Edgar H. Callaway, Jr.

Wireless Sensor Networks

Architectures and Protocols

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Wireless Sensor Networks: Architectures and Protocols

by Edgar H. Callaway

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This informative text describes how to build wireless sensor networks from the layers of the communication protocol through the design of network nodes. It also describes the design features of the wireless devices themselves.

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- Analyzes the need for wireless sensor networks in comparison to existing wireless LANs
- Describes a wireless sensor network physical layer designed for long battery life and low-cost implementation
- Details how the Mediation Device protocol enables communication between inexpensive devices with low duty cycle operation
- Explores aspects of device design, including energy scavenging techniques and design techniques for low power operation, electromagnetic compatibility (EMC), and electrostatic discharge (ESD) protection
- Evaluates network topologies in relation to specific applications
- Discusses relevant IEEE standards
- Outlines direction of future research

Because they provide practical machine-to-machine communication at a very low cost, the popularity of wireless sensor networks is expected to skyrocket in the next few years, duplicating the recent explosion of wireless LANs.

Wireless Sensor Networks: Architectures and Protocols describes how to build these networks, from the layers of the communication protocol through the design of network nodes. This overview summarizes the multiple applications of wireless sensor networks, then discusses network device design and the requirements that foster the successful performance of these applications.

The book discusses factors affecting network design, including the partitioning of node functions into integrated circuits, low power system design, power sources, and the interaction between antenna selection and product design. It presents design techniques that improve electromagnetic compatibility and reduce damage from electrostatic discharge.

The text also describes the design features of the wireless devices themselves, presenting a thorough analysis of the technology that engineers and students need to design and build the many future applications that will incorporate wireless sensor networks.

Wireless Sensor Networks-Architectures and Protocols

Edgar H. Callaway, Jr.

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Dedication

To Jan

Acknowledgments

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My parents, Pat and Ed, deserve special thanks for emphasizing the value of education to a young man more often interested in other things. I also recognize my greatest debt of gratitude: to my wife, Jan. Without her support and understanding, this book would not have been possible.

Edgar H. Callaway, Jr.

Note

1. Edgar H. Callaway, Jr., A Communication Protocol for Wireless Sensor Networks, Ph.D. dissertation, Florida Atlantic University, Boca Raton, FL, August 2002.

About the Authors

Edgar H. Callaway Jr. received a B.S. in mathematics and an M.S.E.E. from the University of florida. Gainesville in 1979 and 1983, resectively; an M.B.A. from Nova (now Nova-Southeastern) University, Davia, Florida, in 1987; and a Ph.D. in computer Engineering from florida Atlantic University, Boca Raton, in 2002.

Dr. Callaway joined the land Mobile Division of Motorola in 1984 as an RF engineer working on 800-MHz and (later) 900-MHZ truked radio products. In 1990, he transferred to Motorola's Paging Products Group, Boynton Beach, where he designed pasigned paging receivers for the japanese market.

From 1992 to 2000, Dr. Callaway was engaged in paging receiver and transceiver system design and was the lead receiver designer of Motorola's paging platform. In 2000, he joined Motorola Labs, Plantation, florida, where his interests include the design oflow-power wireless notworks. He is a Registered professional Engineer (Florida). He has published several papers and has had more 20 U.S. patents issued.

[1]Edgar H. Callaway, Jr., A Communication Protocol for Wireless Sensor Networks, Ph.D. dissertation, Florida Atlantic University, Boca Raton, FL, August 2002.

Chapter 1: Introduction to Wireless Sensor Networks

1.1 APPLICATIONS AND MOTIVATION[1][*]

In recent years, the desire for connectivity has caused an exponential growth in wireless communication. Wireless data networks, in particular, have led this trend due to the increasing exchange of data in Internet services such as the World Wide Web, e-mail, and data file transfers. The capabilities needed to deliver such services are characterized by an increasing need for data throughput in the network; applications now under development, such as wireless multimedia distribution in the home, indicate that this trend will continue. Wireless Local Area Networks (WLANs) provide an example of this phenomenon. The original (1997) Institute of Electrical and Electronic Engineers (IEEE) WLAN standard, 802.11, had a gross data rate of 2 megabits per second (Mb/s);[2], [3] the most popular variant now is 802.11b, with a rate of 11 Mb/s;[4] and 802.11a, with a rate of 54 Mb/s, is now entering the market.[5] Wireless Personal Area Networks (WPANs), defined as networks employing no fixed infrastructure and having communication links less than 10 meters in length centered on an individual, form another example: the HomeRF 1.0 specification, released in January 1999 by the Home RF [sic] Working Group, has a raw data rate of 800 kb/s with an optional 1.6 Mb/s mode;[6] the Bluetooth™ 1.0 specification, released in July 1999 by the Bluetooth Special Interest Group (SIG) and later standardized as IEEE 802.15.1,[7] has a raw data rate of 1 Mb/s;[8], [9] and IEEE 802.15.3, released in June 2003, has a maximum raw data rate of 55 Mb/s.[10] Both the 802.11 and 802.15 organizations have begun the definition of protocols with data throughputs greater than 100 Mb/s.

Other potential wireless network applications exist, however. These applications, which have relaxed throughput requirements and are often measured in a few bits per day, include industrial control and monitoring; home automation and consumer electronics; security and military sensing; asset tracking and supply chain management; intelligent agriculture; and health monitoring.[11] Because most of these low-data-rate applications involve sensing of one form or another, networks supporting them have been called wireless sensor networks, or Low-Rate WPANs (LR-WPANs), because they require short-range links without a preexisting infrastructure. An overview of applications for wireless sensor networks follows.

1.1.1 Industrial Control and Monitoring

A large, industrial facility typically has a relatively small control room, surrounded by a relatively large physical plant. The control room has indicators and displays that describe the state of the plant (the state of valves, the condition of equipment, the temperature and pressure of stored materials, etc.), as well as input devices that control actuators in the physical plant (valves, heaters, etc.) that affect the observed state of the plant. The sensors describing the state of the physical plant, their displays in the control room, the control input devices, and the actuators in the plant are often all relatively inexpensive when compared with the cost of the armored cable that must be used to communicate between them in a wired installation. Significant cost savings may be achieved if an inexpensive wireless means were available to provide this communication. Because the information being communicated is state information, it often changes slowly. Thus, in normal operation, the required data throughput of the network is relatively low, but the required reliability of the network is very high. A wireless sensor network of many nodes, providing multiple message routing paths of multihop communication, can meet these requirements.

An example of wireless industrial control is the control of commercial lighting. Much of the expense in the installation of lights in a large building concerns the control of the lights — where the wired switches will be, which lights will be turned on and off together, dimming of the lights, etc. A flexible wireless system can employ a handheld controller that can be programmed to control a large number of lights in a nearly infinite variety of ways, while still providing the security needed by a commercial installation.

A further example is the use of wireless sensor networks for industrial safety applications. Wireless sensor networks may employ sensors to detect the presence of noxious, poisonous, or otherwise dangerous materials, providing early detection and identification of leaks or spills of chemicals or biological agents before serious damage can result (and before the material can reach the public). Because the wireless networks may employ distributed routing algorithms, have multiple routing paths, and can be self-healing and self-maintaining, they can be resilient in the face of an explosion or other damage to the industrial plant, providing officials with critical plant status information under very difficult conditions.

The monitoring and control of rotating or otherwise moving machinery is another area suitable for wireless sensor networks. In such applications, wired sensor and actuators are often impractical, yet it may be important to monitor the temperature, vibration, lubrication flow, etc. of the rotating components of the machine to optimize the time between maintenance periods, when the machine must be taken off-line. To do this, it is important that the wireless sensor system be capable of operating for the full interval between maintenance periods; to do otherwise defeats the purpose of the sensors. This, in turn, requires the use of a wireless sensor network with very low energy requirements. The sensor node often must be physically small and inexpensive as well. Wireless sensor networks may be of particular use in the prediction of component failure for aircraft, where these attributes may be used to particular advantage.[12]

Still another application in this area for wireless sensor networks is the heating, ventilating, and air conditioning (HVAC) of buildings. HVAC systems are typically controlled by a small number of strategically located thermostats and humidistats. The number of these thermostats and humidistats is limited, however, by the costs associated with their wired connection to the rest of the HVAC system. In addition, the air handlers and dampers that directly control the room environment are also wired; for the same reasons, their numbers are also limited.

The heat load generated by people in a building is quite dynamic, however. Diurnal, hebdomadal, seasonal, and annual variations occur. These variations are associated with the distribution of people in the building throughout the day, week, season, and year; important changes also affect the heat load of the building at more irregular intervals. For example, when organizations reorganize and remodel, space previously used for offices may be used by heat-generating laboratory or manufacturing equipment. Changes to the building itself must also be considered: interior walls may be inserted, moved, or removed; windows, curtains, and awnings may be added or removed, etc. Due to all these possible variations and, as nearly anyone who works in an office building can attest, improvement is needed.

The root cause of such unsatisfactory HVAC function is that the control system lacks sufficient information about the environment in the building to maintain a comfortable environment for all. Because they do not require the expense of wired sensors and actuators, wireless sensor networks may be employed to greatly increase the information about the building environment available to the HVAC control system, and to greatly decrease the granularity of its response. Wireless thermostats and humidistats may be placed in several places around each room to provide detailed information to the control system. Similarly, wireless bypass dampers and volume dampers can be used in great number to fine-tune the response of the HVAC system to any situation. Should everyone in an office area move to the conference room for a meeting, for example, the system can respond by closing the volume dampers in the office area, while opening the volume dampers in the conference room. Should the group leave the building, the HVAC system may instruct the wireless bypass dampers to respond to the change in total building heat load. Should the group return during a driving rainstorm, the humidistat in the umbrella and coat closet could detect the increased humidity in that closet. The HVAC system could then place especially dry air there, without affecting the occupants elsewhere in the building.

The wireless HVAC system can also solve one of the great problems facing the HVAC engineer: balancing heating and air conditioning. It is often the case that heat sources are not uniformly distributed throughout a building. In the home, for example, kitchens tend to be warm, due to the heat of cooking, while bedrooms tend to be cool. In winter, more heated air needs to be sent to the bedroom, where it is cooler, and less heated air needs to be sent to the kitchen, where it is warmer. In summer, however, just the opposite is true — more cooled air needs to be sent to the kitchen, where it is warmer, and less cooled air needs to be sent to the bedroom, where it is cooler. This difference between the air distribution of heating and air conditioning is a difficult and expensive problem to solve with wired control systems, because a volume damper to each room in the house must be independently controlled. Often, the dampers are placed in a single, fixed position, leaving some areas perpetually cold and others perpetually warm. With wireless sensors and actuators in the HVAC system, however, the problem becomes trivial; the damper(s) to each room can be controlled by the sensor(s) in each room, leading to perfect system balance at any time of the year.

Such a wireless HVAC system has other advantages. Close monitoring of system performance enables problems to be identified and corrected before occupant complaints arise. In addition to the living-area sensors, wireless sensors may be placed inside air ducts (to monitor the performance of heat exchange apparatus, for example) without requiring maintenance personnel to make manual measurements atop ladders. In addition, sensors may be placed in attics and crawlspaces that contain ductwork; anomalous temperatures in such areas may indicate costly leaks of heated or cooled air. For these reasons, total building HVAC costs should drop, while occupant comfort would increase when wireless sensors and actuators are employed.

1.1.2 Home Automation and Consumer Electronics

The home is a very large application space for wireless sensor networks.[13] Many of the industrial applications just described have parallels in the home. For example, a home HVAC system equipped with wireless thermostats and dampers can keep the rooms on the sunny side of the house comfortable — without chilling the occupants on the shady side of the house — more effectively than a home equipped with only a single, wired thermostat. However, many other opportunities are available.

One application is the "universal" remote control, a personal digital assistant (PDA)-type device that can control not only the television, DVD player, stereo, and other home electronic equipment, but the lights, curtains, and locks that are also equipped with a wireless sensor network connection. With the universal remote control, one may control the house from the comfort of one's armchair. Its most intriguing potential, however, comes from the combination of multiple services, such as having the curtains close automatically when the television is turned on, or perhaps automatically muting the home entertainment system when a call is received on the telephone or the doorbell rings. With the scale and personal computer both connected via a wireless sensor network, one's weight may be automatically recorded without the need for manual intervention (and the possibility of stretching the truth "just this once").

A major use of wireless sensor networks in the home is expected to be for personal computer peripherals, such as wireless keyboards and mice. Such applications take advantage of the low cost and low power consumption that are the sine qua non of wireless sensor networks. Another application in the home is sensor-based information appliances that transparently interact and work symbiotically together as well as with the home occupant.[14] These networks are an extension of the information applicances proposed by Norman.[15]

Toys represent another large market for wireless sensor networks. The list of toys that can be enhanced or enabled by wireless sensor networks is limited only by one's imagination, and range from conventional radio-controlled cars and boats to computer games employing wireless joysticks and controllers. A particularly intriguing field is personal computer (PC)-enhanced toys, which employ the computing power of a nearby computer to enrich the behavior of the toy itself. For example, speech recognition and synthesis may be performed by placing the microphone and speaker in the toy, along with the appropriate analog-to-digital and digital-to-analog converters, but employing a wireless connection to the computer, which performs the recognition and synthesis functions. By not placing the relatively expensive yet limited speech recognition and synthesis circuits in the toy, and using the (much more powerful) computing power already present in the computer, the cost of the toy may be significantly reduced, while greatly improving the capabilities and performance of the toy. It is also possible to give the toy complex behavior that is not practical to implement in other technologies.[16]

Another major home application is an extension of the Remote Keyless Entry (RKE) feature found on many automobiles. With wireless sensor networks, wireless locks, door and window sensors, and wireless light controls, the homeowner may have a device similar to a key fob with a button. When this button is pressed, the device locks all the doors and windows in the home, turns off most indoor lights (save a few night lights), turns on outdoor security lights, and sets the home's HVAC system to nighttime (sleeping) mode. The user receives a reassuring "beep" once this is all done successfully, and sleeps soundly, knowing that the home is secure. Should a door be left open, or some other problem exists, a small display on the device indicates the source of the trouble. The network may even employ a full home security system to detect a broken window or other trouble.

Outside of the home, the location-aware capabilities of wireless sensor networks are suitable for a diverse collection of consumer-related activities, including tourism[17] and shopping.[18], [19] In these applications, location can be used to provide context-specific information to the consumer. In the case of the tourism guide, the user is provided only information relevant to his present view; in the case of the shopping guide, the user is provided information relevant to the products before him, including sale items and special discounts and offers.

1.1.3 Security and Military Sensing

The wireless security system described above for the home can be augmented for use in industrial security applications. Such systems, employing proprietary communication protocols, have existed for several years.[20] They can support multiple sensors relevant to industrial security, including passive infrared, magnetic door opening, smoke, and broken glass sensors, and sensors for direct human intervention (the "panic button" sensor requesting immediate assistance).

As with many technologies, some of the earliest proposed uses of wireless sensor networks were for military applications.[21] One of the great benefits of using wireless sensor networks is that they can be used to replace guards and sentries around defensive perimeters, keeping soldiers out of harm's way. In this way, they can serve the same function as antipersonnel mines, without the attendant hazard mines represent to allied personnel during the battle (or the civilian population afterward). In addition to such defensive applications, deployed wireless sensor networks can be used to locate and identify targets for potential attack, and to support the attack by locating friendly troops and unmanned vehicles. They may be equipped with acoustic microphones, seismic vibration sensors, magnetic sensors, ultrawideband radar, and other sensors.[22]