the wireless technology vendor or installer. Depending on the diversity of noise level in the facility and the complexity of its interior layout, an RF survey can be performed for office buildings with a floor space of 100,000 square feet in 2 to 4 hours.

Although RF surveys are critical for successfully designing and installing a wireless network that uses a star topology, systems using a mesh network topology with sufficient sensor density will ultimately not require RF surveys for installation. With sufficient densities of sensors (i.e., relatively short distances between sensors and multiple neighboring sensors within the communication range of each node), these networks will be self-configuring with the multiple potential transmission paths ensuring reliable, consistent communications. In the near term, care should be exercised in assuming that mesh networks will perform reliably for every application, especially in cases where high sensor density is not anticipated. For low sensor density installations, communication over long distances may require a higher-power repeater to connect a local mesh network to the point where the data are needed or a daisy-chain of nodes to communicate. In these cases, the advantages of mesh networking are lost in the region where individual devices carry all data communicated and those devices become potential single points of failure for the entire mesh that they connect to the point of data use.

Other Practical Considerations

Several other factors should be considered in deciding to use wireless sensing in buildings. Peter Stein [38] provides a nice summary of practical considerations for monitoring with wireless sensor networks. In addition to communication range, some of the key considerations that need to be assessed when selecting a wireless sensing network are:

- component prices
- availability of support
- compatibility with different types of sensors with different outputs
- battery backup for line powered devices
- low-battery indicators for battery-powered devices
- on-board memory
- proper packaging and technical specifications for the environment where devices will be located

- battery life and factors that affect it
- frequency of data collection and its relationship to battery life (where applicable)
- need for and availability of integration boxes or gateways to connect wireless sensor networks to BASs, other local area networks, or the Internet
- availability of software for viewing or processing the data for the intended purpose
- compatibility among products from different vendors--this is rare today but will improve with manufacturer adoption of new standards [e.g. IEEE 802.15.4 [19, 20] with Zigbee [21]]
- tools for configuring, commissioning, repairing, and adding nodes to the sensor network
- software to monitor network performance

Most important is ensuring the selected wireless network meets the requirements of the intended application. All factors need to be considered and assessed with respect to satisfying the requirements of the application and the specific facility. Each installation is unique.

The Future of Wireless Sensing in Buildings

The steadily growing number of technology companies offering products and services for monitoring and control applications fuels the expectation that the sub-$10 wireless sensor is likely to be available in the near future [22]. When we reach that point of technological advancement, the cost of the battery may then be the single largest cost item of a wireless module. Even the battery may be replaceable by ambient power scavenging devices that obviate the need for a battery as a power source. A self-powered sensor device creates fundamentally new measurement applications, unthinkable with battery- or line-powered technology. For instance, sensors could be fully embedded in building materials, such as structural members or wall components. They can measure properties in the host material that currently cannot be accessed easily or continuously by external measurement probes. In the energy efficiency domain, new diagnostic methods could be envisioned that use embedded sensors for early fault detection and diagnostics to prevent equipment failure and degradation of energy efficiency. Researchers are exploring different ambient sources for the extraction of electric power. Mechanical vibration emanating from rotary energy conversion equipment, such as internal combustion engines, pumps, compressors, and fans can be converted into electric power by induction driving a magnetic element inside a coil. Alternatively, piezo-electric materials can generate an electric potential when mechanically strained. Present research and technology development focuses on maximizing the energy extraction of mechanical energy by adaptive techniques that sense and adjust to a given vibration frequency and amplitude to maximize power extraction. [39] Thermo-electrical power generators utilize the Seabeck Effect, commonly used in thermocouple probes for temperature measurements. A temperature differential of a few degrees Celsius can, in cleverly designed probes, generate power in the micro-Watt range. [40] The small power generation from ambient power devices can be used to recharge a battery or stored in a super-capacitor to operate the wireless sensors when communication is required. Recent prototypes of ambient energy scavenging devices that generate sufficient electric power to operate a wireless sensor show promise for these revolutionary technologies to soon be commercially available. [41]

With an optimistic outlook on cost projections of wireless sensors and revolutionary self-powering devices, what are the likely impacts and opportunities of this technology for the building sector in general, and for energy efficiency improvement opportunities in buildings in particular? While the scenario of ubiquitous sensing by miniaturizing sensors to the size of paint pigments that can be painted on a wall may be in the realm of science fiction, there are real near-term opportunities for low-cost wireless devices providing value in the building sector now. Some of the applications where wireless sensing should have impact soon include:

HVAC fault detection, diagnostics, and control

- Higher spatial resolution of measurements of zone temperature and humidity to help assure better thermal comfort. Causes of localized hot and cold conditions can be detected and diagnosed. Each office or cubicle would be equipped with one or more temperature/humidity sensors.
- Expand terminal box control from a common single thermostat control point to multiple sensors located throughout the zone served. An average temperature that is more representative of the thermal needs could be used to control terminal boxes.
- Retrofit of terminal boxes for condition and performance monitoring. Because there are hundreds, sometimes thousands, of VAV boxes in commercial buildings, they receive very little inspection or maintenance except when suspected of causing a comfort problem. Wireless sensors placed on these units could be used to measure airflow rates, temperatures, and equipment status to enable central monitoring, performance-based alarms, and diagnostics that would support condition-based maintenance of this largely neglected equipment.
- Additional outdoor-air temperature sensors for improved economizer control. Ideally, place one or more air-temperature sensors near air intakes to air-handlers to minimize bias from radiative heat transfer and sensor failure.
- Equip packaged rooftop HVAC systems with sensors to continuously and automatically monitor performance.

Lighting control and monitoring

- In open-space office buildings, retrofit lighting controls for individual and localized control from the occupants' desks.
- Retrofit reconfigurable lighting systems with individually addressable dimmable ballasts.
- Retrofit light sensors at the work task location to turn off or dim lighting fixtures where daylight is adequate.
- Retrofit wireless occupancy sensors and control points on lighting panels to turn off lights during unoccupied periods.

Security and access control

- Motion sensors and door sensors for physical security systems.
- Environmental monitoring and physical security for IT systems and server rooms.

- Access control systems for retrofits and new construction.

Demand Responsiveness

- Retrofit wireless power meters for electricity end-use metering
- Retrofit wireless power meters and control on major loads to modulate or switch off power during grid emergencies or during periods of high power prices.
- Retrofit large appliances with wireless devices for receiving price signals or load control instructions from the power grid to respond to stress on the power grid.

Conclusion

Application of wireless communication for monitoring the conditions inside buildings and the performance of building equipment is feasible today. For retrofits, wireless sensing can be installed in many situations at lower cost than an equivalent wired system. Savings on energy, extended equipment life, lower total maintenance cost over equipment lifetimes, and maintenance of better conditions for occupants can even justify sensors using wireless communication where wired sensing has not been used previously.

Very few wireless products for building monitoring are available on the market today, but the technology is poised for rapid introduction soon. Generic hardware is available that can be adapted to building applications. Care should be exercised by those considering wireless technology for these purposes to ensure that wireless communication best matches the application requirements and that the specific system selected is the one best meeting needs. Every application is unique, and wireless technologies should be evaluated with respect to each project’s unique requirements. Furthermore, special steps such as RF surveys of facilities in which wireless sensing is planned should be used to plan the proper layout of equipment to ensure reliable communication over the system life.

Data on the condition and performance of equipment can be used to implement condition-based maintenance for building equipment that may previously have been largely run until failure. Information collected from wireless sensor systems installed where no sensing previously existed can be used to improve control by adjusting set points, using sets of measurements throughout a zone rather than measurements at a single point in a zone as inputs for control, and diagnosing hot and cold spots. Control directly from wireless sensors is also possible but less developed and tested than monitoring applications, but today’s wireless networks are not suitable for control requiring rapid response on the order of seconds or less. The network and its adaptation must be matched to the needs of the application.

Although wireless sensing can bring benefits not previously possible with wired systems, it is not a panacea for all monitoring and control applications in buildings. As pointed out recently by an author from a major building controls company:

> Part of the answer, at least for the near term, is that wireless networks can provide tangible benefits to engineers, consultants and clients alike. However, as we have witnessed with so many other fast-growing

> technologies coming of age, only time will tell if the technology will become an accepted and vital part of the HVAC industry. For now, all-wireless control of a facility is neither sensible nor realistic. Conversely, wireless technology cannot be ignored. Although every facility is unique with its own specific requirements, the most sensible building control solution could well be a balanced blend of wired and wireless devices that are strategically integrated for optimum performance and cost savings. [42]

Wireless technology for monitoring and control in buildings is emerging and can be used cost effectively today with care. In the next few years, new technology and products will make application of wireless easier and more reliable. Experience will build widespread support for this technology. Applications of sensors in buildings not fathomable yesterday will emerge based on wireless communication, bringing cost, comfort, safety, health, and productivity benefits.

Acknowledgements

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Table 1. ISM frequency band allocations and applications. (13)

Frequency band	Center Frequency	Band-width	Applications
6,765–6,795 kHz	6,780 kHz	30 kHz	Personal radios
13,553–13,567 kHz	13,560 kHz	14 kHz	
26,957–27,283 kHz	27,120 kHz	326 kHz	
40.66–40.70 MHz	40.68 MHz	40 kHz	Mobile radios
902–928 MHz	915 MHz	26 MHz	In the US, applications includes Railcar and Toll road applications. The band has been divided into narrow band sources and wide band (spread spectrum type) sources. Europe uses this band for cellular telephony services (GSM)
2,400–2,500 MHz	2,450 MHz	100 MHz	A recognized ISM band in most parts of the world. IEEE 802.11, Bluetooth recognizes this band as acceptable for RF communications and both spread spectrum and narrow band systems are in use. Cordless phones
5,725–5,875 MHz	5,800 MHz	150 MHz	Cordless phones. The FCC have been requested to provide a spectrum allocation of 75 MHz in the 5.85-5.925 GHz band for Intelligent Transportation Services use.
24–24.25 GHz	24.125 GHz	250 MHz	Allocated for future use
61–61.5 GHz	61.25 GHz	500 MHz	
122–123 GHz	122.5 GHz	1 GHz	
244–246 GHz	245 GHz	2 GHz	

Table 2. Basic characteristics of some wireless networking standards.

Network Name/Standard	Power Use (Watts)	Data Rate (kb/sec)	Line-of-site Range (meters)
Mobile telecommunications GSM/GPRS/3G	1 to 10	5 to >100	>1000
Wi-Fi **IEEE 802.11b**	0.5 to 1	1000 to 11,000	1 to 100
Wi-Fi **IEEE 802.11g**	0.03 to 0.7	1000 to 54,000	>100
Bluetooth **IEEE 802.15.1**	0.05 to 0.1	100 to 1000	1 to 10
ZigBee with IEEE 802.15.4	0.01 to 0.03	20 to 250	1 to >100

Table 3. Cost ranges of commercially available wireless sensor network components in 2004.

Network Component	Cost Range ($)
Sensor transmitter unit	$50 - $270
Repeaters	$250 - $1050
Receivers	$200 - $900
BAS Integration units	$450*

*Only one is currently commercially available in 2004 specifically for connecting a wireless sensor network to a building automation system.

Table 4. Costs of wireless sensor systems in the two demonstration buildings.

	Cost per unit	**Building 1**		**Building 2**	
		Quantity	**Total**	**Quantity**	**Total**
Temperature sensors	$50	30	$1,500	120	$6,000
Repeaters	$250	3	$750	0	$0
Receivers	$200	1	$200	3	$600
Translators	$450	1	$450	3	$1,350
RF Surveying Labor	$80/hour	2 hours*	$160	2 hours	$160
Integrator configuration labor	$80/hour	4 hours	$320	8 hours	$640
Installation of Integrator labor	$80/hour	8 hours	$640	8 hours	$640
Total Cost			**$4,020**		**$9,390**
Cost per Sensor			**$134**		**$78**

*For an experienced surveyor.

Table 5: Attenuation of an RF signal in free air as a function of distance.

Distance in m (ft)	0.05 (0.2)	1 (3)	2.5 (8)	5 (16)	10 (33)	20 (66)	40 (131)	80 (262)
Signal strength in dB	0	-26	-34	-40	-46	-52	-58	-64
Attenuation along line-of-sight in dB	0	26	34	40	46	52	58	64

Table 6. Signal attenuation for selected building materials for the 902-928 MHz band. (38)

Construction Material	**Attenuation (dB)**
1/4" Drywall	0.2
1/2" Drywall	0.3
3/4" Drywall	0.5
1/4" Plywood (dry)	0.5
1/2" Plywood (dry)	0.6
1/4" Plywood (wet)	1.7
1/2" Plywood (wet)	2
1/4" Glass	0.8
1/2" Glass	2
3/4" Glass	3
1.5" Lumber	3
3" Lumber	3
6.75" Lumber	6
3.5" Brick	4
10.5" Brick	7
8" Reinforced concrete with 1% ReBar mesh	27

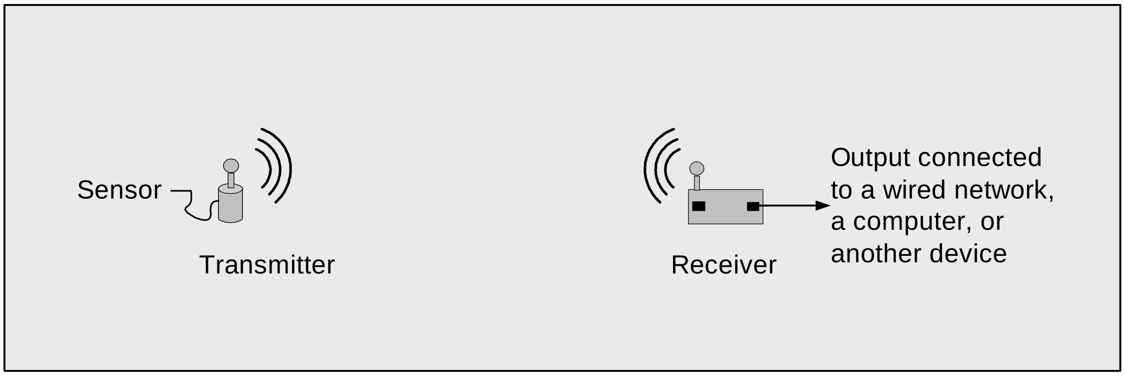

Figure 1. Sensor with simple one-way radio-frequency wireless communication.

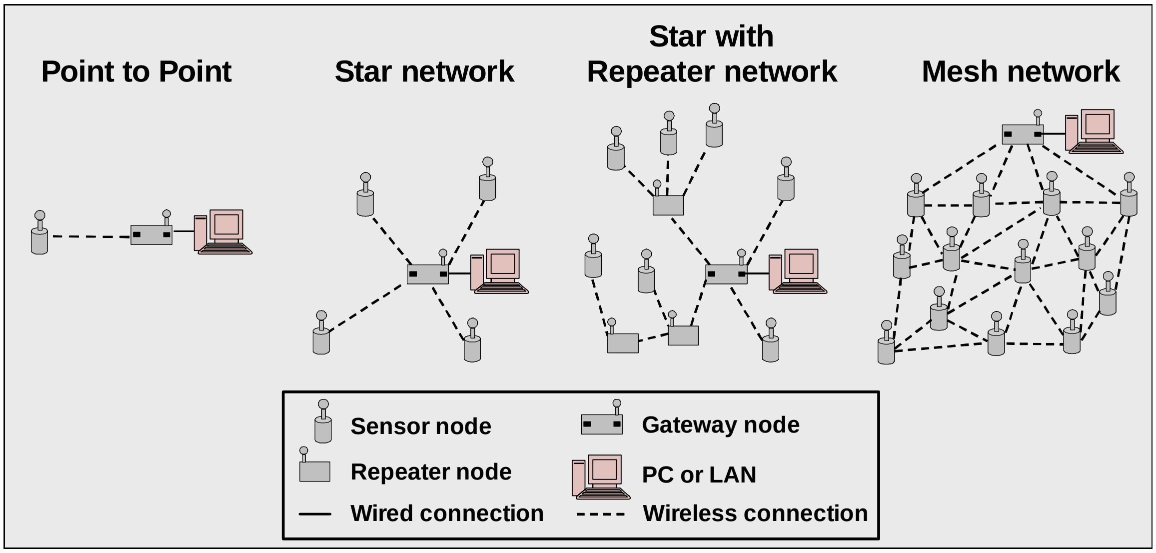

Figure 2. Wireless network topologies

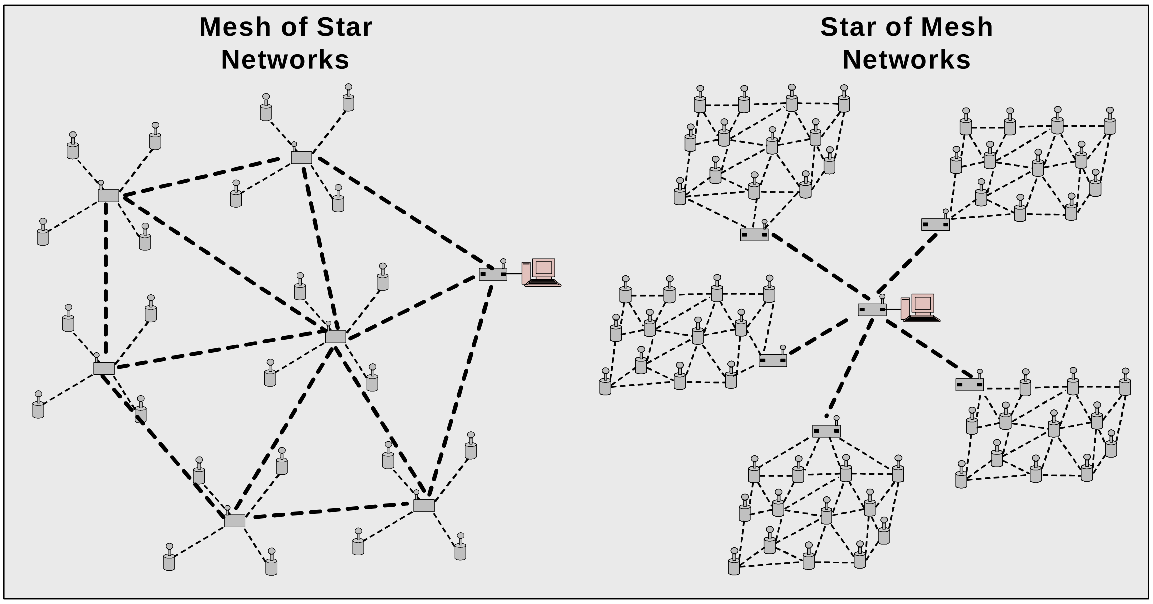

Figure 3. Hybrid networks

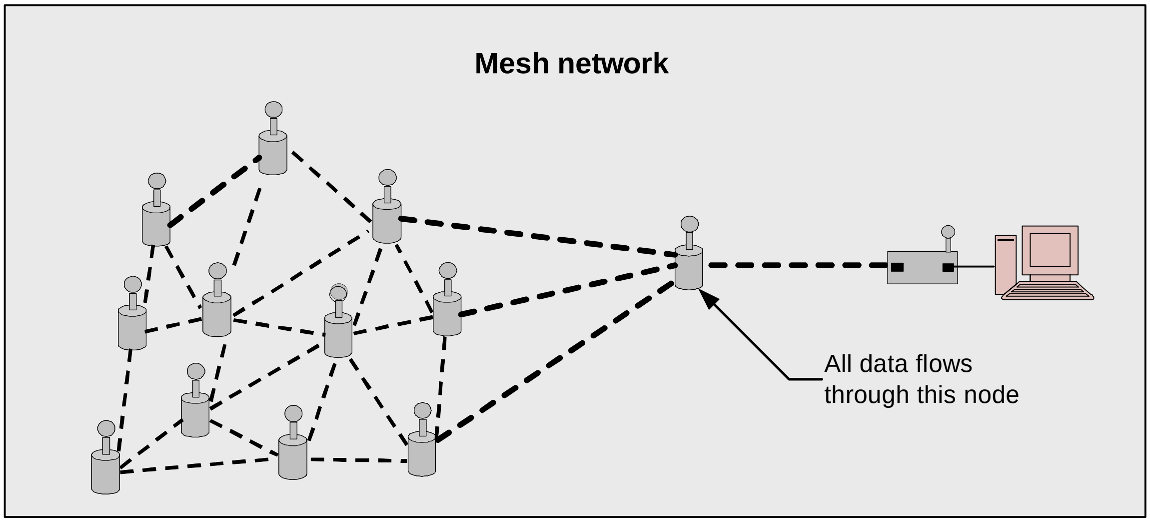

Figure 4. Mesh network with a single high usage node.

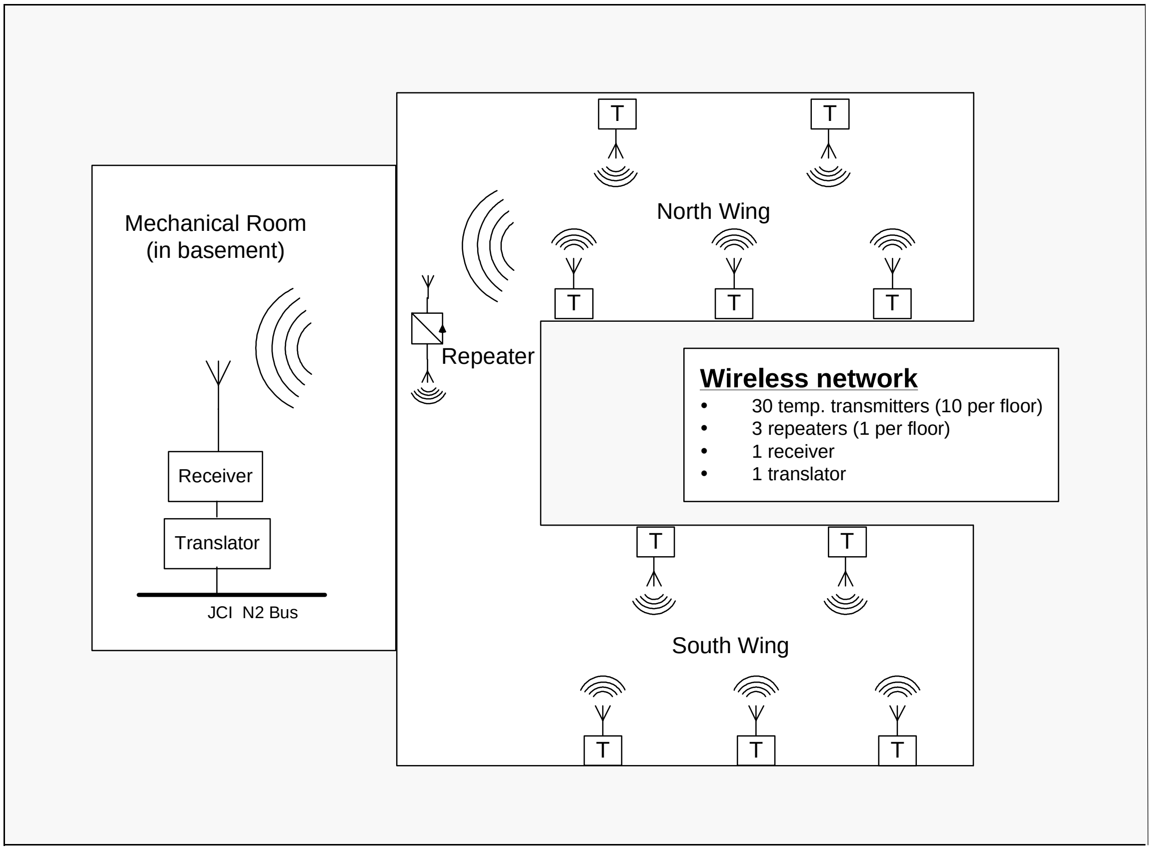

Figure 5. Layout of wireless sensor network for one floor plus the mechanical room in the basement. The floor plan for the u-shaped section is identical for all 3 floors with only the basement having the mechanical room.

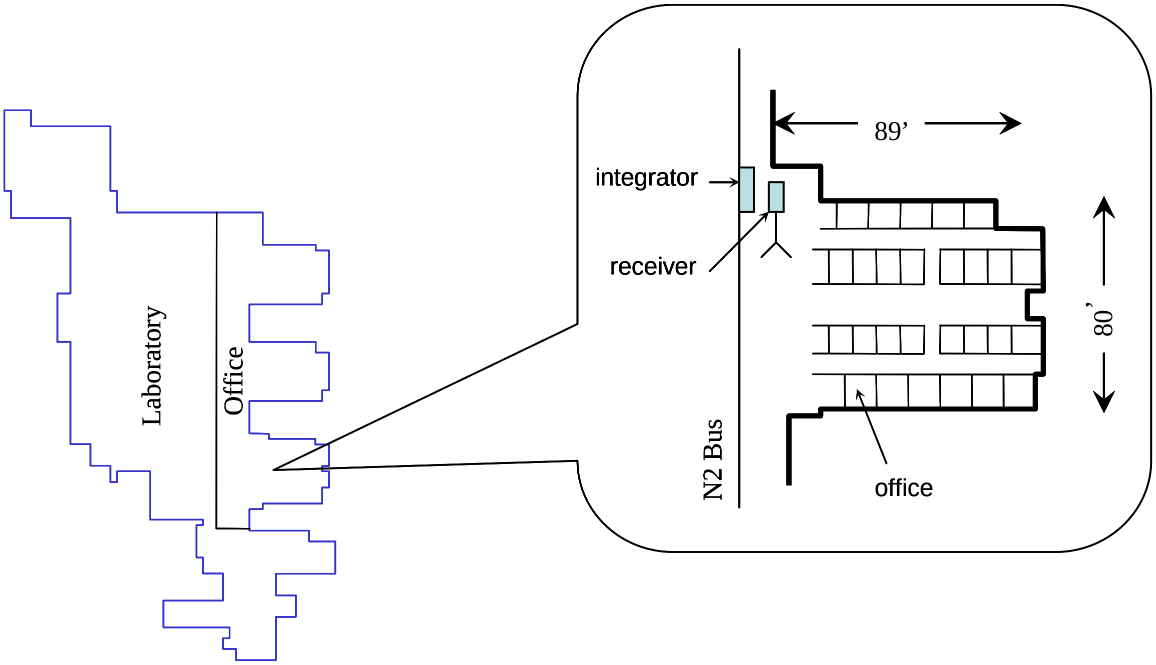

Figure 6. Layout of Building 2. Forty wireless sensors are placed in each office wing for a total of 120 Sensors.

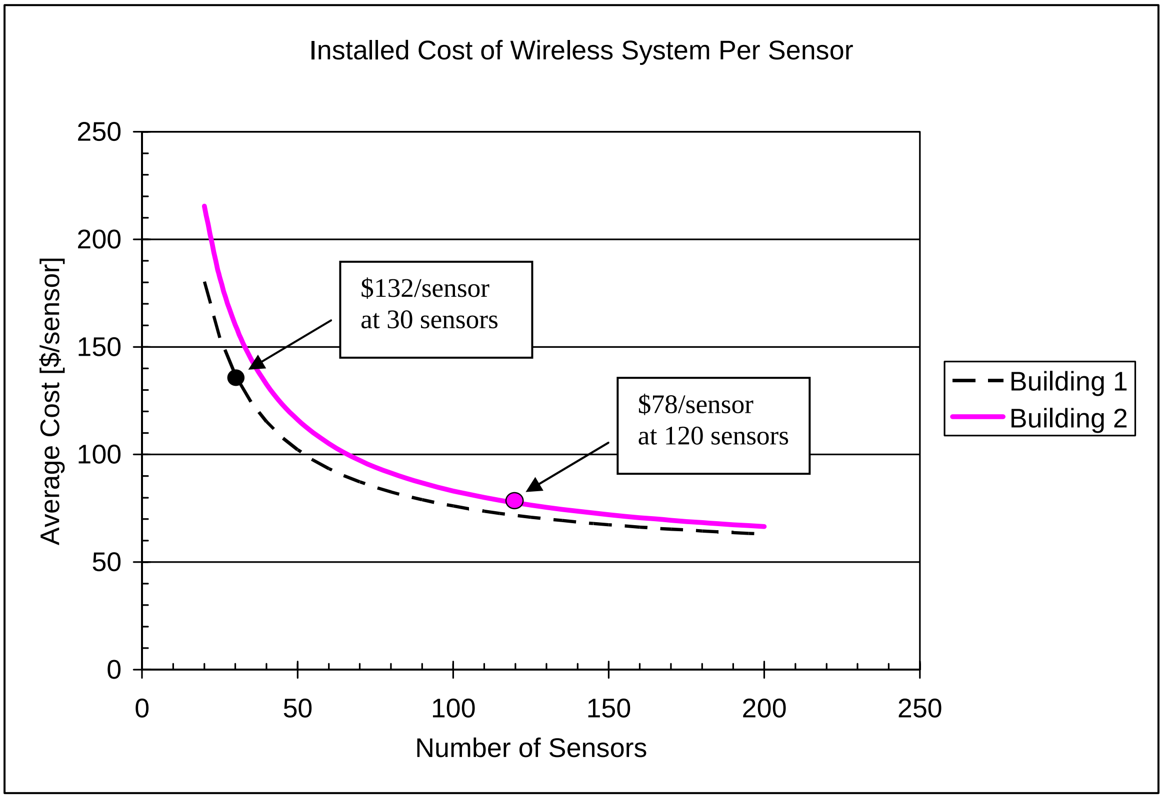

Figure 7. Installed cost per sensor for Buildings 1 and 2.

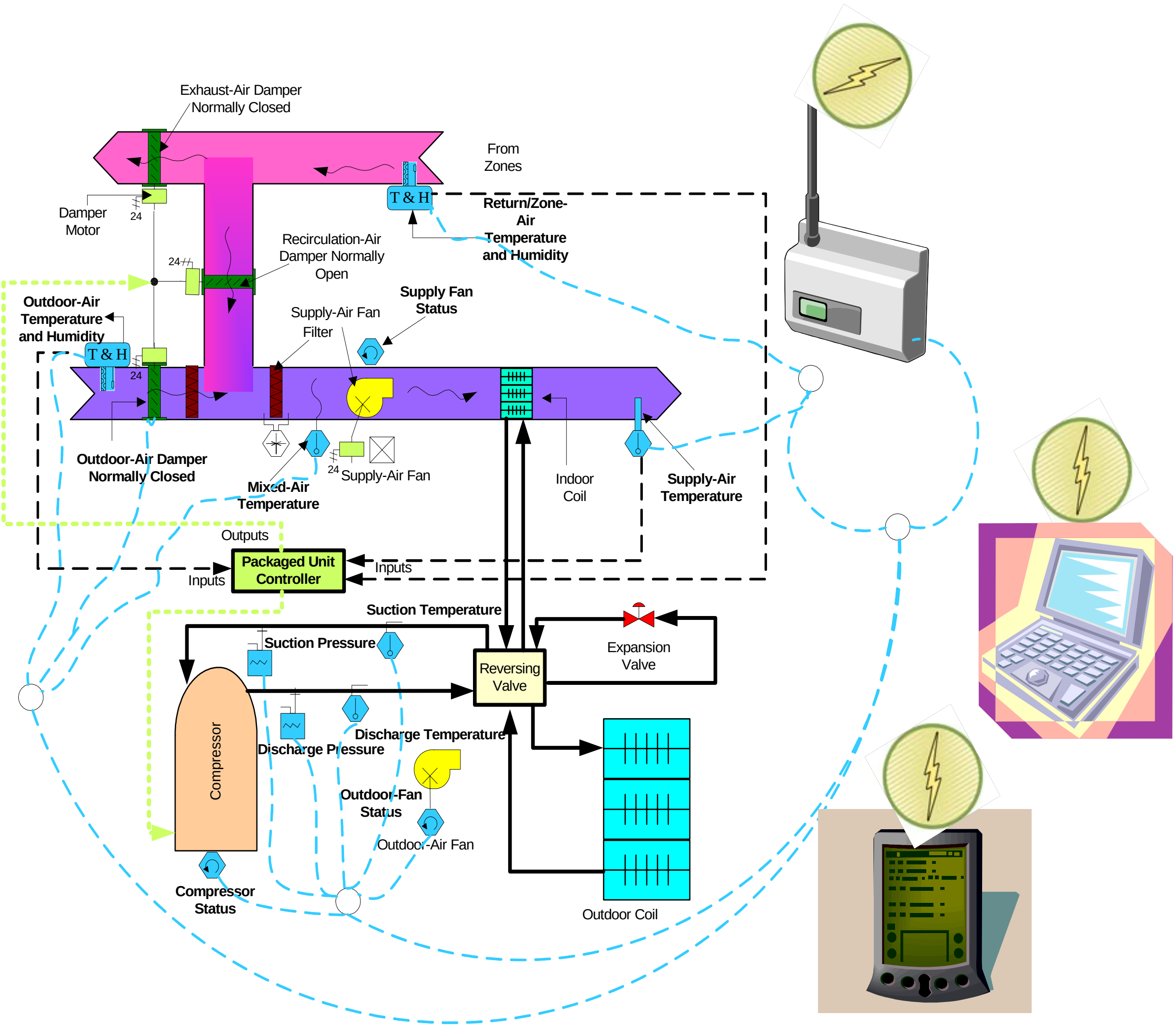

Figure 8. Schematic diagram of a wireless condition monitoring system for rooftop packaged HVAC units.

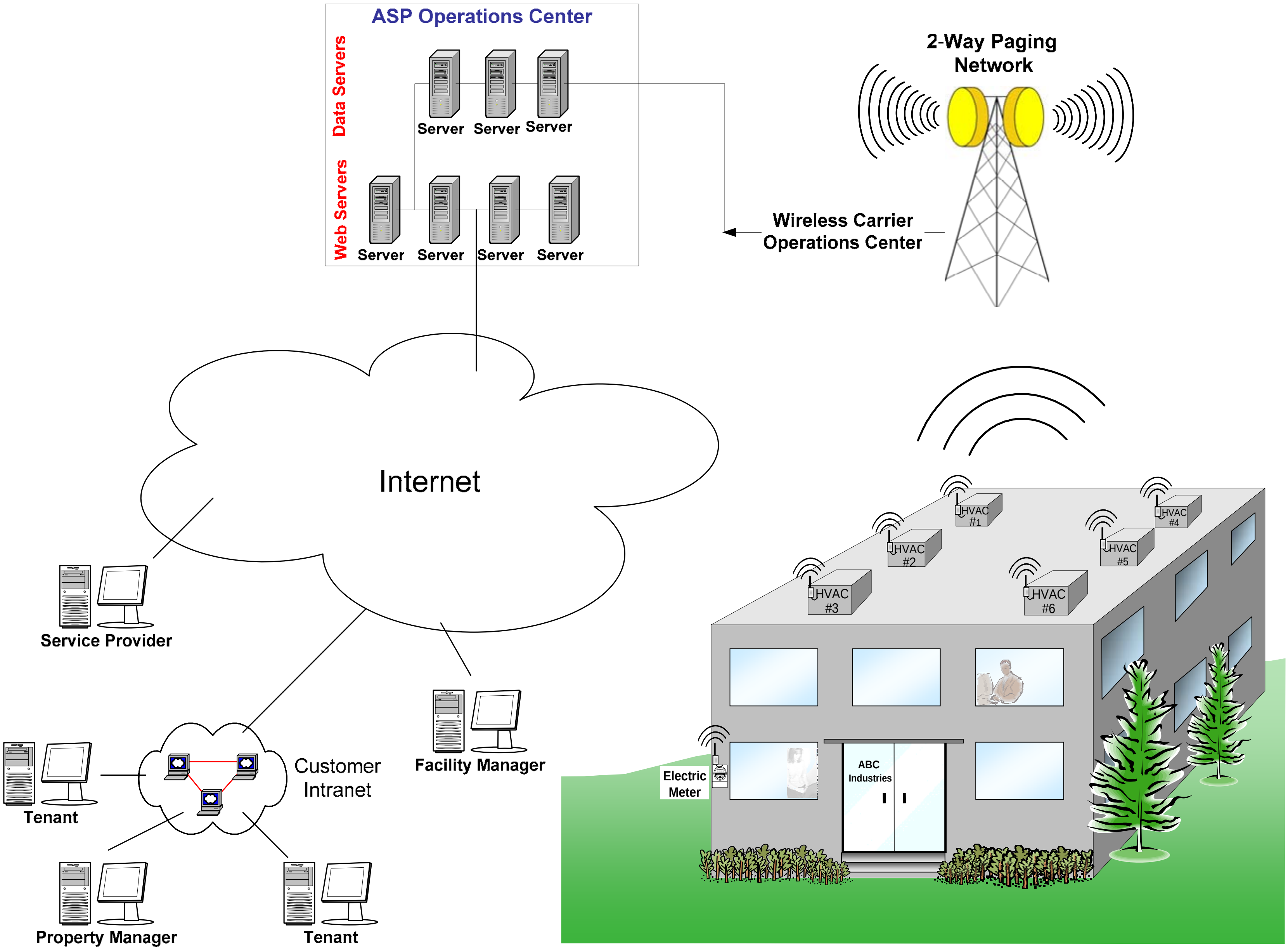

Figure 9. Building monitoring provided by an application service provider using the wireless telemetry network for long-distance data transmission.

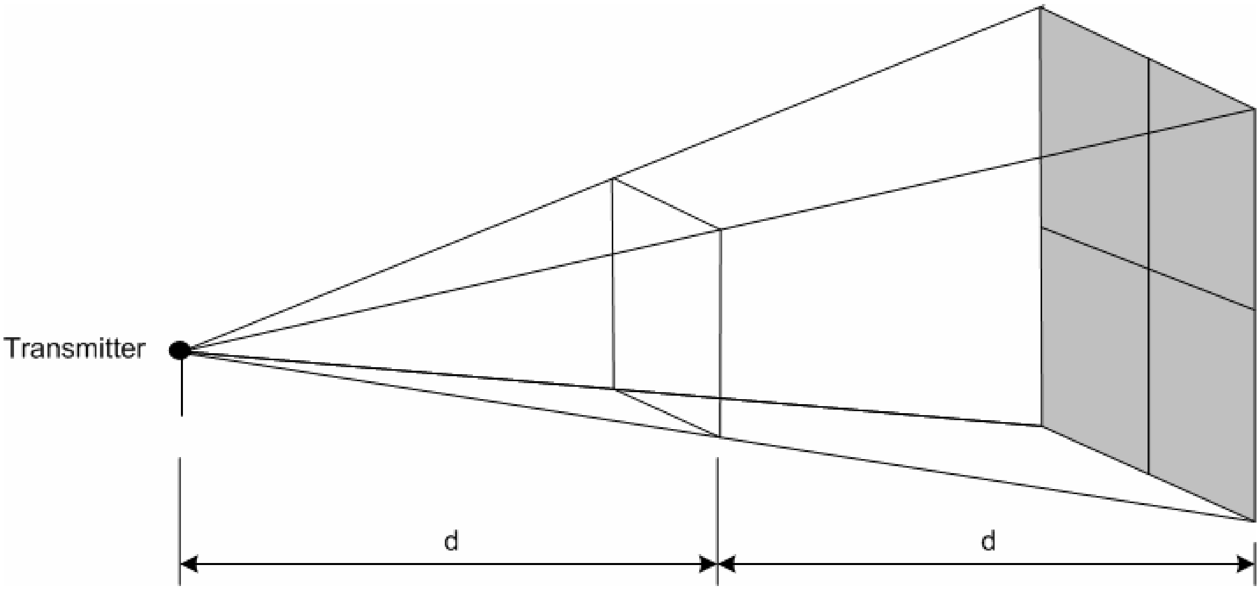

Figure 10. Relation between signal energy per unit area and distance from the transmitter.