IEEE P802.15
Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)	
Title	**Coexistence analysis of IEEE Std 802.15.4 with other IEEE standards and proposed standards**	
Date Submitted	[September, 2010	
Source	[802.15 Working Group] [IEEE 802] []	Voice: [] Fax: [] E-mail: []
Re:	[]	
Abstract	[This document contains the coexistence analysis that was performed forIEEE Std 802.15.4-2003, IEEE Std 802.15.4-2006, IEEE Std 802.15.4a-2007, IEEE Std 802.15.4c-2009 and IEEE Std 802.15.4d-2009. This information was previously an informative annex in the standards, but is now provided as a separate document, as is the convention with current IEEE 802 wireless standards.]	
Purpose	[A coexistence assurance document enable the IEEE 802 LMSC Executive Committee and the IEEE 802 LMSC Coexistence Working Group to determine if a proposed wireless standard has made a reasonable effort to be able to coexist with devices compliant to other IEEE 802 standards in their operating band. Coexistence, however, does not imply that there is no interference. A detailed discussion of coexistence and coexistence methods is found in IEEE Std 802.15.2-2003.]	
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Coexistence analysis of IEEE Std 802.15.4 with other IEEE standards and proposed standards

1. Introduction

While not required by this standard, IEEE 802.15.4 devices can be reasonably expected to “coexist,” that is, to operate in proximity to other wireless devices. This annex considers issues regarding coexistence between IEEE 802.15.4 devices and other wireless IEEE-compliant devices. For UWB devices specifically, additional consideration is given to certain non-IEEE standards.

This is the first IEEE 802® standard defining use of the 780 MHz band (779 MHz to 787 MHz) in China and as such coexistence is not a practical issue at this time. However, the two PHYs specified for use in the 780 MHz band use the exact same channel plan; hence they can potentially cause interference to each other. Due to the short duration (burst nature) of IEEE 802.15.4 packets and use of CSMA-CA, coexistence is not considered to be a problem for the two PHYs when they share a common channel. Similar examples of this are shown in 3.

The use of the 950 MHz band (950 MHz to 956 MHz) for LR-WPAN has only been recently allocated by the Japanese Regulatory committee. This is the first IEEE 802® standard defining use of the 950 MHz band (950 MHz to 956 MHz) in Japan and as such coexistence is not a practical issue at this time. However, the two PHYs specified for use in the 950 MHz band can potentially cause interference to each other. The Japanese regulation includes requirements to address coexistence for devices operating in band, e.g., listen before talk, transmission control, and duty cycle restrictions. Together with the short duration (burst nature) of IEEE 802.15.4 packets and the use of CSMA-CA, coexistence is not considered to be a problem for the two PHYs when they share a common channel. Similar examples of this are shown in 3.

1.1 Standards and proposed standards characterized for coexistence

This clause enumerates IEEE-compliant devices that are characterized and the devices that are not characterized for operation in proximity to IEEE 802.15.4 devices.

This standard is specified for operation in the 800 MHz, 900 MHz, and 2400 MHz bands. In the 800/ 900 MHz bands, there are BPSK, O-QPSK, and ASK PHYs, which can interact with each other. In the 2400 MHz band, there is only an O-QPSK PHY, which can interact with other IEEE 802 wireless devices operating in the 2400 MHz industrial, scientific, and medical (ISM) band.

Standards and proposed standards characterized in this annex for coexistence are as follows:

— IEEE Std 802.11b™-1999 (2400 MHz DSSS)
— IEEE Std 802.15.1™-2002 [2400 MHz frequency hopping spread spectrum (FHSS)]
— IEEE Std 802.15.3-2003 (2400 MHz)

Standards not characterized in this annex for coexistence are as follows:

- IEEE Std 802.11™-2007 , frequency hopping (FH) (2400 MHz FHSS)
- IEEE Std 802.11™-2007, infrared (333 GHz amplitude modulation)
- IEEE Std 802.16™-2004, (2400 MHz OFDM)
- IEEE Std 802.11™-2007, (5 GHz DSSS)

The CSS PHYs for the 2400 MHz ISM band are specified for operation in 14 channels. Channel 0 through channel 13 reside in frequencies from 2412–2484 MHz bands and, therefore, can interact with other IEEE-compliant devices operating in those frequencies.

Standards and proposed standards characterized in this annex for coexistence are as follows:

- IEEE Std 802.11-2007 (ERP)
- IEEE Std 802.11-2007 (2400 MHz DSSS)
- IEEE Std 802.15.1™-2005 [2400 MHz frequency hopping spread spectrum (FHSS)]
- IEEE Std 802.15.3™-2003 (2400 MHz DSSS)
- IEEE Std 802.15.4-2006 (2400 MHz DSSS)
- IEEE Std 802.15.4a-2007 (2400 MHz CSS)

Standards not characterized in this annex for coexistence are as follows:

- IEEE Std 802.11-2007, frequency hopping (FH) (2400 MHz FHSS)
- IEEE Std 802.11-2007, infrared (IR) [333 GHz amplitude modulation (AM)]
- IEEE Std 802.16™-2004 (2400 MHz OFDM)
- IEEE Std 802.11-2007 (5.2 GHz DSSS)

The UWB PHYs for the 250–750 MHz band reside in frequencies that can interact with other IEEE standards in development. UWB PHYs for the 3244–4742 MHz and 5944–10 234 MHz bands can interact with both IEEE-compliant devices and non-IEEE-compliant devices.

Standards and proposed standards characterized in this annex for coexistence are as follows:

- IEEE Std 802.16-2004
- IEEE P802.22
- ECMA 368[1]

1.2 General coexistence issues

This standard provides several mechanisms that enhance coexistence with other wireless devices operating in the 800 MHz, 900 MHz, and 2400 MHz bands. This subclause provides an overview of the mechanisms that are defined in the standard. These mechanisms include

- CCA
- Dynamic channel selection
- Modulation
- ED and LQI
- Low duty cycle

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[1] ECMA 368, High Rate Ultra Wideband PHY and MAC Standard (December 2005) (www.ecma-international.org).

- Low transmit power
- Channel alignment
- Neighbor piconet capability

In addition, this standard provides several mechanisms that enhance coexistence of UWB PHYs with other wireless devices operating in the same spectrum.

- UWB modulation with extremely low PSD
- Low duty cycle
- Low transmit power
- Dynamic channel selection
- Coordinated piconet capabilities

These mechanisms are described briefly in the following subclauses.

1.2.1 Clear channel assessment (CCA)

IEEE 802.15.4 PHYs provide the capability to perform CCA in its CSMA-CA mechanism. The PHYs require at least one of the following three CCA methods: ED over a certain threshold, detection of a signal with IEEE 802.15.4 characteristics, or a combination of these methods. Use of the ED option improves coexistence by allowing transmission backoff if the channel is occupied by any device, regardless of the communication protocol it may use.

1.2.2 Modulation

1.2.2.1 2400 MHz band PHY

The 2400 MHz PHY specified for this standard uses a quasi-orthogonal modulation scheme, where each symbol is represented by one of 16 nearly orthogonal PN sequences. This is a power-efficient modulation method that achieves low signal-to-noise ratio (SNR) and signal-to-interference ratio (SIR) requirements at the expense of a signal bandwidth that is significantly larger than the symbol rate. A typical low-cost detector implementation is expected to meet the 1% packet error rate (PER) requirement at SNR values of 5 dB to 6 dB.

Relatively wideband interference, such as IEEE Std 802.11b-1999 and IEEE Std 802.15.3-2003, would appear like white noise to an IEEE 802.15.4 receiver. The detector performance in this case is similar to noise performance, but the overall SIR requirement is 9 dB to 10 dB lower because only a fraction of the IEEE 802.11b or IEEE 802.15.3 signal power falls within the IEEE 802.15.4 receiver bandwidth.

The use of PN sequences to represent each symbol in this standard offers DSSS-like processing gains to interferers whose bandwidth is smaller than the bandwidth of this standard. For example, this processing gain helps to reduce the impact of an IEEE 802.15.1 interferer, whose 20 dB bandwidth is roughly 50% smaller than the bandwidth of this standard. Whereas the SNR requirement is 5 dB to 6 dB for 1% PER in noise, the equivalent SIR requirement for an IEEE 802.15.1 signal centered within the pass band of the IEEE 802.15.4 receiver is only 2 dB.

In terms of interference to others, this standard appears as wideband interference to IEEE Std 802.15.1-2005, and only a fraction (~50%) of the IEEE 802.15.4 signal power falls within the IEEE 802.15.1 receiver bandwidth. Furthermore, due to the bandwidth ratios and to the frequency hopping used in IEEE Std 802.15.1, IEEE 802.15.4 transmissions will interfere with approximately 3 out of the 79 hops, or approximately 4%. To an IEEE 802.11b receiver, this standard looks like a narrowband interferer, and the processing gain resulting from the spread-spectrum techniques in IEEE Std 802.11b-1999 will help reduce the impact of the IEEE 802.15.4 interferer.

1.2.2.2 800/900 MHz band PHYs

The 800/900 MHz band PHYs specified in this standard each use DSSS modulation. These power-efficient modulation methods achieve low SNR and SIR requirements at the expense of a signal bandwidth that is significantly larger than the symbol rate. A defining feature of systems that use spread spectrum modulation is that they are less likely to cause interference in other devices due to their reduced PSD. For the same reason, spread spectrum devices have some degree of immunity from interfering emitters, making them a good choice for environments where coexistence is an issue.

1.2.2.3 Direct sequence UWB modulation

The UWB PHY specified in this standard uses a UWB direct sequence modulation. This power-efficient modulation method achieves low requirements for signal-to-noise ratio (SNR) and signal-to-interference ratio (SIR) through the use of a signal bandwidth that is significantly larger than the symbol rate. A defining feature of systems that use UWB modulation is that they are less likely to cause interference in other devices due to their reduced PSD. In fact, even the least restrictive regulations for UWB devices today require the emission PSD levels to be at or below the levels allowed for unintentional emissions by other electrical or electronic devices. In some cases, the UWB PSD limits are as much as 35 dB below these same unintentional emissions limits. For the same reason, UWB devices have some degree of immunity from interfering emitters, making them a good choice for environments where coexistence may be an issue.

1.2.3 ED and LQI

The IEEE 802.15.4 PHYs include two measurement functions that indicate the level of interference within an IEEE 802.15.4 channel. The receiver ED measurement is an estimate of the received signal power within an IEEE 802.15.4 channel and is intended for use as part of a channel selection algorithm at the network layer. The LQI measures the received energy level and/or SNR for each received packet. When energy level and SNR data are combined, they can indicate whether a corrupt packet resulted from low signal strength or from high signal strength plus interference.

1.2.4 Low duty cycle

The specifications of this standard are tailored for applications with low power and low data rates (a maximum of 250 kb/s and down to 20 kb/s). Typical applications for IEEE 802.15.4 devices are anticipated to run with low duty cycles (under 1%). This will make IEEE 802.15.4 devices less likely to cause interference to other standards.

In the UWB bands, the data rates have been increased to a nominal mandatory rate of 850 kb/s. Although not designed to provide continuous higher throughputs, the UWB PHY also provides for optional data rates as high as 27 Mb/s. These rates are not designed to support high-rate applications such video transport, but instead are provided to allow devices in close proximity to shorten their transmission duty cycle by as much as a factor of 32 relative to the mandatory rate to further reduce the likelihood that these devices will interfere with or be subject to interference by other devices when conditions allow.

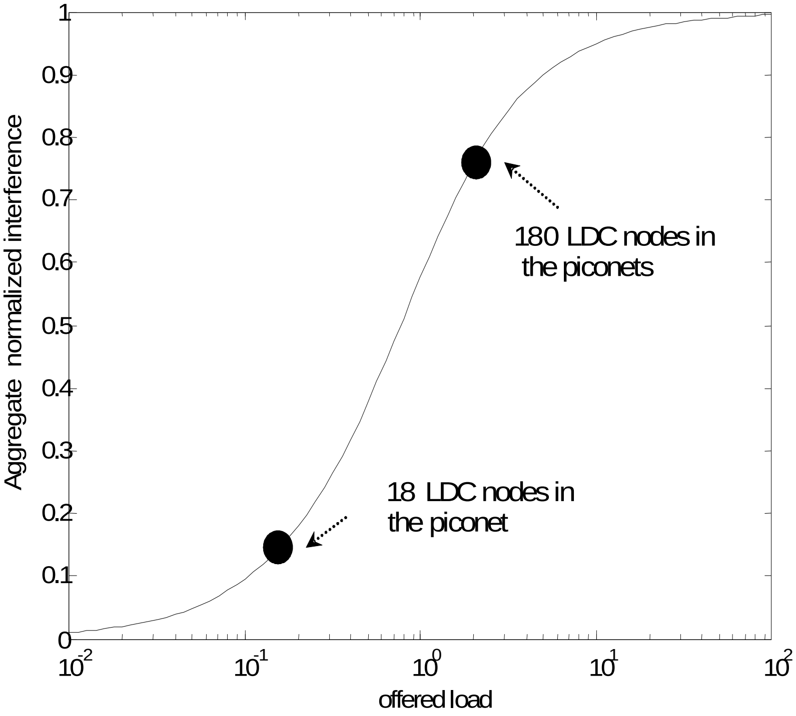
1.2.5 Low-duty-cycle considerations for UWB PHYs

Low-duty-cycle piconet scenarios are used to model the following situations:

- UWB PHY devices are deployed in high density in a limited area, e.g., hot-spot deployment scenarios.

— Some UWB victim systems cover a much larger area than the coverage of a typical UWB PHY piconet, are located well above the local cluster (e.g., IEEE 802.16, radio astronomy service, and satellite service), or are closely located with a piconet coordinator (e.g., devices placed at the same desk or even within the same computer).

In such cases, transmissions from every device in the piconet can affect the victim receiver. For reasons of less complexity, lower power consumption, as well as physical limitations, it is difficult for simple UWB PHY devices to detect victim systems reliably. The aggregate interference from the piconet increases with piconet members. Given 1% average device duty cycle and pure ALOHA protocol, the aggregate interference is 17.6% from a piconet with 18 members, as illustrated in Figure 1. Besides, the channel idle periods are randomly segmented into small pieces. Therefore, it is hard to use the channel effectively. Analyzing the interference in the channel is similar to the collision analysis of a pure ALOHA system.



LDC = low duty cycle

Figure 1—Aggregate normalized interference

The maximal interference level to such kinds of victim systems can be limited by controlling the duty cycle of the piconet through general active/inactive periods, as illustrated in Figure 2. The traffic can occur only in the active period. Victim systems are free of interference in the inactive period. The distribution of active/inactive periods is controlled by the piconet coordinator. This can be implemented by a clock in the application layer. The piconet coordinator defines global time of the piconet and duration of the active period. When a device joins a piconet, it synchronizes its clock with that of coordinator.

The interference level is restricted by the ratio of active period to the total period. The possible packet collision in the active period can be mitigated as follows:

— Adopt CSMA-CA mechanism.

— Adopt channel-dependent ALOHA: The channel-dependent ALOHA is used to set transmission probability related with the channel quality, which can be obtained through listening to a beacon from the coordinator by means of LQI and receiver ED. The function to map channel quality to

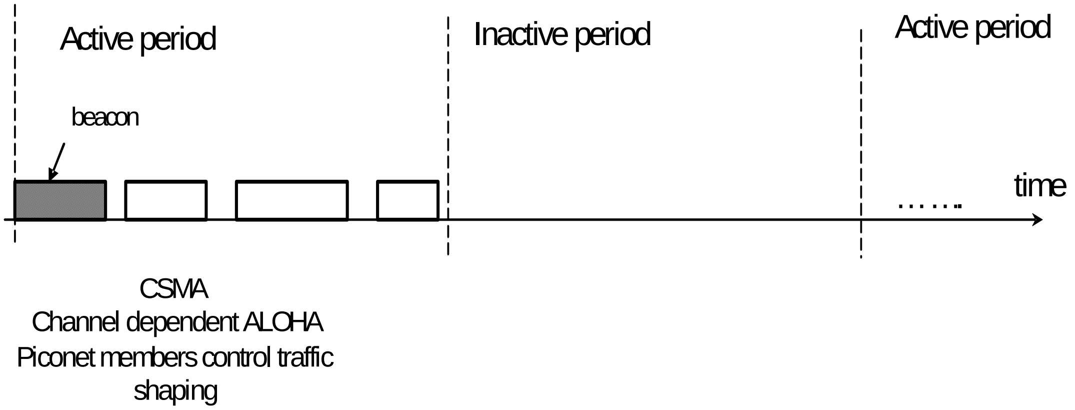


Figure 2—Generalized active/inactive periods

transmission probability is defined at application layer. A simple way is to set a threshold and only enable transmission when the channel quality is above the threshold.

- Limit the number of piconet members through association.
- Use traffic shaping, e.g., a combination of short packet to large packet.

Considering the applications for which the UWB PHY is designed, in application scenarios where a greater number of nodes can be expected, duty cycle (aggregate and individual) can be expected to be orders of magnitude less than the 1% used above. Consider, for example, a sensor application where low-cost sensor nodes are deployed in large number (typically indoors). An individual node may be “awake” only milliseconds per hour. In such scenarios, the aggregate duty cycle would be under the control of the higher layer protocols and very low compared to the 1% used in the above analysis. This observation has two important implications:

- ALOHA is well suited to this application where probability of collision is small and controllable; therefore, the complexity advantage is a good trade-off.
- There is low impact on coexistence due to a large number of IEEE 802.15.4a nodes as the aggregate duty cycle remains very low.

1.2.6 Low transmit power

1.2.6.1 2400 MHz band PHY

Although operation in the 2400 MHz band under Section 15.247 of FCC CFR47 [B5] rules allow transmission powers up to 1 W, IEEE 802.15.4 devices will likely operate with much lower transmit power. A key metric of IEEE Std 802.15.4-2006 is cost, and achieving greater than 10 dBm transmit power in a low-cost system on chip, while feasible, will be economically disadvantageous. Furthermore, European regulations (ETSI EN 300 328 [B3] and [B4]) for out-of-band emissions make it difficult to transmit above 10 dBm without additional, expensive filtering. These factors limit the distribution of devices with greater than 10 dBm transmit power to a few specialized applications.

At the low end, the IEEE 802.15.4 PHY specifies that devices must be capable of at least –3 dBm transmit power. At this level, actual transmit power represents a small fraction of the overall power consumed by the transmitter, so there is little benefit in terms of energy savings to operate below this level. However, this standard does encourage operating with lower transmit power, when possible, to minimize interference.

Thus the majority of IEEE 802.15.4 devices are expected to operate with transmit powers between –3 dBm and 10 dBm, with 0 dBm being typical. IEEE 802.11b devices also operate under Section 15.247 of FCC

CFR47 [B5], where up to 1 W of transmit power is allowed; however, most devices in the market today operate at transmit powers between 12 dBm and 18 dBm. IEEE 802.15.3 devices operate under Section 15.249 of FCC CFR47, which limits transmit power to 8 dBm EIRP. The EIRP measurement for the IEEE 802.15.3 PHY includes the antenna gain; therefore, a 1 dB increase antenna gain requires a 1 dB decrease in transmit power. In contrast, devices operating under Section 15.247 of FCC CFR47 are allowed up to 6 dB of antenna gain without modifications to the transmit power.

Assuming moderate antenna gain (~0 dBi) for typical implementations, the discussion in this subclause implies that a nominal IEEE 802.15.4 transmitter would operate about 8 dB less than the IEEE 802.15.3 transmitter and about 12 dB to 18 dB less than a typical IEEE 802.11b implementation.

1.2.6.2 800 MHz band PHYs

Regulations defined by ERC Recommendation 70-03 [B1] and ETSI EN 300 220-1 [B2] limit transmitter power in the 868 MHz to 25mW (13.9 dBm) maximum. Although devices conforming to IEEE Std 802.15.4-2006 may transmit at this power, the economics of system-on-chip designs will limit the transmit power to around 10 dBm. At the low end, all confirming devices must be capable of at least –3 dBm transmit power. At this power, the transmit power represents a small fraction of the overall power consumed by the device; therefore, there is no significant energy savings for operating below this level. However, this standard does encourage operating with lower power, when possible, in order to minimize interference.

Consequently, it is reasonable to assume that all 868 MHz devices will transmit at a power between –3 dBm and +10 dBm.

1.2.6.3 900 MHz band PHYs

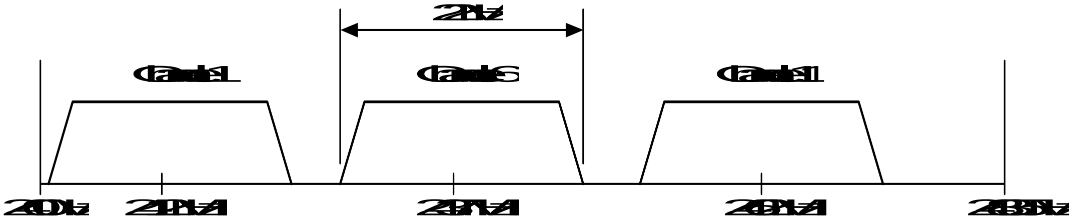
Regulations defined by FCC CFR47 [B5] limit transmitter power in the 868 MHz to 1000 mW (30 dBm) maximum. Although devices conforming to this standard may transmit at this power, the economics of system-on-chip designs will limit the transmit power to around 10 dBm. At the low end, all confirming devices must be capable of at least –3 dBm transmit power. At this power, the transmit power represents a small fraction of the overall power consumed by the device; therefore, there is no significant energy savings for operating below this level. However, this standard does encourage operating with lower power, when possible, in order to minimize interference.

1.2.6.4 UWB PHYs

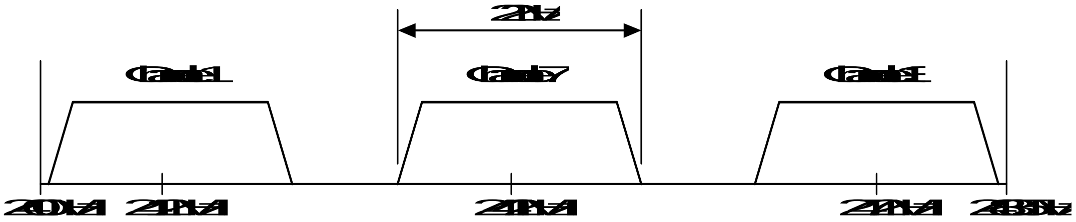
The UWB PHY operates under strict regulations for unlicensed UWB devices worldwide. The least restrictive regulations for UWB are available under the Federal Communications Commission (FCC) rules, US 47 CFR Part 15, subpart F. Under these rules, the highest allowable limits for UWB emissions are based on an equivalent emission PSD of –41.3 dBm/MHz. Other future UWB regulations in other regions will likely be at this same level or even lower. Under these limits, the allowable transmit power for a 500 MHz bandwidth UWB device would be less than –14 dBm, or about 37 μW transmit power. This transmit power level is at or below the limits for unintentional emissions from other electrical or electronic devices, as well as less than the out-of-band emission limits for other unlicensed devices operating in designated bands such as the 2.4 GHz ISM or 5 GHz UNII bands. Additionally, since this transmit power is spread over at least 500 MHz of bandwidth, the highest power in the operating bandwidth of a typical narrowband 20 MHz victim system is less than –28 dBm, or about 1.5 μW of transmit power per 20 MHz. These very low power levels emitted into the operating band of any potential victim system will reduce the likelihood that these devices might interfere with other systems.

1.2.7 Channel alignment

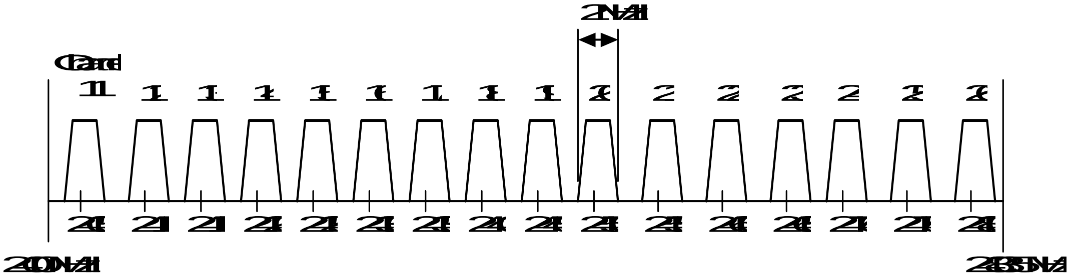
The alignment between IEEE 802.11b (nonoverlapping sets) and IEEE 802.15.4 2400 MHz band channels is shown in Figure 3. There are four IEEE 802.15.4 channels that fall in the guard bands between (or above) the three IEEE 802.11b channels (*n* = 15, 20, 25, 26 for North America; *n* = 15, 16, 21, 22 in Europe). While the energy in this guard space will not be zero, it will be lower than the energy within the channels; and operating an IEEE 802.15.4 WPAN on one of these channels will minimize interference between systems.



a) IEEE 802.11b North American channel selection (nonoverlapping)



b) IEEE 802.11b European channel selection (nonoverlapping)



c) IEEE 802.15.4 channel selection (2400 MHz PHY)

Figure 3—IEEE 802.15.4 (2400 MHz PHY) and IEEE 802.11b channel selection

The alignment between IEEE 802.11 HR/DSSS (nonoverlapping sets) and CSS channels (overlapping sets) is shown in Figure 4. There are 14 CSS channels (*n* = 0, 2, … , 13). Operating an IEEE 802.15.4 CSS WPAN on one of these channels will minimize interference between systems.

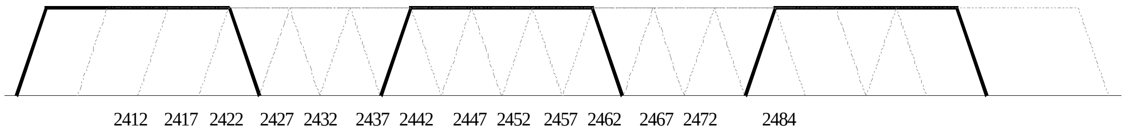


Figure 4—IEEE 802.15.4a CSS channel selection

When performing dynamic channel selection, either at network initialization or in response to an outage, a CSS device will scan a set of channels specified by the ChannelList parameter. For CSS WPANs that are installed in areas known to have high IEEE 802.11 HR/DSSS activity, the ChannelList parameter can be set by the next higher layer in order to enhance the coexistence of the networks.

1.2.8 Dynamic channel selection

When performing dynamic channel selection, either at network initialization or in response to an outage, an IEEE 802.15.4 device will scan a set of channels specified by the ChannelList parameter. For 2400 MHz band IEEE 802.15.4 networks that are installed in areas known to have high IEEE 802.11b activity, the ChannelList parameter can be set by the next higher layer in order to enhance the coexistence of the networks. For 915 MHz IEEE 802.15.4 networks that are installed in areas known to have interference from known sources, the ChannelList parameter can be set by the next higher layer in order to enhance the coexistence of the networks.

When performing dynamic channel selection, either at network initialization or in response to an outage, a UWB device will scan a set of channels specified by the ChannelList parameter. For UWB WPANs that are installed in areas known to have spectrum restrictions, the ChannelList parameter can be set by the next higher layer in order to enhance the coexistence of the networks.

1.2.9 Neighbor piconet capability

Interoperability with other systems is beyond the scope of this standard. However, certain schemes may be envisaged for this purpose, for example, the PAN coordinator can set aside GTSs specifically for use by other systems. This type of neighbor piconet support capability may further alleviate interference with other systems.

2. 2400 MHz band coexistence performance (except for CSS PHYs)

The assumptions made across all standards characterized for coexistence are described in 2.1. Subclauses 2.2 and 2.3 describe the assumptions made for individual standards and quantify their predicted performance when coexisting with IEEE 802.15.4 devices.

2.1 Assumptions for coexistence quantification

2.1.1 Channel model

The channel model is based on IEEE Std 802.11 as adapted by IEEE Std 802.15.2™-2003 and IEEE Std 802.15.3-2003:

$$d = 10^{\frac{(P_t - P_r - 40.2)}{20}} \qquad \text{for } d < 8\text{ m}$$

$$d = 8 \times 10^{\frac{(P_t - P_r - 58.5)}{33}} \qquad \text{for } d > 8\text{ m}$$

2.1.2 Receiver sensitivity

The receiver sensitivity assumed is the reference sensitivity specified in each standards as follows:

a) –76 dBm for IEEE 802.11b 11 Mb/s CCK
b) –70 dBm for IEEE Std 802.15.1-2005
c) –75 dBm for IEEE 802.15.3 22 Mb/s DQPSK
d) –85 dBm for this standard

2.1.3 Transmit power

The transmitter power for each coexisting standard has been specified as follows:

a) 14 dBm for IEEE Std 802.11b-1999
b) 0 dBm for IEEE Std 802.15.1-2005
c) 8 dBm for IEEE Std 802.15.3-2003
d) 0 dBm for this standard

2.1.4 Receiver bandwidth

The receiver bandwidth is as required by each standard as follows:

a) 22 MHz for IEEE Std 802.11b-1999
b) 1 MHz for IEEE Std 802.15.1-2005
c) 15 MHz for IEEE Std 802.15.3-2003
d) 2 MHz for this standard

2.1.5 Transmit spectral masks

The maximum transmitter spectral masks are assumed for the calculations. This assumption is the absolute worst-case scenario; in most cases, the transmitter spectrum will be lower. The transmitter spectral mask for IEEE Std 802.11b is given in Table 1.

Table 1—Transmit mask for IEEE Std 802.11b-1999

Frequency	Relative limit
$f_c - 22$ MHz < f < $f_c - 11$ MHz and $f_c + 11$ MHz < f < $f_c + 22$ MHz	–30 dBr
f < $f_c - 22$ MHz and f > $f_c + 22$ MHz	–50 dBr

The transmit mask for IEEE Std 802.15.1-2005 is given in Table 2

Table 2—Transmit mask for IEEE Std 802.15.1-2005

Frequency offset	Transmit power
± 500 kHz	–20 dBc
$\lvert M - N \rvert = 2$	–20 dBm
$\lvert M - N \rvert \geq 3$	–40 dBm
The transmitter is transmitting on channel *M*, and the adjacent channel power is measured on channel number *N*.	

The transmit mask for IEEE Std 802.15.3-2003 is given in Table 3

Table 3—Transmit mask for IEEE Std 802.15.3-2003

Frequency offset	Relative limit
7.5 MHz < $\mid f - f_c \mid$ < 15 MHz	–30 dBr
15 MHz < $\mid f - f_c \mid$ < 22 MHz	–1 /7[$\mid f - f_c$ (MHz)$\mid$ + 13] dBr
22 MHz < $\mid f - f_c \mid$	–50 dBr

The transmit mask for IEEE 802.15.4 is given in Table 4

Table 4—Transmit mask for this standard

Frequency	Relative limit	Absolute limit
$\mid f - f_c \mid$ >3.5 MHz	–20 dBr	–30 dBm

2.1.6 IEEE 802.11b transmit PSD

Because IEEE 802.11 implementations will generally meet FCC requirements, they will achieve an absolute power of less than –41.3 dBm/MHz at a separation of 22 MHz from the carrier frequency. The reason for this is that there is a restricted band that ends at 2.39 GHz, which is 22 MHz from the center of the lowest channel used for the FCC regulatory domain, as described in 18.4.6.2 in FCC CFR47 [B5]. Thus, the relative power for greater than 22 MHz separation would be +14 dBm – (–41.3 dBm) = 55.3 dB.

2.1.7 Interference characteristics

The effect of the interfering signal on the desired signal is assumed to be similar to additive white Gaussian noise (AWGN) in the same bandwidth.

2.1.8 Bit error rate (BER) calculations

The BER calculations are as described in C3.6 of IEEE Std 802.15.2-2003:

The BER for IEEE Std 802.11b-1999 at 1 Mb/s is given by

$$BER_{802.11,1} = Q(11 \times SINR)$$

The BER for IEEE Std 802.11b at 2 Mb/s is given by

$$BER_{802.11,2} = Q\left(5.5 \times \frac{SINR}{2}\right)^{\frac{1}{2}}$$

The BER for IEEE Std 802.11b at 5.5 Mb/s is given by

$$BER_{802.11,5.5} = \frac{8}{15} \times \left(14 \times Q(8 \times SINR)^{\frac{1}{2}} + Q(16 \times SINR)^{\frac{1}{2}}\right)$$

The BER for IEEE Std 802.11b at 11 Mb/s is given by

$$BER_{802.11,11} = \frac{128}{255} \times \left(24 \times Q(4 \times SINR)^{\frac{1}{2}} + 16 \times Q(16 \times SINR)^{\frac{1}{2}} + 174 \times Q(8 \times SINR)^{\frac{1}{2}} \right.$$
$$\left. + 16 \times Q(10 \times SINR)^{\frac{1}{2}} + 24 \times Q(12 \times SINR)^{\frac{1}{2}} + Q(16 \times SINR)^{\frac{1}{2}} \right)$$

The BER for IEEE Std 802.15.1-2005 is given by

$$BER_{802.15.1} = 0.5 \times e^{\frac{-SINR}{2}}$$

The BER for IEEE Std 802.15.3-2003 at 11 Mb/s is given by

$$BER_{802.15.3} = Q\left(SINR^{\frac{1}{2}} \right)$$

The BER for this standard is given by

$$BER_{802.15.4} = \frac{8}{15} \times \frac{1}{16} \times \sum_{k=2}^{16} -1^{k} \binom{16}{k} e^{\left(20 \times SINR \times \left(\frac{1}{k} - 1 \right) \right)}$$

2.1.9 Packet error rate (PER)

To convert between BER and PER, the following average packet lengths are assumed:

a) Average frame for IEEE Std 802.11b-1999 = 1024 octets
b) Average frame for IEEE Std 802.15.1-2002 = 1024 octets
c) Average frame length for IEEE Std 802.15.3-2003 = 1024 octets
d) Average frame length for this standard = 22 octets

2.2 BER model

This subclause presents the BER for standards characterized for coexistence. The BER results were obtained using the analytical model from IEEE Std 802.15.2-2003. The calculation follows the approach outlined in 5.3.2 of that standard, and the conversion from SNR to BER uses the formulas in 5.3.6 of that standard. Figure 5 illustrates the relationship between BER and SNR for IEEE Std 802.11b-1999, IEEE 802.15.3 base rate, IEEE Std 802.15.1-2005, and this standard.

2.3 Coexistence simulation results

Using the assumptions outlined in 2.2, an analytical simulation tool was developed to quantify the effect of interference between neighboring devices. For each of the cases studied, the receiver under test was presented with a desired signal at 10 dB above the required sensitivity, as described in 2.1.2, and a single interfering device with appropriate transmit power, as described in 2.1.3. The amount of received interference power was determined using the propagation model, as described in 2.1.1, as well as the

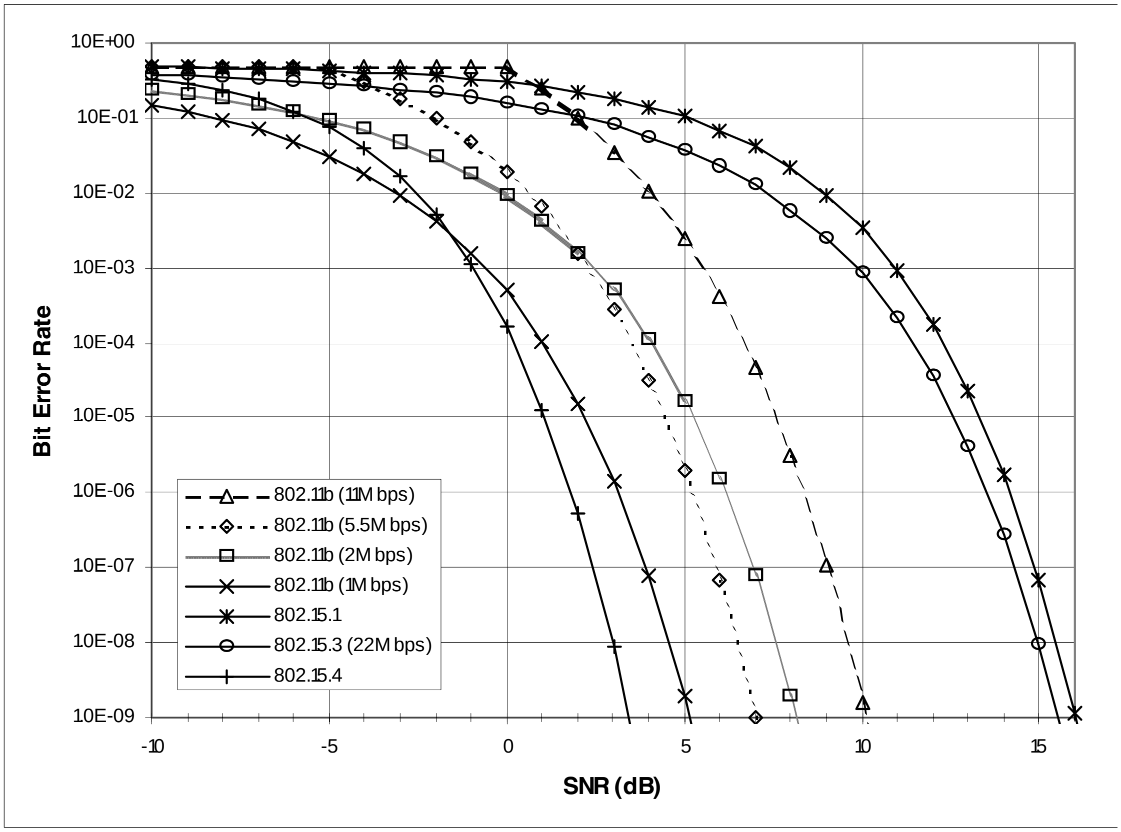


Figure 5—BER results for IEEE Std 802.11b, IEEE Std 802.15.1, IEEE Std 802.15.3, and this standard

transmit PSD, as described in 2.1.5, and receiver bandwidth, as described in 2.1.4, and the resulting SIR level was used to estimate the achievable PER.

The simulation output, illustrated in Figure 6, Figure 7, Figure 8, Figure 9, Figure 10 and Figure 11, shows the PER versus separation distance and frequency offset for various combinations of devices. When comparing the results, some obvious features stand out. First, for the nonhopping systems, large frequency offsets allow close-proximity coexistence (less than 2 m separation), while low-frequency offsets, or co-channel interference, require separation distances in the tens of meters. Therefore, as expected, the ability to detect channel occupancy and perform dynamic channel selection is an important mechanism for coexistence.

A second observation is that transmit power level is the dominant factor in co-channel interference situations. When a low-power IEEE 802.15.4 device is moved toward an IEEE 802.11b or IEEE 802.15.3 device, the IEEE 802.15.4 device is the first to degrade. IEEE Std 802.15.1-2005 and this standard have similar transmit powers, and their interference effects on each other are similar.

Even with its low transmit power level, the results presented here suggest that an IEEE 802.15.4 device can cause degradation to the other devices in co-channel situations with separation distances below 20 m. However, in practice, several IEEE 802.15.4 coexistence features (which were not included in this PHY simulation) will help to further reduce the occurrence and severity of co-channel interference. These include the very low duty cycle operation for typical IEEE 802.15.4 applications, as well as the use of CCA prior to transmission (CSMA-CA).

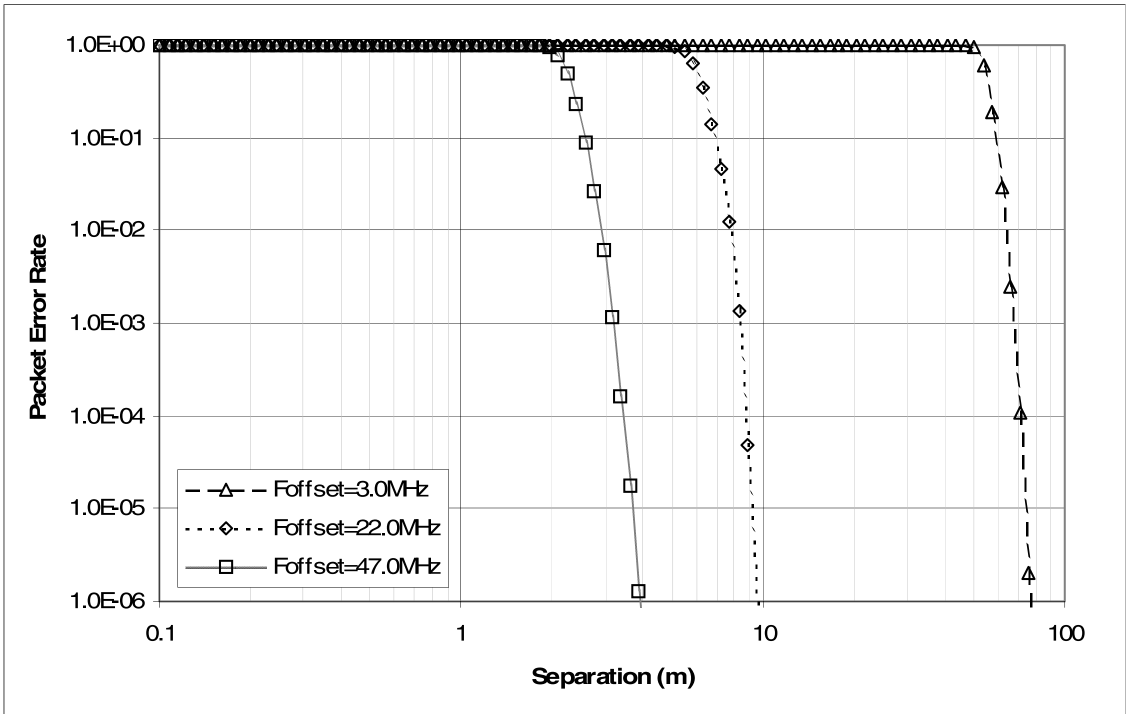


Figure 6—IEEE 802.15.4 receiver, IEEE 802.11b interferer

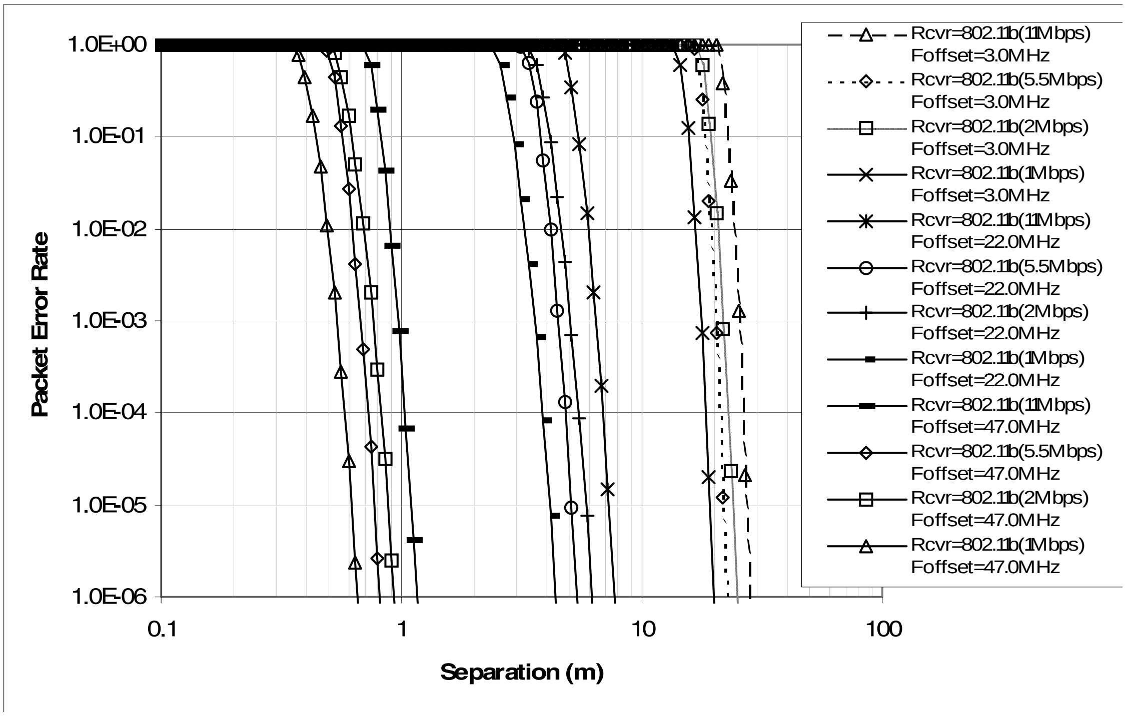


Figure 7—IEEE 802.11b receiver, IEEE 802.15.4 interferer

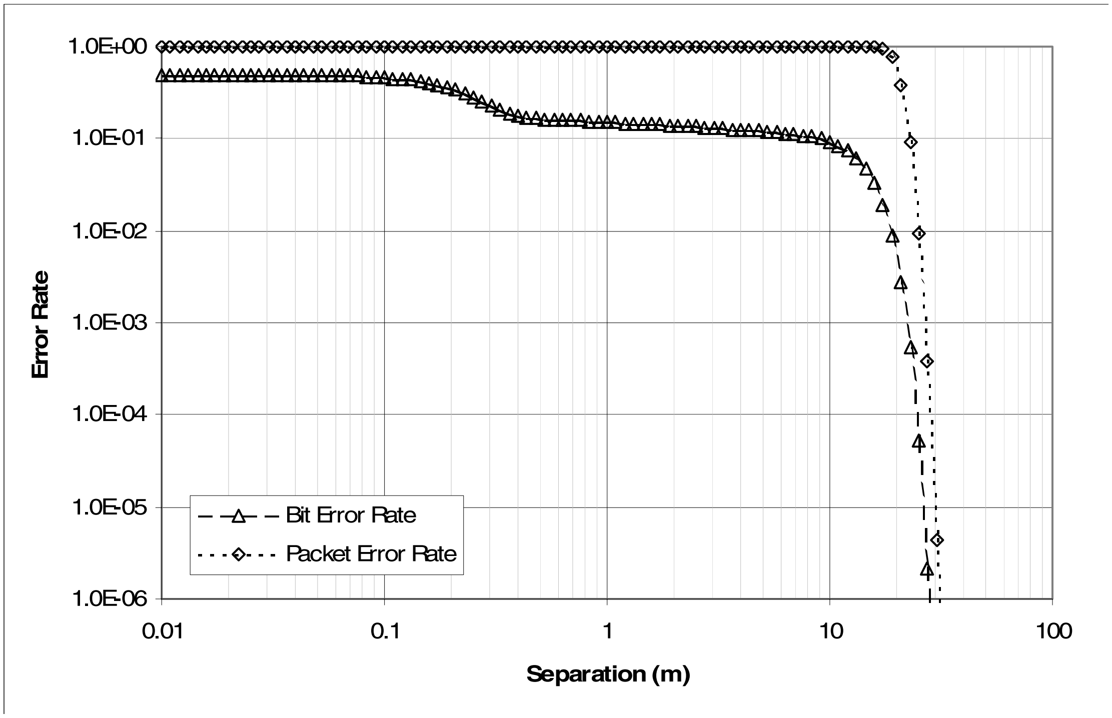


Figure 8—IEEE 802.15.4 receiver, IEEE 802.15.1 interferer

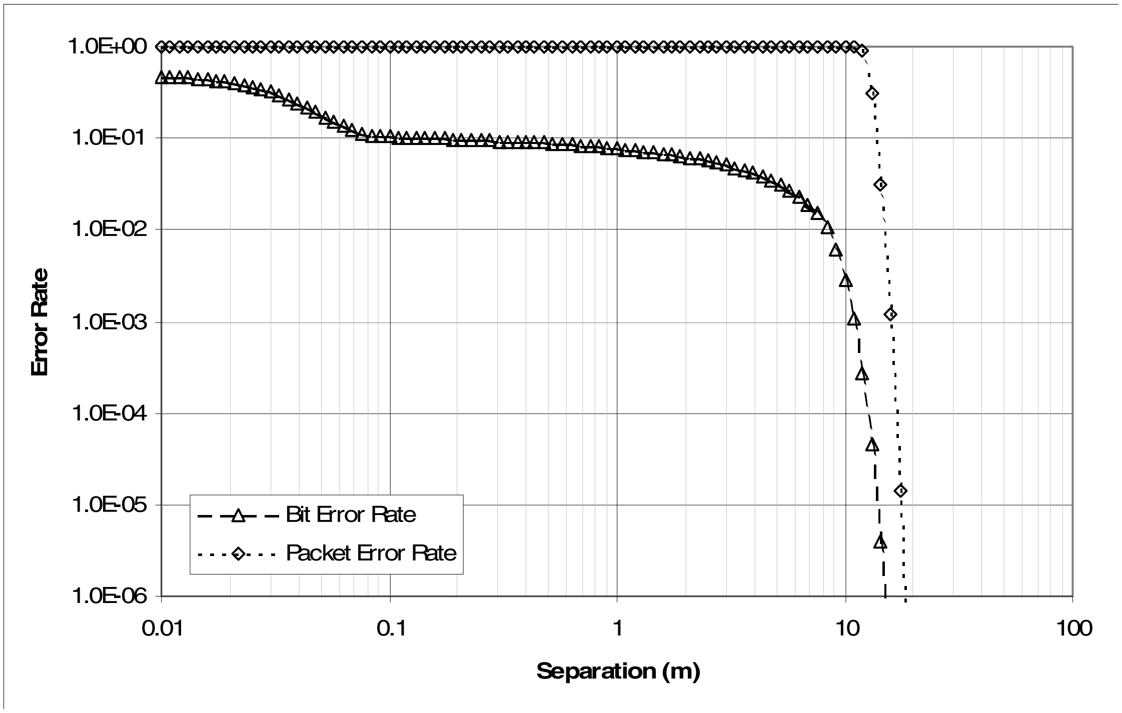


Figure 9—IEEE 802.15.1 receiver, IEEE 802.15.4 interferer

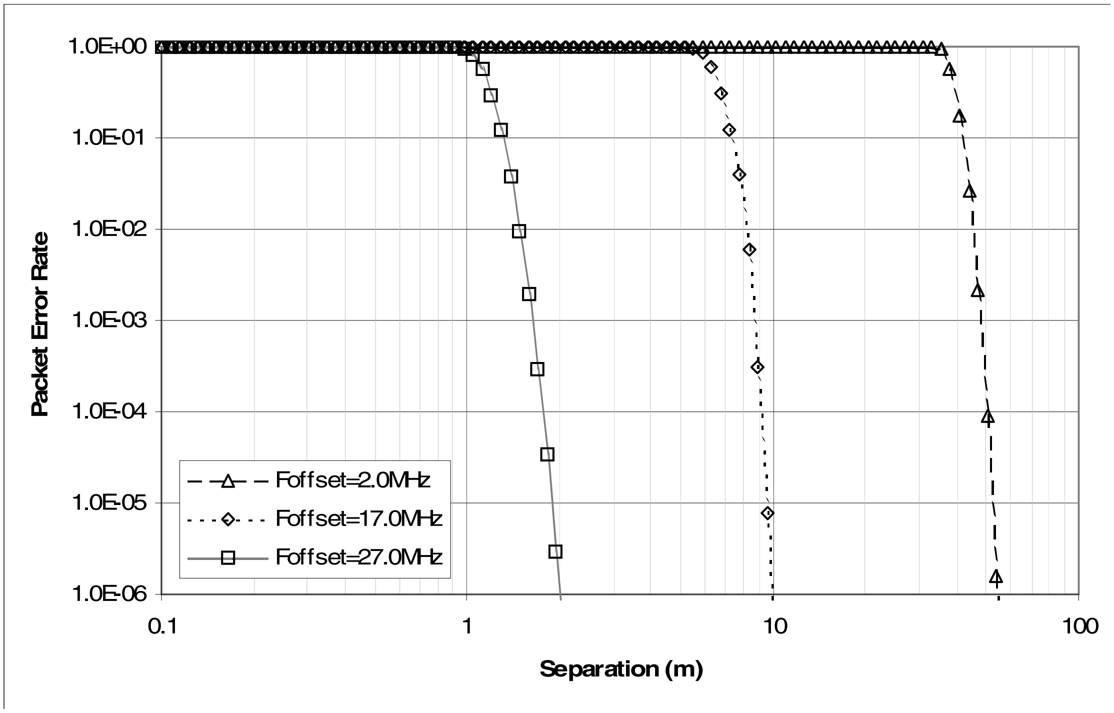


Figure 10—IEEE 802.15.4 receiver, IEEE 802.15.3 interferer

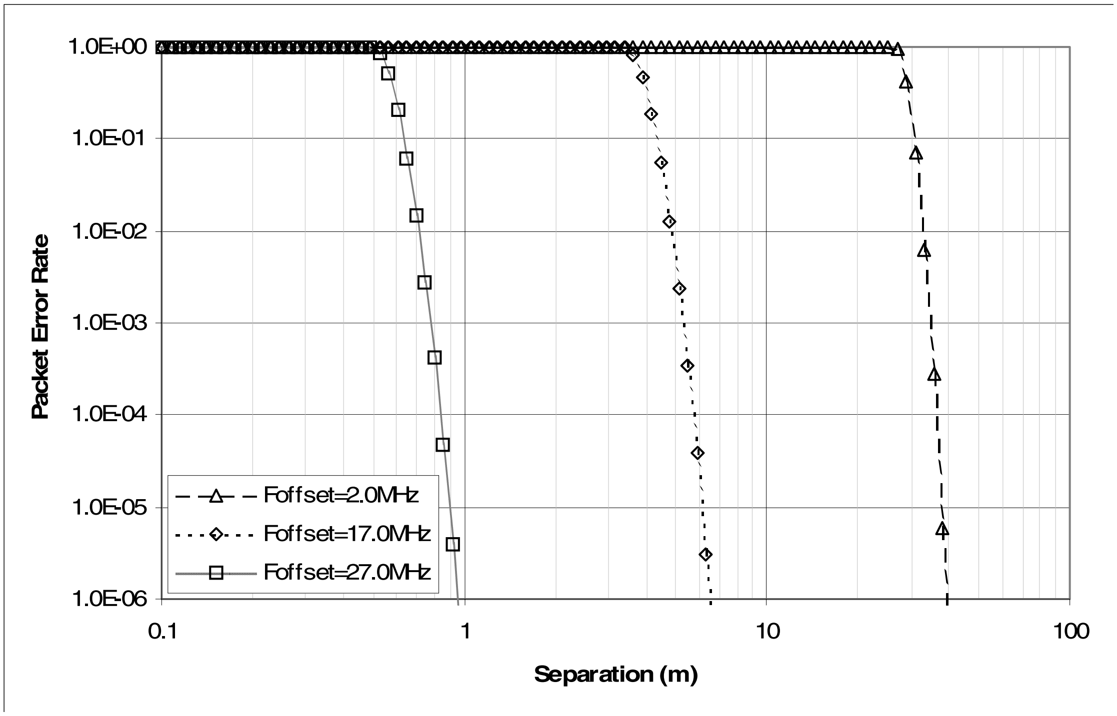


Figure 11—IEEE 802.15.3 receiver, IEEE 802.15.4 interferer

3. 800/900 MHz bands coexistence performance

In order to quantify the coexistence performance of the IEEE 802.15.4 PHYs operating below 1 GHz, the techniques described in Shellhammer [B6] and [B7] have been adopted.

The coexistence assurance methodology predicts the PER of an affected wireless network (AWN, or victim) in the presence of an interfering wireless network (IWN, or assailant). In its simplest form, the methodology assumes an AWN and an IWN, each composed of a single transmitter and a receiver. The methodology takes as input a path loss model, a BER function for the AWN, and predicted temporal models for packets generated by the AWN and for “pulses,” i.e., packets generated by the IWN. Based on these inputs, the methodology predicts the PER of the AWN as a function of the physical spacing between the IWN transmitter and the AWN receiver.

The appeal of the coexistence assurance methodology is that multiple networking standards can be characterized and compared with just a few parameters, notably

- Bandwidth of AWN and IWN devices
- Path loss model for the networks
- BER as a function of SIR of AWN devices[2]

The general assumptions made across all six sub-gigahertz PHYs are described in the followin subclauses.

3.1 Victims and assailants

At present, the six PHYs described in this standard are the only wireless networking standards in the 868 MHz and 915 MHz bands covered under IEEE 802. Because other wireless systems are not characterized here, it is assumed that the PHYs will serve as both *victims* (participants in AWNs) and as *assailants* (participants in IWNs).

3.2 Bandwidth

The three IEEE 802.15.4 PHYs that operate in the 868 MHz band have one channel, approximately 600 kHz wide. The coexistence methodology assumes that any 868 MHz device in an AWN will have the same bandwidth as a device in the IWN.

Similarly, the three PHYs that operate in the 915 MHz band have 10 channels, each one 2 MHz wide. The coexistence methodology assumes that any 915 MHz device in an AWN will be operating in the same channel and have the same bandwidth as a device in the IWN.

3.3 Path loss model

The coexistence methodology uses a variant of the path loss model described in IEEE Std 802.15.2-2003, which stipulates a two-segment function with a path loss exponent of 2.0 for the first 8 m and then a path loss exponent of 3.3 thereafter. The formula given in IEEE Std 802.15.2 is

---

[2] Although the methodology described in Stellhammer [B6] uses symbol error rate (SER) to characterize PHY performance, BER has been used in this standard instead because available error functions are more commonly defined as BER rather than SER.

$$pl(d) = \begin{cases} 40.2 + 20\log_{10}(d) & d \le 8 \text{ m} \\ 58.5 + 33\log_{10}\left(\frac{d}{8}\right) & d > 8 \text{ m} \end{cases}$$

The constants in this formula are based on a 2400 MHz center frequency. To adapt the model to a 900 MHz center frequency, the preceeding equation can be generalized as

$$pl(d) = \begin{cases} pl(1) + 10\gamma_1\log_{10}(d) & d \le 8 \text{ m} \\ pl(8) + 10\gamma_8\log_{10}\left(\frac{d}{8}\right) & d > 8 \text{ m} \end{cases}$$

where

$pl(1)$	is the path loss at 1 m (in dB)
γ_1	is the path loss exponent at 1 m, $\gamma_1 = 2.0$
γ_8	is the path loss exponent at 8 m $\gamma_8 = 3.3$)

The initial condition of *pl*(1) is computed as.

$$pl(1) = 10\gamma_1\log_{10}\left(\frac{4\pi f}{c}\right)$$

where

$\gamma_1 = 2.0$

$f = 900$ MHz

c = speed of light = 299792458 ms^{-1}

which gives $pl(1) = 31.53$ and $pl(8) = 49.59$. The path loss function modified for 900 MHz is then

$$pl(d) = \begin{cases} 31.53 + 20\log_{10}(d) & d \le 8 \text{ m} \\ 49.59 + 33\log_{10}\left(\frac{d}{8}\right) & d > 8 \text{ m} \end{cases}$$

A plot of the path loss function is shown in Figure 12.

3.4 Temporal model

In this standard, packet overhead is kept to minimum. The maximum PSDU size is 128 octets, and a typical packet may be only 32 octets, including PSDU and synchronization octets. For the coexistence methodology, all packets, whether belonging to the AWN or IWN, are assumed to be 32 octets.

As specified in ERC Recommendation 70-03 [B1] and ETSI EN 300 220-1 [B2], the 868 MHz ISM band is limited by European regulations to operate at or under 1% duty cycle. Therefore, all 868 MHz BPSK devices, whether operating in AWNs or IWNs, can be assumed to be operating at 1% worst case.

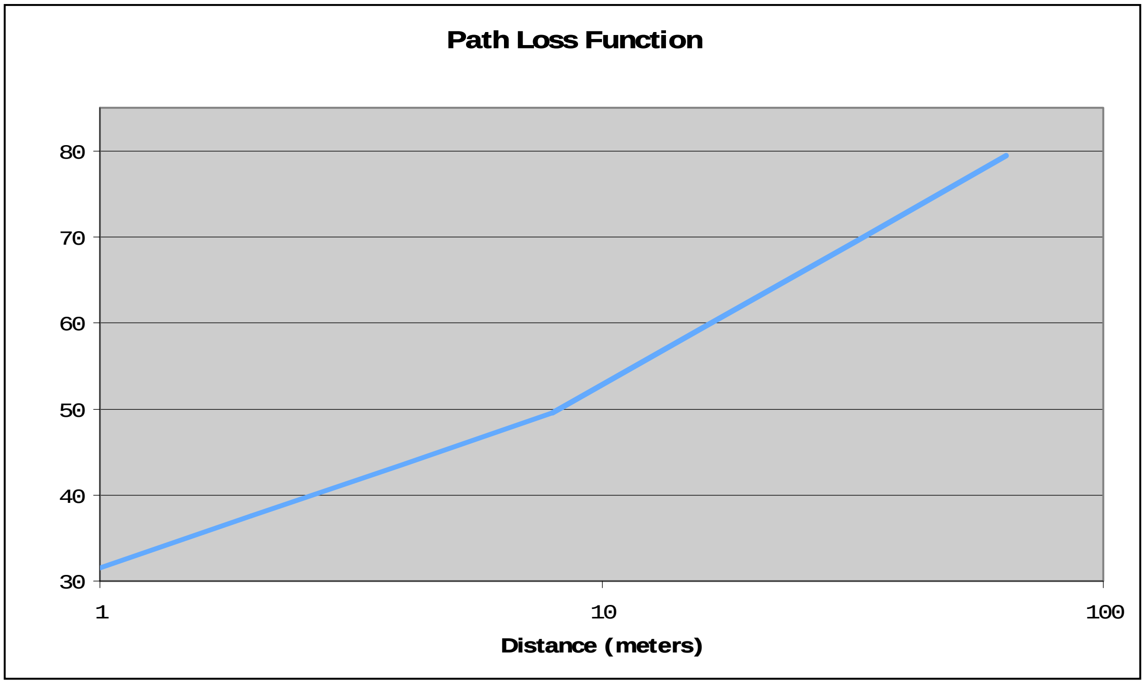


Figure 12—Plot of path loss function for 900 MHz

Although there are no duty cycle limitations in the 915 MHz band, many networks based on this standard are expected to operate at well under 1% duty cycle, particularly devices that are battery powered. It is reasonable to expect that mains-powered devices, such as PAN coordinators and data aggregation points, may operate at duty cycles as high as 10%. For purposes of modeling coexistence, it is assumed that all 915 MHz devices, whether operating in AWNs or IWNs, have a duty cycle of 10%.

3.5 Coexistence assurance results

This subclause describes the parameters that are particular to each PHY covered under this standard and shows the results of the coexistence assurance methodology for each of the sub-gigahertz PHYs.

3.5.1 868 MHz BPSK PHY

3.5.1.1 BER as a function of SIR

IEEE 802.15.4 868 MHz BPSK modulation uses a chip rate R_c of 300 kc/s and a bit rate R_b of 20 kb/s. Conversion from SNR to E_b/N_0 assumes a raised cosine filter which gives

$$\frac{E_b}{N_0} = \frac{0.75 R_c}{R_b} SNR = \frac{0.75 \times 300000}{20000} SNR = 11.25 \times SNR \ .$$

BER P_b is computed for noncoherent BPSK, e.g., from Sklar [B8], as

$$P_b = 0.5 \exp\left(-\frac{E_b}{N_0}\right) .$$

Rolling these together produces the BER function.

$$P_b = 0.5\exp(-11.25 \times SNR)$$

3.5.1.2 Temporal model

With a 1% operating duty cycle and a packet size of 32 octets, the channel will be occupied for

$$\frac{payloadSizex \times 8}{bitsPerSecond} = \frac{256}{20000}S = 12.8\text{ ms}$$

and the channel will be idle for 99 × 12.8 ms = 1.2672 s.

3.5.1.3 Coexistence methodology results

Figure 13 shows the coexistence methodology results for the 868 MHz BPSK PHY.

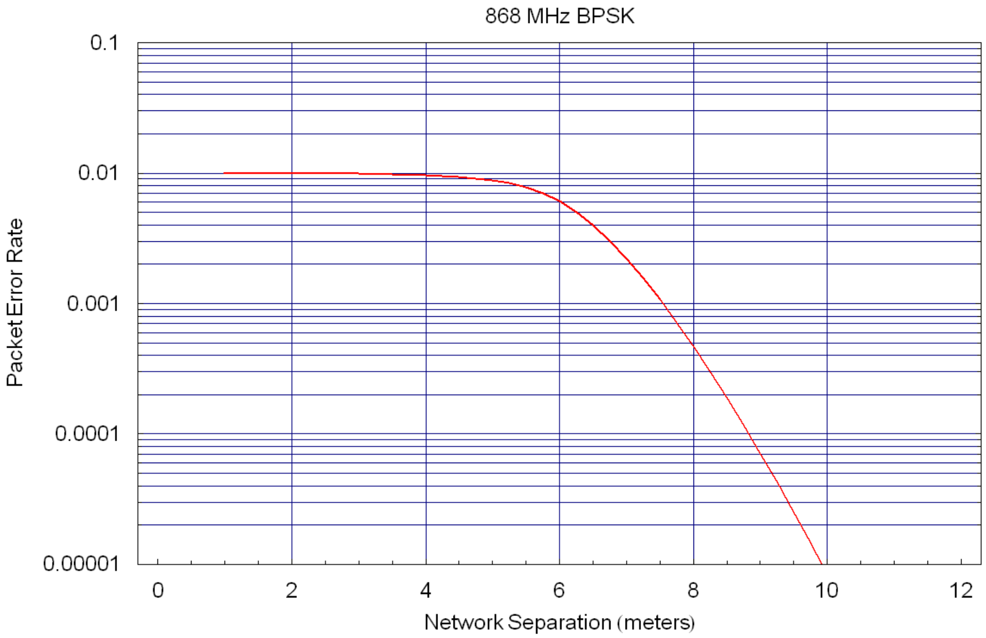


Figure 13—Coexistence methodology results for 868 MHz BPSK PHY

3.5.2 868 MHz O-QPSK PHY

3.5.2.1 BER as a function of SIR

IEEE 802.15.4 868 MHz O-QPSK modulation uses a chip rate R_c of 400 kc/s, a bit rate R_b of 100 kb/s, and a codebook of M = 16 symbols. Conversion from SNR to E_b/N_0 assumes matched filtering and half-sine pulse shaping which results in

$$\frac{E_b}{N_0} = \frac{0.625R_c}{R_b}SNR = \frac{0.625 \times 400000}{100000}SNR = 2.5 \times SNR\ .$$

Conversion from bit noise density E_b/N_0 to symbol noise density E_s/N_0 is given by

$$\frac{E_s}{N_0} = \log_2(M)\frac{E_b}{N_0} = 4\frac{E_b}{N_0}.$$

Symbol error rate (SER) P_s is computed for noncoherent MFSK, e.g., from Sklar [B8], as

$$P_s = \frac{1}{M}\sum_{j=2}^{M}(-1)^j\binom{M}{j}\exp\left(\frac{E_s}{N_0}\left(\frac{1}{j}-1\right)\right).$$

Finally, conversion from SER P_s to BER P_b is given as

$$P_b = P_s\left(\frac{M/2}{M-1}\right) = P_s\left(\frac{8}{15}\right).$$

Rolling these together produces the BER function.

$$P_b = \left(\frac{8}{15}\right)\left(\frac{1}{16}\right)\sum_{j=2}^{M}(-1)^j\binom{16}{j}\exp\left(10\times SNR\times\left(\frac{1}{j}-1\right)\right)$$

3.5.2.2 Temporal model

With a 1% operating duty cycle and a packet size of 32 octets, the channel will be occupied for

$$\frac{payloadSizex8}{bitsPerSecond} = \frac{256}{100000}S = 2.56\text{ ms}$$

and the channel will be idle for 99 × 2.56 ms = 253.44 ms.

3.5.2.3 Coexistence methodology results

Figure 14 shows the coexistence methodology results for the 868 MHz O-QPSK PHY.

3.5.3 868 MHz PSSS PHY

3.5.3.1 BER as a function of SIR

IEEE 802.15.4 868 MHz PSSS uses a form of ASK modulation, for which the BER function is most easily derived by simulation and curve fitting. For SNR values greater than –8 dB, the BER function is approximated as

$$P_b = 0.4146\exp(-6.0871\times SNR).$$

3.5.3.2 Temporal model

With a 1% operating duty cycle and a packet size of 32 octets, the channel will be occupied for

$$\frac{payloadSizex8}{bitsPerSecond} = \frac{256}{250000}S = 1.024\text{ ms}$$

and the channel will be idle for 99 × 1.024 ms = 101.376 ms.

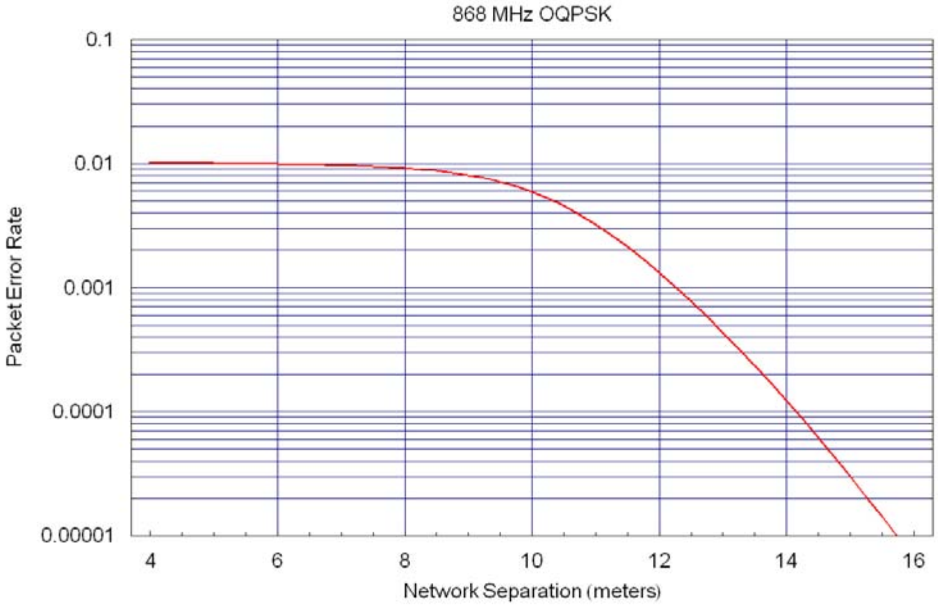


Figure 14—Coexistence methodology results for 868 MHz O-QPSK PHY

3.5.3.3 Coexistence methodology results

Figure 15 shows the coexistence methodology results for the 868 MHz PSSS PHY.

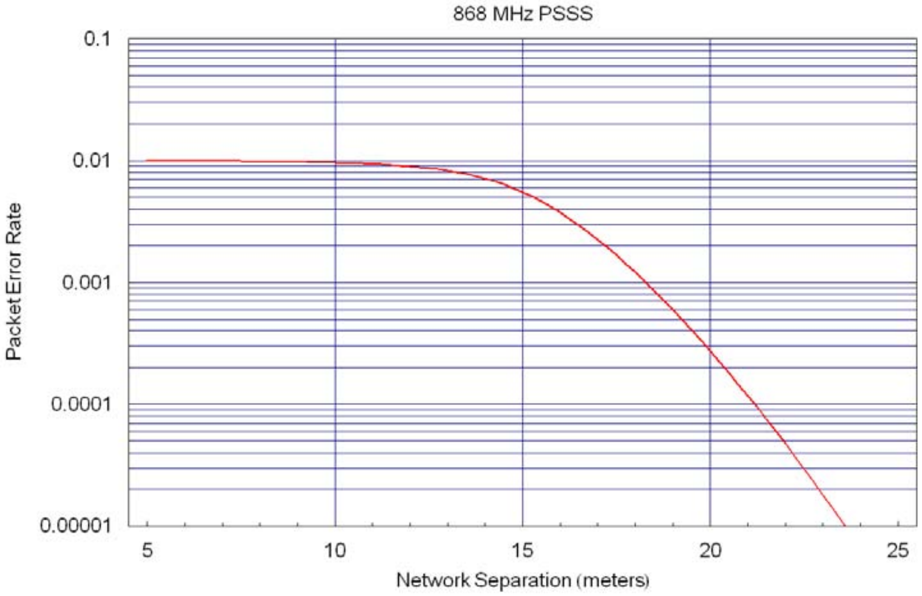


Figure 15—Coexistence methodology results for 868 MHz PSSS PHY

3.5.4 915 MHz BPSK PHY

3.5.4.1 BER as a function of SIR

IEEE 802.15.4 915 MHz BPSK modulation uses a chip rate R_c of 600 kc/s and a bit rate R_b of 40 kb/s. Conversion from SNR to E_b/N_0 assumes a raised cosine filter which results in

$$\frac{E_b}{N_0} = \frac{0.75R_c}{R_b}SNR = \frac{0.75 \times 600000}{40000}SNR = 11.25 \times SNR .$$

BER P_b is computed for noncoherent BPSK, e.g., from Sklar [B8], which results in

$$P_b = 0.5\exp\left(-\frac{E_b}{N_0}\right) .$$

Rolling these together produces the BER function.

$$P_b = 0.5\exp(-11.25 \times SNR)$$

3.5.4.2 Temporal model

With a 10% operating duty cycle and a packet size of 32 octets, the channel will be occupied for

$$\frac{payloadSizex8}{bitsPerSecond} = \frac{256}{40000}S = 6.4\text{ ms}$$

and the channel will be idle for 90 × 6.4 ms = 576 ms.

3.5.4.3 Coexistence methodology results

Figure 16 shows the coexistence methodology results for the 915 MHz BPSK PHY.

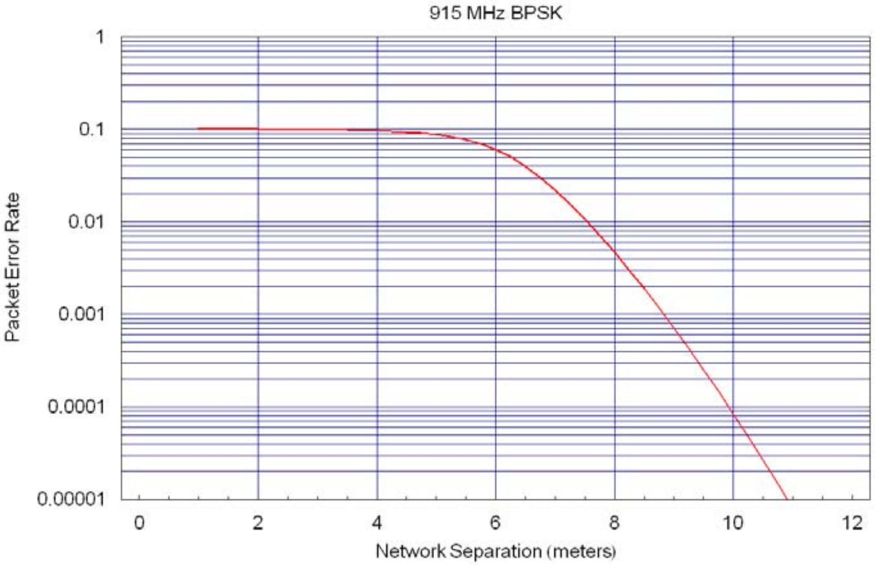


Figure 16—Coexistence methodology results for 915 MHz BPSK PHY

3.5.5 915 MHz O-QPSK PHY

3.5.5.1 BER as a function of SIR

IEEE 802.15.4 915 MHz O-QPSK modulation uses a chip rate R_c of 1000 kc/s, a bit rate R_b of 250 kb/s, and a codebook of M = 16 symbols. Conversion from SNR to E_b/N_0 assumes matched filtering and half-sine pulse shaping which gives

$$\frac{E_b}{N_0} = \frac{0.625 R_c}{R_b} SNR = \frac{0.625 \times 1000000}{250000} SNR = 2.5 \times SNR \ .$$

Conversion from bit noise density E_b/N_0 to symbol noise density E_s/N_0 gives

$$\frac{E_s}{N_0} = \log_2(M)\frac{E_b}{N_0} = 4\frac{E_b}{N_0} .$$

SER P_s is computed for noncoherent MFSK, e.g., from Sklar [B8], as

$$P_s = \frac{1}{M}\sum_{j=2}^{M}(-1)^j\binom{M}{j}\exp\left(\frac{E_s}{N_0}\left(\frac{1}{j}-1\right)\right) .$$

Finally, conversion from SER P_s to BER P_b is given as

$$P_b = P_s\left(\frac{M/2}{M-1}\right) = P_s\left(\frac{8}{15}\right) .$$

Rolling these together produces the BER function as

$$P_b = \left(\frac{8}{15}\right)\left(\frac{1}{16}\right)\sum_{j=2}^{M}(-1)^j\binom{16}{j}\exp\left(10SNR\left(\frac{1}{j}-1\right)\right) .$$

3.5.5.2 Temporal model

With a 10% operating duty cycle and a packet size of 32 octets, the channel will be occupied for

$$\frac{payloadSizex8}{bitsPerSecond} = \frac{256}{250000}S = 1.024 \text{ ms}$$

and the channel will be idle for 90 × 1.024 ms = 92.16 ms.

3.5.5.3 Coexistence methodology results

Figure 17 shows the coexistence methodology results for the 915 MHz O-QPSK PHY.

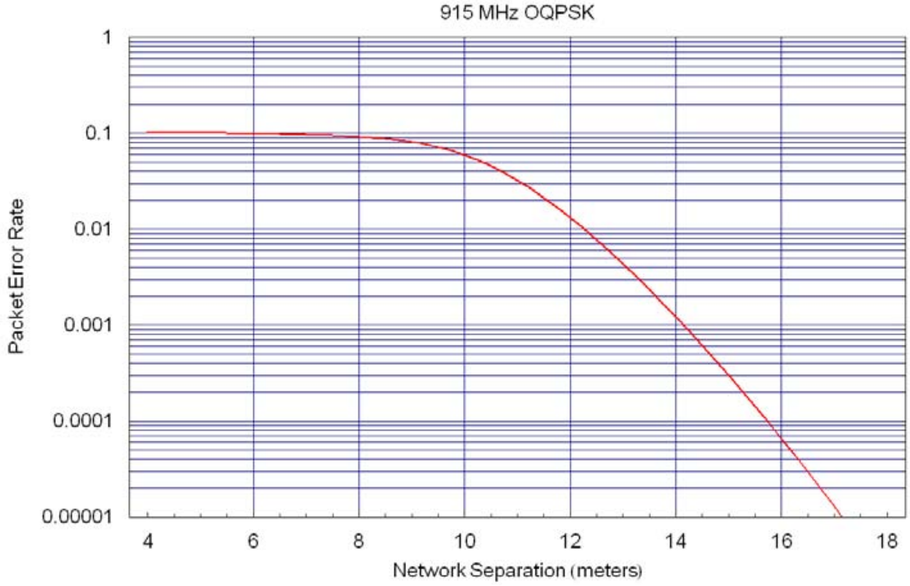


Figure 17—Coexistence methodology results for 915 MHz O-QPSK PHY

3.5.6 915 MHz PSSS PHY

3.5.6.1 BER as a function of SIR

IEEE 802.15.4 915 MHz PSSS uses a form of ASK modulation, for which the BER function is most easily derived by simulation and curve fitting. For SNR values greater than –8 dB, the BER function is approximated as

$$P_b = 7.768\exp(-21.93SNR) - 12.85\exp(-27.53 \times SNR) \ .$$

3.5.6.2 Temporal model

With a 10% operating duty cycle and a packet size of 32 octets, the channel will be occupied for

$$\frac{payloadSizex8}{bitsPerSecond} = \frac{256}{250000}S = 1.024\text{ ms}$$

and the channel will be idle for 90 × 1.024 ms = 92.16 ms.

3.5.6.3 Coexistence methodology results

Figure 18 shows the coexistence methodology results for the 915 MHz PSSS PHY.

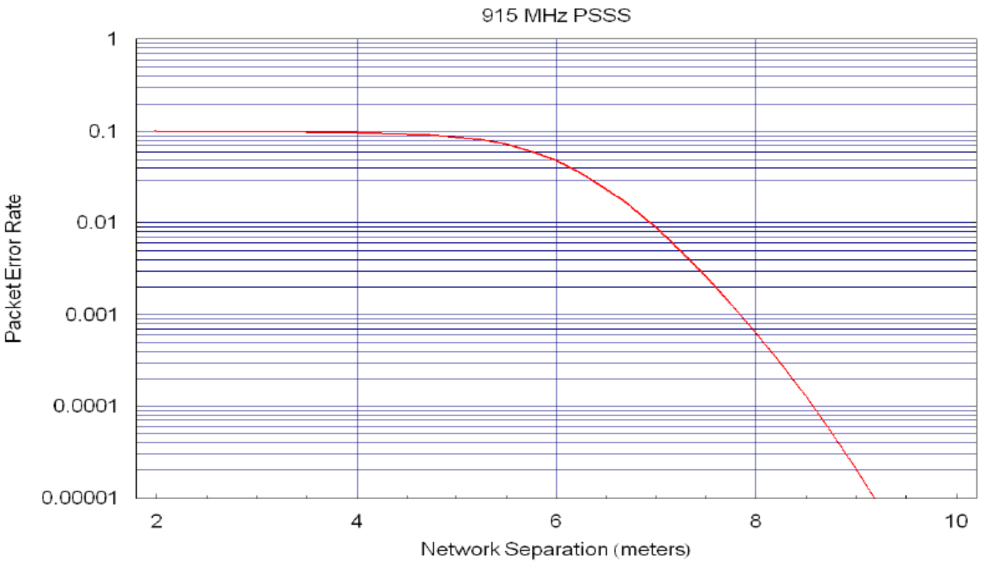


Figure 18—Coexistence methodology results for 915 MHz PSSS PHY

4. 2400 MHz band coexistence performance for CSS PHYs

Subclauses E.3.2 and E.3.4 also describe the assumptions made for individual standards and quantify their predicted performance when coexisting with IEEE 802.15.4a CSS devices.

4.1 Assumptions for coexistence performance

The receiver sensitivity assumed is the reference sensitivity specified in each standard as follows:

- –76 dBm for IEEE 802.11 HR/DSSS 11 Mb/s CCK
- –82 dBm for IEEE 802.11 ERP 6 Mb/s OFDM
- –74 dBm for IEEE 802.11 ERP 24 Mb/s OFDM
- –65 dBm for IEEE 802.11 ERP 54 Mb/s OFDM
- –70 dBm for IEEE 802.15.1 devices
- –75 dBm for IEEE P802.15.3 22 Mb/s DQPSK
- –85 dBm for IEEE 802.15.4 devices
- –85 dBm for IEEE 802.15.4a 1 Mb/s CSS

The transmit power for each coexisting standard has been specified as follows:

- 14 dBm for IEEE Std 802.11 HR/DSSS
- 0 dBm for IEEE Std 802.15.1-2005
- 8 dBm for IEEE Std 802.15.3-2003
- 0 dBm for IEEE Std 802.15.4-2006

— 0 dBm for IEEE 802.15.4a CSS

The bit error rate (BER) calculation for IEEE 802.15.4a CSS is

$$BER_{CSS} = [(M-2) \times Q(\sqrt{SNR_0 \times \log_2(M)}) + Q(\sqrt{SN(R_0 \times 2\log_2(M))})]/2$$

where

1 Mb/s: SNR_0 = SNR × 14 × 1.6667, $M = 8$
250 kb/s: SNR_0 = SNR × 14 × 1.6667 × 4, $M = 64$

For the IEEE 802.11 ERP 6 Mb/s: M-PSK, the BER calculation is

$$BER_{802.11,6}(M = 2) = Q\left(\sqrt{2 \times \frac{E_b}{N_0} \times 10^{\frac{5.7}{10}}}\right)$$

For the IEEE 802.11 ERP 24 Mb/s and 54 Mb/s QAM modes, the BER calculation is

$$BER_{802.11}(M > 2, Cg) = 1 - \left[1 - 2\left(\left(1 - \frac{1}{\sqrt{M}}\right) \times Q\left(\sqrt{\frac{3}{M-1} \times \frac{\log_2(M) \cdot E_b}{N_0} \times 10^{\frac{Cg}{10}}}\right)\right)\right]^{2 \cdot \frac{1}{\log_2(M)}}$$

where M is the number of points in the constellation and C_g is the coding gain. The values for 24 Mb/s and 54 Mb/s are:

24 Mb/s: $M = 16$, $C_g = 5.7$ dB
54 Mb/s: $M = 64$, $C_g = 3.8$ dB

The relationship between E_b/N_0 and SNR is assumed to be computable from the subcarrier spacing $F_s = 0.3125$ MHz and the OFDM symbol rate, $R_s = 0.25$ Msymbol/s as follows:

$$SNR = \frac{E_b}{N_0} \times \frac{F_s}{R_s}$$

The PER is based frame lengths and duty cycles listed in Table 5.

Table 5—Frame length and duty cycles for PER calculations

PHY	Average frame length	Duty cycle
IEEE 802.11 HR/DSSS	1500 octets	50% (average)
IEEE 802.11 ERP	1500 octets	50% (average)
IEEE 802.15.1	2871 bits	50% (average)
IEEE 802.15.3	1024 octets	50% (average)
IEEE 802.15.4	22 octets	1% (normal) 10% (rare, aggregated)
IEEE 802.15.4 CSS	32 octets	0.25%, 1% (normal) 2.5%, 10% (rare, aggregated)

Figure 19 illustrates also the relationship between BER and SNR for IEEE 802.11 HR/DSSS, IEEE 802.15.3 base rate, IEEE 802.15.1, IEEE 802.15.4, and IEEE 802.15.4a CSS PHYs.

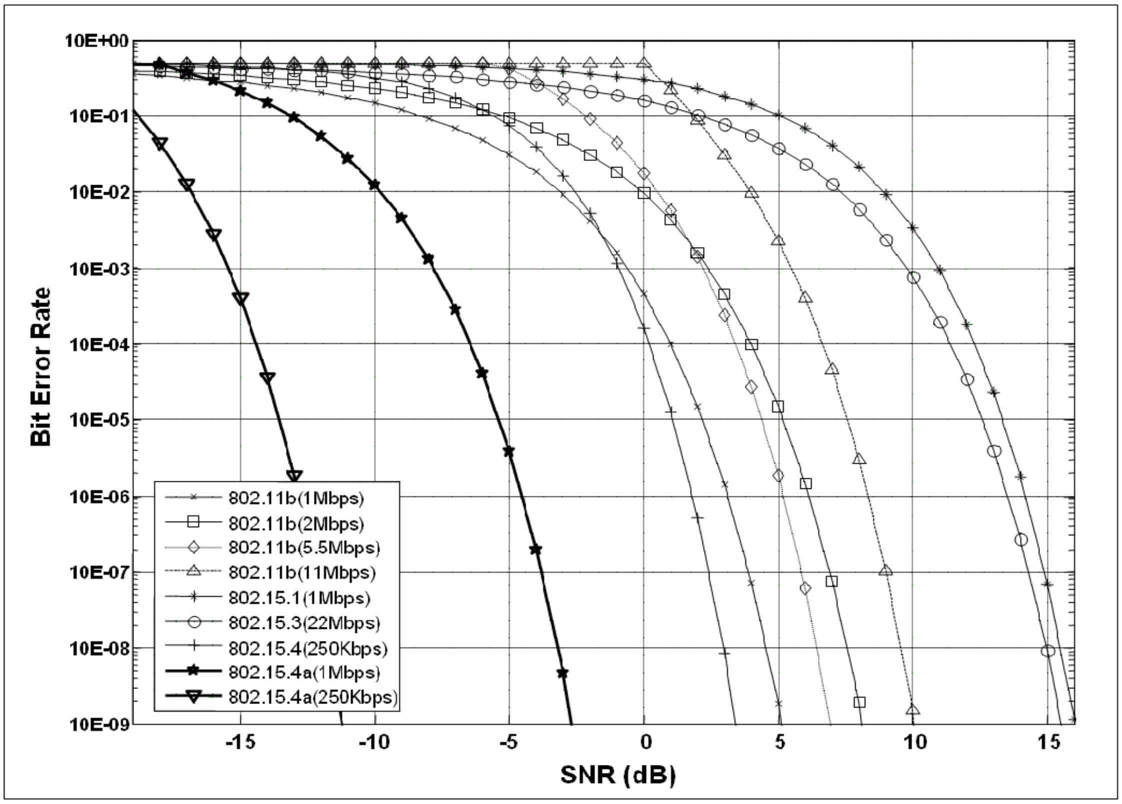


Figure 19—BER results of IEEE 802.11 HR/DSSS, IEEE 802.15.1, IEEE 802.15.3, IEEE 802.15.4 (2400 MHz) and IEEE 802.15.4a CSS PHYs

4.2 Coexistence simulation results

The shapes of the assumed transmit spectra and receive filter shapes are defined in Table 6.

Table 6—Frequency offset (MHz)Attenuation (dB)

IEEE 802	Transmit		Receive	
	Frequency offset (MHz)	**Attenuation (dB)**	**Frequency offset (MHz)**	**Attenuation (dB)**
15.1	0	0	0	0
	0.25	0	0.25	0
	0.75	38	0.75	38
	1	40	1	40
	1.5	55	1.5	55
11 HR/DSSS	0	0	0	0
	4	0	4	0
	6	10	6	10
	9	30	9	30
	15	50	15	50
	20	55	20	55
11 ERP	0	0	0	0
	5	0	5	0
	8	4	8	4
	9	10	9	10
	10	25	10	25
	15	40	15	40
	40	43	40	43
15.3	0	0	0	0
	8	0	8	0
	8	30	8	30
	15	30	15	30
	15	40	15	40
	22	50	22	50

Table 6—Frequency offset (MHz)Attenuation (dB) *(continued)*

IEEE 802	Transmit		Receive	
	Frequency offset (MHz)	**Attenuation (dB)**	**Frequency offset (MHz)**	**Attenuation (dB)**
15.4 (non CSS)	0	0	0	0
	0.5	0	0.5	0
	1	10	1	10
	1.5	20	1.5	20
	2	25	2	25
	2.5	30	2.5	30
	3	31	3	31
	3.5	33	3.5	33
	4	34	4	34
	5	40	5	40
	6	55	6	55
CSS	0	0	0	0
	6	0	6	0
	12	32	12	32
	15	55	15	55

4.3 Low-duty-cycle assumption

In general, IEEE 802.15.4 devices address low-duty-cycle applications. The assumption of 1% duty cycle for IEEE 802.15.4 devices was introduced in 1.2.4. Under the assumption that IEEE 802.15.4 devices are battery-powered and have a lifetime of at least one year, the 1% assumption can be hardened by taking into account state-of-the-art numbers: A typical AA battery has a capacity of 1.8 Ah. A typical IEEE 802.15.4 device operating at 2.4 GHz has a transmit current of 30 mA. If the device only transmits during its entire lifetime, the result would be 30/1800 = 60 h of operation. Over a lifetime of one year (365 × 24 h = 8760 h), the duty cycle would be 0.0068, which is clearly below 1%. In reality, traffic generated by several nodes might accumulate. On the other hand, a significant part of the battery power will be spent in receive mode (which requires more current than the transmit mode for many implementations). Thus the 1% duty cycle also is valid for networks of IEEE 802.15.4 devices. In some rare cases, traffic might aggregate in proximity to coordinator nodes. Thus an aggregated duty cycle of up to 10% can be assumed in rare cases.

4.4 Impact of increased data rate

It should be noted that IEEE 802.15.4 devices will serve applications with similar low required data traffic. Since CSS devices offer a significantly increased data rate (1 Mb/s versus 250 kb/s), the duty cycle of IEEE CSS devices can be expected to be significantly below the duty cycle of other IEEE 802.15.4 devices. Since the 2.4 GHz ISM band has become an extremely busy medium, a low duty cycle achieved by high data rates is crucial for reasonable coexistence performance.

4.5 Co-channel scenario

Operating any two systems at the same location and at the same center frequency is obviously not a desirable situation. As long as no active interference cancellation is provided, the coexistence performance will be determined by the duty cycle behavior of both systems. Applying the duty cycle assumptions on CSS devices as stated above will result in reasonable performance. However, whenever possible, it is recommended that this situation be avoided by using a nonoverlapping channel. When a nonoverlapping channel is not available to the CSS PHY, because other networks (for example, IEEE 802.11 networks) are themselves already using the nonoverlapping channels, the recommendation is to select for the CSS PHY a channel between the channels already in use. It is further recommended that in the case of IEEE 802.11 networks, the CSS center frequency be selected so that the spatially closer IEEE 802.11 network has a frequency offset of at least 15 MHz.

The figures in this subclause show the computed PER versus separation distances (in meters) for co-channel pairings of systems when those systems use the spectra and filter properties given in Table 6.

Figure 20 illustrates the effect on a CSS receiver in the presences of an 802.11 HR/DSSS interferer.

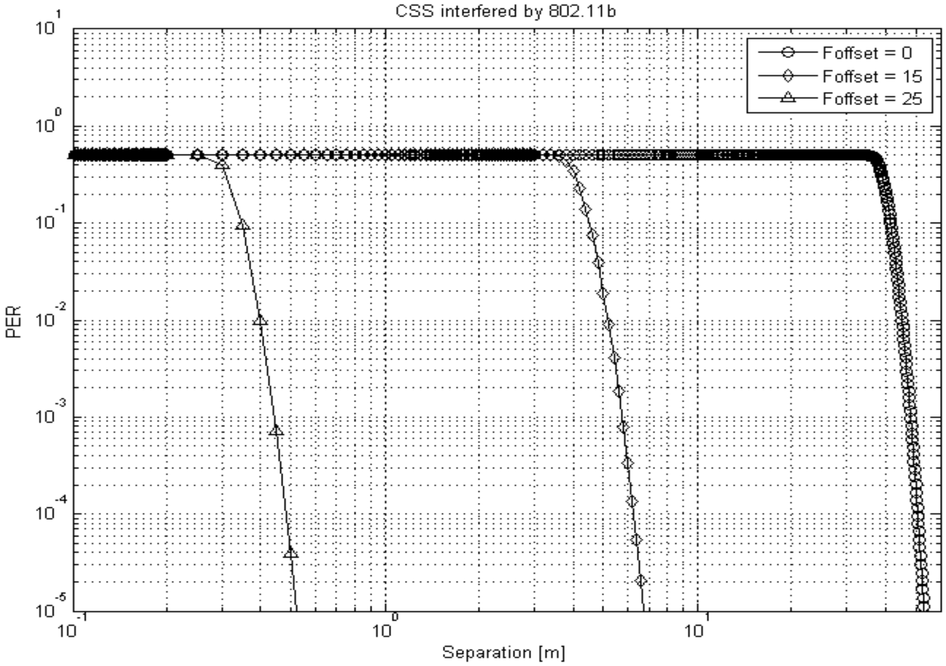


Figure 20—IEEE 802.15.4 CSS receiver, IEEE 802.11 HR/DSSS interferer

Figure 21 illustrates the effect on an 802.11 HR/DSSS receiver in the presence of a CSS interferer with normal duty cycle.

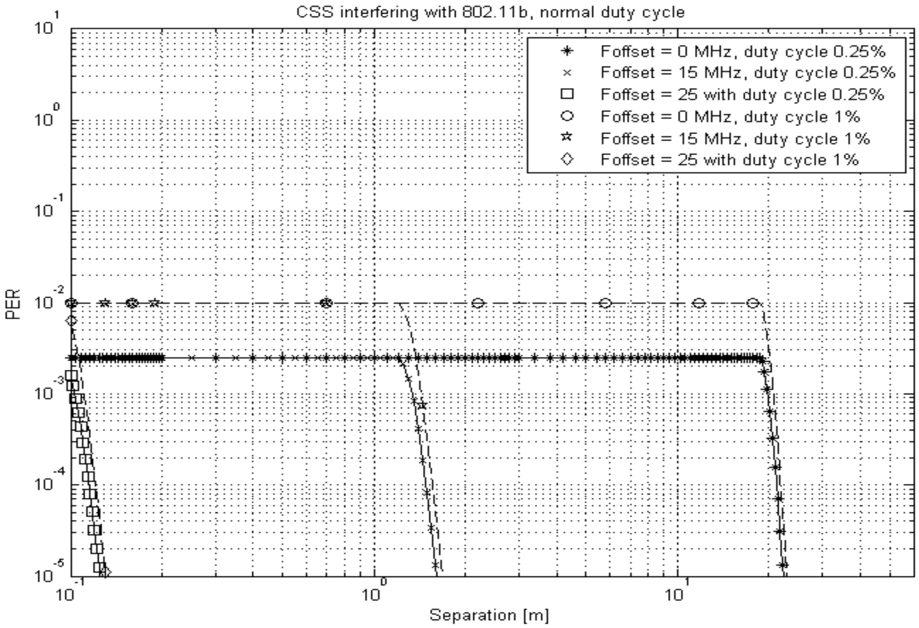


Figure 21—IEEE 802.11 HR/DSSS receiver, IEEE 802.15.4 CSS interferer with normal duty cycle

Figure 22 illustrates the effect on an 802.11 HR/DSSS receiver in the presence of a CSS interferer with rare duty cycle.

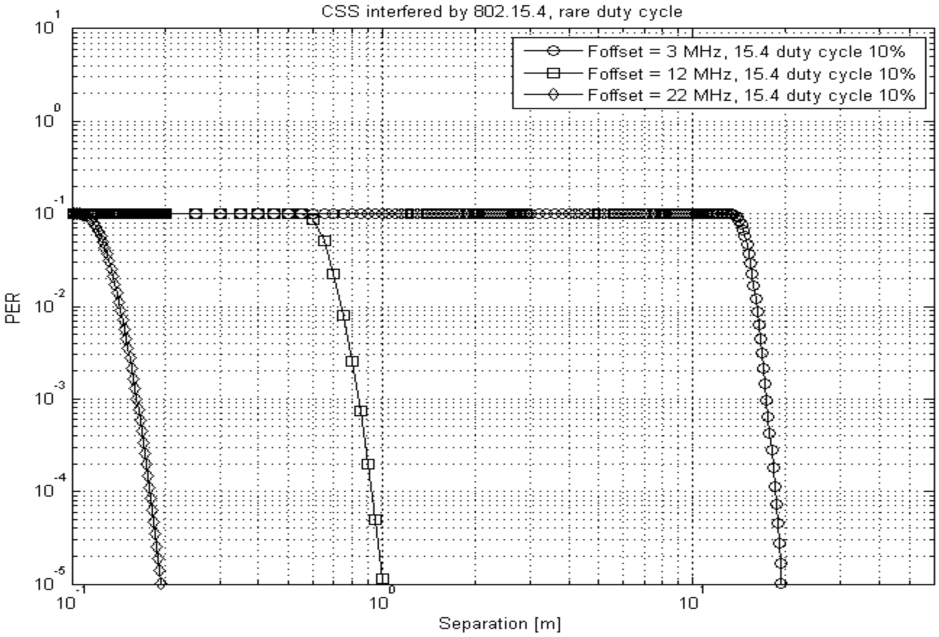


Figure 22—IEEE 802.11 HR/DSSS receiver, IEEE 802.15.4 CSS interferer with rare duty cycle

Figure 23 illustrates the effect on a CSS receiver in the presences of an 802.11 HRP interferer.

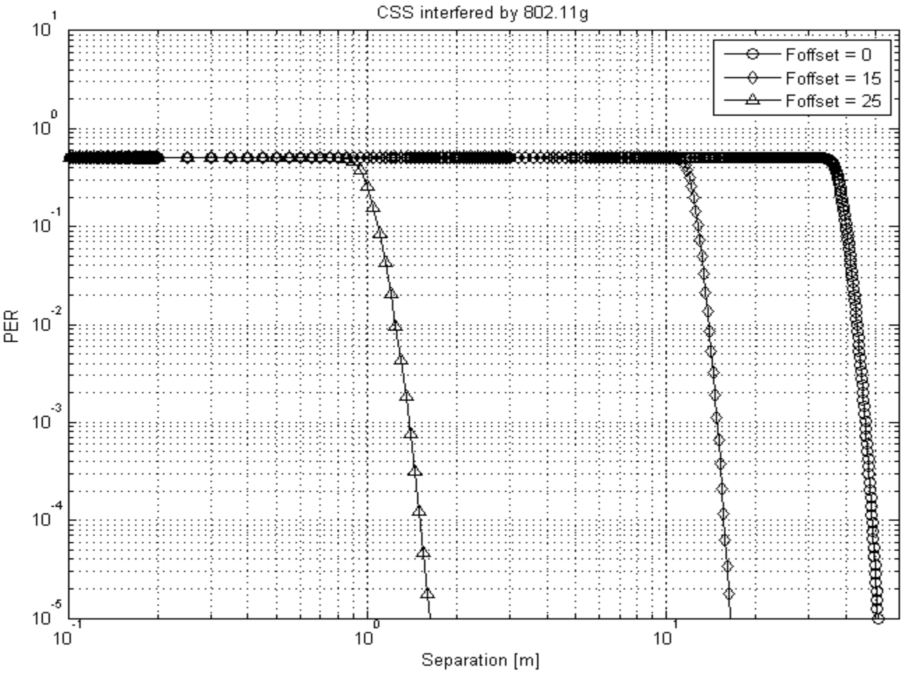


Figure 23—IEEE 802.15.4 CSS receiver, IEEE 802.11 ERP interferer

Figure 24 illustrates the effect on an 802.11 ERP receiver, 6 Mb/s, in the presence of a CSS interferer with normal duty cycle.

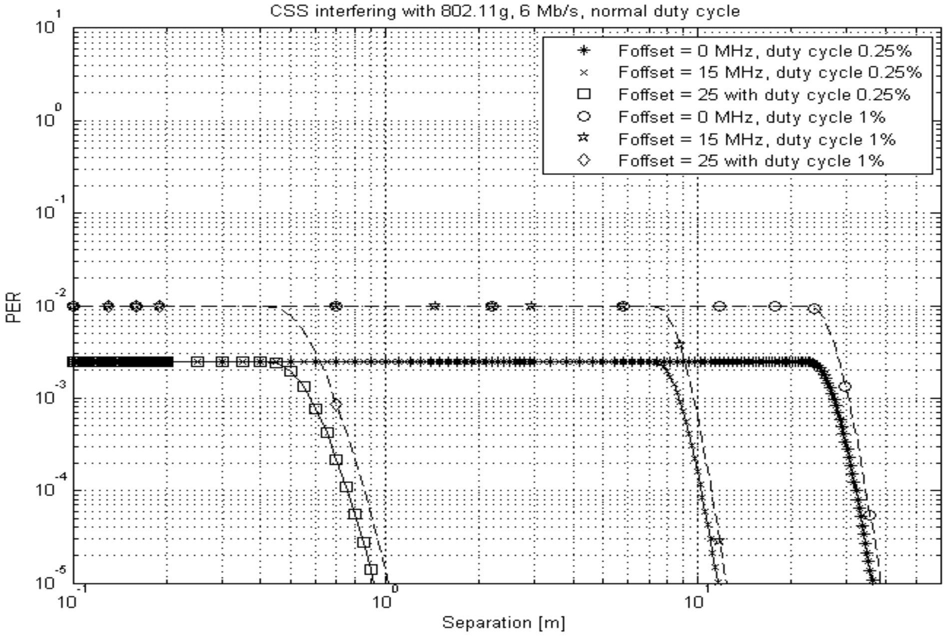


Figure 24—IEEE 802.11 ERP receiver, 6 Mb/s, IEEE 802.15.4a CSS interferer with normal duty cycle

Figure 25 illustrates the effect on an 802.11 ERP receiver, 6 Mb/s, in the presence of a CSS interferer with rare duty cycle.

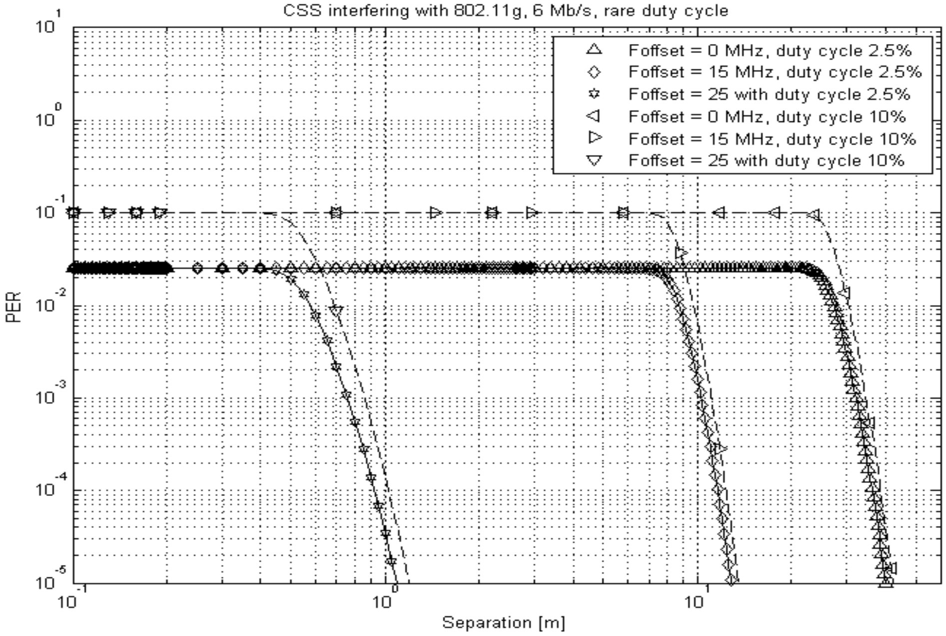


Figure 25—IEEE 802.11 ERP receiver, 6 Mb/s, IEEE 802.15.4 CSS interferer with rare duty cycle

Figure 26 illustrates the effect on an 802.11 ERP receiver, 24 Mb/s, in the presence of a CSS interferer with normal duty cycle.

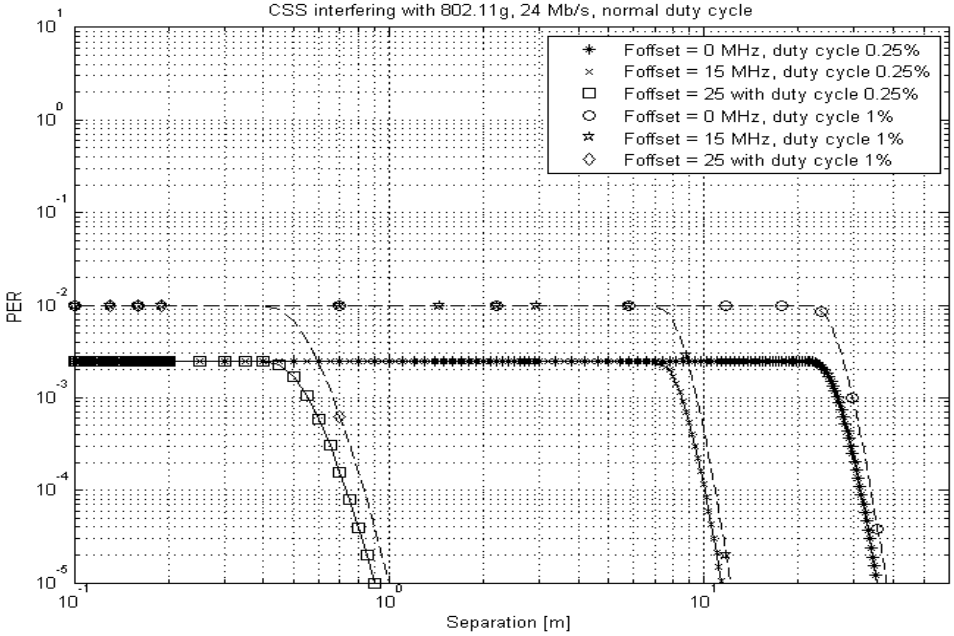


Figure 26—IEEE 802.11 ERP receiver, 24 Mb/s, IEEE 802.15.4a CSS interferer with normal duty cycle

Figure 27 illustrates the effect on an 802.11 ERP receiver, 24 Mb/s, in the presence of a CSS interferer with rare duty cycle.

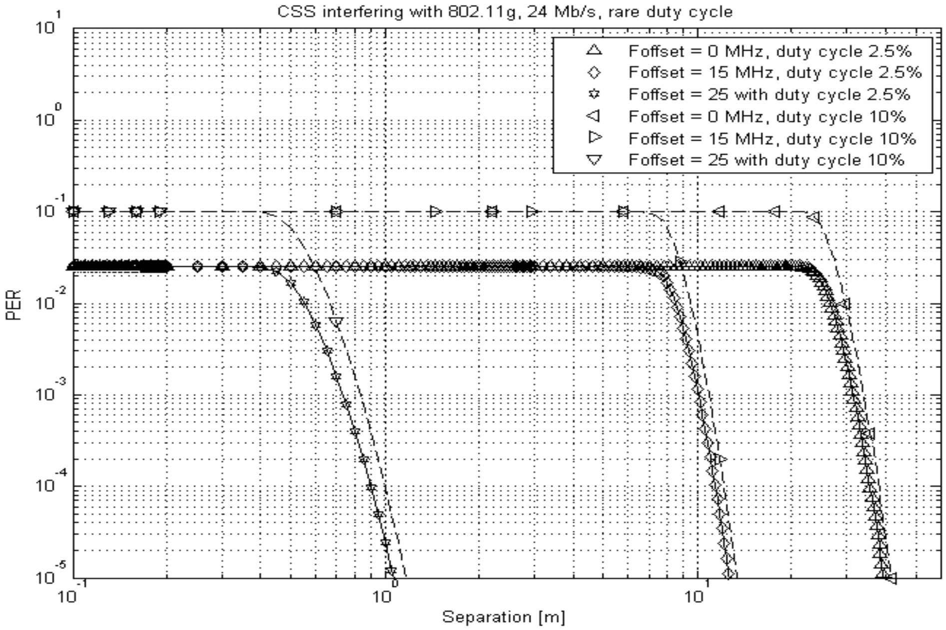


Figure 27—IEEE 802.11 ERP receiver, 24 Mb/s, IEEE 802.15.4 CSS interferer with rare duty cycle

Figure 28 illustrates the effect on an 802.11 ERP receiver, 54 Mb/s, in the presence of a CSS interferer with normal duty cycle.

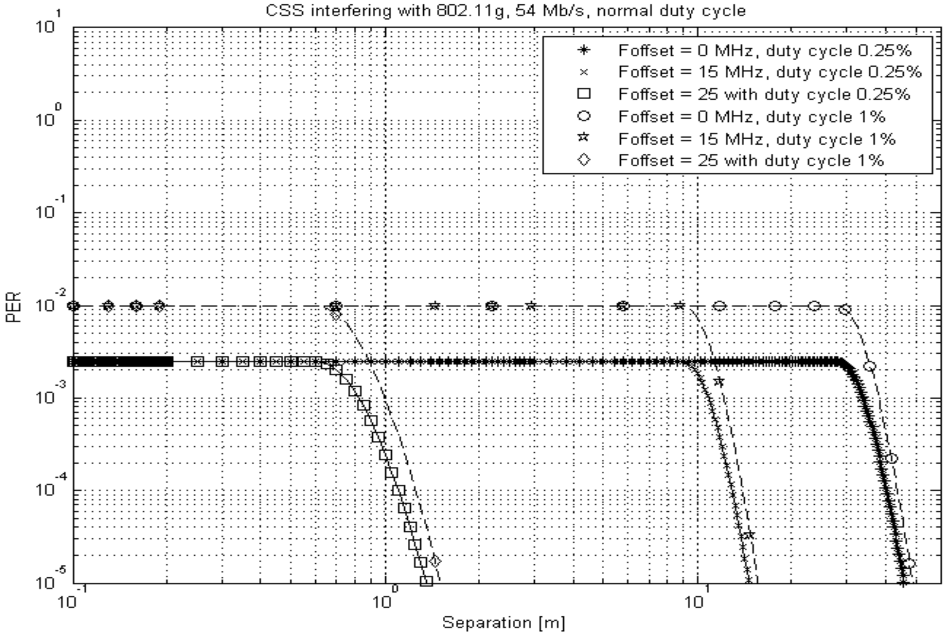


Figure 28—IEEE 802.11 ERP receiver, 54 Mb/s, IEEE 802.15.4a CSS interferer with normal duty cycle

Figure 29 illustrates the effect on an 802.11 ERP receiver, 54 Mb/s, in the presence of a CSS interferer with rare duty cycle.

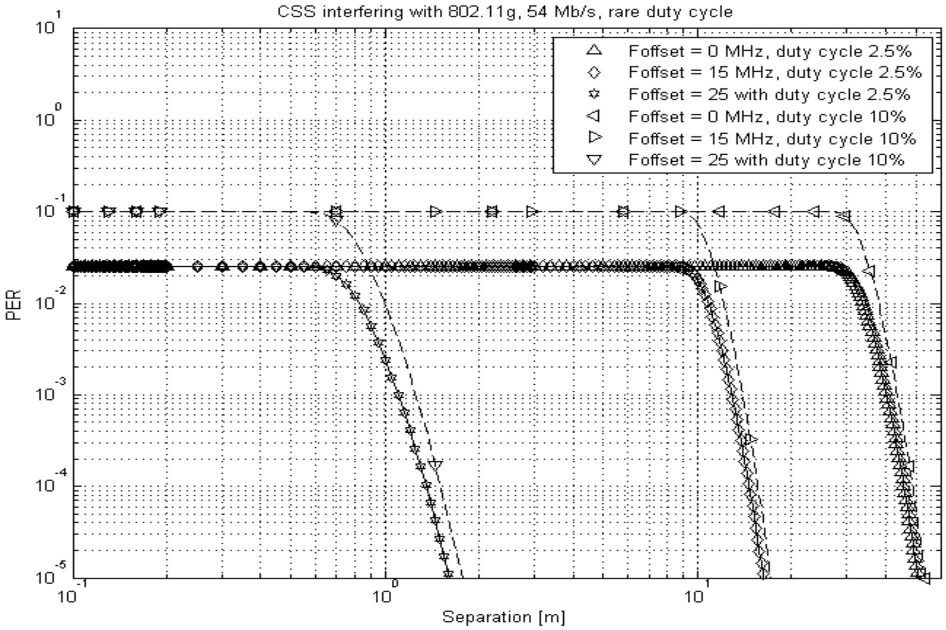


Figure 29—IEEE 802.11 ERP receiver, 54 Mb/s, IEEE 802.15.4 CSS interferer with rare duty cycle

Figure 30 illustrates the effect on a CSS receiver in the presences of an 802.15.1 interferer.

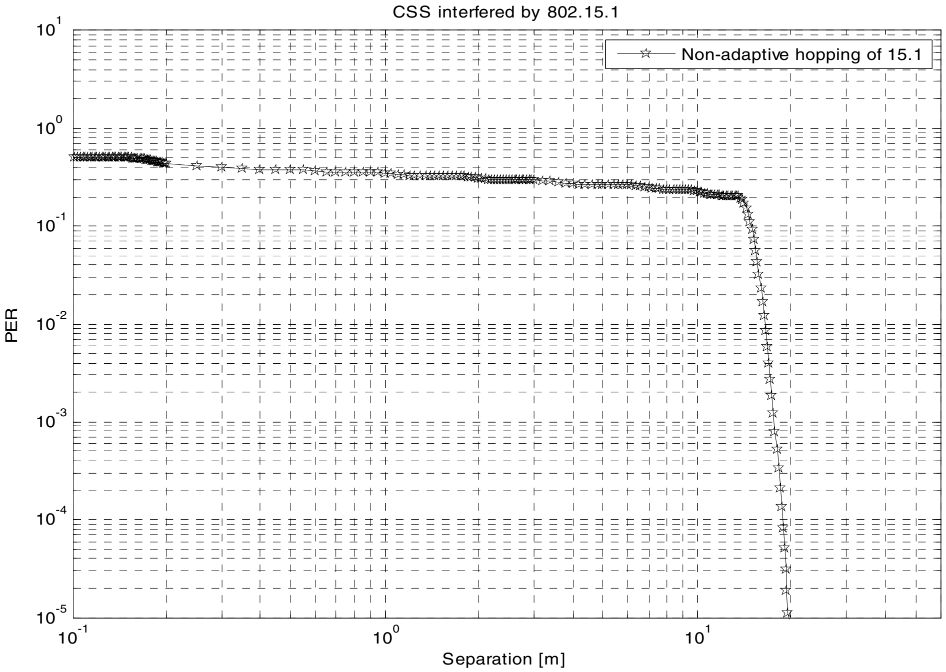


Figure 30—IEEE 802.15.4 CSS receiver, IEEE 802.15.1 interferer

Figure 31 illustrates the effect on an 802.15.1 receiver in the presence of a CSS interferer with normal duty cycle.

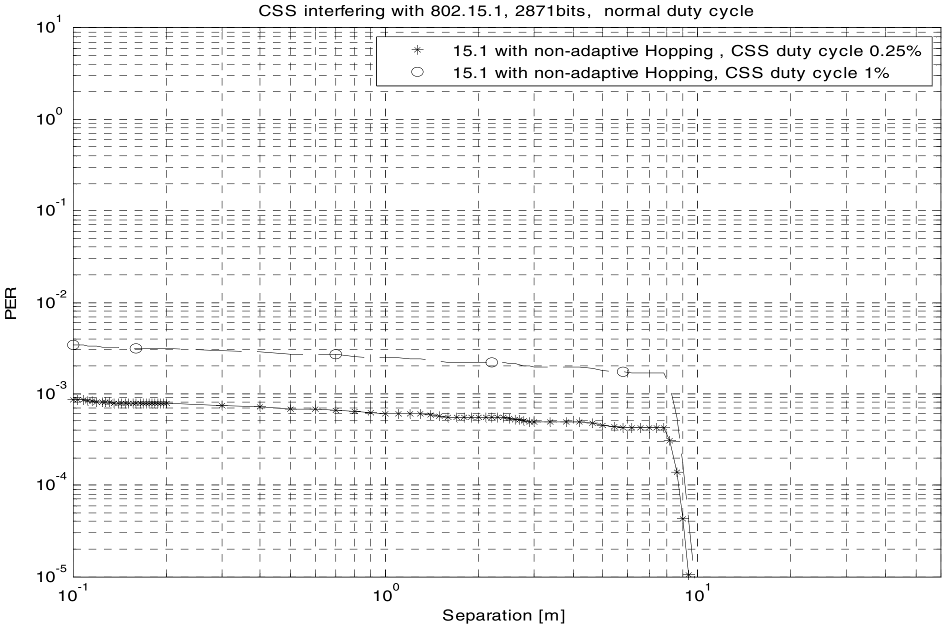


Figure 31—IEEE 802.15.1 receiver, IEEE 802.15.4 CSS interferer with normal duty cycle

Figure 32 illustrates the effect on an 802.15.1 receiver in the presence of a CSS interferer with rare duty cycle.

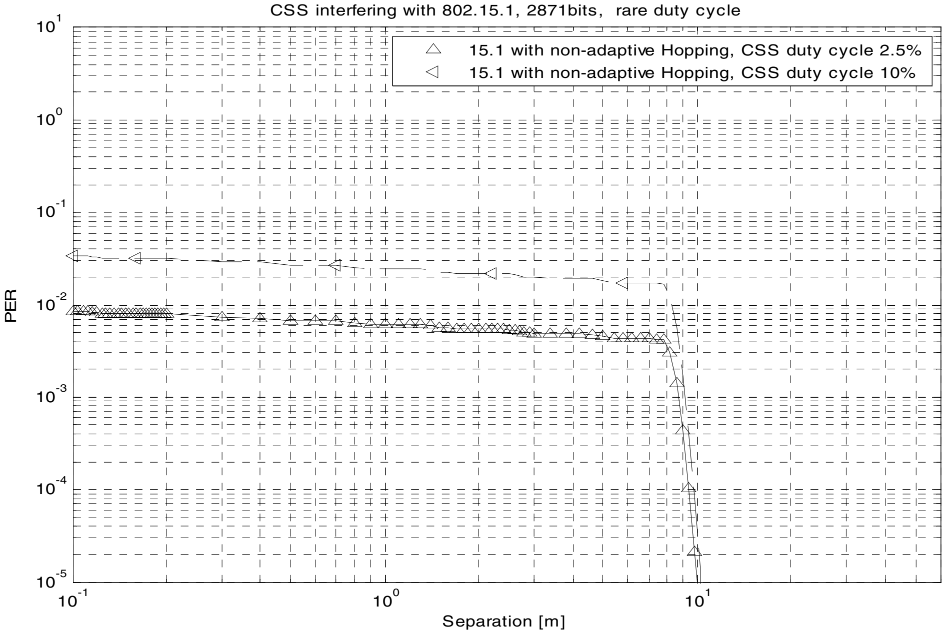


Figure 32—IEEE 802.15.1 receiver, IEEE 802.15.4 CSS interferer with rare duty cycle

Figure 33 illustrates the effect on a CSS receiver in the presences of an 802.15.3 interferer.

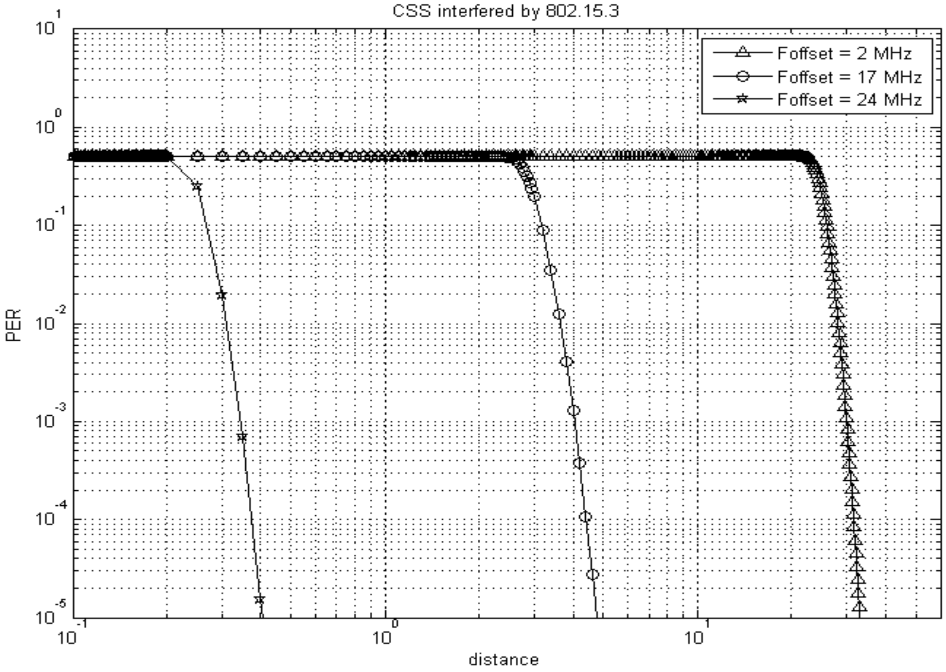


Figure 33—IEEE 802.15.4 CSS receiver, IEEE 802.15.3 interferer

Figure 34 illustrates the effect on an 802.15.3 receiver in the presence of a CSS interferer with normal duty cycle.

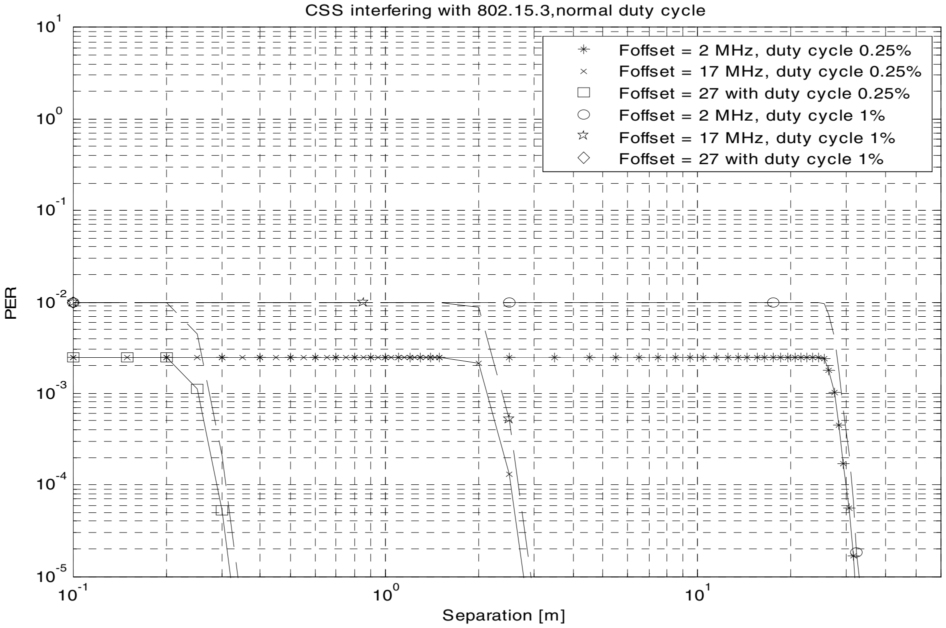


Figure 34—IEEE 802.15.3 receiver, IEEE 802.15.4 CSS interferer with normal duty cycle

Figure 35 illustrates the effect on an 802.15.3 receiver in the presence of a CSS interferer with rare duty cycle.

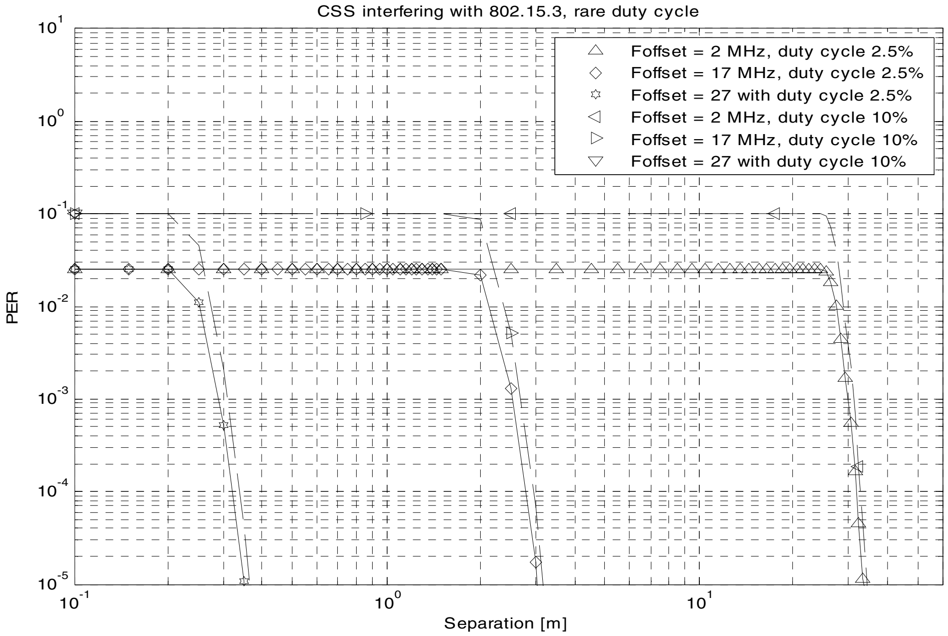


Figure 35—IEEE 802.15.3 receiver, IEEE 802.15.4 CSS interferer with rare duty cycle

Figure 36 illustrates the effect on a CSS receiver in the presence of a O-QPSK interferer with normal duty cycle.

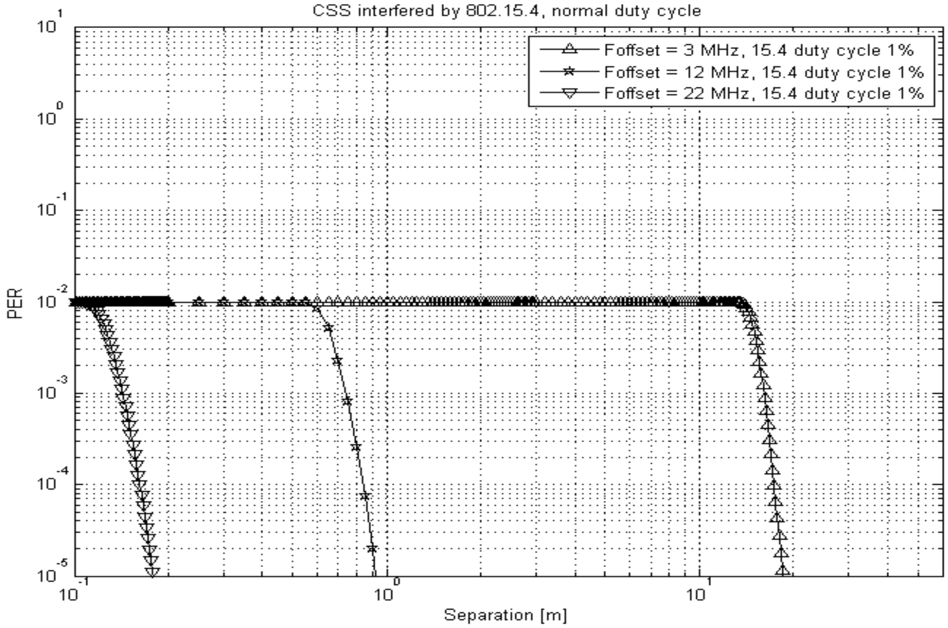


Figure 36—IEEE 802.15.4 CSS receiver, IEEE 802.15.4 O-QPSK interferer with normal duty cycle

Figure 37 illustrates the effect on a CSS receiver in the presence of a O-QPSK interferer with rare duty cycle.

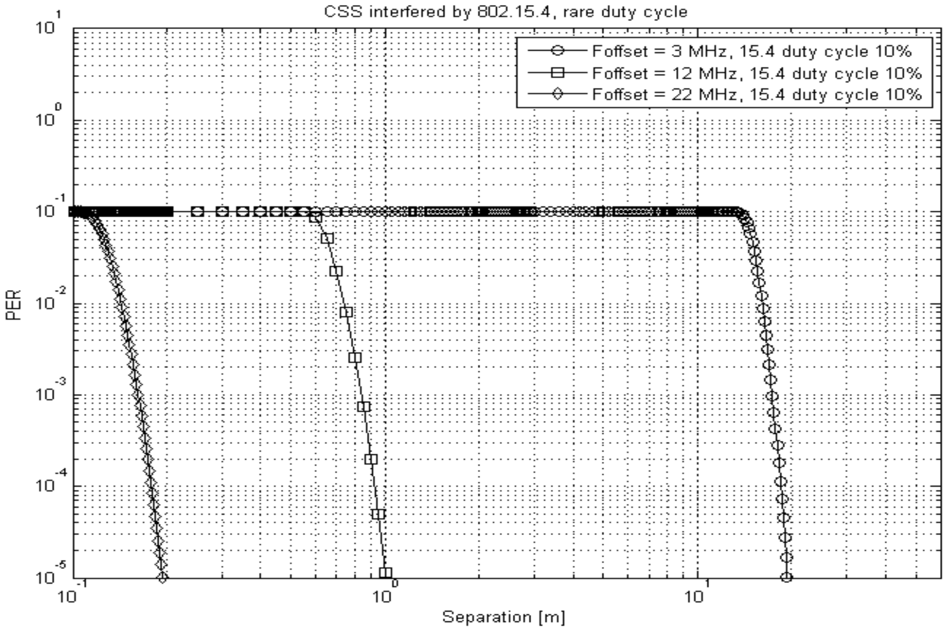


Figure 37—IEEE 802.15.4 CSS receiver, IEEE 802.15.4 O-QPSK interferer with rare duty cycle

Figure 38 illustrates the effect on an O-QPSK receiver in the presence of a CSS interferer with normal duty cycle.

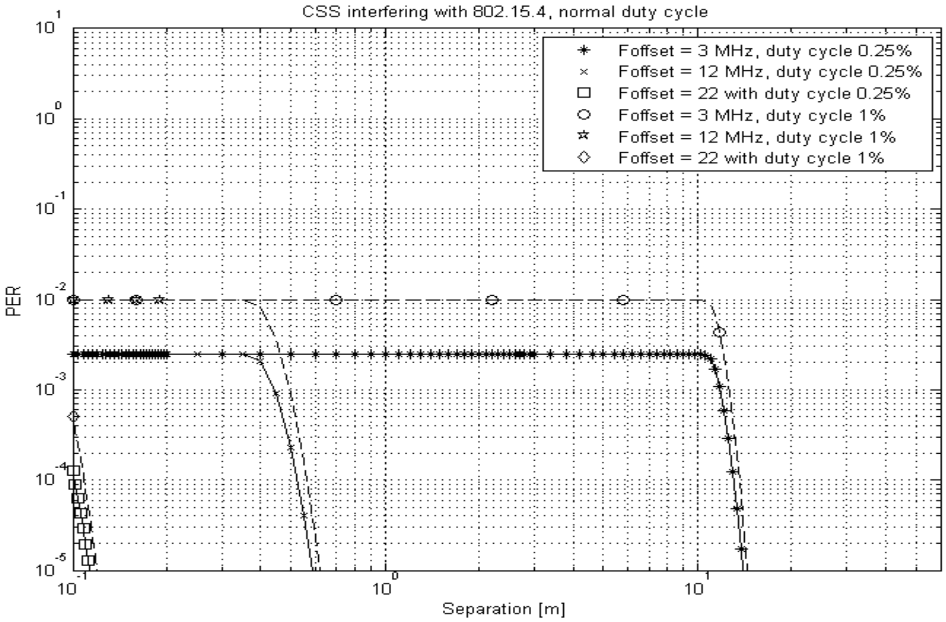


Figure 38—IEEE 802.15.4 O-QPSK receiver, IEEE 802.15.4 CSS interferer with normal duty cycle

Figure 39 illustrates the effect on an O-QPSK receiver in the presence of a CSS interferer with rare duty cycle.

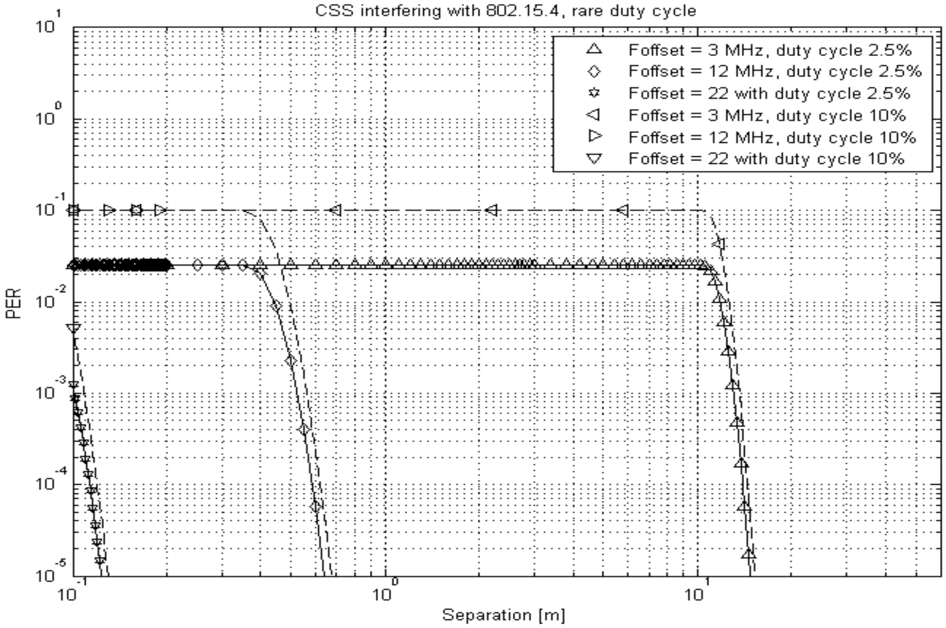


Figure 39—IEEE 802.15.4 O-QPSK receiver, IEEE 802.15.4 CSS interferer with rare duty cycle

5. UWB coexistence performance

5.1 Specific regulatory requirements for UWB coexistence

Surprisingly, despite the wide bandwidth of the UWB PHY, there is only one other IEEE standard waveform that may occupy the same frequency bands, namely, IEEE 802.16 systems below 10 GHz. Cognizant of the potential for coexistence issues, regulators in the parts of the world where IEEE 802.16 systems may be deployed in bands overlaid by UWB spectrum are creating specific regulatory requirements to further reduce the likelihood of any coexistence problems. In both Asia and the European Union, regulators are creating rules for unlicensed UWB operation that will require specific active mitigation mechanisms to ensure peaceful coexistence with IEEE 802.16 systems or other similar systems used for fixed or mobile wireless access.

Additionally, a proposed IEEE standard, P802.22, proposes to occupy parts of the bandwidth in the UWB PHY 150–650 MHz band. In the regulatory domains where this is presently allowed (FCC), the maximum transmit power is specified an additional (approximately) 35 dB lower compared the limits for the 3.1–10 GHz bands. Some regulatory domains (including FCC) have suggested that certain applications, specifically those involving personnel location in emergency response situations, would be allowed at higher PSD levels under specific conditions, where other factors such as operating limitations would provide required protection of incumbent services. Clearly it is beyond the scope of this standard to anticipate specific future regulatory actions. However, in considering the application scenarios presented in the call for applications and responding to specific guidance from regulators in the United States, it can be observed that coexistence with the IEEE P802.22 systems and other known incumbent systems is assured through operating conditions. As a primary mitigation factor, it is unlikely such systems will be operating in near physical proximity at the same time as emergency response teams. Such conditions are the scope of regulatory agencies to define, and it is the responsibility of implementers of this standard to conform with applicable regulations and conditions.

In considering other personnel location scenarios, the mitigations factors described for other UWB applications apply equally to all UWB bands.

5.2 Mitigation of interference from UWB PHY devices using low duty cycle PANs

One proposal is to use a lower duty cycle within a UWB WPAN to reduce potential interference effects. Low-duty-cycle WPAN scenarios could be used in the following situations:

- UWB PHY devices are deployed in high density in a limited area, e.g., hot-spot deployment scenarios.
- UWB victim systems cover much larger area than the coverage of a typical LR-WPAN.

In these cases, transmissions from every device in the WPAN can affect the victim receiver. For reasons of less complexity, lower power consumption, as well as physical limitations, it is difficult for simple UWB PHY devices to detect victim system reliably. The aggregate interference from the WPAN increases with increment in number of WPAN members. The interference to victim systems could be limited by controlling duty cycle of the WPAN through general active/inactive periods. The UWB traffic can occur only in the active period. Victim systems would then be free of interference in the inactive period. The interference level could be controlled by the ratio of active period to the total period.

5.3 Coexistence assurance: methodology and assumptions

In order to quantify the coexistence performance of the IUWB PHY, the techniques described by Shellhammer [B6] have been adapted.

The coexistence assurance methodology predicts the PER of an affected wireless network (AWN, or victim) in the presence of an interfering wireless network (IWN, or assailant). It its simplest form, the methodology assumes an AWN and an IWN, each composed of a single transmitter and a receiver. The methodology takes as input a path loss model, a quantitative model for the BER of the AWN, and predicted temporal models for packets generated by the AWN and for “pulses,” i.e., packets generated by the IWN. Based on these inputs, the methodology predicts the PER of the AWN as a function of the physical spacing between the IWN transmitter and the AWN receiver.

The appeal of the coexistence assurance methodology is that multiple networking standards can be characterized and compared with just a few parameters, notably,

- Bandwidth of AWN and IWN devices
- Path loss model for the networks
- BER as a function of SIR of AWN devices
- Temporal model for AWN packets and IWN “pulses” (interfering packets)

The following subclauses describe the general assumptions made across all of the PHYs covered under this standard.

5.3.1 Victims and assailants

At present, this is the only standard for UWB systems in the UWB bands covered under IEEE Std 802®. The only other IEEE wireless standard waveforms that overlap this same spectrum are IEEE 802.16 systems occupying 3.4–3.8 GHz licensed frequency bands in some regions (parts of Europe and Asia). In addition, the proposed standard IEEE P802.22 would occupy parts of the band between 150 MHz to 650 MHz.

In addition to IEEE standardized wireless systems, another UWB standard produced by ECMA is specified in ECMA 368. A limited analysis of the coexistence between this system and UWB PHY waveform is given here.

In this analysis, the assumption is made that the PHYs will serve as both victims (i.e., participants in AWNs) and as assailants (i.e., participants in IWNs).

5.3.2 Bandwidth for UWB systems

The UWB PHYs in this standard that operate in any of the three UWB bands have one or more channels, approximately 500 MHz wide or, optionally, 1300 MHz wide. The ECMA 368 PHY has a nominal bandwidth of 1500 MHz. In contrast to these UWB systems, the narrowband IEEE 802.16 PHYs that operate in the 2–10 GHz band have multiple defined channels, each 20 MHz wide or less. IEEE P802.22 would have multiple defined channels, each 6 MHz to 8 MHz wide. The coexistence methodology assumes that any UWB device in an AWN or IWN will have a much greater bandwidth than a narrowband device in a corresponding AWN or IWN.

5.3.3 Path loss model

The coexistence methodology uses a variant of the path loss model described by Shellhammer [B7] which stipulates a two-segment function with a path loss exponent of 2.0 for the first 8 meters and then a path loss model of 3.3 thereafter. The generalized form developed in 3.3 is used in this analysis:

Using *f* = 3400 MHz, then *pl*(1) = 43.03 and *pl*(8) = 61.09. The path loss function modified for 3400 MHz is, therefore,

$$pl(d) = \begin{cases} 43.08 + 20\log_{10}(d) & d \le 8 \text{ m} \\ 61.09 + 33\log_{10}\left(\frac{d}{8}\right) & d > 8 \text{ m} \end{cases}$$

Using *f* = 400 MHz for the sub-gigahertz UWB band, then *pl*(1) = 24.49 and *pl*(8) = 42.55. The path loss function for 400 MHz center frequency is then

$$pl(d) = \begin{cases} 24.49 + 20\log_{10}(d) & d \le 8 \text{ m} \\ 42.55 + 33\log_{10}\left(\frac{d}{8}\right) & d > 8 \text{ m} \end{cases}$$

A plot of the path loss as a function of device separation distance is shown in Table 40.

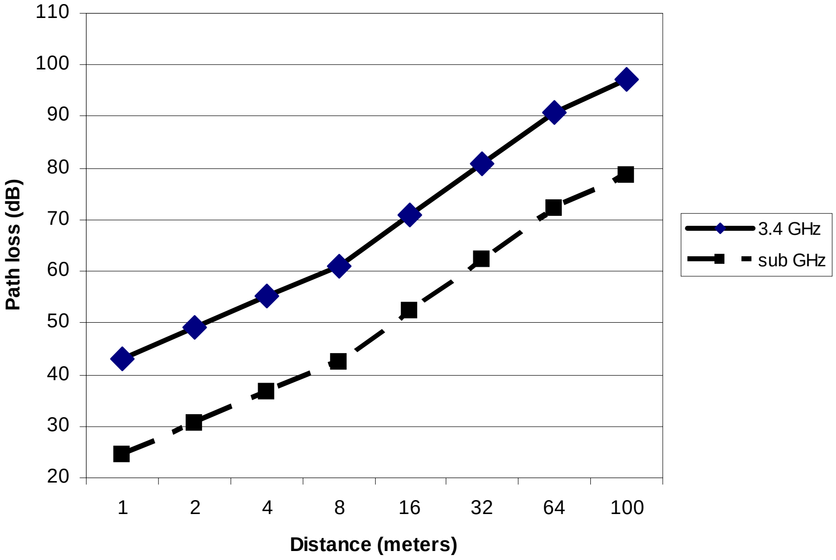


Figure 40—Path loss function

5.3.4 BER as a function of SIR

For the PHY specifications analyzed in this standard, there are no analytic expressions for the BER or symbol error rate (SER) of the signal due to the use of FEC methods to improve reliability.

In this analysis, a method is used that is equivalent to using interpolation of table values. In order to simplify the calculations and still provide meaningful results, the relationship is approximated between the changes in BER (on a logarithmic scale) and varying SNR as a linear with a slope of 0.6 dB per order of magnitude (10×) change in BER over the range of BER that is relevant to this analysis (about 1e–8 to 1e–5 BER). This approximation is reasonable for the FEC methods used for IEEE Std 802.16-2004 (Reed-Solomon block code), ECMA 368, IEEE P802.22, and the UWB PHY in this standard (convolutional coding).

For each of the systems, the effect of the IWN on the AWN is characterized by computing the rise in the effective operating noise floor of the AWN by the interference of the IWN (modeled as uncorrelated wideband noise). The analysis will assume a baseline operating effective noise floor (including effects of thermal noise floor, noise figure, and operating margin to account for other real-world effects such as multipath propagation effects and co-channel or adjacent channel interference). This approach allows the characterization of the effect of the IWN on the AWN as the IWN is moved from a large separation distance (when the AWN has a baseline nominal PER) to a very close distance where the interference effect of the IWN dominates the PER during periods of operation (subject to duty cycle assumptions).

Although this analysis approach is perhaps not as elegant as the use of an analytic expression (not possible in these cases), it will provide a good characterization of the coexistence of these systems under real-world conditions and can be used to estimate a range of effects for an equivalent range of assumptions about operating margin.

5.3.5 Temporal model

For the UWB PHY, packet overhead is kept to minimum. The maximum PSDU size is 128 octets, and a typical packet is only 32 octets, including PSDU and synchronization octets. For this coexistence methodology, all packets, whether belonging to the AWN or IWN, are assumed to be 32 octets.

Although there is no duty-cycle limitation in the authorized UWB bands at this point, many IEEE 802.15.4 UWB PHY networks are expected to operate at well under 5% duty cycle, particularly devices that are battery-powered. This 5% duty cycle level has also been used by regulators as a high value for expected UWB communications device operating levels on various coexistence studies. In addition, the UWB PHYs in this standard use an ALOHA contention-based access mechanism that is intended to support only lower duty cycle applications. Based on these factors, it is reasonable to expect that UWB PHY piconets used for many applications will operate at duty cycles as high as 10%. For purposes of modeling coexistence, the assumption is made that all UWB PHY devices operating in piconets will have a shared duty cycle of 10% and that such piconets will operate within a range of a few tens of meters. Based on this and a typical active device population of five devices per piconet, an average operating duty cycle of 2% is assumed for any particular device within a piconet.

For the other wireless systems considered in this analysis (IEEE 802.16, IEEE P802.22, and ECMA 368), anticipated applications are focused on higher bandwidth connectivity over wide areas for IEEE 802.16 and IEEE P802.22 systems and over short WPAN ranges for ECMA 368 systems. Because these systems are not deployed in great numbers, it is not possible to qualify typical operating duty cycle. For this analysis, therefore, the initial assumption is a very conservative continuous operation as a baseline worst-case scenario.

5.4 Coexistence analysis

This subclause details the assumptions for the coexistence analysis and presents the results for each of the cases analyzed.

5.4.1 Impact of UWB PHY devices on IEEE 802.16 networks

The assumptions for this scenario are:

— The IEEE 802.16 receiver is the victim (AWN) and is an indoor fixed or nomadic client node of the network. The base station node will not be susceptible to IEEE 802.15.4a UWB interference due to site positioning. The AWN operates in 3.4–3.8 GHz licensed bands (available in most of the world except the United States).

— The IEEE 802.16 receiver is operating in a real-world environment in the presence of multipath fading and interference, and a 3–10 dB margin above sensitivity functions well. The baseline PER is 1e–6 at 3 dB above sensitivity in the absence of any UWB device effects, and the receiver noise floor is 6 dB.

— UWB interference is wideband uncorrelated noise since the bandwidth is much wider than victim receiver. The difference in antenna gains is 10 dB since the indoor or outdoor IEEE 802.16 antenna will have gain in the direction of the desired base station downlink signal. The UWB device will not directly block the LOS.

Table 7 shows the calculation of the allowable path loss that would result in an IEEE 802.15.4a UWB emission level at the AWN equal to the effective operating noise floor.

Table 7—Computation of acceptable levels of UWB PHY device emissions for an operating IEEE 802.16 client node

Quantity	Symbol	Value	Units	Notes
UWB transmit PSD limit	$\mathrm{P}_{\mathrm{lim}}$	–41.3	dBm/MHz	Set by regulatory authority.
Average margin to limit	M_{B0}	1.7	dB	Transmit power back-off due to spectral ripple (0.5+ dB) and ~1 dB margin for manufacturing tolerance, etc.
Average UWB antenna gain	G_{UWB}	–2	dBi	Average gain from small, low-cost UWB antenna to arbitrary victim receiver over 360°.
Average emissions PSD seen by IEEE 802.16 device receiver	–	–45	dBm/MHz	Average PSD seen in direction of arbitrary victim receiver. ($P_{lim} – M_{B0} + G_{\mathrm{UWB}}$)
IEEE 802.16 thermal noise floor	kTB	–114	dBm/MHz	Thermal noise floor (room temperature).
IEEE 802.16 noise figure	NF_{16}	6	dB	Noise figure for indoor IEEE 802.16 terminal.
Average IEEE 802.16 antenna gain in direction of interfering UWB	G_{16}	–4	dBi	Gain of IEEE 802.16 antenna in main beam (to desired IEEE 802.16 base station) is 6–7 dBi and to nearby UWB interferer (not blocking antenna main beam)
IEEE 802.16 operating margin	M_{16}	3–10	dB	Operating margin for acceptable performance in presence of multipath fading and adjacent cell/channel interference.
IEEE 802.16 effective operating noise floor for UWB interference susceptibility	–	–101 to –94	dBm/MHz	The effective operating noise floor level for the IEEE 802.16 operating receiver. ($kTB + NF_{16} – G_{16} + M_{16}$)
Level of wideband UWB PHY interference that result in a 3 dB rise in IEEE 802.16 effective operating noise floor	–	–101 to –94	dBm/MHz	For 3 dB rise, wideband UWB emissions in-band can be at the same level as effective operating noise floor for indoor IEEE 802.16 node receiver.
Path loss (range) from UWB to IEEE 802.16 receiver (average case) for 3 dB rise in effective operating noise floor	–	49 to 56 (2 to 4.5)	dB (m)	For 3 dB rise, wideband UWB emissions in-band can be at the same level as effective operating noise floor for indoor IEEE 802.16 node receiver.
Path loss (range) from UWB to IEEE 802.16 receiver (average case) for 1 dB rise in effective operating noise floor	–	55 to 61 (4 to 8)	dB (m)	For 1 dB rise, wideband UWB emissions in-band must be 6 dB below effective operating noise floor for indoor IEEE 802.16 node receiver.

Based on this path loss, the effect on AWN PER is computed as a function of separation distance, shown in Figure 41.

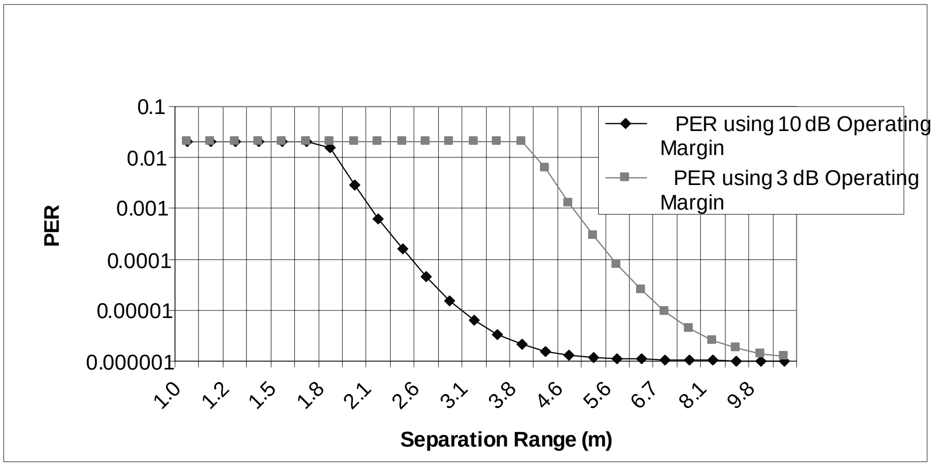


Figure 41—Effect on IEEE 802.16 AWN as a function of separation distance from a UWB PHY device

5.4.2 Impact of an IEEE 802.16 device on IEEE 802.15.4a UWB networks

The assumptions used in this analysis are:

- The IEEE 802.15.4a UWB device is the affected device (AWN). The IEEE 802.16 device is the interferer (IWN) and is an indoor fixed or nomadic client node of the network. The base station node will have less interference effects on IEEE 802.15.4a UWB devices due to UWB device deployment much closer to subscriber or mobile IEEE 802.16 devices. The IWN operates in 3.4–3.8 GHz licensed bands (available in most of the world except the United States). For this analysis, the IWB operates at a conservative 50% duty cycle (IEEE 802.16 subscriber uplink).
- The IEEE 802.15.4a UWB receiver is operating in a real-world environment in the presence of multipath fading and interference, and the margin above sensitivity is 3 dB during operation. The baseline PER is 1e–7 at 3 dB above sensitivity in the absence of any UWB device effects, and the receiver noise floor is 10 dB.
- UWB interference is wideband uncorrelated noise since the bandwidth is much wider than victim receiver. The difference in antenna gains is 10 dB since the indoor or outdoor IEEE 802.16 antenna will have gain in the direction of the desired base station downlink signal. The UWB device will not directly block the LOS.

Table E.7 shows the calculation of the allowable path loss that would result in a IEEE 802.15.4a UWB emission level at the AWN equal to the effective operating noise floor.

Table 8—Computation of acceptable levels of IEEE 802.15.4a device emissions for an operating IEEE 802.16 client node

Quantity	Symbol	Value	Units	Notes
IEEE 802.16 client device transmit power	P_{16}	17	dBm	Assumes subscriber station in small cell.
IEEE 802.16 client device bandwidth	B_{16}	5	MHz	
UWB device bandwidth	B_{UWB}	500	MHz	
Average IEEE 802.16 antenna gain	G_{16}	–2	dBi	Average gain from antenna to arbitrary victim receiver over 360° (IWN typically not in main beam).
Average emissions PSD seen by UWB PHY device receiver	–	–12	dBm/MHz	Average PSD seen in direction of arbitrary victim receiver (assumes that UWB receiver can spread interference power into receiver bandwidth). $P_{16} + G_{16} - 10\log(B_{\mathrm{UWB}})$
UWB PHY thermal noise floor	kTB	–114	dBm/MHz	Thermal noise floor (room temperature).
UWB PHY noise figure	NF_{UWB}	10	dB	Noise figure for low-cost UWB PHY device.
UWB PHY operating margin	M_{UWB}	3	dB	Operating margin for acceptable performance in presence of multipath fading (assumes no interference other than IWN).
UWB PHY effective operating noise floor for UWB interference susceptibility.	–	–101	dBm/MHz	The effective operating noise floor level for the IEEE 802.15.4a operating receiver. $kTB + NF_{\mathrm{UWB}} + M_{\mathrm{UWB}}$
Level of interference power density to achieve a 3 dB rise in UWB PHY effective operating noise floor	–	–101	dBm/MHz	For 3 dB rise, IEEE 802.16 power emissions in-band can be at the same level as effective operating noise floor for UWB receiver.
Path loss (range) from IEEE 802.16 to UWB receiver (average case) for 3 dB rise in effective operating noise floor	–	89 (48)	dB (m)	For 3 dB rise, IEEE 802.16 power emissions in-band can be at the same level as effective operating noise floor for UWB receiver.
Path loss (range) from IEEE 802.16 to UWB receiver (average case) for 1 dB rise in effective operating noise floor	–	95 (75)	dB (m)	For 1 dB rise, wideband UWB emissions in-band must be 6 dB below effective operating noise floor for indoor IEEE 802.16 node receiver.

Base on this path loss, the effect on AWN PER is computed as a function of separation distance, shown in Figure 42.

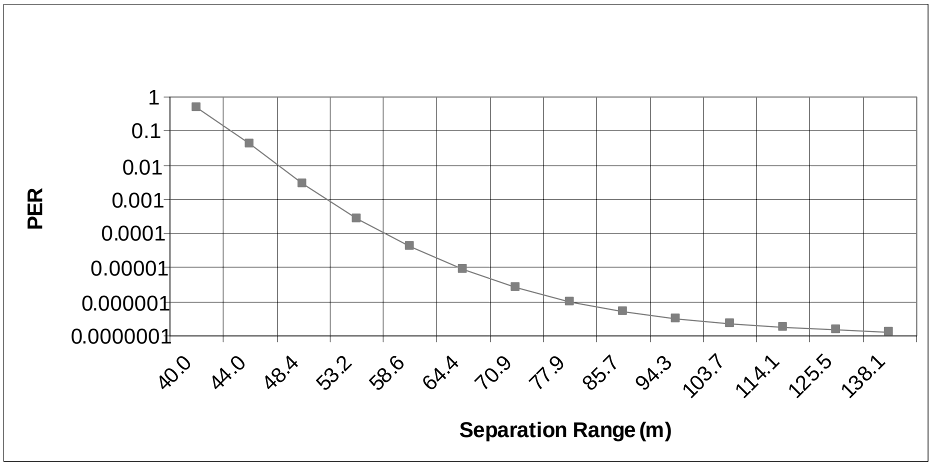


Figure 42—Effect on a UWB PHY device as a function of separation distance from an IEEE 802.16 IWN device

5.4.3 Low-duty-cycle UWB PHY interferring with a WiMAX link

These results are an extract from a French contribution to Electronic Communications Committee (ECC) Task Group 3 meeting #15.

The impact of UWB on a fixed broadband wireless access system is measured on video streaming is listed in Table 9. Video streaming is considered a relevant service in term of vulnerability, bandwidth use, and timing constraint.

Table 9—Impact of UWB on fixed broadband wireless access system measured on video streaming

Degradation (dB)		**Distance (m)**			
AF (T_{on}/T_{off} ms)		0.5	1	2	4
2%	075/38	1	N/A	1	N/A
	5/245	0	N/A	0	N/A
	10/490	1	N/A	1	N/A
5%	2/38	2	1	0	N/A
	5/95	1	N/A	1	N/A
	10/190	0	N/A	1	N/A
10%	2/18	3	N/A	0	0
	5/45	3	2	0	0
	10/90	2	N/A	1	0.5

The methodology used is the following:

- Set the WiMAX received signal strength at equipment at minimum sensitivity level (–98 dBm).
- Get a reference measure without UWB (depending on each test case).
- Measure the degradation with low-duty-cycle UWB emission [for any considered activity factor (AF) and distances]. Degradation is, in decibels, the increase of power needed by the WiMAX receiver to reestablish the reference link quality.

Table E.9 shows the evolution of the lowest needed receive signal strength indicator (RSSI) to achieve a reliable 1 Mb/s throughput with respect to UWB activity. The reference level is –98 dBm (i.e., without UWB activity).

Table 10—Lowest RSSI to achieve reliable 1 Mb/s throughput

RSSI needed to achieve 1 Mb/s data rate (dBm)		**Distance (m)**		
AF (T_{on}/T_{off} ms)		0.5	2	4
2%	075/38	–98 (–98)	–98 (–98)	N/A
	5/245	–98 (–98)	–98 (–98)	N/A
	10/490	–97 (–98)	–97 (–98)	N/A
5%	2/38	–98 (–98)	–98 (–98)	N/A
	5/95	–98 (–98)	–98 (–98)	N/A
	10/190	–97 (–98)	–98 (–98)	N/A
10%	2/18	–97 (–98)	–98 (–98)	N/A
	5/45	–98 (–98)	–98 (–98)	N/A
	10/90	–97 (–98)	–98 (–98)	N/A

5.4.4 Impact of UWB PHY devices on ECMA 368 networks

The assumptions in this analysis are:

- The ECMA 368 receiver is the victim (AWN). The AWN operates using frequency hopping in bands across the 3.1–4.8 GHz unlicensed UWB bands (available only in the United States at this time), but the IEEE 802.15.4a device operates only in band 3 (mandatory).
- The ECMA 368 receiver is operating in a real-world environment in the presence of multipath fading and interference, and a 5 dB margin above sensitivity functions well. The baseline PER is 8e–2 at sensitivity (8e–7 at 3 dB above sensitivity) in the absence of any UWB device effects, and the receiver noise floor is 6 dB.

Table 11 shows the calculation of the allowable path loss that would result in an IEEE 802.15.4a UWB emission level at the AWN equal to the effective operating noise floor.

Table 11—Computation of acceptable levels of a UWB PHY device emissions for an operating ECMA 368 device

Quantity	Symbol	Value	Units	Notes
UWB Transmit PSD Limit	P_{LIM}	–41.3	dBm/MHz	Set by regulatory authority
Average margin to limit	M_{BO}	1.7	dB	Due to spectral ripple (0.5+ dB) and ~1 dB margin for manufacturing tolerance, etc.
Average UWB antenna gain	G_{UWB}	–2	dBi	Average gain from small, low-cost UWB antenna to arbitrary victim receiver over 360°
Average emissions PSD	–	–45	dBm/MHz	Average PSD seen in direction of arbitrary victim receiver. $P_{LIM} - M_{BO} + G_{\mathrm{UWB}}$
ECMA 368 victim thermal noise floor	kTB	–114	dBm/MHz	Thermal noise floor (room temperature)
ECMA 368 victim noise figure	NF_{ECMA}	6	dB	Noise figure for the ECMA 368 receiver
ECMA victim frequency diversity	D_{FD}	3	dB	ECMA UWB system uses 2x band frequency diversity for then encoding of each bit as part of its frequency hopping scheme
UWB victim operating margin	M_{ECMA}	5	dB	Operating margin for acceptable performance in presence of multipath fading and RF interference
ECMA 368 effective operating noise floor for UWB interference susceptibility:	–	–100	dBm/MHz	The effective allowable interference power level for the ECMA 368 operating receiver ($kTB + NF_{\mathrm{ECMA}} + D_{FD} + M_{\mathrm{ECMA}}$)
Level of wideband UWB emissions that result in 3 dB rise in ECMA 368 effective operating noise floor	–	–100	dBm/MHz	For 3 dB rise, IEEE 802.15.4a UWB emissions in-band can be at the same level as effective operating noise floor for AWN device receiver
Path loss (range) from UWB to ECMA 368 receiver (average case) for 3 dB rise in effective operating noise floor	–	55 (3)	dB (m)	For 3 dB rise, wideband UWB emissions in-band can be at the same level as effective operating noise floor for AWN device receiver
Path loss (range) from UWB to ECMA 368 receiver (average case) for 1 dB rise in effective operating noise floor	–	61 (6)	dB (m)	For 1 dB rise, wideband UWB emissions in-band must be 6 dB below effective operating noise floor for indoor IEEE 802.16 node receiver

Base on this path loss, the effect on AWN PER is computed as a function of separation distance, shown in Figure 43.

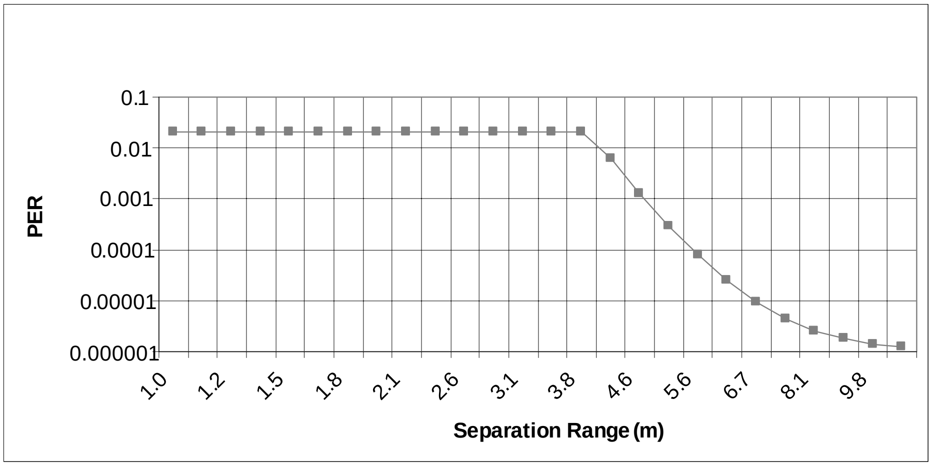


Figure 43—Effect on an ECMA 368 AWN device as a function of separation distance from a UWB PHY device

5.4.5 Impact of IEEE 802.15.4a devices on IEEE P802.22 networks

Based on the currently available draft of IEEE P802.22, the operating conditions are generally similar to IEEE Std 802.16-2004. The primary operating considerations include the following:

- The IEEE P802.22 network is a fixed-point-to-multipoint network, operating in a narrow band (6–8 MHz) widely spaced between 54 MHz and 862 MHz; the fixed node will not be susceptible to IEEE 802.15.4a interference due to positioning.
- The UWB PHY channel at 150 MHz to 650 MHz is operating, on average, at least –75 dBm (set by regulation, using current FCC limits), which is at approximately 34 dB lower power than the higher band UWB PHY (–41.3 dBm).
- UWB interference is wideband uncorrelated noise since the bandwidth is much wider than the victim receiver. A 10 dB difference in antenna gain is assumed in anticipation that the IEEE P802.22 antenna will require gain in the direction of the desired fixed node (base station) downlink signal, and it is also assumed that the UWB device will not directly block the LOS.

At the time of this analysis, the characteristics of the IEEE P802.22 AWN were not completely defined. Assuming similar characteristics to an IEEE 802.16 device with the operating frequencies specified above, note that the 150–650 MHz UWB PHY has a similar path loss curve to the 3100–4800 MHz UWB PHY with the noted 6–8 dB difference along the curve. Note further that the maximum radiated power is 34 dB lower and the effective interference seen by the AWN will be lower than shown for the IEEE 802.16 case.

5.5 Conclusions

These analyses characterize the expected coexistence behavior between UWB PHY devices and IEEE 802.16 devices. Also described are the expected effects of a UWB PHY device on an ECMA 368 receiver and the proposed IEEE P802.22 devices. One conclusion that can be drawn is that the relative effects of the UWB PHY device and IEEE 802.16 device to each other are quite different. The UWB PHY device is impacted by the IEEE 802.16 device at much longer range than vice versa. The implication is that the UWB PHY device would not be able to operate at all at ranges where its emissions would impact the IEEE 802.16 device because of the large asymmetry in the transmit power levels (+17 dB for the IEEE 802.16 device versus –15 dBm for the UWB PHY device). In such a case, either the UWB PHY device would accept the much higher PER, or else it could simply use a different channel or some other form of interference mitigation.

A similar conclusion can be reached regarding proposed IEEE P802.22 devices; there is an even greater asymmetry in power levels, as the sub-gigahertz band is operated at a substantially lower level than the higher UWB bands. One form of mitigation (in both directions) is to observe that when considering the application environment in which the sub-gigahertz UWB band has greatest advantage and is, therefore, most likely to be used, the operation of IEEE P802.22 devices in near proximity is unlikely. In application scenarios where it is expected that UWB PHY sub-gigahertz devices may operate in proximity to IEEE P802.22 devices, the UWB PHY devices may need to employ some other forms of interference mitigation. Additional mitigation is available to the IEEE P802.22 device. Note that a great number of potential channels are available above 650 MHz and provide the option to the IEEE P802.22 device to change to a channel outside the operating range of the UWB PHY sub-gigahertz devices.

6. Notes on the calculations

The calculations for this annex were based on the formulas and descriptions from IEEE Std 802.15.2-2003.

7. Bibliography

[B1] ERC Recommendation 70-03, Relating to the Use of Short Range Devices (SRDs), April 2002.[3]

[B2] ETSI EN 300 220-1, Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Short Range Devices (SRDs); Radio equipment to be used in the 25 MHz to 1 000 MHz frequency range with power levels ranging up to 500 mW; Part 1: Technical characteristics and test methods.[4]

[B3] ETSI EN 300 328-1, Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Wideband Transmission Systems; Data transmission equipment operating in the 2,4 GHz ISM band and using spread spectrum modulation techniques; Part 1: Technical characteristics and test conditions.

[B4] ETSI EN 300 328-2, Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Wideband Transmission Systems; Data transmission equipment operating in the 2,4 GHz ISM band and using spread spectrum modulation techniques; Part 2: Harmonized EN covering essential requirements under article 3.2 of the R&TTE Directive.

[B5] FCC Code of Federal Register (CFR), Part 47, Section 15.35, Section 15.205, Section 15.209, Section 15.231, Section 15.247, and Section 15.249. United States.[5]

[B6] Shellhammer, S. J., "Estimating Packet Error Rate Caused by Interference—A Coexistence Assurance Methodology," IEEE 802.19-05/0029r0, September 14, 2005.

[B7] Shellhammer, S. J., "Estimation of Packet Error Rate Caused by Interference using Analytic Techniques—A Coexistence Assurance Methodology," IEEE 802.19-05/0028r2, September 14, 2005.

[B8] Sklar, Bernard, Digital Communications: Fundamentals and Applications. New Jersey: Prentice Hall, 1988.

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[3] ERC publications are available from the European Communications Office (http://www.erodocdb.dk/).

[4] ETSI publications are available from the European Telecommunications Standards Institute (http://www.etsi.org).

[5] FCC publications are available from http://www.fcc.gov