For each of these four frame types, the MPDU is further encapsulated with an additional preamble and PHY header to form the physical layer service data unit (PSDU). This complete data structure allows a receiver to achieve symbol synchronization with the frame and obtain the frame length information for checking purposes.

Chapter 4 Physical Layer

...from bytes to watts

The physical layer (PHY) provides the interface with the physical medium where the actual communications occurs. The PHY layer is the lowest component in the ISO/OSI model and is in charge of providing control (activation and deactivation) of the radio transceiver, energy detection, link quality, clear channel assessment, channel selection, and the transmission and reception of message packets through the physical medium [26].

Regulatory Considerations

Governments around the world regulate and administer the radio-frequency spectrum. In most cases, there are band allocations for unlicensed operation, given that the manufacturer can ensure operation within some pre-established limits in output power, duty cycle, modulation, and other parameters. Station licenses, along with an identification call sign, are issued to transmitters for many of the allowed services, but there is also a provision for the operation of some devices that do not require station licenses. The particulars of unlicensed services vary throughout the world, but generally, the devices must conform to a set of regulatory limitations that are specific for each operation. Transmitters for each operation must pass a testing protocol to ensure that they meet the specific requirements. Once a particular design has passed the regimen of testing, it is issued a certification or type approval for that service. IEEE Std 802.15.4 devices are targeted toward type approval.

Implementations of IEEE Std 802.15.4 will have to conform to local regulations of the country where it will operate. In the case of Europe, Japan, Canada, and the United States the regulation consists in unlicensed but type-approved DSSS service. It is the constraint for unlicensed, but type-approved compliance that dictates the frequency bands of operation, as well as a few of the other characteristics of the service.

IEEE Std 802.15.4 is written so that conforming devices can be manufactured to operate in any of three particular bands. Two of these bands are limited to specific geographical regions, but one band is available for nearly worldwide service. Details of these bands are presented next.

European Regional Case

In Europe, the European Telecommunications Standards Institute (ETSI) has published recommendations that are recognized generally by all regulatory agencies, but each service area falls under individual national type-approval authority. Within the European service area, there is one common band with operation allowed between 868.0 and 868.6 MHz that supports a single channel of low data rate service with less than 1% transmission duty cycle [4], [5]. Again, this band is unique to European service, and regulations elsewhere preclude operation of unlicensed devices in this band.

IEEE Std 802.15.4 868/915 MHz PHY requires that a compliant device be capable of operation on both the 868 and 915 MHz bands. For the purposes of the standard, they are considered to be a single, contiguous band.

> In May 2002, the Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT) released their strategic plan for the future use of the frequency band 862–870 MHz. This plan delineates a roadmap to increase the frequency band available for spread spectrum devices. The allocated band would operate in the 865–868 MHz band, allowing the addition of at least three radio channels to a future release of IEEE Std 802.15.4.

North American Regional Case

Within the United States, the national regulatory agency is the Federal Communications Commission (FCC). The FCC has specific authority only within the United States; however, the FCC regulations are used as a model by many other nations in the Americas and the Pacific Rim. Just as in Europe, there is a unique band available for service; this band is called the 915 MHz band and it covers the range between 902 and 928 MHz. This band enables the provision of ten channels of low data rate service. With some exceptions, unlicensed operation in this band is unique to North America, and regulations elsewhere preclude operation of unlicensed devices in this band.

Worldwide Case

To obtain economies of scale in product design, marketing, and distribution, and to enable applications that may require roaming between different regulatory regions, it is desirable to employ a single band that is available on a nearly worldwide basis. The ideal band would be unlicensed, have sufficient width to enable the use of many channels, and be high enough in the spectrum so that relatively efficient antennas are possible without being so high that single-chip implementations employing low-cost integrated circuit processes are precluded.

The band selected as best meeting these requirements is the 2.4 GHz Industrial, Scientific, and Medical (ISM) band, which extends from 2400 to 2483.5 MHz. This band, with very few exceptions, is available worldwide without licensing [6], [22], [23] and, with a wavelength of 12.25 cm, enables reasonably efficient yet physically small antennas. Further, it is compatible with modern silicon integrated circuit processes, and the wider bandwidth available enables the provision of sixteen channels of higher data rate service.

IEEE Std 802.15.4 was designed for regulatory compliance in each of these bands. For example, in the 868 MHz band, the product duty cycle is limited; the non-beacon mode of IEEE Std 802.15.4 may be used to minimize the duty cycle of devices in this band. In many cases, some type of spread spectrum operation is required for operation in unlicensed bands. The use of DSSS in IEEE Std 802.15.4 allows this regulatory requirement to be met, while also enabling a low-cost product implementation with good transmission range.

Frequency Bands and Data Rates

In response to the regulatory availability of the three bands for unlicensed operation, IEEE Std 802.15.4 specifies technical objectives for operation within each band:

- *868–868.6 MHz Band:* This unlicensed band is available in most European countries for a 20 kb/s DSSS service. IEEE Std 802.15.4 also refers to this band as the "868 MHz" band.
- *902–928 MHz Band:* Some portions of this unlicensed band are available in North America, Australia, New Zealand, and some countries in South America for 40 kb/s DSSS service. IEEE Std 802.15.4 also refers to this band as the "915 MHz" band (which represents the middle frequency of the band).

> The IEEE Std 802.15.4 868/915 MHz PHY requires that a compliant device be capable of operation on both the 868 and 915 MHz bands. For the purposes of the standard, they are considered to be a single, contiguous band.

- *2.4000–2.4835 GHz Band:* This third unlicensed band is available in most countries worldwide for the faster 250 kb/s DSSS service. This band is referred to as the 2.4 GHz band.

Due to its nearly world-wide availability, the 2.4 GHz PHY may be the first choice for many IEEE Std 802.15.4 applications, especially those involving products, such as wireless luggage tags, that involve travel between regulatory regions. Even for non-mobile applications, the 2.4 GHz band offers advantages of scale, distribution, and marketing: A single product can be sold in multiple locations around the globe, without concern for the regulatory region in which it will be used. This drives down production costs, while eliminating the supply chain expense of tracking multiple products to multiple destinations.

However, for these same reasons, the 2.4 GHz band is used by many other services, from microwave ovens to WPANs and WLANs. This can result in congestion that is unacceptable for some applications and markets. To address this issue, the IEEE Std 802.15.4 868/915 MHz bands are available as an alternative. This feature allows system designers to use these regional bands in order to avoid the potentially crowded 2.4 GHz band. The regional bands may be a good design choice for applications such as utility meter reading that are inherently regional in nature and have limited device mobility. Similarly, diverse sensors in different industrial segments can make use of this feature.

Data Rates

Due to the physical characteristics of each band and the regulations where they are used, IEEE Std 802.15.4 specifies different data rates and modulations for the three bands used in the two PHYs.

Table 4–1 shows the data rates (bit and symbol) and the direct sequence spread spectrum parameters specified in each band.

A more detailed explanation of the modulation parameters will be introduced in the band specification sections below.

Table 4–1: IEEE Std 802.15.4 frequency band and modulation parameters

Band	Frequency Band	Bit Rate	Symbol Rate	DSSS Spreading Parameters	
				Modulation	Chip Rate
868 MHz	868–868.6 MHz	20 kb/s	20 ksymbols/s	Binary Phase Shift Keying (BPSK)	300 kchip/s
915 MHz	902–928 MHz	40 kb/s	40 ksymbols/s	Binary Phase Shift Keying (BPSK)	600 kchip/s
2.4 GHz	2.4–2.4835 GHz	250 kb/s	62.5 ksymbols/s	Offset Quadrature Phase Shift Keying (O-QPSK)	2 Mchip/s

Channel Assignment

IEEE Std 802.15.4 specifies a total of 27 channels across the three frequency bands. The channels are numbered 0 to 26; one channel is available in the 868 MHz band, 10 channels in the 915 MHz band, and 16 channels in the 2.4 GHz band. The center frequencies of these channels are shown in Table 4–2.

Table 4–2: IEEE Std 802.15.4 channel assignment

	Channel	Center Frequency (MHz)	Availability
868 MHz Band	0	868.3	
915 MHz Band	1	906	
	2	908	
	3	910	
	4	912	
	5	914	
	6	916	
	7	918	
	8	920	
	9	922	
	10	924	
2.4 GHz Band	11	2405	
	12	2410	
	13	2415	
	14	2420	
	15	2425	
	16	2430	
	17	2435	
	18	2440	
	19	2445	
	20	2450	
	21	2455	
	22	2460	
	23	2465	
	24	2470	
	25	2475	
	26	2480	

PHY Bit Level Communication

The PHY level of the IEEE Std 802.15.4 protocol is responsible for the establishment of the RF link between two devices. The PHY is also responsible for bit modulation, demodulation, and synchronization between the transmitter and receiver. Finally, the PHY also is responsible for packet level synchronization.

IEEE Std 802.15.4 specifies three different data rates in each of the three different bands. The two lower rates, used in the 868/915 MHz PHY layer, are specified using a BPSK modulation scheme, and the highest rate, used in the 2.4 GHz PHY layer, is specified using the O-QPSK modulation scheme with an m-ary quasi-orthogonal modulation technique.

2.4 GHz Band Specification

The 16-ary quasi-orthogonal modulation technique specified in the IEEE Std 802.15.4 2.4 GHz PHY layer is a method of data modulation that utilizes a particular 32-chip, pseudo-random sequence to represent four bits and simultaneously accomplish the spreading modulation. The data modulation is performed by means of cyclic rotation and/or conjugation (inversion of chips with odd indices) of the sequence. The pseudo-random sequence is started in different places, depending on the modulating data, transmitting four bits in each symbol period.

While five bits could be transmitted by the choice of 32 chips, four were chosen for the 2.4 GHz PHY to minimize implementation complexity. The transmitted 32-chip pseudo-random sequence is allowed to start only at every fourth chip of the sequence. Symbols 0–7 represent cyclic shifts in multiples of four chips. Symbols 8–15 use the same shifts as symbols 0–7, respectively, but use the conjugated sequence (i.e., the odd-indexed chips are inverted).

The IEEE Std 802.15.4 2.4 GHz PHY layer specifies a symbol rate of 62.5 ksymbols per second with four bits in each symbol; therefore, 250 kb/s service is attained. The 32-chip pseudo-random sequence to be transmitted is split between the orthogonal I and Q channels of the O-QPSK modulator, with the even-indexed chips placed on the I channel and the odd-indexed chips placed on the Q channel. A one-half chip delay is placed in the Q channel, creating the offset for O-QPSK. Because 32 (now complex) chips are transmitted in one symbol time (16 μs), the overall chip rate is 2 Mc/s. The chip rate in either I or Q channel, however, is 1 Mc/s.

The bit level processing consists of assembling four bits into a symbol, converting that symbol to a cyclically-rotated 32-chip sequence as shown in Table 4–3, and modulating that chip sequence on the I or Q channel, respectively. The process is diagrammed in Figure 4–1.

The resulting combination of complex modulation, including the offset between I and Q channels is shown in Figure 4–2.

Initially two distinct pseudo-noise (PN) sequences were considered for the I and Q channels of the quasi-orthogonal modulation in the O-QPSK, but the two were later combined to use a single PN sequence separated into even and odd bits between the I and Q channels. The advantage of a single PN sequence lies in that a single correlator is required that can be shared between the I and Q channels, thereby reducing implementation complexity.

Table 4–3: Symbol to chip mapping

Data Symbol (decimal)	Data Symbol (binary) (b3 b2 b1 b0)	Chip Values (c0 c1... C30 C31)
0	0000	11011001110000110101001000101110
1	0001	11101101100111000011010100100010
2	0010	00101110110110011100001101010010
3	0011	00100010111011011001110000110101
4	0100	01010010001011101101100111000011
5	0101	00110101001000101110110110011100
6	0110	11000011010100100010111011011001
7	0111	10011100001101010010001011101101
8	1000	10001100100101100000011101111011
9	1001	10111000110010010110000001110111
10	1010	01111011100011001001011000000111
11	1011	01110111101110001100100101100000
12	1100	00000111011110111000110010010110
13	1101	01100000011101111011100011001001
14	1110	10010110000001110111101110001100
15	1111	11001001011000000111011110111000

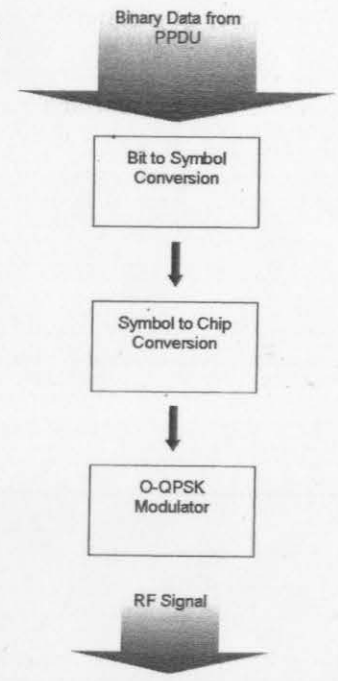


Figure 4–1: 2.4 GHz modulation and spreading

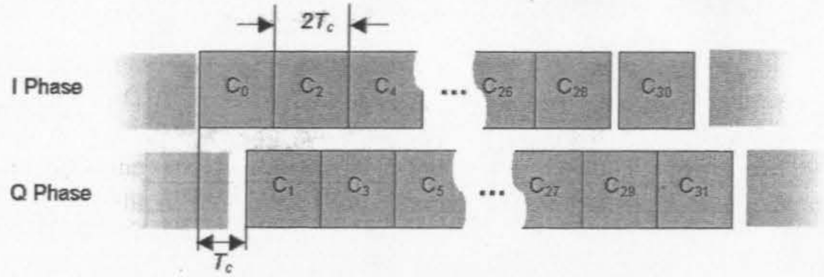


Figure 4–2: O-QPSK chip offsets

Because 32 chips are transmitted in one symbol time (16 µs), the overall chip rate is 2 Mc/s, and the length of a chip is Tc = 0.5 µs. Successive chips in each of the I and Q channels start every 2 Tc.

868/915 MHz Band Specification

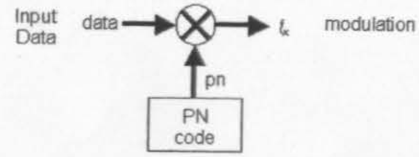
The 868/915 MHz PHY layer specifies DSSS employing BPSK, with a data rate of 20 kb/s in the 868 MHz band and 40 kb/s in the 915 MHz band. A complex signal path is not required.

The 868/915 MHz PHY specifies differential encoding of the transmitted data bits. If the raw data bit is "0," the BPSK data bit is transmitted in the same phase as the previous BPSK data bit, while if the raw data bit is "1," the BPSK data bit is transmitted in phase opposite to the previous BPSK bit.

The 868/915 MHz PHY specifies "conventional" DSSS, in which a single, 15-chip, pseudo-random sequence is transmitted in a symbol period to represent a "1," and the inverse of the sequence is transmitted to represent a "0." This process is illustrated in Figure 4–3. The chip rate is specified as 300 kc/s in the 868 MHz band, for a data rate of 20 kb/s; in the 915 MHz band, the specified chip rate of 600 kc/s enables a data rate of 40 kb/s. The reception process used to recover the transmitted data is shown in Figure 4–4.

The 868/915 MHz modulation and spreading process is illustrated in Figure 4–5.

The BPSK modulation utilizes a different PN sequence, but it shares that sequence between the two lower data rates. The difference in data rates is due to the difference in chip rates, but the number of chip bits per data bit and the bit pattern are the same between the two.



		Band	
		868 MHz	915 MHz
T_b	bit period	50 us	25 us
R_b	bit rate	20 kb/s	40 kb/s
T_c	chip period	3.33 us	1.66 us
R_c	chip rate	300 kc/s	600 kc/s
N_c	chips per symbol	15	

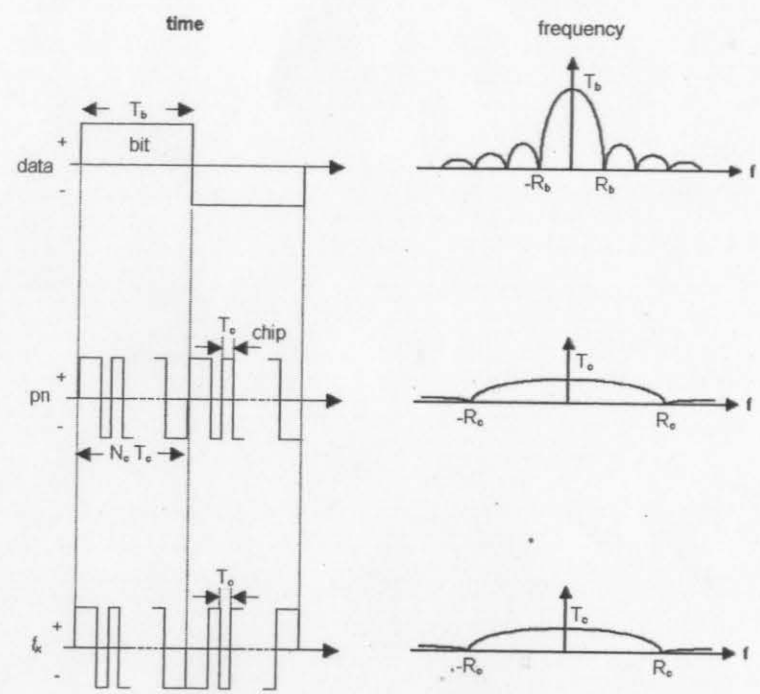
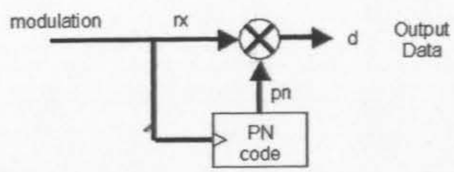


Figure 4–3: DSSS modulation



		Band	
		868 MHz	915 MHz
T_b	bit period	50 us	25 us
R_b	bit rate	20 kb/s	40 kb/s
T_c	chip period	3.33 us	1.66 us
R_c	chip rate	300 kc/s	600 kc/s
N_c	chips per symbol	15	

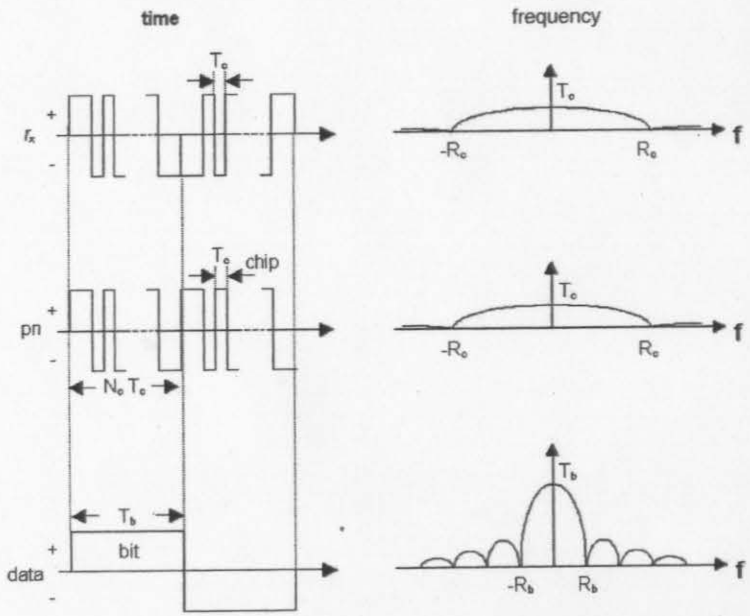


Figure 4–4: DSSS demodulation

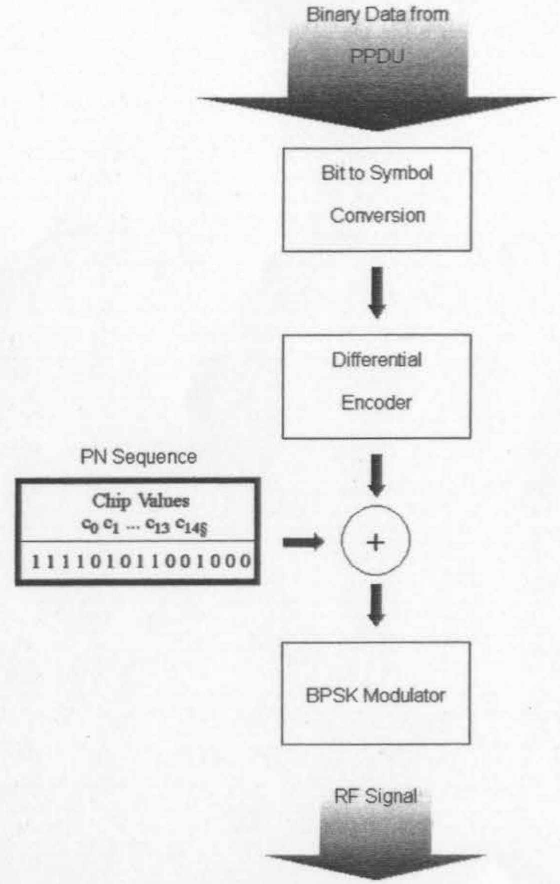


Figure 4–5: 868/915 MHz modulation and spreading

RADIO CHARACTERISTICS

IEEE Std 802.15.4 radio specification was designed to allow the implementation of low-cost digital integrated circuit designs. Most of the technical radio specification can be considered relaxed with respect to other radio technologies. The following paragraphs present some of the characteristics of the IEEE Std 802.15.4 radio.

Power Outputs

IEEE Std 802.15.4 provides for a wide transmitter output power range, but the device must be capable of transmitting –3 dBm. The upper limit of power output is designated by the regulatory agency associated with the local use. For example, in the United States, some services using DSSS in the 2.4 GHz band are allowed up to 1 Watt of transmitter power [22], however, in Europe the limit is 100 milliwatts in the same band [6].

Sensitivity

IEEE Std 802.15.4 specifies that the receiver must be capable of correctly decoding a signal with an input power of –85 dBm or less in the 2.4 GHz band. In the lower frequency bands where BPSK is used, the receiver must be capable of correctly decoding a signal with an input power of –92 dBm or less. Better sensitivity is not prohibited.

Range

In free space, the path loss between a transmitter and a receiver is dependent solely on the distance between them, and is independent of the frequency used. There is therefore no inherent difference in range between the IEEE Std 802.15.4 frequency bands. The type of antenna used, however, can give the illusion of a frequency-dependent path loss: A constant-gain antenna, such as a half-wave dipole, has an effective aperture (area) that decreases as the frequency of operation increases. (The dipole gets physically smaller as the frequency increases, leading to a reduction of its effective area.) At higher frequencies, the dipole therefore intercepts less of the transmitted radiation and produces less received signal at its terminals. Users of a communication link employing dipole antennas on both transmitter and receiver would therefore notice a range reduction as the frequency of operation increased, although the effect was due to the antennas employed, rather than an increase in path loss.

> Antennas that have a constant effective aperture exist; such antennas have gain that increases as the frequency of operation increases. An example of such an antenna is the parabolic dish antenna. Users of a communication link employing parabolic dish antennas of fixed dimensions on both transmitter and receiver would notice a range extension as the frequency of operation was increased—just the opposite effect of that seen by the users employing dipole antennas.

The above notwithstanding, many implementations of the IEEE Std 802.15.4 are expected to employ constant gain (dipole) antennas. For these implementations,

and in the case of free space, the ratio of the power at a receiving antenna to the power at a transmitting antenna is given by the Friis model:

$$\frac{P_R}{P_T} = G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2 = G_T G_R \left(\frac{c}{4\pi f d}\right)^2$$

where P_R and P_T are the power values at the receiving antenna and transmitting antenna, respectively, (in watts); G_R and G_T are the power gains of the receiving antenna and transmitting antenna, respectively; λ is the wavelength (in meters); f is the frequency (in Hertz); and c is the speed of light (in meters/second).

This same equation can be expressed as a basic path loss L_B in decibel form, with the appropriate substitutions for the constants as:

$$L_B(dB) = 32.44 + 20\log_{10} f_{\mathrm{MHz}} + 20\log_{10} d_{km}.$$

For simplification, we treat the 868 and 915 MHz bands as approximately 1 GHz and the 2.4 GHz band as approximately 2 GHz so that the losses can be expressed as:

$$L_{B\,@\,1\mathrm{GHz}}(dB) \approx 92 + 20\log_{10} d_{km}$$

$$L_{B\,@\,2\mathrm{GHz}}(dB) \approx 92 + 20\log_{10} d_{km}.$$

Because lower frequency bands must exhibit a sensitivity of at least –92 dBm, for a transmitter rated at 0 dBm, and path loss of 92 dB, the maximum free space range is approximately 1 km ($\log_{10}[1]=0$).

> Notice
>
> Beware that the above derivations are using the free-space radio propagation model. These calculations are ideal; make sure you finish reading this section where a real-life model is used.

For the higher 2.4 GHz band, the receiver must exhibit a sensitivity of –85 dBm; for a transmitter rated at 0 dBm, similar calculations will show a maximum free space range of approximately 220 meters.

These ranges are for free space, isotropic antennas, and a perfect power match, without interference, and represent the maximum theoretical distances. The free-space model does not consider several environment parameters that impair the RF propagation, including wave reflection, diffraction, and scattering. A commonly used model that approximates the propagation behavior in RF channels in real environments is the log-normal shadowing model. Figure 4–6 illustrates a typical indoor propagation effect and the variance in range obtained due to the effect of shadowing (transmitting a message with an output power of 0 dBm). As it can be seen, the distance covered is a function of the frequency used. Similarly, the variability shown is a function of the characteristic of the wireless channel. The path loss coefficient in indoor environments can vary between $n = 2$ and $n = 4$ typically. Furthermore, the indoor variance in the received power ranges from $\sigma = 3$ to $\sigma = 11$.

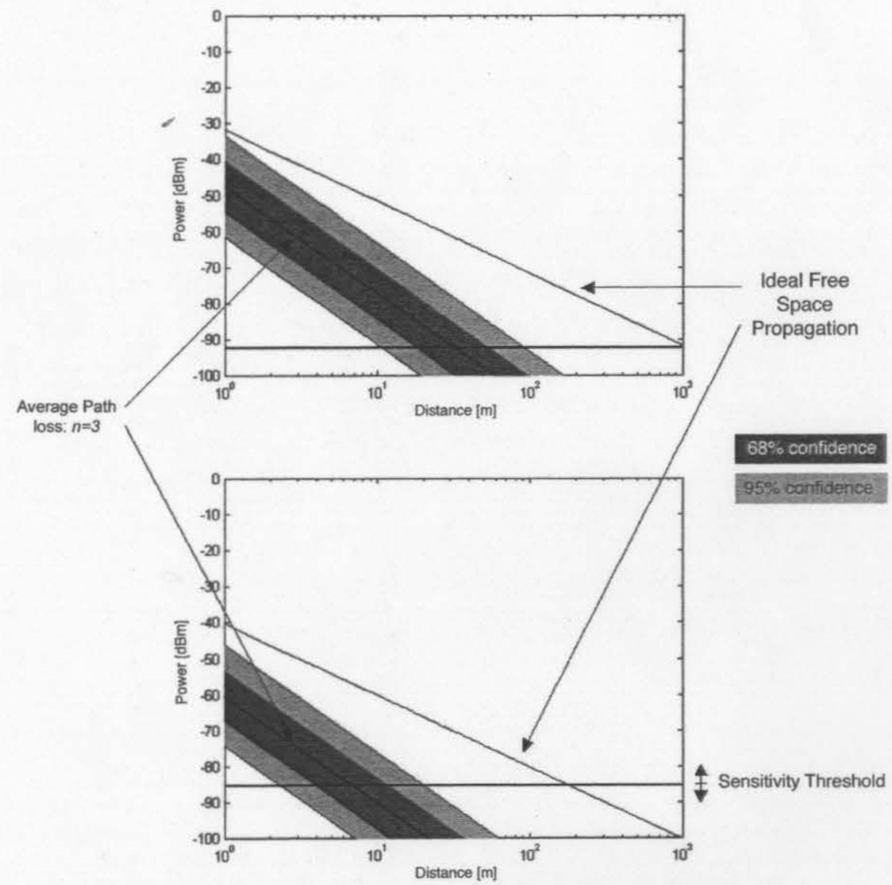


Figure 4–6: Typical indoor range (0 dBm transmission) with normal distribution (σ = 7dB): (a) 915 MHz, (b) 2.4 GHz

Receiver Selectivity

The DSSS signal is, by definition, a wideband variation of the modulated data signal. The DSSS spreading provides the communications benefits already discussed, and it provides a relaxed RF selectivity requirement. In addition, IEEE Std 802.15.4 channels are widely spaced (5 MHz in the 2.4 GHz band) relative to

their own bandwidth (3 MHz null-to-null; about 1.5 MHz noise bandwidth in the 2.4 GHz band). With the 0 dB adjacent channel requirement, as well as the relaxed requirement for channels further away, little selectivity is needed by the implementer to achieve the requirements.

Channel Selectivity and Blocking

IEEE Std 802.15.4 specifies an adjacent channel rejection for service in the 902–928 MHz band, where 10 channels are allowed, and in the 2.4 GHz band, where 16 channels are allowed. In the 868 MHz band only one channel exists and an adjacent channel specification is not meaningful. For the 902–928 MHz and 2.4 GHz bands, the receiver must reject an interfering adjacent channel signal that is at the same level (0dB difference) as a simultaneous on-channel signal. One interfering signal at a time is specified at that level.

In addition, IEEE Std 802.15.4 also specifies an "alternate" channel rejection for service in the 902–928 MHz and 2.4 GHz bands. The alternate channel is the next nearest channel to the adjacent channel, or two channels away from the channel of operation. The receiver must reject an interfering alternate channel signal that is at a level 30 dB higher than a simultaneous on-channel signal. One interfering signal at a time is specified at that level.

The specification of these interference levels ensures reliable communication in the presence of multiple colocated WPANs, each on a different channel. The specification of a single interference signal reflects the relatively low traffic envisioned for the service.

To ensure that the receiver does not behave badly in other strong signal conditions, the specification provides a maximum acceptable input level that must not cause an excessive error rate. The IEEE Std 802.15.4 receiver must withstand a signal input of at least –20 dBm without unacceptable error rates.

There is no intermodulation specification in either IEEE Std 802.15.4 PHY layer.

PHY Services

The PHY layer provides an interface between the physical radio channel and the MAC sublayer, through the use of two services. These services are the PHY data service and the PHY management service (called the PHY layer management entity or PLME) and are accessed by the PHY layer data service access point (PD-SAP)

The services of the PHY layer are the capabilities it offers to the MAC sublayer.

and the PHY layer management entity service access point (PLME-SAP), respectively.

There are four types of service primitives. They are as follows:

- *Request:* The request primitive is passed from the calling layer (also called the user layer) to request that a service is initiated.
- *Indication:* The indication primitive is passed from the service layer to the user layer to indicate an internal event of significance. This event may be logically related to a remote service request, or it may be caused by a service layer internal event.
- *Response:* The response primitive is passed from the user layer to the service layer to complete a procedure previously invoked by an indication primitive.
- *Confirm:* The confirm primitive is passed from the service layer to the user layer to convey the results of one or more associated previous service requests.

PHY Data Services

The PHY data service provides three primitives to the MAC sublayer: data-request, confirm, and indication as shown in Figure 4–7. The asynchronous design of this service does not require the use of a data-response primitive.

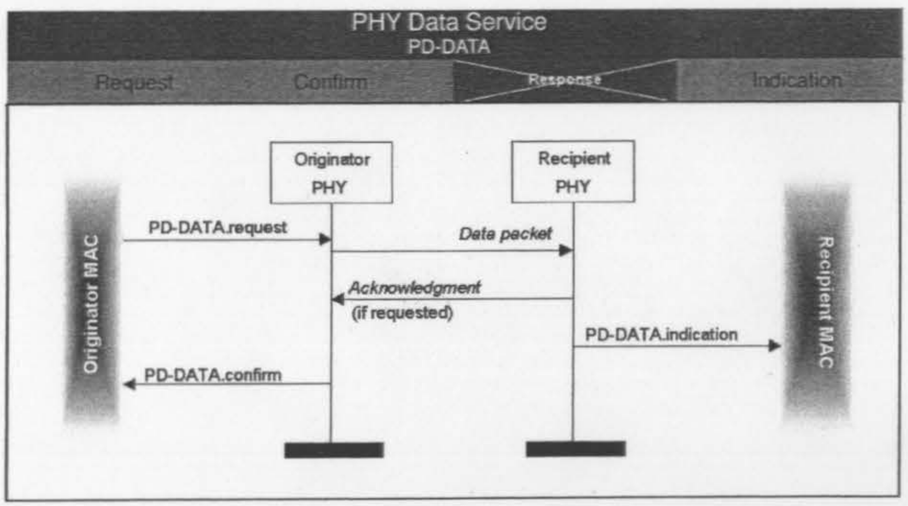


Figure 4–7: Message sequence diagram for data packet exchange mechanism

PHY Management Services

The PHY management service provides support for commands to control communication settings and the radio control functionality. The PLME primitives are summarized in Figure 4–8. The following paragraphs provide an overview of these primitives.

Primitive	Category	Description	Request	Confirm	Response	Indication
GET	Communication Settings	PHY PAN information base management	x	x		
SET			x	x		
SET-TRX-STATE	Radio Control	Enables/Disables radio system	x	x		
CCA	RF Energy Sensing	RF energy sensing: Clear Channel Assesment	x	x		
ED		Energy Detection	x	x		

Figure 4–8: PHY management service primitives

PHY PAN Information Base Management Primitives

The PHY PAN Information Base (PIB) contains configurable attributes to manage the PHY layer. These attributes can be read or written by the PLME-GET and PLME-SET primitives.

Figure 4–9 shows the message sequence diagrams for the procedure of reading or writing the PIB attributes.

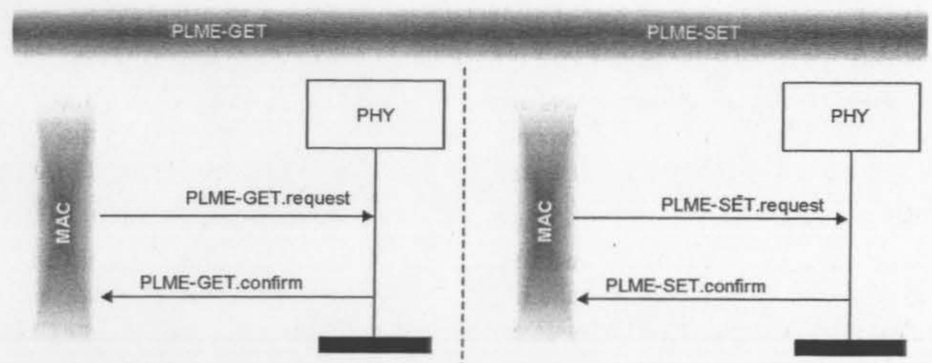


Figure 4–9: Message sequence diagram for PHY PIB reading and writing mechanism

Enabling and Disabling the PHY

The radio receiver can be enabled or disabled by means of the PLME-SET-TRX-STATE primitive. The purpose of this primitive is to control the radio transceiver and enable lower power consumption. Figure 4–10 shows the message sequence diagram for this primitive.

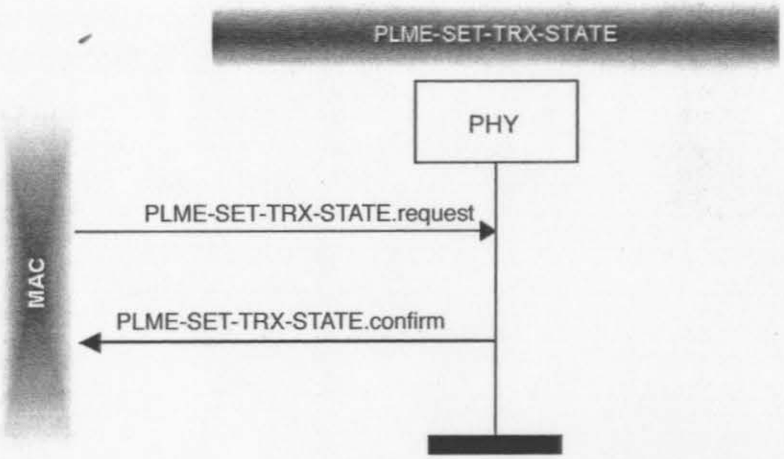


Figure 4–10: Message sequence diagram for transceiver enabling mechanism

Clear Channel Assessment

Before the transmission of packets in a non–beacon-enabled network or in the contention access period of a beacon-enabled network, the MAC instructs the PHY to perform a clear channel assessment (CCA) before sending data and MAC command frames.

When the clear channel assessment is requested, the PHY layer enables the receiver, performs a CCA measurement, and then disables the receiver. Once the clear channel assessment measurement is completed, the PHY layer issues an PLME-CCA.confirm indicating if the channel is busy or not. Figure 4–11 illustrates the CCA mechanism using the PLME-CCA primitives. The figure also shows the message sequence chart for the clear channel assessment mechanism.

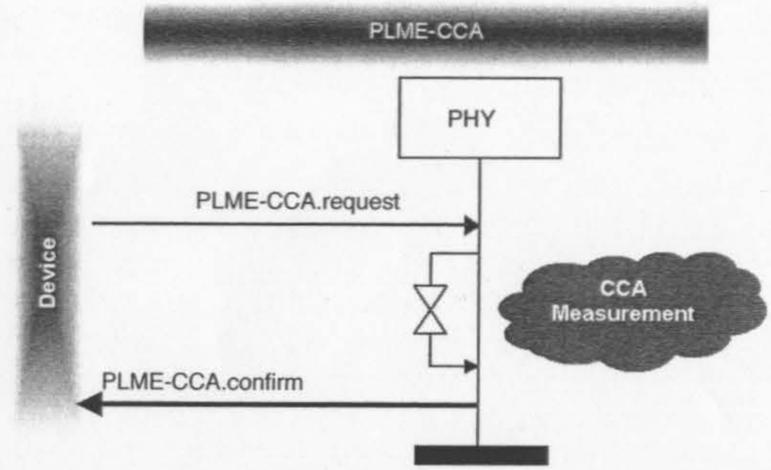


Figure 4–11: Message sequence diagram for the clear channel assessment mechanism

Energy Detection

The PLME-ED primitive allows a device to perform RF energy detection in the actual channel where it is operating. The measurement performed is similar to the one carried in PLME-CCA, but with higher resolution, it returns an energy level that ranges from 0 to 255. The use of this primitive can enhance the functionality of the network layers. Figure 4–12 shows the message sequence diagram for the energy detection process.

PHY Packet Structure

The PHY Protocol Data Unit (PPDU) is the packet data structure at the PHY protocol level that modulates the wireless transmitter. The PPDU encapsulates all data structures from higher levels of protocol. The PPDU consists of three components: first, a synchronization header; second, a PHY header; and third, a variable length payload containing the PHY layer service data unit.

***PPDU synchronization header* —** The PPDU header consists of two fields, a preamble and a start-of-frame delimiter. The preamble consists of 32 bits, all set to binary zero (recall that a binary zero gets encoded in a chip pattern). The preamble field allows a receiver a sufficient number of bits to achieve chip synchronization and bit synchronization. The start-of-frame delimiter consists of the 8-bit pattern

"0xe6" (11100101), and allows the receiver to establish the beginning of the packet in the stream of bits.

PHY header — The PHY header is a single 8-bit field with the MSB reserved and the remaining low-order bits used to designate frame length information. Packet lengths of 0 to 4 and 6 to 7 bytes are reserved. Packets of length 5 bytes are MPDU acknowledgment packets, and packets with 9 or more bytes are MPDU payloads for the MAC protocol layer service.

PHY payload — The PHY payload is composed of only one field called the physical layer service data unit (PSDU). The PSDU is variable length in nature and carries the data payload of the PPDU. All packets carry an MPDU payload for the MAC layer.

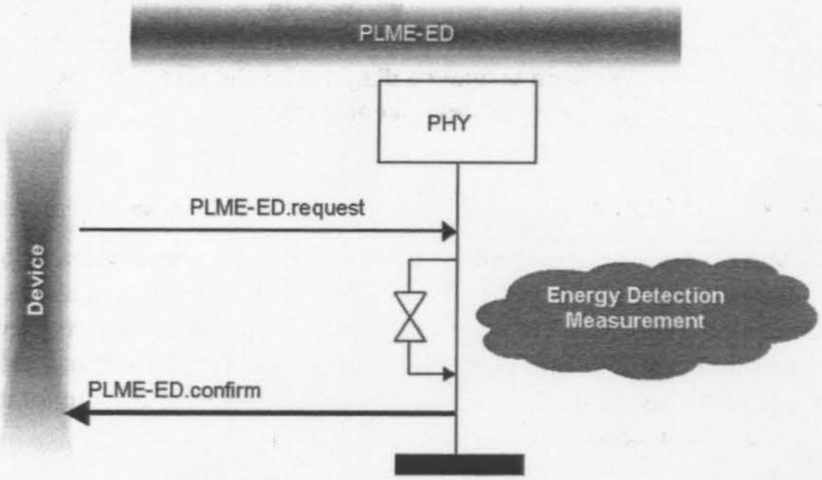


Figure 4–12: Message sequence diagram for the energy detection mechanism

Figure 4–13 shows the structure of the PPDU.

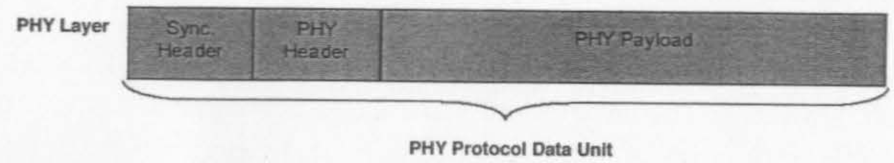


Figure 4–13: PPDU structure