

Commercial Applications of Wireless Sensor Networks Using ZigBee

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ABSTRACT

After around a decade of active research on wireless sensor networks, recent standards released are stimulating the development of commercial products. One of these standards is ZigBee. This article highlights some of the lessons from the field that went into the standard. It also describes the ecosystem emerging around Zigbee, and the enabling trends in that ecosystem. New areas of activity in the ZigBee standards body are highlighted as well.

INTRODUCTION

Wireless sensor networks have been an active research topic for around a decade. The recent release of standards in the field, such as IEEE 802.15.4 and ZigBee, brought the technology out of research labs and stimulated the development of numerous commercial products. Moving from early research in military applications, sensor networks now are widely deployed in diverse applications including home automation, building automation, and utility metering. Although many early sensor networks used proprietary routing algorithms and RF technology, most recent products use standards-based networking and RF solutions.

A key enabling standard for much of the commercial activity in the wireless sensor network area is the IEEE 802.15.4 standard. This PHY and MAC (media access control) layer standard defined a 250kb/s direct sequence spread spectrum (DSSS) radio operating in the 2.4GHz unlicensed band with lower bit-rate alternatives in the 868 MHz and 900 MHz bands. This standard now enjoys extensive silicon support, primarily in the 2.4GHz band. On top of this PHY and MAC layer standard, several proprietary and standards-based sensor network systems emerged. The one with the most vendor and end-product support is the ZigBee standard. This article presents a survey of the most active application areas that use ZigBee and the trends that drive them, focusing on systems that are commercially available.

The ZigBee standard has evolved since its original release in 2004. Several years of field trials and product development experience were

rolled into a new revision of the standard set, to be ratified in early 2007, known as ZigBee Pro. This article highlights some of the field learning that went into the standard and what has changed in the specification to address field lessons and commercial feedback. Much of what makes possible more commercial applications is the emergence of a more complete ecosystem around the standard. Major enabling trends in this ecosystem also are examined. Finally, new areas of activity in the standards body are highlighted.

THE EMERGENCE OF THE ZIGBEE STANDARD

Early research on wireless sensor networking grew out of broader research initiatives focused on general wireless mesh networks. Many of the early applications that were envisioned for the technology were military in nature, reflecting an early source of funding for this research. A number of major initiatives in the field, such as the TinyOS community [1], grew out of DARPA (Defense Advanced Research Projects Agency) funded research. Several companies, including Ember, Dust, Sencisat, and others, started to capitalize on the commercial prospects of sensor network technology between 2000–2002. Each of these companies had proprietary networking technology. At the same time, several wireless component vendors and potential sensor network users started to move forward with an industry standards body that came to be called ZigBee. Requiring a PHY and MAC layer on which to build a network and application layer, they initiated the 802.15.4 task group within the IEEE. The group charter was to standardize a PHY and MAC optimized for low-cost, low-power, and robust RF performance. Primary contributors were ZigBee member companies, including major contributions from Philips and Motorola. This effort led to the ratification in 2003 of a standard in the 2.4GHz, 900MHz, and 868MHz unlicensed bands [2]. The 802.15.4 standard is low-bit rate, operating at 250kb/s in the 2.4GHz band and 40kb/s/20kb/s in the 900/868MHz bands. Since that time, numerous vendors introduced silicon support for 802.15.4, primarily at the 2.4GHz band. Several compa-

nies who had proprietary network systems, such as Ember, began actively working on the ZigBee standard as it emerged, believing that a standardized system would be of great benefit in accelerating the adoption of wireless sensor networking technology.

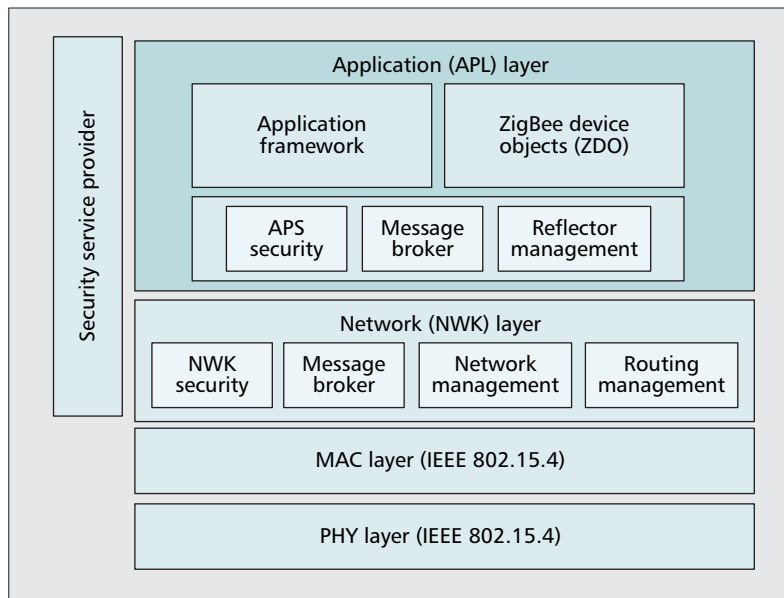
The ZigBee standard builds on top of the 802.15.4 MAC and PHY layers and encompasses a complete network stack for wireless sensor networking focused on sensor and control networking. A stack diagram showing major components is in Fig. 1. Major functionality provided by the stack includes device association and addressing, network routing, security, and device management. The ZigBee standard also defines application profiles that specify device types for various applications with over-the-air interfaces that must be supported by these device types. The original version of the standard was ratified in 2004 [3].

Since the original ratification of the standard, numerous OEM companies as well as silicon and system suppliers, became involved in the standards group. ZigBee now has 13 promoter companies and over 200 member and adopter companies that represent both technology suppliers and OEM device manufacturers who use the technology. System-on-chip (SoC) or system-in-package (SiP) devices containing an 802.15.4 radio, a microprocessor, and sensor I/O are now available from a variety of silicon suppliers, including Ember, ST Microelectronics, Freescale, Texas Instruments, Jennic, Integration, and others. The low cost of materials and the easier RF design enabled by SoC devices helped increase adoption of the standard.

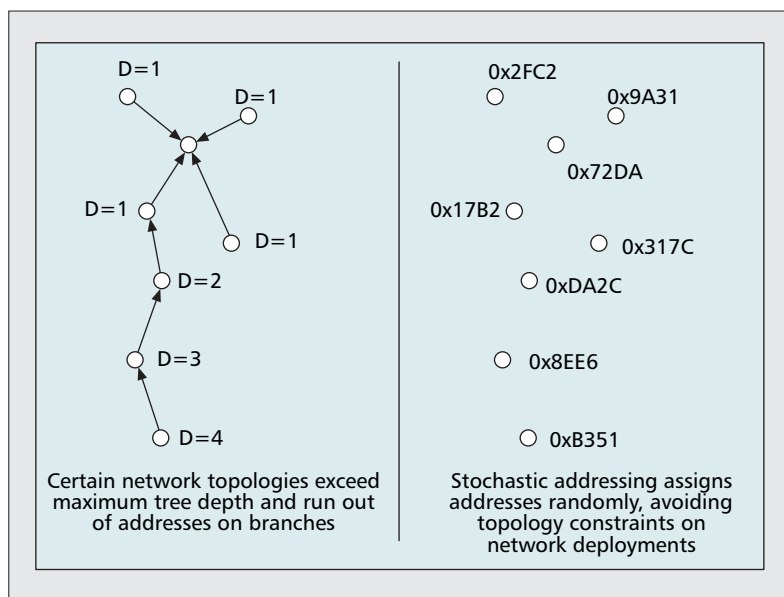
Both technology vendors and OEM product companies have gained a significant amount of field experience over the past several years. Some of this experience is from legacy proprietary systems that predated ZigBee. Other experience came from using the first version of the ZigBee standard in the field. This field experience has identified a variety of enhancements and changes required to improve the scalability and robustness of the ZigBee standard. The ZigBee Alliance is preparing to release a major enhancement to the standard that incorporates many of these changes. The new stack, called ZigBee Pro, is due to be ratified in early 2007. Some of the lessons learned in the field have come from Ember customer deployments, as well as large scale test networks (~500 nodes) used by Ember for development. A few of the major changes are highlighted below.

STOCHASTIC ADDRESSING

The 2004 ZigBee standard used a tree structure for addressing as dictated by the cluster tree routing that forms the primary routing mode of the stack. A single coordinator node routes the network and address tree. Addresses are distributed in a tree fashion as devices join the network. Cluster tree routing minimizes route storage. By using a destination address and a formula, any node can route along the tree. Real world deployment constraints identified several limitations in this addressing and routing method. In large scale deployments (usually hundreds of devices), constraints on the depth of the tree and limitations on the number of children a device



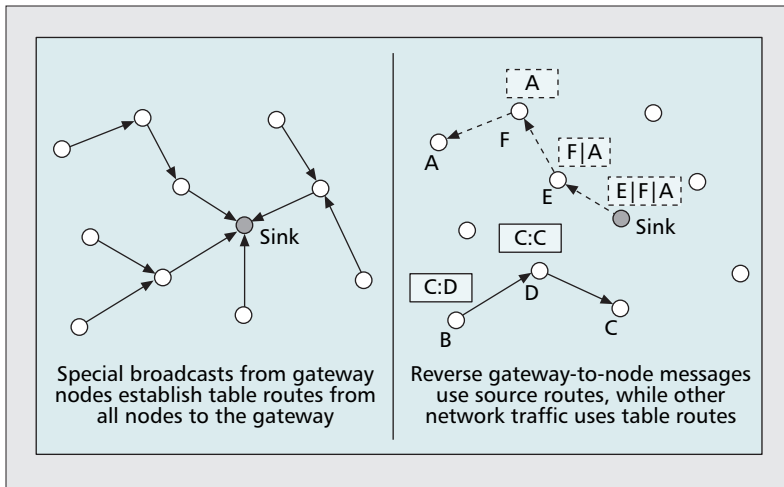
■ Figure 1. ZigBee stack diagram.



■ Figure 2. Tree-based addressing and stochastic addressing.

could have, meant that it was likely that certain physical topologies would run out of addresses while deploying. Customers of Ember, such as Philips Lighting, have systems that reach hundreds of nodes per floor in commercial buildings. Without carefully planning deployment in large-scale networks, networks can run out of addresses in long branches of the tree structure. This type of careful deployment planning, with the idea of avoiding these situations, is unacceptable to many users in the building automation area. For example, Philips did not want to require its installers to learn network architecture.

The ZigBee Pro standard introduces a much more scalable addressing scheme based on the random assignment of addresses as used in Ember's pre-ZigBee proprietary system, EmberNet. New devices joining a network pick an address from the address space at random. With



■ **Figure 3.** Multiple simultaneous routing techniques.

a 16-bit address space and individual networks typically reaching only a few thousand devices at a maximum, collisions are not very common. Additionally, the network stack contains address conflict resolution mechanisms so that address conflicts are detected based on unique IEEE MAC addresses and resolved with minimal impact to the network. This addressing system was used for the first deployments of the Philips Lighting wireless systems and also was field tested in deployments reaching thousands of devices in an Asian utility metering product. Extensive field testing ensured that the stability and scalability of the feature were proven before being included in the specification.

MULTIPLE ROUTING ALGORITHMS

A lesson learned from both research and implementation of commercial systems is that any single routing algorithm is unlikely to be optimal for all traffic patterns when both memory overhead and network traffic overhead must be minimized. ZigBee devices tend to have only 4–8 kilobytes of RAM to minimize cost. Many algorithms commonly used in wireless sensor networks require an entry to be added for each route a node participates in. Algorithms such as AODV (ad hoc on demand distance vector) have this characteristic. In systems where most traffic is local, this can be efficient.

ZigBee Pro makes use of two routing algorithms in the same network to minimize both storage and network overhead for several common traffic patterns. A few types of traffic appear frequently in wireless sensor networks. One is best described as any-to-any traffic, involving two devices in a network that must communicate. In a control system, this might be a sensor and actuator forming a control loop in a larger system. For this common type of traffic, ZigBee Pro makes use of a TinyAODV [4] derivative. This table-driven on-demand routing protocol is reasonably efficient in networks that are largely static in connectivity and primarily have localized traffic. Each device participating in a route must store a table entry for that route, consuming memory. For localized traffic, the memory overhead is constrained to devices on the route.

Another common traffic scenario involves a large number of sensors reporting information into a gateway. To enable two-way communication to occur from the gateway back out to the sensors using table-driven routing, a large amount of memory would be required, especially on devices close to the gateway. Additionally, if a table-driven approach were used, each sensor node would be required to perform a broadcast-based route discovery to the gateway. Broadcasts are very expensive in terms of bandwidth as they are repeated across the network. The ZigBee Pro stack uses proactive construction of routes from sensors into the gateway by providing a mechanism for gateway devices to broadcast their presence, creating table routes to the gateway in all other devices (i.e., next-hop type of routes). The reverse path is accomplished with no stored memory overhead to network devices by using source routing. When sensors send data into the gateway, a reverse source route is built up in the packet. The gateway device can immediately send a reply without saving the route, or if it has extra memory, can save the route for use at any time. Periodic communication into the gateway from sensors ensures that the source routes do not become stale as network connectivity changes. Although this trades off some network traffic overhead in each packet and is limited in the size of the path that can be used, practical applications tend to be more concerned about the cost of each device than about strict bandwidth efficiency.

Developers making use of the ZigBee Pro standard have both these routing mechanisms available to them via an explicit selection mechanism. When setting up connections, communications can be defined as a point-to-point connection or a many-to-one connection.

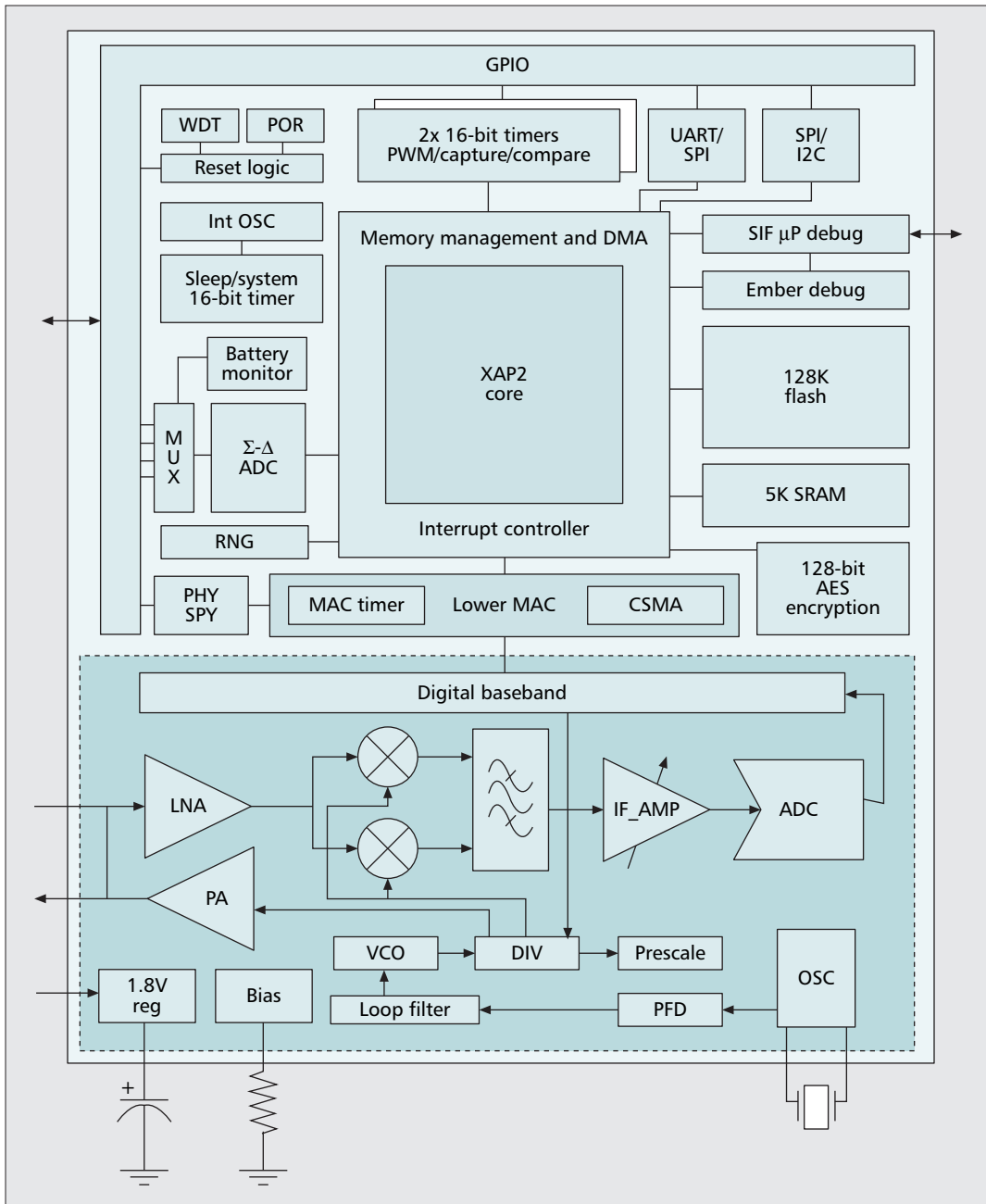
ASYMMETRIC LINK DETECTION

A frequent problem with early research algorithms and with the original ZigBee 2004 specification is their inability to avoid asymmetric links. Real radio systems in the field often have asymmetric links due to manufacturing variances in the radios. Two devices with slightly different sensitivities, perhaps due to components in the radio front-end, will experience asymmetry in the reliability of the link between them. Since many routing algorithms, including TinyAODV, actually construct paths using links in the reverse direction, a routing path may be created that is functional in the destination to source direction, but not in the forward direction from source to destination. ZigBee Pro adds functionality to detect asymmetrical links and construct paths using forward links instead of reverse links. Each routing device periodically exchanges link reliability information with its neighbors, informing them of its measure of link reliability to each neighbor. This information enables devices to weight links during route discovery using metrics based on the reliability in the direction the link actually will be used.

ECOSYSTEM DEVELOPMENT

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As the ZigBee standard matured, an ecosystem formed, supplying the tools and components that developers require to design, develop, produce, and install wireless sensor networks. Various important steps were taken in each of these areas.



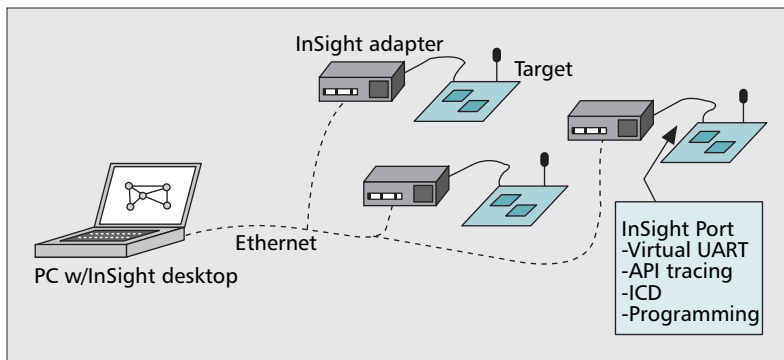
■ Figure 4. Typical ZigBee system-on-chip block diagram.

and install wireless sensor networks. Various important steps were taken in each of these areas. Developers of wireless sensor network systems for commercial use often do not have a wireless communication background because the typical applications are in areas that have had little deployment of wireless systems to date.

One of the important ecosystem developments is the emergence of fully integrated system-on-chip products that permit the development of many sensor and control devices by using a single IC. A typical system-on-chip device for ZigBee use consists of an 802.15.4 RF front-end, the associated baseband circuitry, a microprocessor, flash, RAM, and a complement of general purpose I/O. Since much of the appeal of wireless sensor networks is their ability to make various sensing and control applications more cost effective,

low-cost system-on-chip devices are important in moving applications from research into commercialized products. Multiple silicon vendors, including Ember, ST Microelectronics, TI, Freescale, Jennic, Integration, and others, now provide system-on-chip devices for the 2.4GHz 802.15.4 standard, with associated microprocessors ranging from 8-bit to 32-bit cores. The tight integration of RF and microprocessor enables clocking and peripherals to be designed with low-power battery operated systems in mind.

Another important area of ecosystem development is the area of developer tools. Typical debugging tools for wireless networks, such as packet sniffers, were the only tools available early on. For large-scale sensor network development, packet sniffers quickly become unwieldy, providing a level of detail that is usual-



■ **Figure 5.** Ethernet-based back channel for debugging.

ly at a much lower layer than is useful for application development.

Instead of looking at individual packets, it is more useful to look at end-to-end application-level flows and transactions across the network. A new set of tools called *network analyzers* emerged that permit this through both visualization and programmatic analysis. They were augmented with even more functionality due to on-chip support for network debugging in some of the system-on-chip silicon platforms, such as Ember's. A typical problem with over-the-air analysis of packet traffic in a multi-hop network is that a promiscuous mode sniffer device may hear packets that network devices do not hear and may miss packets that were heard by an actual device in the network. Some system-on-chip devices, such as Ember's EM250 and EM260 now include interface ports that provide a non-intrusive trace of all packets sent from or received at a device. Using an adapter that communicates with the debugging application via TCP/IP over Ethernet, PC-based debugging tools can take advantage of the on-chip debugging I/O. Although this is not a practical method of debugging networks in the field, it provides a highly useful tool during lab development. The wired debugging channel also provides significant bandwidth for the transfer of other types of debugging data about application behavior. Unlike higher bit-rate wireless systems, wireless sensor networks can easily be swamped by trying to send out debugging traffic in addition to application traffic and thus, these wired debugging channels are valuable for application debugging.

CURRENTLY DEPLOYED APPLICATION AREAS

The majority of applications currently deployed using the ZigBee standard fall into three application areas: home automation and monitoring, building automation, and utility meter reading and control. The following section focuses on each area in turn, examining their drivers and some examples of commercially available systems using Ember's chipsets.

HOME AUTOMATION

Possibly the highest volume shipping application using ZigBee mesh networks today, home automation originally was not one of the typically envi-

sioned applications for sensor networking. A variety of factors, including the speed at which consumer products are designed and brought to market has caused this market to move quickly. Initial applications brought to market focused on two primary areas: comfort and awareness/safety. Products that focused on comfort and convenience fit into the traditional home automation applications such as lighting control and audio/video control. However, sensor networking is used in the home for much more than the traditional home automation uses. Some products focus on providing home owners with more awareness of the state of their homes without requiring a full-blown security system. Others are starting to focus on using sensor and control technology to save energy.

Eaton's Home Heartbeat system [5] is a home awareness system that is essentially a sensor network for a house. The system consists of a variety of sensors that can monitor a home. A gateway device can send messages to a mobile phone when the home owner is away from the house, or to a keychain display when a home owner is at home. The Home Heartbeat system can monitor events such as water leaks via a water presence sensor, small appliance usage via a power sensor, door and windows with an open/close sensor, or presence via an occupancy sensor. At any time, the state of each sensor can be checked via the keychain or a mobile phone interface. Alerts can be set on the keychain so that the user can be informed of state changes in any of the sensors. Intended to be an awareness system rather than a security system, it is designed to be installed by an end consumer and is marketed through both electronics stores and home improvement stores. The system also brings some control elements into the network in the form of a water shut-off valve and switchable outlet.

To bring sensor network technology to the mass-market consumer, several design and technology problems must be overcome. The first can be termed the commissioning problem. During installation, consumers must be able to indicate to the system what a sensor is monitoring and where it is (e.g., basement sump pump leak detector as opposed to upstairs bathroom leak detector). The solution in the Home Heartbeat system uses a keychain fob with an LCD and scroll-wheel as a commissioning device to ensure that even consumers without a computer, or with limited computer experience, can still use the system. Each sensor has a groove built into its design that can accommodate the key-like end of the keychain fob. On insertion, a magnetic switch triggers the sensor to enter a mode where it searches for networks with joining permitted. The key fob's trigger causes the network to enter a state where a sensor join is briefly permitted. Users are presented with a menu on the key fob with naming options relevant to the sensor just triggered. In this way, users have an easy way to name sensors without using a PC and can indicate the network to join by virtue of a physical action rather than by dealing with network names or IDs.

The other architectural design decision, at first glance, may seem counter to the spirit of self-organizing networks, but is done to prevent user confusion, an important consideration in wireless systems aimed at consumers. Each sen-

sensor device is a non-routing member of the network. Explicit *range-extender* devices are provided to form a mesh network within a house. Using devices whose sole purpose is to form a network rather than to also accomplish sensor tasks does increase the cost of the system, but also increases predictability in a situation where the user of the system has little or no ability to analyze the network. It also increases the predictability of battery life of the sensor devices. Consumers can more easily understand the concept of a range extender and scatter a few around a house, rather than grasping that each device is a mesh router. As each sensor is installed, it must be in range of one of the extenders. This prevents each sensor that is added from affecting the network coverage. The risk of the network being partitioned (by a sensor being removed) or running out of batteries is also minimized.

In addition to the Home Heartbeat system, numerous other products that offer traditional home automation functionality such as lighting control, home theater control, and sophisticated heating control are now available and make use of ZigBee. Well known automation companies such as Crestron and AMX have released wireless mesh variants or extensions for their products and are joined in the market by newer companies such as Control 4 who base their products entirely on wireless mesh networking. Each of these companies selected wireless mesh networking to enable home automation technology to be applied to retrofit situations or to provide whole house mobility to devices such as remote controls. Today, these companies work primarily through professional installers, and therefore do not have the same requirements as the Home Heartbeat system for ease of installation by non-technical consumers. This permits them to provide more complex programmability than a consumer-installed system could have. Systems like Control 4, which is based on the ZigBee standard, also make use of the open nature of the standard to enable other vendors' devices to attach to the system, tapping the whole emerging ecosystem of ZigBee products.

BUILDING AUTOMATION

Another application area that experienced substantial commercial deployment is building automation. This relatively broad term can cover all aspects of building system control including heating and air conditioning (HVAC), lighting control, and security systems. The relatively high cost of energy and a growing movement toward energy efficiency has made energy management one of the key drivers in the adoption of wireless sensor networks in commercial buildings. Similar to the residential market, a substantial market exists in retrofitting existing buildings. Traditional wired building automation networks usually are used only in new construction or major retrofits. The low installation cost of mesh-based wireless systems allows the larger retrofit market to be addressed. Unlike residential automation systems, the relatively frequent repartitioning of commercial space as tenants come and go makes a wireless system (that can be easily moved and reconfigured) an even better proposition than it may appear at first. Finally, the granularity with

which sensors such as temperature and occupancy can be placed permits a level of control that would be prohibitive with wired systems.

An example of energy management systems using wireless sensor networking is the WiSuite automation system from Riga Development [6]. This energy management system is targeted initially at hotel and motel properties. Consisting primarily of thermostat devices and control interfaces for in-room heating and cooling units, the system interfaces into the hotel reservation system for occupancy information. When a room is occupied, temperature can be set using the in-room thermostat. When a room becomes unoccupied, the system automatically dials back the set point on the thermostat to minimize energy usage. Using just this relatively simple concept, the system permits building operators to realize substantial energy savings. Because of the relatively low hardware and installation costs when using a wireless mesh for communications, the cost of energy saved on a monthly basis usually exceeds the monthly payments for a system financed over just a few years. This enables an installation to be cash-flow positive on installation and minimizes the amount of capital required.

From the perspective of a network architecture, this application is a mix of line-powered and battery-powered devices. Heating and cooling units require line power to operate, so interface units connected to these devices can form an always-on mesh network. Thermostat devices can be battery powered and wake infrequently to communicate with the control system. The WiSuite system is using the ecosystem of ZigBee standard products to provide additional energy savings by also controlling other in-room systems, such as mini-bars and lighting. The energy savings alone can justify the entire system; however, the presence of a communication network and sensors in the hotel also permits run-time analysis of the performance and state of the HVAC units. The thermostat devices can detect catastrophic failures when temperature does not change in response to control. The system also can monitor the rate of temperature change and provide early detection of improperly functioning heating and cooling units. Blocked filters or failing compressors can easily be detected by changes in the rate of heating or cooling. In addition to improving comfort by ensuring proper operation, additional energy is saved by catching inefficient unit operation early. The WiSuite system provides maintenance alerts through multiple means including email and SMS (short message service) services.

Another building automation system that was commercially released using ZigBee networking is commercial lighting control. The Equos lighting system from Philips Lighting consists of digital fluorescent ballast units with a ZigBee network interface. Although digital ballast units can self-diagnose themselves and detect bulb failure, the existing wired lighting control buses do not provide mechanisms to extract this information. By including a wireless mesh networking interface, the system can provide both diagnosis and control. Commercial buildings, which often undergo substantial reconfiguration of internal partitioning, present particularly compelling cases for wireless based lighting control. As

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internal partitions are moved, lights can easily be assigned to different zones of control.

The Equos system consists primarily of three components: lighting ballasts, lighting controllers, and switches/sensors. Since the lighting ballasts require line power, their radios can form an always-on network backbone, while the switches and sensors can be battery powered, waking only to send control and status messages. Wireless sensor networks are typically characterized by relatively long latencies, especially over large multi-hop areas. Lighting control poses particular challenges, because people are used to rapid (<200ms) response from light switches. Fluorescent devices have slightly less challenging response time requirements than other fixtures, as people are used to a slight delay when the lights are turned on. The Philips system makes use of the new multicast feature in the ZigBee Pro network stack to obtain low latency response to a large number of devices. Lights in a single control group are assigned to one or more multicast groups, and switches control a multicast group. On a state change from the switch, a multicast message is sent out. The underlying implementation used is a radius constrained broadcast. This simple multicast mechanism is reasonably optimal in situations where multicast group members are primarily in physical proximity to each other. In a lighting system, that is the normal case.

The system also uses the many-to-one routing function to provide maintenance information about the state of the ballast and lights. The efficiency and energy consumption of the ballasts can be monitored through the system with bulb state. Although many large commercial buildings regularly replace all bulbs based on their MTTF (mean time to failure), this process can be more cost efficient by batching jobs of bulbs that are nearing their end of life, permitting more bulbs to be used longer. By monitoring energy usage at the ballast, building operators can spot ballasts that are no longer performing efficiently. The lighting system also can be augmented with several other low-cost sensors, whose installation is made significantly more cost-effective due to the presence of the wireless infrastructure provided by the ballasts. These include light level sensors and occupancy sensors. Lighting control units can take advantage of both to use energy more efficiently. Light level sensors can allow the brightness of lighting ballasts to be adjusted based on the ambient light present from natural light. Occupancy sensors permit lighting zones to be turned off when unoccupied. Although both these technologies were possible before the advent of wireless lighting ballasts, their installation costs were often prohibitive due to wiring.

The trend to increase the energy efficiency of buildings, and the desire to make this possible on the large existing set of commercial buildings, is helping to drive the adoption of wireless sensor networks in buildings. The frequent need to reconfigure physical spaces within office buildings to meet the requirements of new tenants increases the appeal of a wireless-based control system, even in new construction where the cost of wiring is much lower.

UTILITY METER COMMUNICATION

A large percentage of the residential utility meters (water, gas, electric) in the U.S. and Europe are read remotely using a variety of technologies. A growing number in other places are rapidly being converted to remote reading. Although radios based on 802.15.4 2.4GHz technology do not have the point-to-point range required for many metering applications, in some situations, it is a compelling technology. In areas where utility meters are densely deployed, such as large apartment or condominium buildings or dense urban areas, sub-metering solutions using ZigBee wireless sensor networks are being fielded.

One area of utility metering that is experiencing a large amount of interest is in energy savings and demand control. Upcoming legislation in California (Title 24) [7], regarding energy efficiency of buildings, requires a certain amount of electricity demand management to be available. One commonly discussed form is a meter that can communicate into the house to indicate more dynamic pricing of electricity, as well as turn down air conditioning (increase the set temperature) in situations where the electricity grid is nearing failure. With ZigBee increasingly present in home automation systems, several utilities are strongly considering it for the communication mechanism to satisfy the upcoming Title 24 requirements. At least one major brand of thermostat, ritetemp, is rolling out ZigBee-based wireless thermostats. The initial versions were created in a way to make it easy to relocate thermostats in a house, but future versions are being developed to comply with the Title 24 legislation. As in other areas of automation, devices that can be controlled for energy management easily can be extended by making use of other home automation products that already support ZigBee.

FUTURE DIRECTIONS

The commercial field of wireless sensor networks is still emerging, and a large amount of development activity is going into both the system components, as well as the commercial system using the sensor networks. Several technologies are emerging from research into commercial implementation that promise to change the way that these networks are used and programmed.

LOCATION DETECTION

The promise of asset tracking through supply chains helped propel the adoption of RFID (radio frequency identification) in both retail and military applications. Although passive RFID is useful in situations where items pass through doors that can be outfitted with readers or will sit on shelves that also can be outfitted, a wide variety of assets are better suited to being tracked with an active RF device. In a situation such as tracking medical equipment inside a hospital, it would be cost prohibitive to cover enough of the area with RFID readers to find the equipment. In these situations, a wireless sensor network that could report the locations of critical equipment is valuable. While 802.15.4 does not lend itself well to precise time-of-flight measurements due to its narrow bandwidth (~2MHz), it can be used to obtain a signal

strength measurement. Signal strength (RSSI) is not a good way to measure distance, given the high variation seen due to small scale fading (often 20dB or more) and very different path loss characteristics found in typical buildings. However, when enough different readings are combined with a priori knowledge of the building or network layout, accuracy in the range of a few meters is obtainable. Various algorithms were proposed in the literature [8], and several commercial implementations are starting to be fielded. This promises to open the field of asset tracking to wireless sensor networking and also enable richer current applications. When a light in a commercial lighting system is failing, the rough location of the ballast can be found without a requirement that it be entered manually at installation.

SYSTEM-LEVEL PROGRAMMING AND IT INTEGRATION

The method for treating entire wireless sensor networks as a single entity to be programmed is another topic that received wide coverage in research literature [9]. Today, commercial systems are largely programmed at the device level, leading to difficult debugging and a frequent failure to view the application running across the network as a distributed application. Research methods have included treating a network of sensors as a database on which queries can be run or as a distributed set of processors on which programs can be parallelized. These approaches hold the promise of making the task of programming these devices easier and more efficient. However, to be practical in commercial settings, they require a great deal of tool chain development. Today's research tools tend to have too many limitations in the types of applications they can handle. This is rapidly changing as several companies begin to commercialize technology in this area. At the same time, more people are treating these networks as an extension of the Internet and viewing them as something to be integrated into the IT structure and connected to business process systems rather than to be used and managed only by traditional facilities systems. Today, IT and facilities management are typically very separate functions, but with the inclusion of more networked systems in a building and a desire to remotely manage them, higher integration of these two areas is likely.

CONCLUSION

After years of active research, wireless sensor networks emerged as a viable commercial technology. What began as a significant research activity moved into commercial deployment several years ago. Since that time, a major shift occurred from largely proprietary systems, closely related to their research predecessors, to standards-body based activity. The standardization of radio and network layers via groups like ZigBee led to wide-spread availability of low-cost system-on-chip devices. This in turn led to large-scale commercial deployments.

Today, applications in the areas of home automation, building automation, and utility meter reading represent the bulk of the deployed wireless sensor network devices. The current

deployments are largely wireless adaptations of existing applications. The initial impetus for the use of wireless technology was access to retrofit markets and lower installation costs compared to traditional wired systems. Increasingly, commercial users of wireless sensor networks are taking advantage of the technology to provide services and features that were impossible or cost prohibitive in the past. Predictive maintenance of HVAC and lighting systems and advanced energy management through utility meters are good examples of this trend.

With ZigBee Pro arriving this year and other competing standards and propriety systems experiencing continued development, wireless sensor networking is a very dynamic field and likely will remain so over the next few years. Today's applications will give way to new applications that are more novel and less about replacing costly communication technologies. As the cost of wireless sensor network devices falls with widespread deployment, many new application areas can be opened. The research into finding higher level methods of programming these devices will become important in developing applications that can effectively use large quantities of wireless sensors. The killer application for wireless sensor networks has not emerged yet, but as the underlying layers solidify, price per device falls, and more advanced programming tools emerge, inevitably it will be developed.

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BIOGRAPHY

ANDREW WHEELER (andy@ember.com) holds Bachelor's and Master's degrees from MIT in electrical engineering and computer science. Currently, he serves as chief technology officer of Ember Corporation, a leading provider of ZigBee silicon and software solutions and a promoter-level member of the ZigBee Alliance. Prior to taking the role of CTO at Ember, he co-founded Ember and served as vice president of engineering. As CTO, he drives the company's technical roadmap and is actively involved with planning future products. Prior to starting Ember, he developed RFID car access systems for Zipcar. His embedded systems background includes system and board-level hardware design, component design, and embedded software programming at Walt Disney Imagineering, Woodward McCoach Inc., and the MIT Media Lab, where he designed and deployed the first large-scale implementation of Ember's patented technology under a DARPA grant. He was named one of the world's Top Young Innovators in 2003 by *Technology Review*.

With ZigBee Pro arriving this year and other competing standards and propriety systems experiencing continued development, wireless sensor networking is a very dynamic field and likely will remain so over the next few years.