Lessons Learned in Wireless Monitoring

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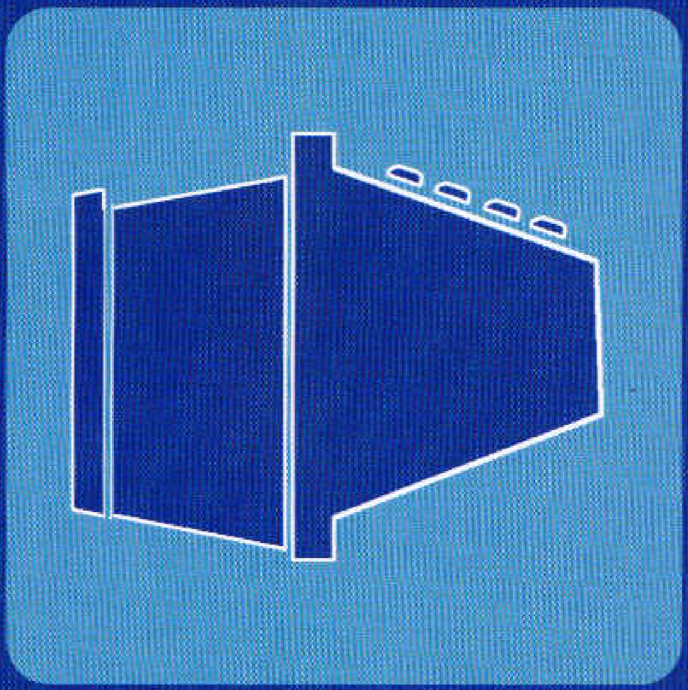

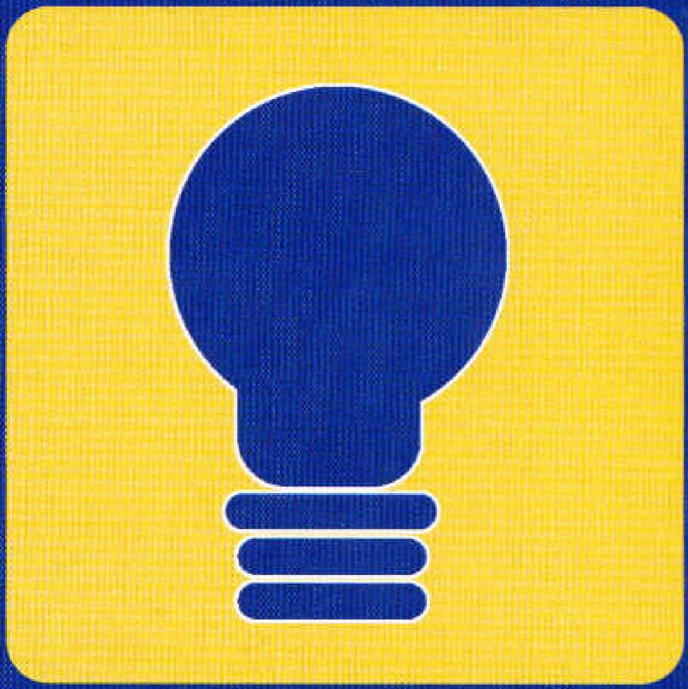

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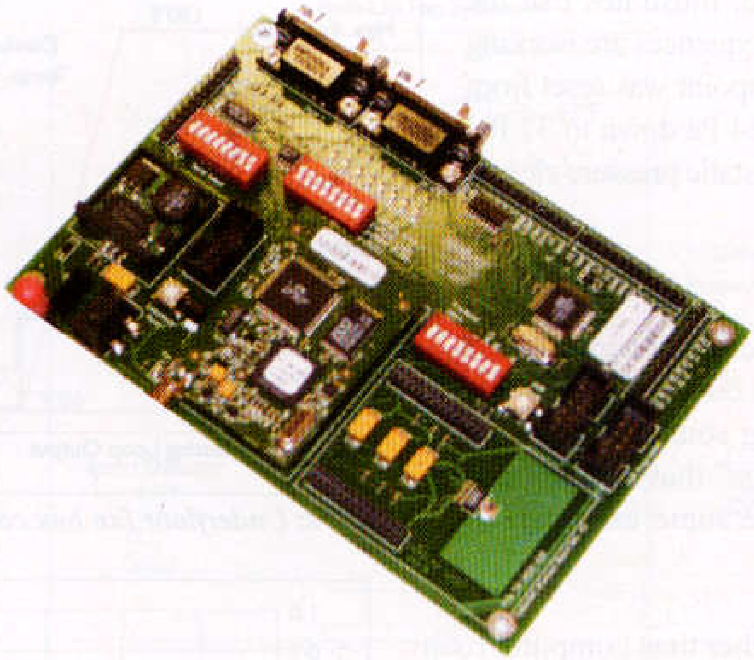

Lessons Learned in Wireless Monitoring

By William M. Healy, Ph.D., Member ASHRAE

While the use of wireless sensing technology appears cutting-edge and interesting, it is unclear where its true value lies for the building community. What benefits can be derived from advanced sensor technology, whether it is wireless or wired? The technology must somehow reduce operation costs or provide added comfort to occupants compared to conventional technologies.

Several discussions of the advantages and disadvantages of wireless sensor technology for building applications have been published recently. Kintner-Meyer and Brambley[1] and Kintner-Meyer, et al.,[2] demonstrated wireless sensor technology by instrumenting an office building with 30 wireless temperature sensors and by installing a wireless monitoring system on a rooftop HVAC unit. Wills[3] provides a recent update of the state of the available technology and discusses advantages and disadvantages. It is apparent that building operators and researchers are still waiting to see whether these technologies can simplify building maintenance, forensics, or control to an extent that will justify the cost and the learning curve needed for adopting these technologies.

This article discusses one type of wireless sensing platform. The sensor network monitored the energy performance of a residential heat pump system and was later expanded to monitor the performance of the water heating system and the hygrothermal state of a wall. This demonstration has shed some light on the intricacies of deploying wireless sensors and has shown obstacles that may be faced by building operators or researchers in adopting these technologies.

Sensor Network Architectures

Sensor networks and wireless technologies can be characterized in a number of ways.[4] One way to characterize them is by considering the arrangement of sensing nodes. *Figure 1* shows three possible architectures that can be used.

The first layout depicts a set of sensors broadcasting messages to a central re-

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ceiver in a setup commonly referred to as a star network. A bus topology is shown in *Figure 1b*, in which sensors send signals through a common line to the data collection point. This topology makes sense for wired communications, but it is not relevant to wireless data communications.

The third network architecture (*Figure 1c*) is a mesh network, which is the one used in this study. In this scenario, sensors can communicate with all other sensors and can relay messages from other sensors. A central receiving point is simply another node in this network that is devoted to collecting the data that are being passed throughout the network. This architecture has the potential of allowing individual sensor nodes to bypass a central station to transmit data only to those nodes that use the data, thereby minimizing the transfer of unnecessary information. The cost and complexity of implementing such a network, however, becomes unbearable with a wired network because of the challenges in wiring all sensors together. For this reason, this topology has only become practical with wireless communications.

For the current application, this topology was chosen for the following reasons: ease of installation, ability to be expanded and self-healing properties.

The mesh topology promised to allow for installation without expert knowledge of the electromagnetic state of the residence. As designed, sensors could be dropped in the desired location, and the network would set itself up automatically to route the signal to its intended destination regardless of radio frequency (RF) interference or barriers.

Hardware Description

A commercially available development kit was used to implement this mesh network. The kit consisted of several development boards and software to implement a mesh network. A node that contains the radio and microprocessors that govern the transmission and reception of signals is placed on the board. The radio uses Direct Sequence Spread Spectrum in the 902 MHz to 928 MHz band, and the radio power was set at 4 mW for this application.

The larger board is a product meant for application development that accepts analog or digital sensor input and carries out operations on these inputs. Line power was used in this application because of its availability in places where the sensor boards would be placed. In this respect, the boards are only partially wireless. Only the transmission of data occurs in a wireless manner. The application board contains a microprocessor with an analog-to-digital converter, a multiplexer, eight analog inputs, a 5V output source, and two interrupts that are used to monitor counters. Sensors are attached to pins on the boards.

This board was designed for developmental purposes. Smaller boards could be developed and connected to the wireless node for applications that require small sizes. It is also recognized that, since the units were connected to electrical outlets, communication over power line carriers is also possible, but the focus here was on the transmission of data in a wireless manner.

An identical application board was used to collect data from all sensors and relay them to a computer where the data are stored. The board is connected to a computer through a serial port and has been programmed to act as a data sink so that all wireless messages received by the antenna are echoed through the serial port to the computer.

Software Description

In setting up the sensor network, three distinct software pieces were needed. First, software was needed to coordinate communications between the sensors. This software was developed by the hardware vendor. Development of the second and third pieces of the software was the responsibility of the application developer.

The first of these sets of code was written to the sensor node and handled application level instructions. This code regulated the acquisition of analog signals from the various sensors and converted those signals to digital messages containing environmental information. Measurements were obtained and messages passed to the central station once every minute. Each sensor node has a two-symbol designation that is announced with each message.

Following the sensor identifier, eight data values are sent corresponding to each of the eight possible channels available on the board. If no sensor is attached to a particular channel, a value of –99.9 is sent in that channel place to indicate the absence of a signal. A sample message is shown below for data from a board making two indoor ("ID") temperature measurements and one relative humidity measurement:

```
Data from ID: 020.1 019.3 039.2 -099.9 -099.9
-099.9 -099.9 -099.9
```

This software was developed in the C programming language on a personal computer and was transferred to the development board through a cable.

The third piece of software needed for the operation of the wireless sensor network was host-based software that compiled the data. The data collection point was programmed to dump received messages to a personal computer where they were logged to a text file. Software was written on the host computer to process the data.

The application that was selected for deployment of the wireless sensor network was the monitoring of a number of critical energy consumers in a residence along with the moisture levels of a wall. The disparate goals were selected to investigate the potential to examine different building phenomena using a single sensor network. The installation was also carried out in a manner to simulate the changing needs of a sensor network in a building. Therefore, different sensors were installed at different times to investigate the adaptability of the monitoring scheme.

The investigation was carried out in a three-story townhouse. *Figure 2* shows approximate locations of the wireless nodes used in this study. This house had an office in a third floor bedroom in which the data acquisition computer was located. A utility room on the first floor housed the air handler, water heater, and wall that was investigated for moisture issues.

Tasks

1. The first task involved the monitoring of a heat pump/air-conditioner unit. To determine the duct temperatures and humidities, thermistors and capacitive RH probes were installed inside the duct and wires from these sensors were fed through the duct to the sensor board.

An energy meter was installed in the air-handler unit to measure the energy consumption of the blower fan. No measurement was made of the energy consumption of the auxiliary heating elements in the air handler though the author acknowledges the fact that the energy performance of the system in the heating mode cannot thoroughly be characterized without this measurement.

Separate boards were placed for determining the indoor temperature and humidity, the outdoor temperature and humidity, and the energy consumption of the heat pump compressor and outdoor fan.

2. Three months after installation of the sensor network to monitor performance of the heat pump system, sensors were installed for a new purpose—to determine the performance of the water heater. A flow meter was installed on the inlet piping to the water heater, and thermistors were placed in the piping on the inlet side and on the outlet side to determine the water temperature.

Additional temperature sensors were placed inside the insulation jacket of the water heater near the upper thermostat and in the utility room to get an estimate of the ambient temperature to which standby heat loss would occur. The electrical power to the water heater was monitored with an in-line power meter. Once the sensor boards were turned on, the network recognized the sensor data immediately and seamlessly integrated these boards in the network.

3. The third application was implemented three months after the water heater sensors were installed. This application involved a slightly different focus than that of the previous two in which determining the energy performance of equipment was the aim.

In this application, the aim was to install a network of sensors to investigate the hygrothermal state of a wall. Combination temperature and humidity sensors were installed at four locations in a wall facing the building exterior to determine if any moisture gradient was evident in the wall. Once again, these sensors seamlessly integrated themselves into the existing wireless sensor network.

Lessons Learned

The sensor installation went relatively smoothly. The setup of the mesh network was made straightforward by the commercially available hardware and the accompanying software that monitored sensor communications. Setup was surprisingly simple, even for engineers without in-depth knowledge of wireless networking or RF physics, and the network was easily expanded. While the environment was not as challenging as a large industrial setting because of the lack of substantial metal obstructions and the relatively small space involved, some lessons have been learned regarding the installation of a wireless sensor network in buildings.

- **Need for more sensors incorporated in wireless boards.** In this application, significant effort went into the connection of the sensors to the boards and the programming to process the signals from the sensors. Currently, it does not appear that a wide array of systems are available that contain the variety of sensors needed for building studies. To avoid creating custom solutions for each application, it would be beneficial if manufacturers could equip their wireless nodes with the sensors that are needed for building applications. Sensors of interest include those that measure quantities such as temperature, relative humidity, electrical power, water flow, gas flow, air flow, carbon dioxide concentration, smoke presence, light intensity, and radiant energy. Ready-made wireless nodes would speed the adoption of wireless sensors in building applications, but it is acknowledged that sensor manufacturers will first need to be confident that a sufficient market exists for such products.
- **Need for more straightforward ways to program boards.** In developing the sensor application, a significant learning curve was encountered when attempting to program the microprocessors. While many engineers may be comfortable with such programming, it is presumed that many others would prefer to stick with a programming environment that does not require bit-level operations. Development of integrated sensors may eliminate the need for low-level commands, freeing the application engineer to focus on the higher level application programming.

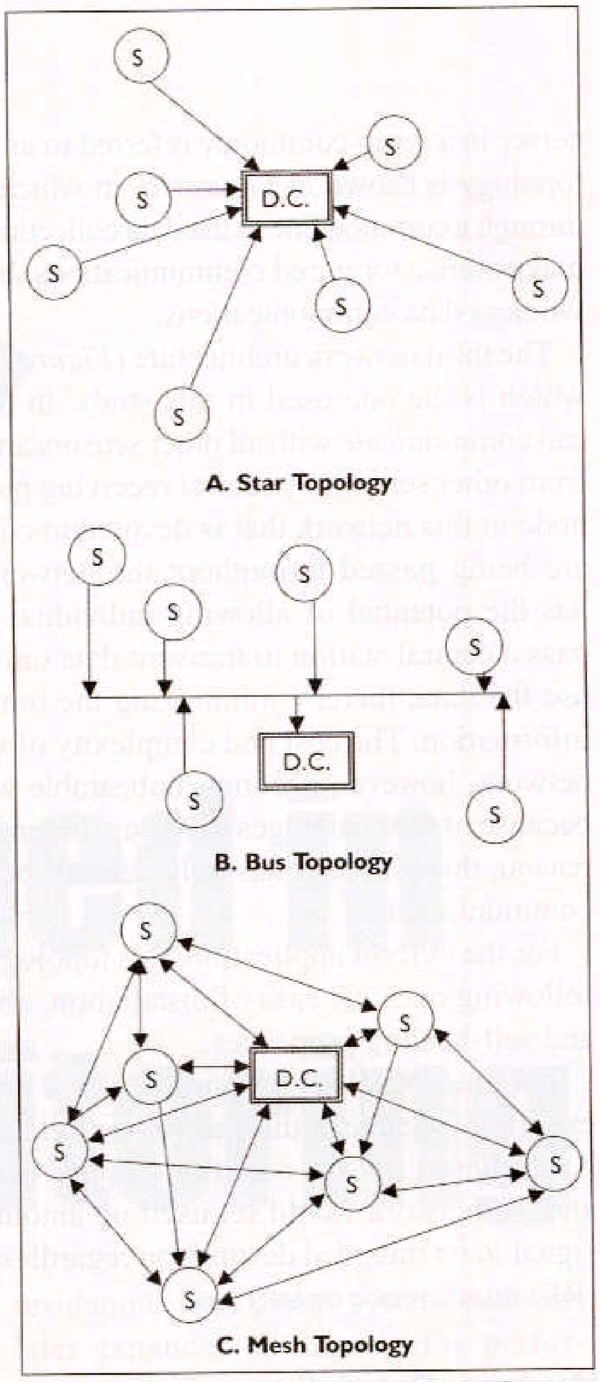

Figure 1: Sensor network topologies. (S = sensor location. D.C. = data collection point.)

- **Line power can be a suitable option, but batteries would be better.** The use of line power has certain advantages over batteries, especially in a building where electricity wires are often within short distance of the sensor nodes. The most obvious benefit is the elimination of any need to change batteries. Even in a building where line power is available, running power wires can be cumbersome if multiple sensor nodes are used. Manufacturers are keenly aware of the need to decrease power consumption so that batteries will last longer. Additional work aimed at scavenging energy from the environment adds even more exciting possibilities to the power dilemma.
- **Reliability still is uncertain.** The boards suffered from several reliability issues, the cause of which was not specifically determined. Reliability may be affected by interference, as the radios use the 900 MHz band that also is used by devices such as cordless telephones and wireless Ethernet. No systematic study was undertaken to identify sources of interference. It is not expected that building partitions played a large role, as the wood frame construction changed little during the time frame of the study and would not account for the decrease in reliability.

  Figure 3 shows a plot of the availability of data as a function of date. Availability is defined as the number of data values that are obtained from each board divided by the maximum possible number of data values that could have been obtained as prescribed by the total number of minutes for that day of data acquisition. Initially, the radios performed quite admirably, with only the outdoor transmitter failing to register availabilities near 100% (the outdoor board was enclosed in a weather-tight case).

  As time passed, however, more transmitters started to fail, and large decreases in availability were observed during the latter stages of the study. Availability problems were often rectified by manually resetting the operating system via a button on the board when a problem was observed. As these were older radios, it is hoped that manufacturers will improve operations of these radios since manual reset will not always be practical.
- **Data transmission errors can be costly.** Again for unknown reasons, data transmission errors seem to be an occasional event with these sensors. Such sporadic errors have minor effects when determining average values over a day, but seemingly subtle errors could cause significant problems when consumption values are erroneously reported. For example, occasional errors in the water consumption data message incorrectly increased the daily amount of water used by 380 L (100 gallon). This single minute's data point brought significant errors into calculations of water heater efficiency. These problems also occur with wired sensors, but interference with wireless data transmission may exacerbate the problem and create a need for more significant error monitoring and correction.
- **The need for time synchronization.** Sensor nodes in the current study were not synchronized in time, but time synchronization will be necessary when doing more in-depth demand studies that require specific knowledge of the time at which water or energy is being consumed. One possible standard that may be applicable is IEEE 1588.[5] This standard should be investigated to determine its applicability to sensors for building systems.
- **Standard identification protocols for building sensors.** One simplified technique was developed to easily integrate new sensors into the network. Work should be undertaken to standardize such protocols by creating tags for sensors that are acceptable to a large range of users. Such standardization could speed adoption of sensors in buildings by ensuring interoperability. IEEE 1451[6] should be investigated to determine if it meets the needs of the building community.
- **Sensor security should not be overlooked.** No provisions were taken in this study to ensure the security of these sensors. Unprotected wireless nodes may open a door of a network to

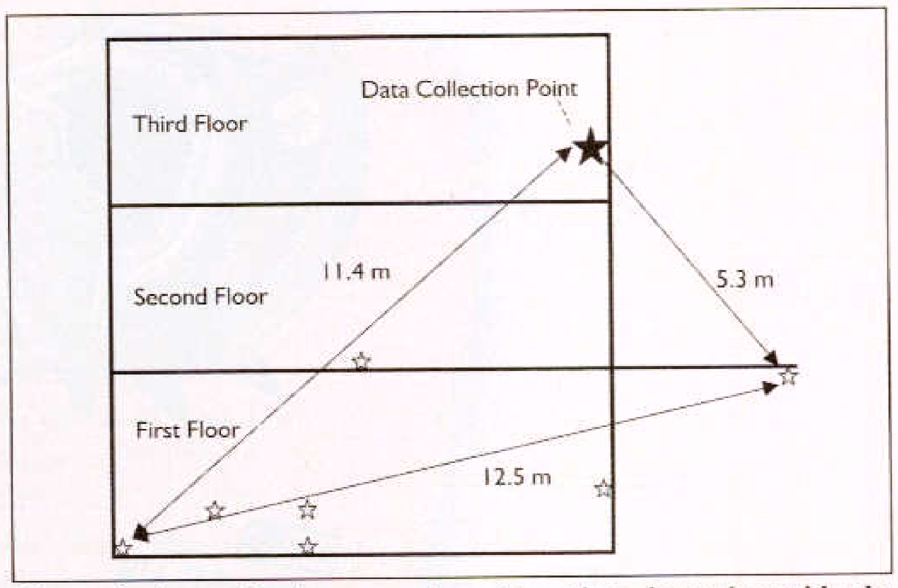

Figure 2: Approximate sensor board locations in and outside the townhouse with distances between furthest nodes. Open stars represent locations of the sensor boards while the closed star shows the location of the data acquisition node (not to scale).

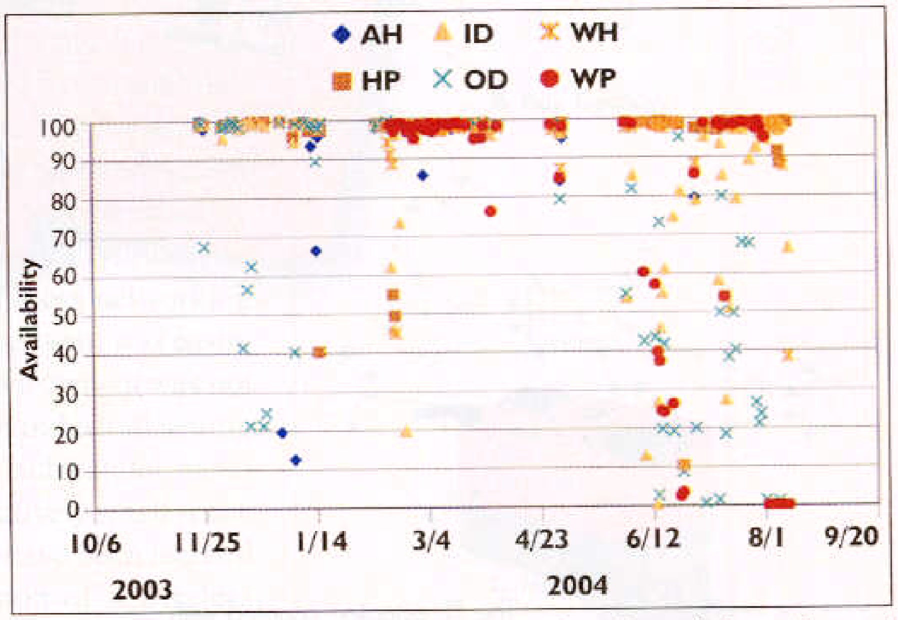

Figure 3: Sensor node availability as a function of date. Legend indicates sensor board (AH: air handler, HP: heat pump compressor and fan, ID: indoor conditions, OD: outdoor conditions, WH: water heater flow rates and water temperatures, WP: water heater energy consumption).

Wireless Sensor Network Standards

In selecting a suitable wireless sensor platform, few standards are currently entrenched in the market to assist in the decision. Standards such as the IEEE 802.11 family[7] and Bluetooth have name recognition, but they are geared toward high data rate applications such as wireless Ethernet and computer network cable replacement. For some sensor applications, the high data rates specified by these standards are overkill. In addition, power consumption by these radios has been a concern, particularly for battery-powered applications.

To address these concerns, IEEE has formed task group 802.15.4[8] to devise standards for a physical layer for low power and low data rate applications. The ZigBee Alliance is an industry consortium that is promoting the use of such standardized protocols by setting parameters for the radio spectrum, the energy consumption, and chipsets.[9]

While these efforts aim to provide protocols for the physical layer of a wireless sensor network, others have focused on setting protocols for the format of transmitted data. The proposed IEEE 1451[6] standard sets rules for sensor data communications and interface specifications in wired and wireless sensor networks.[10]

Another technique that is being developed is SensorML, a markup language that aims to enable the information that is produced by sensors to be recognizable by generic browsers just as XML enables Web pages to be viewed regardless of platform.[11] The ZigBee Alliance is also promoting application interface layers that will further enable the adoption of wireless sensor technology.

creative hackers, and ways to prevent this possibility must be conveyed to users of wireless sensors and/or built in automatically by manufacturers.

A word should also be mentioned regarding system costs. While the tolerable cost for a typical installation, be it residential or commercial, is highly dependent on the end user, it is felt that the costs of wireless sensors must still drop for them to be a viable option for widespread use in either setting. At the time of this study, sensor nodes cost about $100 each. For an installation such as the one discussed here, which included 19 measurements, a rough cost estimate for the equipment would be $1,900. Manufacturers do claim that drastic price reductions will occur with more widespread use, bringing typical prices per sensing node to approximately $5. At such price points, equipment costs may be reasonable to expect more widespread deployment in buildings.

Conclusion

A wireless sensor installation in a home showed the ease with which a sensor mesh network can be installed for energy monitoring purposes. Significant time was saved during the installation since no signal wire needed to be routed from the sensor nodes to the data collection point. The homeowner also did not have to deal with the disruptions that may have been caused by having these sensor wires in his house. In this application, it was found that the robustness of the radios degraded over time, but it is expected that better engineering of the radios could alleviate this problem. It was also found that the lack of availability of off-the-shelf sensors incorporated on the radios created the most challenging obstacles for setup of the wireless sensor network.

The promise of mesh technology is that sensor networks can be easily set up in a robust manner, and this promise generally proved true. While the matter of robustness is still under question, the allure of wireless sensors for building monitoring was evident in the ease with which this sensor network was set up and the way in which the network was easily expanded.

Note: Certain technologies are mentioned in this paper to accurately describe equipment and protocols. These mentions do not imply endorsement by the National Institute of Standards and Technology.

References

1. Kintner-Meyer, M., M.R. Brambley. 2002. "Pros & cons of wireless." *ASHRAE Journal* 44(11):54–61.

2. Kintner-Meyer, M., et al. 2002. "Wireless sensors: technology and cost-savings for commercial buildings." *Teaming for Efficiency: Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings* 7(8):7.121–7.134.

3. Wills, J. "Will HVAC control go wireless?" *ASHRAE Journal* 46(7):46–52.

4. Manges, W.W. 2000. "Wireless sensor network topologies." *Sensors* May.

5. Eidson, J.C., K.B. Lee. 2003. "Sharing a Common Sense of Time." *IEEE Instrumentation and Measurement Magazine* 6:1, 26–32, March.

6. IEEE 1451.2: Standard for a Smart Transducer Interface for Sensors and Actuators—Transducer to Microprocessor Communication Protocols and Transducer Electronic Data Sheet (TEDS) Formats. 1997. N.Y.: The Institute of Electrical and Electronic Engineers.

7. IEEE 802: Standard for Local and Metropolitan Area Networks. 2001. N.Y.: The Institute of Electrical and Electronic Engineers.

8. IEEE 802.15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs). 2003. N.Y.: The Institute of Electrical and Electronic Engineers.

9. Adams, J. 2003. "Meet the ZigBee standard." *Sensors* 20(6):14–19.

10. Brooks, T., S. Chen, and K. Lee. 2003. "IEEE 1451-Based Smart Wireless Machinery Monitoring and Control for Naval Vessels." Thirteenth International Ship Control Systems Symposium (SCSS).

11. Botts, M., H. Niedzwiadek, S. Cox. 2004. "Setting the stage for sensor web standards." *Geointelligence* pp. 20–27, July/August.