

# Home Networking with IEEE 802.15.4: A Developing Standard for Low-Rate Wireless Personal Area Networks

*Ed Callaway, Paul Gorday, and Lance Hester, Motorola Laboratories*

*Jose A. Gutierrez and Marco Naeve, Eaton Corporation*

*Bob Heile, Apparent Technologies*

*Venkat Bahl, Philips Semiconductors*

## ABSTRACT

This article presents the IEEE 802.15.4 draft standard and its home networking applications. The main features of the standard are network flexibility, low cost, and low power consumption; the standard is suitable for many applications in the home requiring low-data-rate communications in an ad hoc self-organizing network.

## INTRODUCTION

There have been several attempts to network the home environment through proprietary solutions, and through standards such as HomePNA, the Homeplug Powerline Alliance, CEA R-7, HomeRF, and Echonet. The approaches to achieve this goal can easily be classified in two groups: wired and wireless networks.

In the wired arena, telephone lines (analog, basic digital, and DSL-like), cable modems, and power line carriers are the main drivers [1]. Each one offers several advantages and disadvantages that depend on bandwidth capacity, installation, maintenance, and cost, among others.

Recently, wireless communications has become a disruptive technology for home networking and home automation designers. A key motivation for use of wireless technology is the reduction in installation cost, since new wiring is not needed. Wireless networking conveys information exchange with minimal installation effort. This trend follows from the wider availability of cheaper and highly integrated wireless components and the success of other wireless communication technologies such as cellular and Wi-Fi™, IEEE 802.11b.

Various in-home applications are driving the need for communications. Broadly speaking,

these can be classified as Internet connectivity, multi-PC connectivity, audio/video networking, home automation, energy conservation, and security. Each of these comes with different requirements for bandwidth, cost, and installation procedure. With the explosive growth of the Internet, the major focus to date has been in satisfying the need for shared high-speed connectivity.

On the other side of the spectrum, applications such as home automation, security, and gaming have relaxed throughput requirements. These applications cannot handle the complexity of heavy protocol stacks that impact power consumption and utilize too many computational resources. Of course, this has a direct implication on cost.

Consider a small temperature sensor at a window. This sensor may need to report its temperature only a few times per hour, be inconspicuous, and have a very low selling price. This application is an excellent candidate for a low-throughput low-cost wireless communications link. The use of wires (for communication or power) is impractical because of the use of a house window. Furthermore, the wired installation cost would exceed by several times the cost of the sensor. On the technology side, extremely low power consumption is needed, since frequent battery replacement is impractical. Obviously, 802.11 is an overkill technology for this application, satisfying only the connectivity requirement. Bluetooth was originally conceived as a cable replacement, but has since followed a "high complexity" trend, making it unsuitable for low-power-consumption applications. The complexity trend has also increased the threshold of its promised cost. Both 802.11 and Bluetooth devices would require battery replacement several times per year; this is

clearly impractical if many windows are involved in the application (e.g., in a typical home).

In 2000 two standards groups, ZigBee, a HomeRF spinoff, and IEEE 802 Working Group 15, combined efforts to address the need for low-power low-cost wireless networking in the residential and industrial environments. In December of that year the IEEE New Standards Committee (NesCom) officially sanctioned a new task group to begin the development of a low-rate wireless personal area network (LR-WPAN) standard, to be called 802.15.4. The goal of this group was to provide a standard with ultra-low complexity, cost, and power for low-data-rate wireless connectivity among inexpensive fixed, portable, and moving devices. The scope of Task Group 4 is to define the physical (PHY) and media access control (MAC) layer specifications [2]. Some of the high-level characteristics of 802.15.4 are summarized in Table 1.

Currently the IEEE 802.15.4 standardization effort is approaching an initial release, and semiconductor manufacturers are getting ready to start production of the first integrated circuits (ICs) to implement the draft standard. In parallel, users of the technology are shifting their focus toward the definition of application profiles for the first products, an effort organized by the ZigBee Alliance.

This article reviews the main features of the IEEE 802.15.4 draft standard and shows how they satisfy the requirements of the applications that drove their development.

## APPLICATIONS

IEEE 802.15.4 is designed to be useful in a wide variety of applications, including industrial control and monitoring; public safety, including sensing and location determination at disaster sites; automotive sensing, such as tire pressure monitoring; smart badges and tags; and precision agriculture, such as the sensing of soil moisture, pesticide, herbicide, and pH levels [3]. However, one of the largest application opportunities for IEEE 802.15.4 is home automation and networking.

Inside the home, one may consider several possible market sectors: PC peripherals, including wireless mice, keyboards, joysticks, low-end PDAs, and games; consumer electronics, including radios, televisions, VCRs, CDs, DVDs, remote controls, and so on, and a truly universal remote control to control them; home automation, including heating, ventilation, and air conditioning (HVAC), security, lighting, and the control of objects such as curtains, windows, doors, and locks; health monitoring, including sensors, monitors, and diagnostics; and toys and games, including PC-enhanced toys and interactive gaming between individuals and groups. The maximum required data rate for these applications is expected to range from 115.2 kb/s for some PC peripherals to less than 10 kb/s for some home automation and consumer electronics applications. Similarly, maximum acceptable message latency is expected to range from approximately 15 ms for PC

Property	Range
Raw data rate	868 MHz: 20 kb/s; 915 MHz: 40 kb/s; 2.4 GHz: 250 kb/s
Range	10–20 m
Latency	Down to 15 ms
Channels	868/915 MHz: 11 channels 2.4 GHz: 16 channels
Frequency band	Two PHYs: 868 MHz/915 MHz and 2.4 GHz
Addressing	Short 8-bit or 64-bit IEEE
Channel access	CSMA-CA and slotted CSMA-CA
Temperature	Industrial temperature range –40 to +85 C

**Table 1.** Summary of high-level characteristics. CSMA-CA: carrier sense multiple access with collision avoidance.

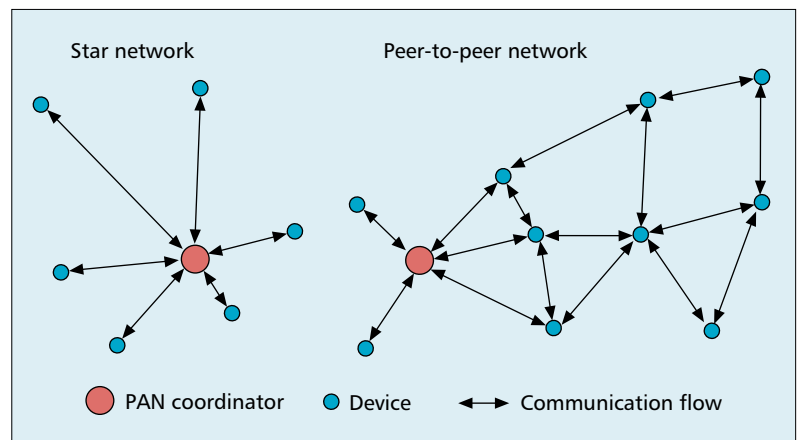
peripherals to 100 ms or more for home automation applications.

## THE NETWORK LAYER

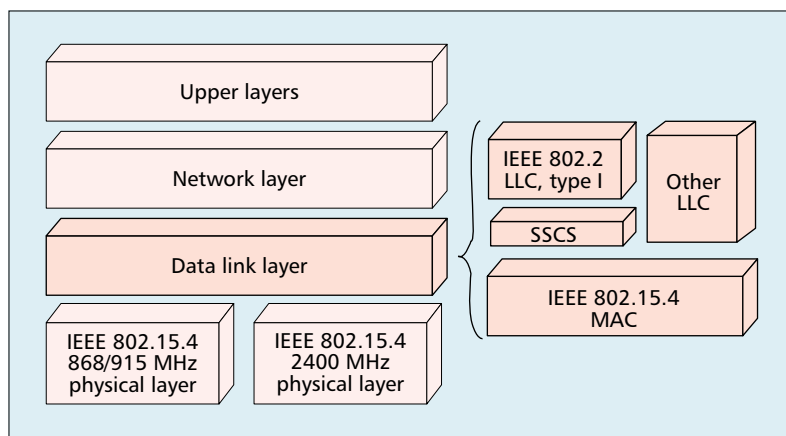
Like all IEEE 802 standards, the IEEE 802.15.4 draft standard encompasses only those layers up to and including portions of the data link layer (DLL). Higher-layer protocols are at the discretion of the individual applications utilized in an in-home network environment. In particular, this section considers the issues and obstacles surrounding the *network layer*.

In traditional wired networks, the network layer is responsible for topology construction and maintenance, as well as naming and binding services, which incorporate the necessary tasks of addressing, routing, and security [4]. The same services exist for wireless in-home networks, but are far more challenging to implement because of the premium placed on energy conservation. In fact, it is important for any network layer implementation built on the already energy conscious IEEE 802.15.4 draft standard to be equally conservative. Network layers built on the standard are expected to be self-organizing and self-maintaining, to minimize total cost to the consumer user.

The IEEE 802.15.4 draft standard supports multiple network topologies, including both star



**Figure 1.** Star and peer-to-peer networks.



■ **Figure 2.** *IEEE 802.15.4 in the ISO-OSI layered network model.*

and peer-to-peer networks (Fig. 1). The topology is an application design choice; some applications, such as PC peripherals, may require the low-latency connection of the star network, while others, such as perimeter security, may require the large-area coverage of peer-to-peer networking. Multiple address types, including both physical (i.e., 64-bit IEEE) and short (i.e., 8-bit network-assigned) are provided.

## THE DATA LINK LAYER

The IEEE 802 project [5] splits the DLL into two sublayers, the MAC and logical link control (LLC) sublayers. The LLC is standardized in 802.2 [6] and is common among the 802 standards such as 802.3, 802.11, and 802.15.1, while the MAC sublayer is closer to the hardware and may vary with the physical layer implementation. Figure 2 shows how IEEE 802.15.4 fits into the International Organization for Standardization (ISO) open systems interconnection (OSI) reference model [7]. The IEEE 802.15.4 MAC provides services to an IEEE 802.2 type I LLC through the service-specific convergence sublayer (SSCS), or a proprietary LLC can access the

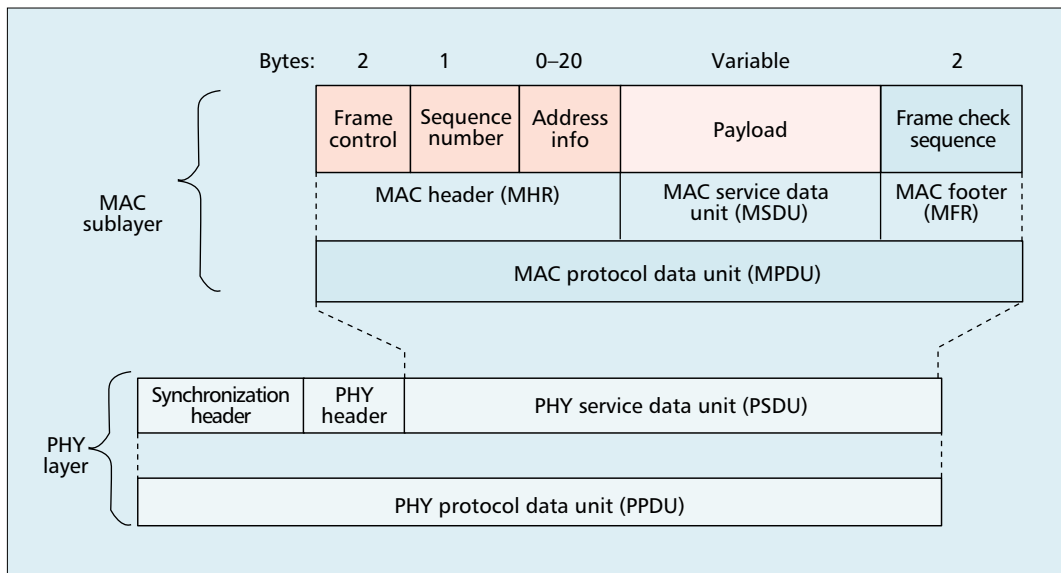
MAC services directly without going through the SSCS. The SSCS ensures compatibility between different LLC sublayers and allows the MAC to be accessed through a single set of access points. Using this model, the 802.15.4 MAC provides features not utilized by 802.2, and therefore allows the more complex network topologies mentioned above.

The features of the IEEE 802.15.4 MAC are association and disassociation, acknowledged frame delivery, channel access mechanism, frame validation, guaranteed time slot management, and beacon management. These items will be introduced in the following subsections. The MAC sublayer provides two services to higher layers that can be accessed through two service access points (SAPs). The MAC data service is accessed through the MAC common part sublayer (MCPS-SAP), and the MAC management services are accessed through the MAC layer management entity (MLME-SAP). These two services provide an interface between the SSCS or another LLC and the PHY layer.

The MAC management service has 26 primitives. Compared to 802.15.1 (Bluetooth™), which has about 131 primitives and 32 events, the 802.15.4 MAC is of very low complexity, making it very suitable for its intended low-end applications, albeit at the cost of a smaller feature set than 802.15.1 (e.g., 802.15.4 does not support synchronous voice links).

## THE GENERAL MAC FRAME FORMAT

The MAC frame structure is kept very flexible to accommodate the needs of different applications and network topologies while maintaining a simple protocol. The general format of a MAC frame is shown in Fig. 3. The MAC frame is called the MAC protocol data unit (MPDU) and is composed of the MAC header (MHR), MAC service data unit (MSDU), and MAC footer (MFR). The first field of the MAC header is the frame control field. It indicates the type of MAC frame being transmitted, specifies the format of the address field, and controls the



■ **Figure 3.** *The general MAC frame format.*

acknowledgment. In short, the frame control field specifies how the rest of the frame looks and what it contains.

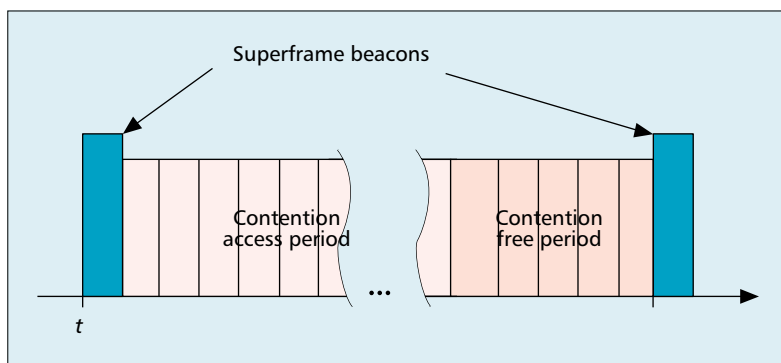
The size of the address field may vary between 0 and 20 bytes. For instance, a data frame may contain both source and destination information, while the return acknowledgment frame does not contain any address information at all. On the other hand, a beacon frame may only contain source address information. In addition, short 8-bit device addresses or 64-bit IEEE device addresses may be used. This flexible structure helps increase the efficiency of the protocol by keeping the packets short.

The payload field is variable in length; however, the complete MAC frame may not exceed 127 bytes in length. The data contained in the payload is dependent on the frame type. The IEEE 802.15.4 MAC has four different frame types. These are the beacon frame, data frame, acknowledgment frame, and MAC command frame. Only the data and beacon frames actually contain information sent by higher layers; the acknowledgment and MAC command frames originate in the MAC and are used for MAC peer-to-peer communication.

Other fields in a MAC frame are the sequence number and frame check sequence (FCS). The sequence number in the MAC header matches the acknowledgment frame with the previous transmission. The transaction is considered successful only when the acknowledgment frame contains the same sequence number as the previously transmitted frame. The FCS helps verify the integrity of the MAC frame. The FCS in an IEEE 802.15.4 MAC frame is a 16-bit International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) cyclic redundancy check (CRC).

### THE SUPERFRAME STRUCTURE

Some applications may require dedicated bandwidth to achieve low latencies. To accomplish these low latencies, the IEEE 802.15.4 LR-WPAN can operate in an optional superframe mode. In a superframe, a dedicated network coordinator, called the PAN coordinator, transmits superframe beacons in predetermined intervals. These intervals can be as short as 15 ms or as long as 245 s. The time between two beacons is divided into 16 equal time slots independent of the duration of the superframe. A device can transmit at any time during a slot, but must complete its transaction before the next superframe beacon. The channel access in the time slots is contention-based; however, the PAN coordinator may assign time slots to a single device requiring dedicated bandwidth or low-latency transmissions. These assigned time slots are called *guaranteed time slots* (GTS) and together form a contention-free period located immediately before the next beacon (Fig. 4). The size of the contention-free period may vary depending on demand by the associated network devices; when GTS are employed, all devices must complete their contention-based transactions before the contention-free period begins. The beginning of the contention-free period and duration of the superframe are communicated to the attached network devices by the PAN coordinator in its beacon.



■ Figure 4. The LR-WPAN superframe structure.

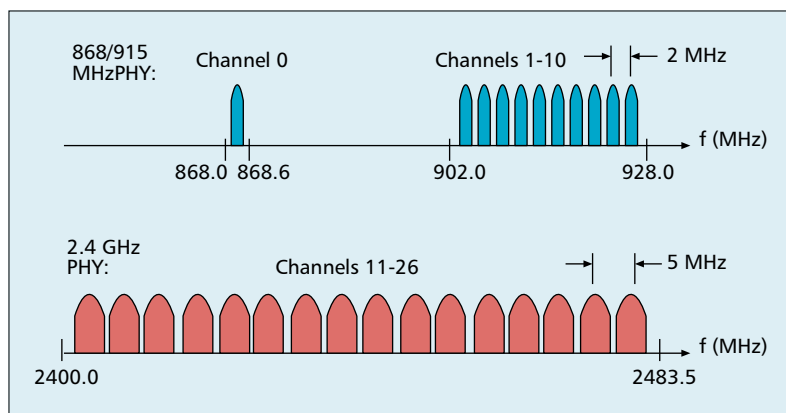
### OTHER MAC FEATURES

Depending on network configuration, an LR-WPAN may use one of two channel access mechanisms. In a beacon-enabled network with superframes, a slotted carrier sense multiple access with collision avoidance (CSMA-CA) mechanism is used. In networks without beacons, unslotted or standard CSMA-CA is used. This works as follows. When a device wishes to transmit in a non-beacon-enabled network, it first checks if another device is currently transmitting on the same channel. If so, it may back off for a random period, or indicate a transmission failure if unsuccessful after some retries. Acknowledgment frames confirming a previous transmission do not use the CSMA mechanism since they are sent immediately following the previous packet.

In a beacon-enabled network, any device wishing to transmit during the contention access period waits for the beginning of the next time slot and then determines if another device is currently transmitting in the same slot. If another device is already transmitting in the slot, the device backs off for a random number of slots or indicates a transmission failure after some retries. In addition, in a beacon-enabled network, acknowledgment frames do not use CSMA.

An important function of the MAC is confirming successful reception of a received frame. Successful reception and validation of a data or MAC command frame is confirmed with an acknowledgment. If the receiving device is unable to handle the incoming message for any reason, the receipt is not acknowledged. The frame control field indicates whether or not an acknowledgment is expected. The acknowledgment frame is sent immediately after successful validation of the received frame. Beacon frames sent by a PAN coordinator and acknowledgment frames are never acknowledged.

The IEEE 802.15.4 draft standard provides for three levels of security: no security of any type (e.g., for advertising kiosk applications); access control lists (noncryptographic security); and symmetric key security, employing AES-128. To minimize cost for devices that do not require it, the key distribution method (e.g., public key cryptography) is not specified in the draft standard but may be included in the upper layers of appropriate applications.



■ **Figure 5.** *The IEEE 802.15.4 channel structure.*

Channel number	Channel center frequency (MHz)
$k = 0$	868.3
$k = 1, 2, \dots, 10$	$906 + 2(k - 1)$
$k = 11, 12, \dots, 26$	$2405 + 5(k - 11)$

■ **Table 2.** *IEEE 802.15.4 channel frequencies.*

## THE PHYSICAL LAYER

### MULTIBAND, MULTIRATE

IEEE 802.15.4 offers two PHY options that combine with the MAC to enable a broad range of networking applications. Both PHYs are based on direct sequence spread spectrum (DSSS) methods that result in low-cost digital IC implementation, and both share the same basic packet structure for low-duty-cycle low-power operation. The fundamental difference between the two PHYs is the frequency band. The 2.4 GHz PHY specifies operation in the 2.4 GHz industrial, scientific, and medical (ISM) band, which has nearly worldwide availability, while the 868/915 MHz PHY specifies operation in the 868 MHz band in Europe and 915 MHz ISM band in the United States [8, 9]. While mobility between countries is not anticipated for most home networking applications, the international availability of the 2.4 GHz band does offer advantages in terms of larger markets and lower manufacturing costs. On the other hand, the 868 MHz and 915 MHz bands offer an alternative to the growing congestion and other interference (microwave ovens, etc.) associated with the 2.4 GHz band, and longer range for a given link budget due to lower propagation losses.

A second distinguishing PHY characteristic of interest to network and application designers is transmission rate. The 2.4 GHz PHY provides a transmission rate of 250 kb/s, while the 868/915 MHz PHY offers rates of 20 kb/s and 40 kb/s for its two bands, respectively. The higher rate in the 2.4 GHz PHY is attributed largely to a higher-order modulation scheme (described later), in which each data symbol represents multiple bits. The different transmission rates can be exploited to achieve a variety of different goals. For example, the low rate of the 868/915 MHz PHY can

be translated into better sensitivity and larger coverage area, thus reducing the number of nodes required to cover a given physical area, while the higher rate of the 2.4 GHz PHY can be used to attain higher throughput, lower latency, or lower duty cycle. It is expected that each PHY will find applications for which its strengths are best suited.

## CHANNELIZATION

Twenty-seven frequency channels are available across the three bands (Fig. 5 and Table 2). The 868/915 MHz PHY supports a single channel between 868.0 and 868.6 MHz, and 10 channels between 902.0 and 928.0 MHz. Due to the regional support for these two bands, it is unlikely that a single network would ever use all 11 channels. However, the two bands are considered close enough in frequency that similar, if not identical, hardware can be used for both, lowering manufacturing costs. The 2.4 GHz PHY supports 16 channels between 2.4 and 2.4835 GHz with ample channel spacing (5 MHz) aimed at easing transmit and receive filter requirements.

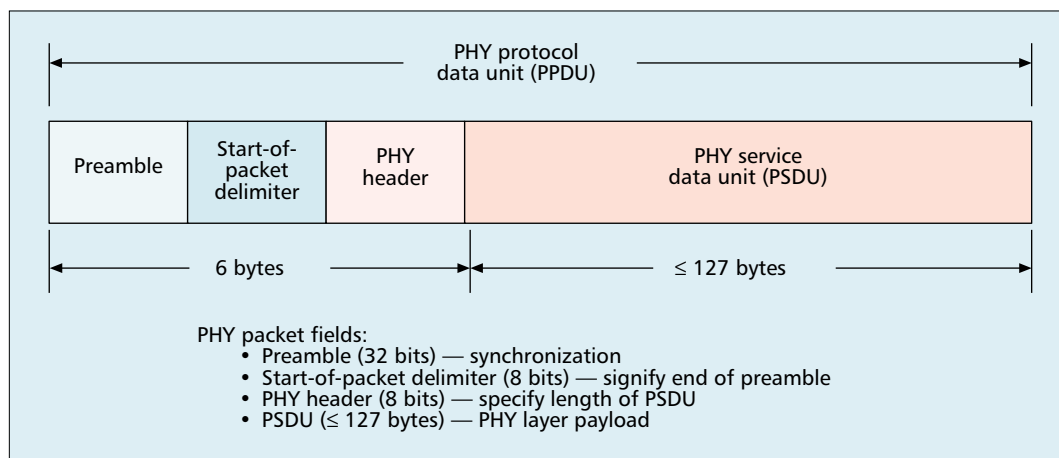
Since the home is likely to contain multiple types of wireless networks vying for the same frequency bands, as well as unintentional interference from appliances, the ability to relocate within the spectrum will be an important factor in network success. Accordingly, the standard includes the necessary hooks to implement dynamic channel selection, although the specific selection algorithm is left to the network layer. The MAC layer includes a scan function that steps through the list of supported channels in search of a beacon, while the PHY layers contain several lower-level functions, such as receiver energy detection, link quality indication, and channel switching, which enable channel assessment and frequency agility. These functions are used by the network to establish its initial operating channel and to change channels in response to a prolonged outage.

### THE PACKET STRUCTURE

To maintain a common simple interface with the MAC, both PHY layers share a single packet structure (Fig. 6). Each packet, or PHY protocol data unit (PPDU), contains a synchronization header (preamble plus start of packet delimiter), a PHY header to indicate the packet length, and the payload, or PHY service data unit (PSDU). The 32-bit preamble is designed for acquisition of symbol and chip timing, and in some cases may be used for coarse frequency adjustment. Channel equalization is not required for either PHY due to the combination of small coverage area and relatively low chip rates. In particular, typical root mean square (RMS) delay spread measured in residential homes is reported to be 25 ns [10], which corresponds to only 2.5 percent of the shortest spread spectrum chip period used in IEEE 802.15.4.

Within the PHY header, 7 bits are used to specify the length of the payload (in bytes). This supports packets of length 0–127 bytes, although due to MAC layer overhead, zero-length packets will not occur in practice. Typical packets sizes





■ **Figure 6.** IEEE 802.15.4 physical layer packet structure.

for home applications such as monitoring and control of security, lighting, air conditioning, and other appliances are expected to be on the order of 30–60 bytes, while more demanding applications such as interactive games and computer peripherals, or multihop applications with more address overhead, may require larger packet sizes. Adjusting for the transmission rates in each band, the maximum packet durations are 4.25 ms for the 2.4 GHz band, 26.6 ms for the 915 MHz band, and 53.2 ms for the 868 MHz band.

### MODULATION

The 868/915 MHz PHY uses a simple DSSS approach in which each transmitted bit is represented by a 15-chip maximal length sequence (m-sequence). Binary data is encoded by multiplying each m-sequence by +1 or –1, and the resulting chip sequence is modulated onto the carrier using binary phase shift keying (BPSK). Differential data encoding is used prior to modulation to allow low-complexity differentially coherent reception.

The 2.4 GHz PHY employs a 16-ary quasi-orthogonal modulation technique based on DSSS methods (with similar properties, e.g., processing gain). Binary data are grouped into 4-bit symbols, and each symbol specifies one of 16 nearly orthogonal 32-chip pseudo-noise (PN) sequences for transmission. PN sequences for successive data symbols are concatenated, and the aggregate chip sequence is modulated onto the carrier using minimum shift keying (MSK), which is equivalent to offset quadrature phase shift keying (O-QPSK) with half-sine pulse shap-

ing. The use of a “nearly orthogonal” symbol set simplifies the implementation in exchange for a relatively small performance penalty (< 0.5 dB). Key modulation parameters for both PHYs are summarized in Table 3.

Optimum detection curves for both modulation schemes are readily available from most communications textbooks (e.g., [11]). In terms of efficiency (required energy per bit), orthogonal signaling performs 2 dB better than differential BPSK at the expense of increased receiver complexity. However, in terms of receiver sensitivity, the 868/915 MHz PHY has a 6–8 dB advantage due to its lower bit rates. Of course, in both cases implementation losses due to synchronization, pulse shaping, detector simplifications, and so on will result in deviations from these optimum curves.

### SENSITIVITY AND RANGE

IEEE 802.15.4 currently specifies receiver sensitivities of –85 dBm for the 2.4 GHz PHY and –92 dBm for the 868/915 MHz PHY. These values include sufficient margin to cover manufacturing tolerances as well as to permit very low-cost implementation approaches. In each case, the best devices may be on the order of 10 dB better than the specification.

Naturally, the achievable range will be a function of the receiver sensitivity as well as transmit power. The standard specifies that each device shall be capable of transmitting at least 1 mW, but depending on the application needs, the actual transmit power may be lower or higher (within regulatory limits). Typical devices (1 mW) are expected to cover a 10–20 m range;

PHY	Frequency band	Data parameters			Spreading parameters	
		Bit rate (kb/s)	Symbol rate (kbaud)	Modulation	Chip rate (Mchips/s)	Modulation
868/915 MHz PHY	868.0–868.6 MHz	20	20	BPSK	0.3	BPSK
2.4 GHz PHY	902.0–928.0 MHz	40	40	BPSK	0.6	BPSK
	2.4–2.4835 GHz	250	62.5	16-ary orthogonal	2.0	O-QPSK

■ **Table 3.** IEEE 802.15.4 modulation parameters.

IEEE 802.15.4 currently specifies receiver sensitivities of –85 dBm for the 2.4 GHz PHY and –92 dBm for the 868/915 MHz PHY. These values include sufficient margin to cover manufacturing tolerances as well as to permit very low-cost implementation approaches.

Since IEEE 802.15.4 devices may be sleeping as much as 99.9 percent of the time they are operational, and employ low-power spread spectrum transmissions, they should be among the best of neighbors in the 2.4 GHz band.

however, with good sensitivity and a moderate increase in transmit power, a star network topology can provide complete home coverage. For applications allowing more latency, mesh network topologies provide an attractive alternative for home coverage since each device needs only enough power (and sensitivity) to communicate with its nearest neighbor.

#### INTERFERENCE TO AND FROM OTHER SERVICES

Devices operating in the 2.4 GHz band must accept interference caused by other services operating in the band. This is compatible with IEEE 802.15.4 applications, which have relatively low quality of service (QoS) requirements, do not require isochronous communication, and may be expected to perform multiple retries on occasion to complete packet transmissions. Conversely, a primary requirement of IEEE 802.15.4 applications is excellent battery life; this is achieved in the draft standard by the use of low transmit power and very low duty cycle operation. Since IEEE 802.15.4 devices may be sleeping as much as 99.9 percent of the time they are operational, and employ low-power spread spectrum transmissions, they should be among the best of neighbors in the 2.4 GHz band.

### CONCLUSION

With the standardization of the MAC and PHY almost complete, the focus is now on the upper protocol layers and application profiles. The ZigBee Alliance is taking the lead in this effort, and a first generation of results is expected by late 2002. In parallel, several leading semiconductor manufacturers are expected to announce the first generation of ICs.

The development of this wireless solution within the standards organization has the advantage of bringing several views together to define a better solution. The quick development of the standard was due to the proactive participation of several developers and users of the technology. The focus of 802.15.4 development was on maintaining simplicity by concentrating on the essential requirements that will leverage a successful standard.

The standard is targeting the residential and industrial market. It is expected that the industrial market will be the first to enable new products with focus on adding value through installation ease. The residential market will follow, taking advantage of lower cost due to the volume already driven by the industrial segment.

IEEE 802.15.4 has already caught the attention of other communities, such as IEEE 1451 with a focus in sensor networking. It is expected that several users of proprietary wireless technologies will shift toward the standard solution due to the expected lower cost and performance improvement.

The main goal of this effort has been to address applications that could benefit from wireless connectivity and enable new ones that cannot use higher-end wireless technologies. The value will be in the application, not in the technology. LR-WPAN is thus designed to be an

enabler technology. The IEEE 802.15.4 complements other wireless networking technologies by occupying the lower end of the power consumption and data throughput space.

#### ACKNOWLEDGMENTS

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#### BIOGRAPHIES

ED CALLAWAY [SM] (ed.callaway@motorola.com) received a B.S. degree in mathematics and an M.S.E.E. degree from the University of Florida in 1979 and 1983, respectively, an M.B.A. degree from Nova (now Nova-Southeastern) University in 1987, and a Ph.D. degree in computer engineering from Florida Atlantic University in 2002. He joined the Land Mobile Division of Motorola in 1984 as an RF engineer working on trunked radio products, and in 1990 transferred to Motorola's Paging Products Group, where he designed paging receivers for the Japanese market. From 1992 to 2000 he 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, where his interests include the design of low-power wireless networks. He is a Registered Professional Engineer (Florida), and has 19 issued patents and several published papers.

VENKAT BAHL is product manager for ZigBee. He is marketing chair of the ZigBee Alliance, and the liaison between IEEE 802.15.4 and the ZigBee Alliance. Before joining the ZigBee team early in 2001, he was responsible for marketing of CDMA systems, and helped penetrate the Chinese market. Prior to the VLSI/Philips merger, he was wireless ASIC marketing manager, focused on the GSM and IS-136 standards. He has worked with VLSI for three years and was previously responsible for GSM marketing in the United States. He completed his Master's degree in economics, as well as several technical and over 30 business courses.

PAUL GORDAY [SM] is a research engineer for Motorola Labs (Florida Communications Research Lab) in Plantation, Florida.

da. He received his B.S.E.E. and M.S.E.E. from the University of Florida in 1987 and 1989, respectively. Since joining Motorola in 1990, he has worked in research and development of one-way and two-way paging systems, advanced cellular systems, wireless home networking, and, most recently, low-power wireless networks. He is currently serving as a physical layer editor for the IEEE 802.15.4 LR-WPAN task group.

JOSE A. GUTIERREZ received a B.S. in electronic engineering in Caracas, Venezuela, in 1991 from University Simon Bolivar and an M.Sc. in electrical engineering from the University of Wisconsin-Milwaukee in 2001. He is presently a Ph.D. candidate at the same institution in the field of wireless communications and information technology. He currently works as a principal engineer at the Innovation Center of Eaton Corporation, RF/Communication Group, leading the Wireless Networking Program. He is an active member of the IEEE 802 LAN/MAN Standards Committee and technical editor for IEEE 802 Working Group 15 TG4, focused on the development of a standard for low-rate WPAN.

LANCE HESTER (lancehester@motorola.com) received his B.S. degree in electrical engineering from the University of Maryland College Park, and both his M.S. and Ph.D. in electrical and computer engineering from Northwestern University, Evanston, Illinois. He is currently with the Florida Communications Research Labs of Motorola Labs. His research interests include wireless communications, sensor and ad hoc wireless networks, and communication network performance evaluation.

MARCO NAEVE (MarcoNaeve@eaton.com) is a research engineer for the Communication and RF group of the corporate research and development unit (Innovation Center) of Eaton Corporation. He received his B.S. degree in elec-

trical engineering from the Milwaukee School of Engineering, Wisconsin in 1996. He also holds the equivalent degree of a Diplom Ingenieur (FH) in electrical engineering with focus on RF and telecommunication systems, which he received from the Fachhochschule Luebeck in Germany. His work at Eaton Corporation includes low-rate wireless personal area networks, wireless local area networks, and wired industrial communication systems. He is an active member of the IEEE and currently holds the position of the secretary of the IEEE 802.15.4 LR-WPAN task group.

ROBERT F. HEILE is a 20-year veteran in the field of data communications and wireless data with several articles and workshops to his credit. He is a founding member and chair of 802.15, the IEEE working group on wireless personal area networks, chair of the ZigBee Alliance, and one of the organizers for the 5gig global harmonization effort. In 1990 he was one of the founding members of 802.11 and continues in an active role today. He is currently CTO for Appairant Technologies and most recently did wireless communications consulting for several high profile companies. Before that he was with GTE, responsible for wireless opportunity business development. He joined BBN in early 1997, prior to its acquisition by GTE, with the mission of commercializing wireless ad hoc networking and wireless PAN technologies. From 1990 to 1996 he was VP of engineering and business development for TyLink Corp., a bootstrap startup in high-speed digital access products and network and circuit management software, and was a co-founder of Windata, Inc., a developer and manufacturer of wireless LANs. From 1980 to 1990, he was with Codex, a subsidiary of Motorola, where he was VP/GM of the company's modem business. He holds a B.A. degree from Oberlin College, and M.A. and Ph.D. degrees in physics from The John Hopkins University.

*With the standardization of the MAC and PHY almost complete, the focus is now on the upper protocol layers and application profiles. The ZigBee Alliance is taking the lead in this effort, and a first generation of results is expected by late 2002.*