IEEE 802.15.4: A Developing Standard for Low-Power Low-Cost Wireless Personal Area Networks

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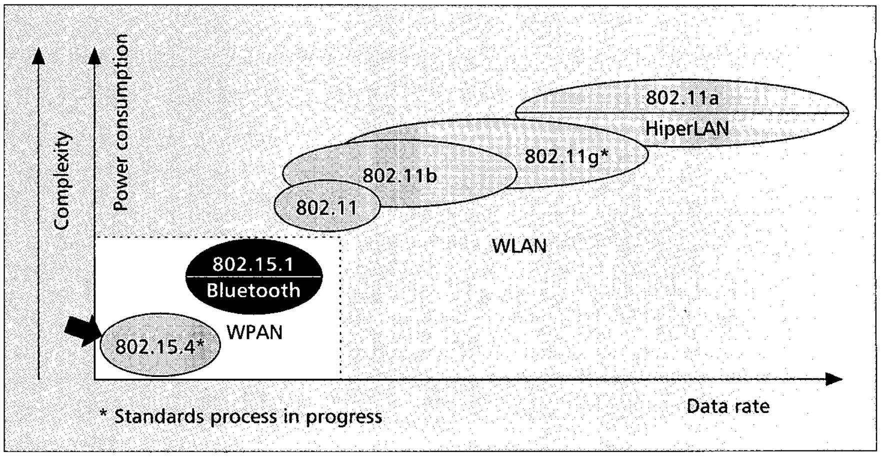
Abstract

A low-rate wireless personal area network, or LR-WPAN, is a network designed for low-cost very-low-power short-range wireless communications. Until now, the main focus in the wireless industry has been on communication with higher data throughput, leaving out a set of applications requiring simple wireless connectivity with relaxed throughput and latency requirements. LR-WPANs will connect devices that previously have not been networked and allow applications that cannot use current wireless specifications, including applications in fields such as industrial, agricultural, vehicular, residential, medical sensors, and actuators. Task Group 4 of the IEEE 802.15 Wireless Personal Area Network working group is currently working to define a wireless communication standard for LR-WPANs. This article discusses the technical considerations and system requirements necessary when implementing a low-cost low-power wireless personal area network and provides an overview of the unique applications such a technology will enable.

In recent years, wireless communication has experienced exponential growth caused by the need for connectivity. Wireless networking has followed a similar trend due to the increasing exchange of data in services such as the Internet, e-mail, and data file transfer. The capabilities needed to deliver such services are characterized by an increasing need for data throughput.

Other applications in fields such as industrial, agricultural, vehicular, residential, medical sensors, and actuators have more relaxed throughput requirements. Moreover, these applications require substantially lower power consumption than is currently provided in existing standard implementations. For instance, battery-powered devices for certain types of industrial and medical sensors, smart tags, and badges should last from several months to many years. In addition, cost plays a fundamental role in applications requiring wireless connectivity for inexpensive or disposable devices and for applications with a large number of wireless nodes in the personal operating space (POS). These intended applications require low-complexity wireless links that are low in cost relative to the device cost. Until now, these devices either have used proprietary wireless technologies or were deemed too expensive to implement. Thus, in order to reduce the cost of the components and facilitate volume production of such devices, the development of standardized solutions is necessary.

The above constraints suggest the design of a low-complexity wireless transceiver with minimal requirements to sustain a communications link with the least amount of overhead. Furthermore, the combination of low cost and low power con-



■ Figure 1. *The operating space of various WLAN and WPAN standards.*

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sumption implies that this definition would provide a limited data rate for applications that do not require a large bandwidth.

There are other efforts addressing these types of requirements. Among them are the SensIt project from the Defense Advanced Research Projects Agency (DARPA), which focuses on wireless ad hoc networks for large distributed military systems, and ZigBee, a spinoff group of HomeRF with roots in home automation that has recently expanded its charter to include industrial and vehicular applications.

Recently, IEEE 802 Working Group 15 was created to develop a set of standards for short-range wireless communications commonly referred as *wireless personal area networks* (WPANs) [1]. To address the need for low-power low-cost wireless networking, the IEEE New Standards Committee (NesCom) officially sanctioned a new task group in December 2000 to begin the development of a low-rate WPAN (LR-WPAN) standard, to be called 802.15.4. The goal of Task Group 4, as defined in the Project Authorization Request [2, 3], is to provide a standard having ultra-low complexity, cost, and power for low-data-rate wireless connectivity among inexpensive fixed, portable, and moving devices. Location awareness is being considered as a unique capability of the standard. The scope of Task Group 4 is to define the physical and media access control (MAC) layer specifications [2].

This task group is developing specifications in the industrial, scientific, and medical (ISM) bands due to their unlicensed nature and the available bandwidth. These bands are occupied by devices that implement other wireless specifications, so coexistence is an important aspect to consider. Coexistence issues will be addressed in a joint effort with the IEEE coexistence task groups, such as 802.15.2 and 802.11/ETSI-BRAN/MMAC 5GSG.

Some of the expected characteristics of the LR-WPAN are shown in Table 1 and have been translated into a selection criteria document [4] by Task Group 4 to aid in the definition of the LR-WPAN standard.

Property	Range
Raw data rate	2–250 kb/s
Range	Typical 10 cm to 10 m or up to 100 m with trade-offs
Battery life	Application-dependent and optimized for long battery life; asymmetrical power consumption nodes; might operate without battery (power scavenging); expected battery life might be as long as the shelf life itself
Latency	10–50 ms; or larger than 1 s
Location awareness	Optional
Nodes per network	Up to 65,534 (exact number to be determined)
Topology	Star and mesh are desired
Complexity	Lower than current standards
Types of traffic	Asynchronous data-centric; option to support synchronous communication
Desired frequency band	Unlicensed and international band
Temperature	Industrial temperature range –40° to +85° C

■ Table 1. *Expected characteristics of the LR-WPAN standardization effort.*

WPANs vs. LR-WPANs

To better understand LR-WPANs, it is appropriate to define WPANs and their market space. WPANs have just arrived on the scene and, at first glance, may appear to be in competition with wireless local area networks (WLANs). However, significant differences justify both network types. Figure 1 illustrates the operating space of the various 802 wireless standards and activities.

WPANs are focused around the POS, that is, a space around a person or object that typically extends up to 10 m in all directions and envelops the person whether stationary or in motion. In contrast, the desirable traits of a WLAN system are long range, complexity to handle seamless roaming, message forwarding, and hundreds if not thousands of nodes attached and ready for instant communication.

WPANs focus on low cost, low current drain, and very small size. As a point of reference, the peak current drain of the typical WLAN is about five times that of a low-power WPAN. Furthermore, a typical WLAN device is designed as a PC card suitable for a desktop or laptop PC, while the WPAN is the size of a compact flash card, suitable for a palm-size or handheld PC.

The IEEE 802.15 working group has defined three classes of WPANs that are differentiated by data rate, battery drain, and quality of service (QoS). The high-data-rate WPAN (802.15.3) is suitable for multimedia applications that require very high QoS. Medium-rate WPANs (802.15.1/Bluetooth™) will handle a variety of tasks ranging from cell phones to PDA communications and have a QoS suitable for voice applications. The last class of WPANs, the LR-WPAN (802.15.4), is intended to serve a set of industrial, residential, and medical applications with low power consumption and cost requirements not considered by the above WPANs and with relaxed needs for data rate and QoS.

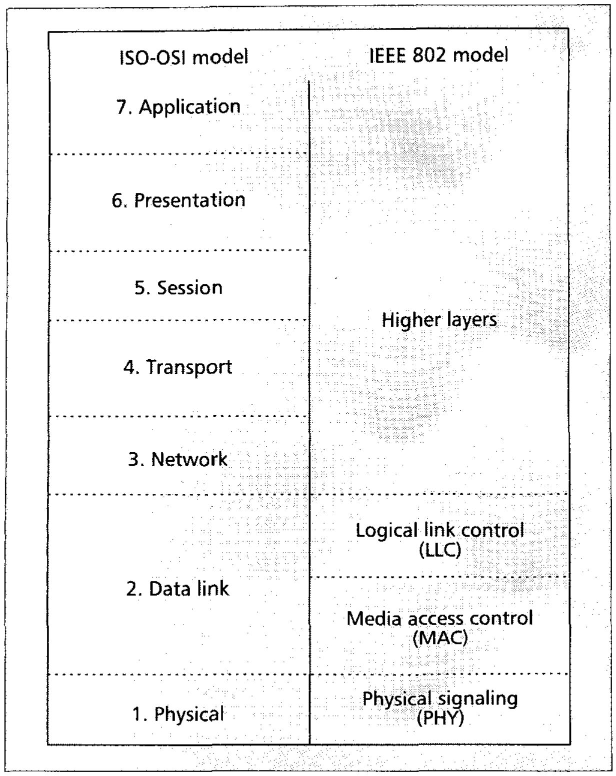
Table 2 shows a general summary of the characteristics of an LR-WPAN compared with 802.11b and a standard WPAN such as Bluetooth.

In accordance with IEEE 802 practices, the 802.15.4 task group is planning to create specifications for the physical and MAC layers. The physical and MAC proposals presented to Task Group 4 at the IEEE meetings are in [5].

Provisions must be made in the higher communications layers to interface an LR-WPAN network to other existing network standards and to provide authentication and security

	WLAN	BT-based WPAN	Low-rate WPAN
Range	~100 m	~10–100 m	10 m
Data throughput	~2–11 Mb/s	1 Mb/s	<0.25 Mb/s
Power consumption	Medium	Low	Ultra low
Size	Larger	Smaller	Smallest
Cost/complexity	> 6	1	0.2

■ Table 2. *A comparison of LR-WPAN with other wireless technologies.*



■ Figure 2. *The seven-layer ISO-OSI and IEEE 802 standards models.*

services if necessary. Figure 2 shows the International Organization for Standards' (ISO's) Open System Interconnect (OSI) model with IEEE 802's model.

The intent of an LR-WPAN is to pursue those applications where existing WPAN solutions are still too expensive and the performance of a technology such as Bluetooth is not required. LR-WPANs complement other WPAN technologies by providing very low power consumption capabilities at very low cost and enabling applications that were previously impractical. To summarize, LR-WPANs are characterized by:

- Low data rate
- Very low power consumption — battery operation from several months to years
- Variable network topologies
- Location awareness

The most obvious defining characteristic of an LR-WPAN is its data throughput, which ranges from a few bits per day to a few kilobits per second. Many low-end applications do not generate large amounts of data and therefore only require limited bandwidth. Often these applications do not require real-time data transmission or continuous updates. However, there are exceptions that will be shown later in this article in the LR-WPAN applications section.

The low data rate enables the LR-WPAN to consume very little power. Many applications that suit LR-WPANs, such as the monitoring and control of industrial equipment, require exceptionally long battery life so that the existing maintenance schedules of the monitored equipment are not compromised. Other applications, such as environmental monitoring over large areas, may require a very large number of devices that make frequent battery replacement impractical. There are still other applications for which batteries themselves are impractical, and energy for the LR-WPAN transceiver and the device must be extracted or "mined" from the environment.

System Design

Technology Requirements

The main design consideration for LR-WPANs is low power consumption, and therefore long battery life. Some of the techniques that help achieve low average power consumption are:

- Reduction of the amount of data transmitted
- Reduction of the transceiver duty cycle and the frequency of data transmissions
- Reduction of frame overhead
- Implementation of strict power management mechanisms, such as power-down and sleep modes

As an example, a goal in a particular application may be to obtain two years of battery life, employing an alkaline AAA battery. Knowing that the typical capacity of a AAA battery is 750 mAh and that there are 8760 h in a year, and assuming a 1 V system design that employs a linear voltage regulator (so the supply current equals the load current), the required average current drain Iavg needed to meet this specification is

$$I_{avg} = \frac{750\ \text{mAh}}{2 \cdot 8760\ \text{h}} = 42.8\ \mu\text{A}. \quad (1)$$

I_{avg}, of course, is the time average of the transmit, receive, and standby currents:

$$I_{avg} = T_{rxon} \cdot I_{rxon} + T_{txon} \cdot I_{txon} + (1 - T_{rxon} - T_{txon}) \cdot I_{stby}, \quad (2)$$

where

I_{avg} = Required average current drain from the battery

I_{rxon} = Current drain from the battery when the receiver is on

I_{txon} = Current drain from the battery when the transmitter is on

I_{stby} = Current drain from the battery when both receiver and transmitter are off

T_{rxon} = Fraction of time the receiver is on

T_{txon} = Fraction of time the transmitter is on

Interestingly, for low-power devices operating in the 2.4 GHz ISM band, the transmitter and receiver currents are often similar. If one assumes they are the same, and makes the additional simplifying assumption that the network communication links are symmetrical (meaning the average transmit and receive times of individual devices is the same), the average battery current equation reduces to

$I_{avg} = T_{on} \cdot I_{on} + (1 - T_{on}) \cdot I_{stby}$,

where

T_{on} = Fraction of time either receiver or transmitter is on

I_{on} = Current drain from the battery when either the receiver or transmitter is on

From this equation and estimates of the current consumption of practical hardware, the maximum acceptable T_{on} may be determined as a function of the device average battery current. For example, if I_{on} = 10 mA, I_{stby} = 10 μA, and I_{avg} = 43 μA,

T_{on} = 0.0033, or 0.33%.

Given these currents, the network design must allow the device to remain asleep, on average, for 99.67 percent of the time it is operational. Note that this analysis assumes message traffic is infrequent enough, and has length short enough, that the transmission and reception of the messages themselves does not have a significant effect on battery life. This is a good assumption for most expected applications of LR-WPANs.

Location awareness is another unique aspect under consideration by the LR-WPAN working group, although the topic is also being considered as a future addition to Bluetooth. Mobile wireless low-rate networks are exceptional candidates for precision location technology. Applications may include the tracking of assets, people, or anything that can move in various environments, including industrial, retail, hospital, residential, or office environments, while maintaining low-rate data communications for monitoring, messaging, or control.

Technology Options

Many engineering choices and trade-offs must be made in the design of an LR-WPAN network standard. Many of these, such as balancing the desire to optimally satisfy the largest number of applications with the need to have a simple standard that minimizes market confusion and the possibility of incompatibility problems, are common to many communication network designs. Others are unique to the application space in which an LR-WPAN operates; some of these design choices will be discussed in this section.

Every detail of the LR-WPAN design, from the system view down to the transistor level, must focus on low power consumption. Thus, the power consumption will be influenced in one way or another by every decision made during the design process. Modulation and channel coding, for instance, have a significant impact on the design. Choosing the right modulation scheme helps lower the power consumption. For example, possible choices include on-off keying (OOK) and amplitude shift keying (ASK), which send digital information by encoding the binary symbols onto the amplitude of the RF carrier. The difference between these two modulation techniques is that for OOK the two binary states are represented by carrier on and carrier off, while ASK uses higher and lower levels of carrier amplitude to encode the information. Assuming an equal probability of occurrence of the binary symbols, the transmitter will consume higher power 50 percent of the transmission time. Furthermore, modulation schemes like the ones just mentioned allow the use of very simple threshold detectors, which consume very little power. The main disadvantage of this approach is the susceptibility of amplitude modulation to additive noise and interference. However, the short range of the LR-WPAN links minimizes this factor.

The network topology has a considerable impact on the low power strategy [6], since a node may possibly act as a repeater for messages sent by other nodes. An application-dependent synchronization strategy is needed to circumvent a high duty cycle for these "repeater" nodes. The main emphasis of Bluetooth networks is on the star configuration (piconets). This configuration does not present a significant challenge in the sense shown above, since the function of the master node may be exchanged between identical Bluetooth devices in many of their envisioned applications; in heterogeneous networks containing dedicated masters, the masters must be assumed to have higher power capabilities.

The Physical Layer

Frequency Band — Many standards and specifications for unlicensed wireless communication devices, including the Bluetooth WPAN and the IEEE 802.11b WLAN, have chosen the 2.4 GHz ISM band for operation, due to its unique combination of near worldwide availability, suitable bandwidth, and technical feasibility for low-cost designs. However, this popular choice has led to a "tragedy of the commons," in that interference between these multiple incompatible services may be severe. The existence of microwave ovens in the band, as well as amateur radio service in some parts of the world, only adds to the din.

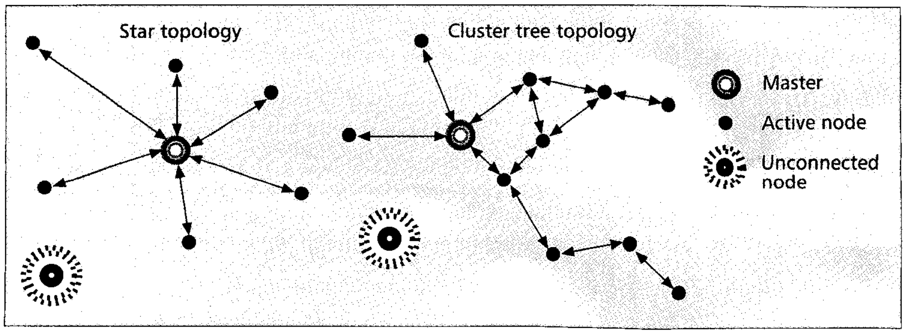
Besides being a requirement for some mobile applications (e.g., wireless luggage tags), having a single band for worldwide operation greatly simplifies device manufacture and distribution; this is especially important for the very low cost goals of the IEEE 802.15.4 task group and is a major point in favor of the use of 2.4 GHz for LR-WPANs. However, many, perhaps most, LR-WPAN applications do not involve mobility; for these systems use of a frequency band that does not offer worldwide operation, but avoids some of the interference problems of the 2.4 GHz ISM band, is an attractive alternative. With this in mind, a combination of the 868 MHz band in Europe, the 902 MHz band in Australia, and the 915 MHz band in the United States is a good choice. These bands are close enough in frequency that similar, if not identical, hardware may be used for them (lowering manufacturing costs), with just a change in synthesizer programming necessary. An additional advantage of these bands is the lower power consumption of the device's synthesizer and RF circuits compared to operation in the 2.4 GHz band.

Narrowband vs. Spread Spectrum — In most areas of the world, both narrowband and spread spectrum systems are permitted in the unlicensed bands suitable for an LR-WPAN, and the choice between them is a complicated one, involving both technical and nontechnical factors. (To add to the complexity, spread spectrum systems may be of the frequency hopping or direct sequence type, or a hybrid of the two.) Some of the technical factors to be studied are the problem of coexistence with other services in the band, system complexity and cost, power consumption, the ability to perform fast system acquisition (to optimize battery life and user satisfaction), and the number of available communication channels. Nontechnical factors include government regulatory requirements (which differ in allowed power output, modulation index, processing gain, etc. for the different approaches) and the targeted applications.

Coexistence with existing services in the proposed frequency band, which may be quite crowded, is a thorny problem. Consider the possible interference from another service that implements frequency hops. A frequency-hopping signal is less likely to "land" on a narrowband signal than a wideband, direct sequence signal, since the narrowband signal occupies less spectrum space. However, the wideband signal is less likely to be corrupted by the interferer, due to its inherent processing gain. Turning to the prevention of interference to other services, a narrowband channelized system may advantageously place its channels between the channels of other services (e.g., between IEEE 802.11b channels), while a wideband system centered there must place some signal energy in the channel of the other service.

In a world of integrated circuits, particularly standard-cell synthesizable digital integrated circuits, system complexity equals cost only to the extent that system complexity affects the die size and number of external parts. Narrowband systems, which do not need correlators or frequency hopping control logic, often require much less digital logic than wideband systems; however, they require channel filters (or antialiasing filters) with a lower corner frequency than wideband systems that, if integrated, may require larger capacitors and hence more die area than the corresponding channel filters of a wideband system. The overall trade-off between channel filter size and digital logic size is difficult to evaluate in the abstract, and made more difficult when one considers that, even though standard cell logic density is doubling every 18–24 mo according to Moore's Law, the analog circuitry does not shrink along with the digital circuitry. In fact, the analog circuitry becomes more expensive with each new IC generation as IC costs per unit die area rise (although IC costs per function — e.g., a logic gate — fall). In this scenario, a narrowband device, made on an old IC process, may be cheaper to manufacture than a wideband device made on a state-of-the-art process.

Closely related to complexity is the issue of power drain; a wideband system has channel filters, amplifiers, analog-to-digital converters, and signal processors operating at higher frequencies, and hence drawing more power, than a comparable



■ **Figure 3.** *Star and cluster tree topologies.*

narrowband system. However, a direct sequence receiver is capable of obtaining symbol synchronization in a single symbol period (by correlating to a transmitted spreading code), while a narrowband system typically requires a preamble (a 1-0 pattern) of 8–16 symbols in length to obtain synchronization at low signal-to-noise ratios without falsing excessively. This extra warmup period may be a significant fraction of the total time the receiver is active, due to the short message length expected in LR-WPANs, and thus may negatively affect the unit's duty cycle and hence its battery life. Narrowband systems may compensate by employing the clock used for protocol timing for symbol synchronization; once synchronization is achieved, the value is "remembered" by the phase of the protocol timer and is available immediately when the receiver is next activated. At each activation only the independent drift of the transmitter and receiver time bases must be compensated; if the period of receiver activation is not too long, and the time base is capable of reasonable stability (or correlated via automatic frequency control), a very short preamble may be used.

Acquisition time (the time needed for a device to detect and synchronize to a network) is also affected by the narrowband/wideband decision. It is often difficult for frequency hopping systems to achieve low acquisition times, since before synchronization the receiver must search multiple frequencies at multiple times to find the transmitter. Since the transmitter is assumed to have a low duty cycle, this can be a lengthy process. Narrowband systems may do considerably better by identifying a channel or small set of channels on which the inquiring device may look to detect a network; the inquiring device must then perform a symbol rate detection algorithm, symbol-synchronize with the transmitter, and finally find some type of system identification in the data stream. If the system identification is placed in the spreading code, a direct sequence receiver can achieve acquisition in one symbol time; it performs a correlation against the desired spreading code. When that correlation is achieved, the receiver has both identified the transmitting system and achieved symbol synchronization, at the cost of running a correlator. However, if the device is searching for *any* system, not a particular one with a particular spreading code, this can become a disadvantage: multiple correlations must be performed, which waste both time and power.

Narrowband systems may employ frequency-division multiple access (FDMA) to have a large number of available communication channels at one physical location. This may be done at relatively low additional complexity, since only programming a synthesizer is required. Wideband systems may similarly employ code-division multiple access (CDMA), if programmable correlators and decorrelators are employed.

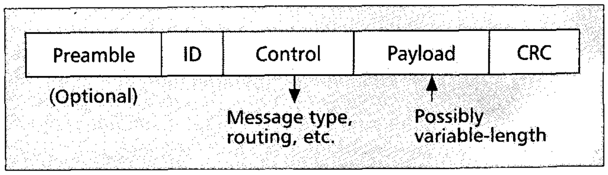
Government regulations differ around the world and vary with time, but for an indication of how they affect network physical layer design, the regulations of the U.S. Federal Communications Commission (FCC) for the 2.4 GHz ISM band may be examined. The FCC limits narrowband emissions in the band to a maximum electric field strength of 50 mV/m at a range of 3 m, or slightly less than 1 mW power output if an isotropic radiator is assumed for the transmitting antenna (section 15.249). However, the FCC permits up to 1 W power output if spread spectrum devices are used, subject to some restrictions (section 15.247). Thus, if spread spectrum techniques were used, individual network devices would potentially be capable of greater range. Depending on the application, however, this may or may not be desirable due to interference, power consumption, or channel reuse concerns: devices operating from coin cell batteries would not be capable of generating 1 W, for example. In addition, it must be borne in mind that conventional wireless transceivers have nonradiated power consumption on the order of 10 mW (due to synthesizers etc.); reducing the transmitted power output of such a transceiver below 1 mW or so in an effort to improve battery life is not a productive endeavor.

Data Rate — Since LR-WPANs may send only a few bits per hour in many applications, at first glance the transmitted data rate specification may seem to be almost irrelevant: almost any raw data rate will be high enough to support the data throughput required of LR-WPANs. However, as previously stated, the critical performance metric of LR-WPANs is not data throughput, but power consumption and battery life, and here the raw transmitted data rate can have a significant effect. In addition, there are some LR-WPAN applications, such as wireless mice and keyboards, which require message latency measured in milliseconds and a data throughput greater than 1 kb/s. Furthermore, network range is strongly determined by data rate. For these reasons, the network raw data rate is a critical design parameter.

Like paging systems, minimizing the device duty cycle in an LR-WPAN network maximizes the battery life of its devices. For a given amount of data to be transmitted, the battery life is maximized by transmitting the data at the maximum possible speed. For networks in the unlicensed bands, government regulations do not directly restrict the transmitted data rate; however, as the data rate increases, signal processing power increases as well, as does signal processing complexity to recover from intersymbol interference caused by nonidealities of the wireless channel. To directly compare proposals with different data rates, modulation formats, and estimated power consumption, the IEEE 802.15.4 task group uses energy dissipated per transmitted payload bit (in joules) as a normalized metric, keeping in mind that some applications have primary power sources with very limited instantaneous power sourcing capability. This metric is powerful in that it considers not only the transmitted data rate but also MAC layer overhead.

Media Access Control Layer

Network Topology — Generally an LR-WPAN network is organized as a star or some type of extended connection topology, (e.g., a cluster tree, mesh, or ring) depending on the application. Figure 3 shows examples of both star and cluster tree networks. An example application for the star topology is wireless computer games (wireless joystick, mouse, etc.), for which the number of devices is relatively small. A more powerful master/controller device resides at the center of the star, and all other devices, which must be within range of the master/controller, serve as slaves. A cluster tree topology is more suited to networks that cover larger physical areas, such as



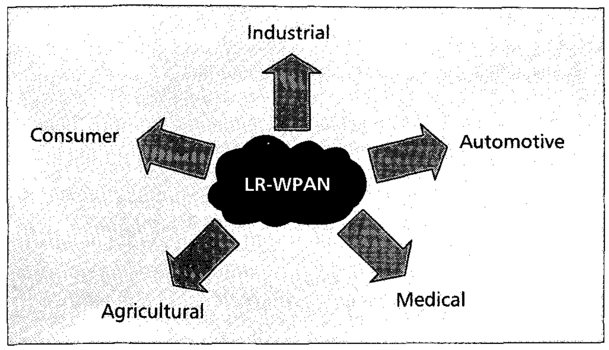
■ Figure 4. *A possible frame structure for an LR-WPAN message.*

those used in wireless sensor precision agriculture, where no single device has the range to establish a communication link with every other device. The large cluster tree network self-organizes into smaller subnets, each of which has a dominant master node (a cluster head) [7]. Data flows from an LR-WPAN device to its master node, through a gateway node to a higher subnet, and continues upward until reaching a central collection device. The central collection device is more powerful in terms of processing power and memory than an ordinary LR-WPAN device. In both the star and cluster tree configurations, network formation and maintenance are automatically performed through interdevice communication, implying that there is no human intervention necessary for network setup, expansion, or reduction. In a star network, these tasks are achieved through master-slave communications, while a cluster tree network requires peer-to-peer communications. A hybrid scenario exists where there are only two devices in the network; for this case, the topology resembles a star with one slave, but the communication link is actually peer to peer. In most applications of these simple peer-to-peer links, one device is devoted to scanning and the other to inquiry. An example application is using a handheld wireless controller to operate a door lock or light switch.

A star network is simple to control and synchronize, since all slave devices by definition can hear, and be heard by, the master/controller, and the master/controller defines the network's time-division duplex (TDD) and TDMA slot timing. It is more difficult to control and synchronize extended connection networks, since any control or synchronization information must be routed via multiple communication links. This, in turn, makes the achievement of very low-duty-cycle operation, needed for good battery life, more difficult.

As mentioned before, network topology may considerably affect the overall power consumption of the system. For an extended connection network configuration, some nodes are required to relay messages coming from other nodes; this implies a higher duty cycle to monitor these messages. To alleviate this issue, a well-designed synchronization strategy is required. A star topology does not face this issue since the communication from a node is always directed to the master, which is assumed to have more power available.

Single- vs. Multiple-type Devices — In any system design, the question of whether to employ a network of heterogeneous or homogeneous devices arises. In some applications, such as IEEE 802.11b and the simple peer-to-peer LR-WPAN network described above, having different types (heterogeneous) of devices in the same network is the obvious choice. However, in many other applications the decision is much more difficult. For example, in star networks the master/controller handles more message and control data than do slaves, so it is natural to consider it a different, and perhaps more expensive, type of device than a slave device, which could be made with less memory. However, this designation limits the flexibility and mobility of the network (the network follows the master device, not the slave devices), and the user must be aware of the need to purchase two different types of devices for proper network operation. Bluetooth, in fact, is the premier example of a homogeneous star network. A similar, and in some ways more severe, trade-off between device cost minimization and



■ Figure 5. *The LR-WPAN application space.*

market confusion exists with cluster tree networks: devices that are leaves on the tree need not pass any message traffic — just source and sink it — and so could be significantly less expensive that higher-level devices, which must store routing information. However, cluster tree networks may be very large, and careful network planning is required to ensure that no leaf device is required to pass messages, which is exactly the kind of network maintenance chore one would like to avoid. For this reason most cluster tree networks are homogeneous (with the possible exception of gateway devices).

Message Structure — A possible generic message structure for an LR-WPAN is shown in Fig. 4. The message frame contains five fields serving different tasks. These fields are the preamble, the ID field, the control field, the payload, and the cyclic redundancy check (CRC) field. The preamble is required for certain types of receivers to train their threshold detection. An ID field is needed for the addressing of specific nodes. The control field stores information related to type of frame (i.e., command, data and synchronization, and routing information). The payload contains the data, which is context-sensitive and may be variable in length, and the final field is a CRC field for error detection. The length of each of these fields depends on the addressing model, routing scheme, and network topology. In addition, the application will mandate the amount of data bytes per frame, which in most cases is expected to be a few bytes. This structure is highly simplistic in the context of other WLAN/WPAN standards, but uses very short messages to conserve power.

LR-WPAN Applications

This section explores a broad range of potential applications requiring low-power low-throughput wireless communication networks. Figure 5 shows the general application space for LR-WPANs. In response to a Call for Applications [8] by Task Group 4, several ideas were presented [9–17] at the IEEE 802 meeting in January 2001. Some of these applications are discussed in the following paragraphs.

The industrial market is a natural place for sensor networks. Using a combination of sensors and LR-WPAN devices, data will be gathered, processed, and analyzed to determine whether or when user interaction is required. Examples of wireless sensor applications include detecting emergency situations, such as hazardous chemical levels and fires, and monitoring and maintenance of rotating machinery. An LR-WPAN would significantly reduce the installation cost of new sensor networks and simplify expansion of existing network installations. The initial implementations will most likely occur in monitoring applications with noncritical data where longer latencies are acceptable. These industrial monitoring applications, in general, do not need high data throughput or constant updating. Instead, emphasis is placed on low power consumption in order to maximize the lifetime of the battery-powered devices that make up the network.

Wireless communication is finding its way into cars, as driver comfort and the number of features increase. In a similar manner, the number of wires required in a car has grown significantly, having a great impact on installation cost. In contrast to the home or office environment, the automotive environment represents a relatively underdeveloped application field regarding the provision of new services or updating existing services. One of the key factors missing for accomplishing this task is an appropriate wireless delivery medium based on standard specifications. The wireless option introduces flexibility in installation and an advanced alternative to wired connections. A special challenge for automotive applications is meeting the harsh automotive environment with a solution low enough in cost to find volume applications. Some of the applications WPANs can address in a vehicle are control and monitoring of noncritical sensors. An application example is a tire pressure monitoring system. The system consists of four pressure sensors, one mounted on each tire, and a central station to receive the collected data. Since the pressure sensors have to be mounted on the tires, this application does not permit the use of any communication wires or power cables. Therefore, sensors have to be battery-powered. Since it is impractical to replace the sensors or their batteries between tire changes, it is required that the sensor batteries last at least three, preferably up to five, years. This puts significant constraints on the power consumption of the electronic components and requires power management capabilities. The data that needs to be communicated is, in most cases, only a few bits in size and indicates the measured tire pressure. This information is transmitted about every 1–10 min under non-alarm conditions. Unless there is a fast loss of pressure, the message latency is not of significant concern. In case of sudden pressure loss, the central control unit should be notified immediately, in which case power consumption is not of concern since most likely the tire has to be replaced. Extreme automotive environmental conditions and the metallic structure hinder RF propagation. In addition, the shape of the rim has a significant impact on the radiation pattern from the wireless sensor. To overcome this issue, repeater nodes, which will not add significant cost to the system, can be added to the network to increase communications reliability.

Another challenging application for LR-WPANs is precision farming, also called precision agriculture. Precision agriculture is an environment-friendly system solution that optimizes product quality and quantity while minimizing cost, human intervention, and variation caused by unpredictable nature. Today agriculture is still both user- and environment-demanding. It is mainly hardware-oriented with manual and on-site control using independent dumb machines, which produces unpredictable quality and quantity. With the new paradigm of precision agriculture, farming would become more information- and software-oriented, using automatic and remote-controlled networked smart machines. The drivers for this new paradigm are industrial mergers and consolidations, increased global competition, and increased environmental concerns. This application requires large mesh-type networks consisting of potentially thousands of LR-WPAN devices linked with sensors. These sensors will gather field information such as soil moisture content, nitrogen concentration, and pH level. Weather sensors for measuring rainfall, temperature, humidity, and barometric pressure will also provide the farmer with valuable information. Each sensor will pass the measured data to its corresponding LR-WPAN device, which in turn will pass it through the network to a central collection device. In order for the sensor data to be useful, location awareness technology is necessary for correlating each sensor with its specific location in the field. The combined information will give the farmer an early alert to potential problems and allow him to achieve higher crop yields.

The precision agriculture application is at the low end of the LR-WPAN application range, requiring the transmission of only a few bits of data per day by each deployed device. The data flow will be asynchronous in nature, with minimal restrictions on data latency. This combination of factors is advantageous for achieving long battery life. The challenge of this application is the topology of the network, since the application requires a mesh topology: some nodes serve as repeaters for others, relaying messages to the final destination, while still being power-conscious to obtain the required usage life. The network should also be self-configuring since manual setup of a network of the proposed size is not feasible.

The consumer and home automation market presents significant potential because of its size. LR-WPAN devices will replace wires in consumer electronics at very low cost due to the reduced capability set (e.g., a lower data rate) while still enhancing everyone's life and entertainment experience. Types of potentially networked devices include televisions, VCRs, PC peripherals, and interactive toys and games, and the applications may include monitoring and control of the home's security system, lighting, air conditioning system, and appliances. Most of these devices have an industry group interested in using a low-cost low-data-rate wireless solution. The potential for such networked devices within the home may be as high as 100–150 devices, and is well suited to a star topology.

A unique application scenario, falling within the consumer market, is a classroom calculator network. This network would operate in a master-slave mode in a star topology. The teacher workstation, the network master, would send tasks and math problems to each of the student's graphic calculators, the network slaves. After completion, the students would upload their solutions back to the teacher workstation. This network would need to support only a small number of nodes, typically around 30, and would require disallowing any peer-to-peer communication to prevent students from exchanging the solutions. The typical payload would be 100–500 bytes of information, sent several times per student per hour. It is desired that the batteries to power the calculator and communication function last the duration of a semester. While this is definitely a more throughput-consuming application than those presented so far, it is still well suited to an LR-WPAN.

Conclusions

While most ongoing work in IEEE 802 wireless working groups is geared to increase data rates, throughput, and QoS, the 802.15.4 LR-WPAN task group is aiming for other goals. The focus of 802.15.4 is on very low power consumption, very low cost, and low data rate to connect devices that previously have not been networked, and to allow applications that cannot use current wireless specifications.

Working within a standards organization to develop a wireless solution has the advantage of bringing developers and users of such a technology together in order to define a better solution. The work also fosters high-level connectivity to other types of networks and enables low-volume products that do not justify a proprietary solution to be wirelessly connected.

Just prior to the last revision of this article, the baseline physical and MAC layer proposals were selected at the IEEE 802 Plenary meeting in Portland, Oregon, in July 2001. Two physical layer specifications were chosen to cover the 2.4 GHz worldwide band and the combination of the 868 MHz band in Europe, the 902 MHz band in Australia, and the 915 MHz band in the

United States. Both physical layers are direct sequence spread spectrum (DSSS) solutions. The selected MAC proposal supports the implementation of both star and cluster tree networks, in order to satisfy the variety of application scenarios described here. For further information, the selected proposals can be downloaded from the 802.15 Web site [5].

The efforts of the IEEE 802.15.4 task group will bring us one step closer to the goal of a wirelessly connected world.

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