Annex E

(informative)

Coexistence with other IEEE standards and proposed standards

E.1 Introduction

Insert the following after first paragraph

This annex also considers Amendment 4a devices. For UWB devices specifically, additional consideration is given to certain non-IEEE standards.

E.2 Standards and proposed standards characterized for coexistence

Change the sentence of the 1st paragraph as follows:

This clause also enumerates IEEE-compliant devices that are characterized and the devices that are not characterized for operation in proximity to IEEE P802.15.4REVb/D6 devices <u>or for IEEE P802.15.4AMMa/D3 devices</u>.

Insert the following paragraphs prior clause E.3

IEEE P802.15.4AMMa/D3 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 MHz to 2484 MHz bands and, therefore, may interact with other IEEE compliant devices operating in those frequencies.

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

- 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 DSSS)
- IEEE Std 802.15.4-2003 (2400 MHz DSSS)
- IEEE P802.15.4a (2400 MHz CSS)

Standards not characterized in this annex for coexistence are:

- IEEE Std 802.11, 1999 Edition, frequency hopping (FH) (2400 MHz FHSS)
- IEEE Std 802.11, 1999 Edition, infrared (IR) (333GHz AM)
- IEEE Std 802.16-2001 (2400 MHz OFDM)
- IEEE Std 802.11a-1999 (5.2GHz DSSS)

IEEE P802.15.4AMMa/D3 UWB PHYs for 150 MHz to 650 MHz band reside in frequencies that may interact with other IEEE standards in development. UWB PHYs for the 3244 MHz to 4742 MHz and 5944 MHz to 10234 MHz may interact with both IEEE compliant devices and non-IEEE compliant devices.

{add the enumeration for standards, in-development, and non-IEEE standards considered in this annex}

E.3 General coexistence issues

E.3.1 General Coexistence Issues for the UWB PHY

The draft standard created by TG4a provides several mechanisms that enhance coexistence with other wireless devices operating in the same spectrum. This section describes the mechanisms that are defined in the standard, which include:

- "UWB modulation with extremely low power spectral density (PSD)
- "Low duty cycle
- "Low transmit power
- "Dynamic Channel Selection
- "Coordinated Piconet Capabilities

These mechanisms are each described briefly in the following sub-sections.

E.3.2 Modulation

Insert the following subclause

E.3.2.3 Direct Sequence Ultra-Wideband Modulation

The UWB PHY specified for IEEE STD 802.15.4a 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 power spectral density. 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.

E.3.4 Low Duty Cycle

Insert the following after the 1st paragraph of this subclause.

An important contribution of the TG4a work is the definition of new a new UWB PHY with higher optional bits rates. 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 higher 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, further reducing the likelihood that these devices will interfere with or be subject to interference by other devices when conditions allow.

Insert the following subclauses after last paragraph of E.3.4

E.3.4.1 Low duty cycle considerations for UWB PHYs

Low duty cycle piconet scenarios are used to model situation where:

- IEEE 802.15.4a devices are deployed in high density in a limited area, e.g., hot-spot deployment scenarios;
- Some UWB victim systems cover much larger area than the cover range of a typical IEEE 802.15.4a piconet, locate well above the local cluster (e.g. IEEE 802.16, radio astronomy service and satellite service), or closely locate with piconet coordinator (e.g. devices placed at the same desk or even within the same computer).

In this case, 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 IEEE 802.15.4a devices to detect victim system reliably. The aggregate interference from the piconet increases with increment in number of piconet members. Given 1% average device duty cycle and pure ALOHA protocol, the aggregate interference is 17.6% from a piconet with 18 members. Besides, the channel idle periods are randomly segmented into small pieces. Therefore it is hard to be used efficiently. It is similar to the collision analysis of pure ALOHA system.

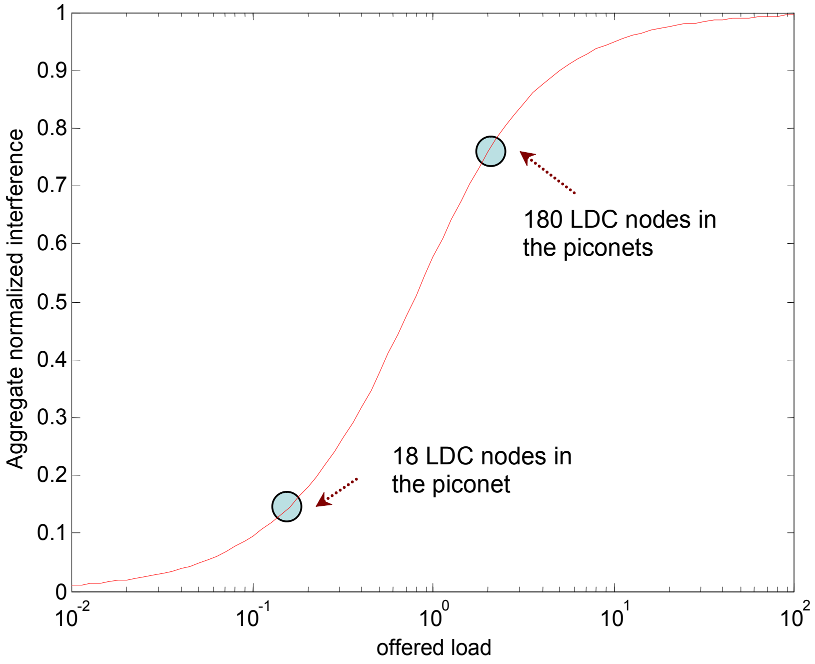

Figure E1a—Aggregate normalized interference

The maximal interference level to such kind of victim systems can be limited by controlling duty cycle of the piconet through general active/inactive period. The traffic can only occur in the active period. Victim systems are free of interference in the inactive period. The distribution of active/inactive period 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 to set transmission probability related with the channel quality which can be obtained through listening beacon from coordinator

by means of LQI and receiver ED. The function to map channel quality to 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;
- Traffic shaping, e.g. combination of short packet to a 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 an 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, so the complexity advantage is a good trade-off;
- There is low impact on coexistence due to a large number of 802.4a nodes as the aggregate duty cycle remains very low;

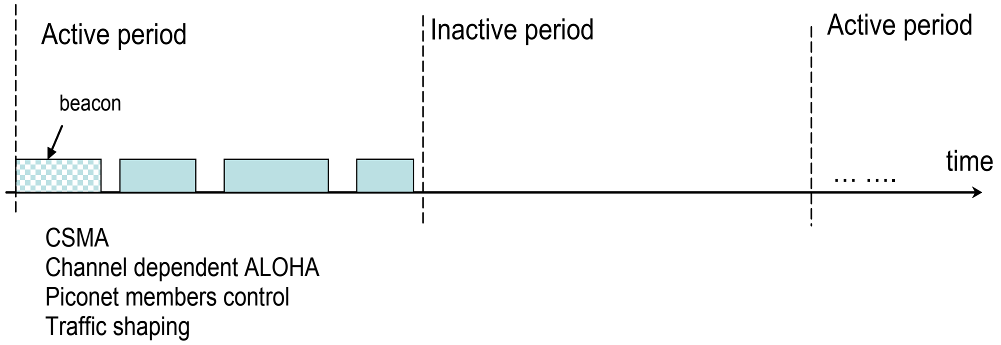

Figure E1b—Generalized active/inactive periods

E.3.5 Low transmit power

Insert the following subclause

E.3.5.4 UWB PHYs

The UWB PHY defined by Task Group 4a will operate under strict regulations for unlicensed UWB devices worldwide. At the time of this writing, the least restrictive regulations for UWB are available under the 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 microWatts 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 transmission 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 microWatts 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.

E.3.6 Channel alignment

Insert the following after the 1st paragraph

The alignment between IEEE 802.11b (nonoverlapping sets) and IEEE P802.15.4a CSS channels (overlapping sets) are shown in Figure E1c. There are 14 IEEE P802.15.4a CSS channels (n = 0, 2, … , 13). Operating an IEEE P802.15.4a network on one of these channels will minimize interference between systems.

When performing dynamic channel selection, either at network initialization or in response to an outage, an IEEE P802.15.4a CSS device will scan a set of channels specified by the ChannelList parameter. For IEEE P802.15.4a networks that are installed in areas known to have high IEEE 802.11b activity, the ChannelList parameter can be defined from the above set in order to enhance the coexistence of the networks.

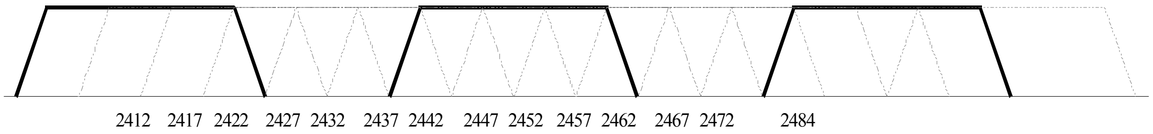

Figure E1c—IEEE P802.15.4a CSS channel selection

E.3.7 Dynamic channel selection

Insert the following after the 1st paragraph

When performing dynamic channel selection, either at the time of network initialization or in response to an outage, a UWB IEEE 802.15.4a device will scan a set of channels specified by the ChannelList parameter. For UWB IEEE 802.15.4a networks that are installed in areas known to have spectrum restrictions, the ChannelList parameter can be defined as the above sets in order to enhance the coexistence of the networks.

Change the title as shown

E.4 2400 MHz band coexistence performance (except for CSS PHYs)

Insert the following subclauses after E.5

E.6 2400 MHz band coexistence performance for CSS PHYs

Subclauses E.3.2 and E.3.2 also describe the assumptions made for individual standards and quantify their predicted performance when coexisting with IEEE P802.15.4a CSS devices.

E.6.1 Assumptions for coexistence performance

E.6.1.1 Receiver sensitivity

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

- -76 dBm for IEEE 802.11b 11 Mb/s CCK
- -70 dBm for IEEE 802.15.1
- -75 dBm for IEEE P802.15.3 22 Mb/s DQPSK
- -85 dBm for IEEE 802.15.4
- -85 dBm for IEEE 802.15.4a 1 Mb/s CSS

E.6.1.2 Transmit power

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

- 14 dBm for IEEE 802.11b
- 0 dBm for IEEE 802.15.1
- 8 dBm for IEEE 802.15.3
- 0 dBm for IEEE 802.15.4
- 0 dBm for IEEE P802.15.4a CSS

E.6.1.3 Bit error rate (BER) calculations

BER for IEEE 802.15.4a CSS =

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

where SNR0=SNR x 14 x 1.6667, M = 8 for 1Mb/s

SNR0=SNR x 14 x 1.6667 x 4, M = 64 for 250Kb/s

E.6.1.4 PER

- Average frame length for IEEE P802.11b: 1500 bytes
- Average duty cycle for IEEE P802.11b: 50%
- Average frame length for IEEE P802.11g: 1500 bytes
- Average duty cycle for IEEE P802.11g: 50%
- Average frame length for IEEE P802.15.1: 1024 bytes
- Average duty cycle for IEEE P802.15.1: 50%
- Average frame length for IEEE P802.15.3: 1024 bytes
- Average duty cycle for IEEE P802.15.3: 50%
- Average frame length for IEEE P802.15.4: 22 bytes
- Normal duty cycle for IEEE P802.15.4: 1%
- Rare (aggregated) duty cycle for IEEE P802.15.4: 10%
- Average frame length for IEEE P802.15.4a CSS: 32 bytes
- Normal duty cycle for IEEE P802.15.4a CSS: 0.25%, 1%
- Rare (aggregated) duty cycle for IEEE P802.15.4a CSS: 2.5%, 10%

E.6.1.5 BER model for IEEE802.15.4a

Modify the numbering of Figure E.2 mentioned above to Figure E.3.2.1, and add the following text :

Figure E.3.2.2 illustrates also the relationship between BER and SNR for IEEE 802.11b, IEEE 802.15.3 base rate, IEEE 802.15.1, IEEE 802.15.4, and IEEE P802.15.4a CSS.

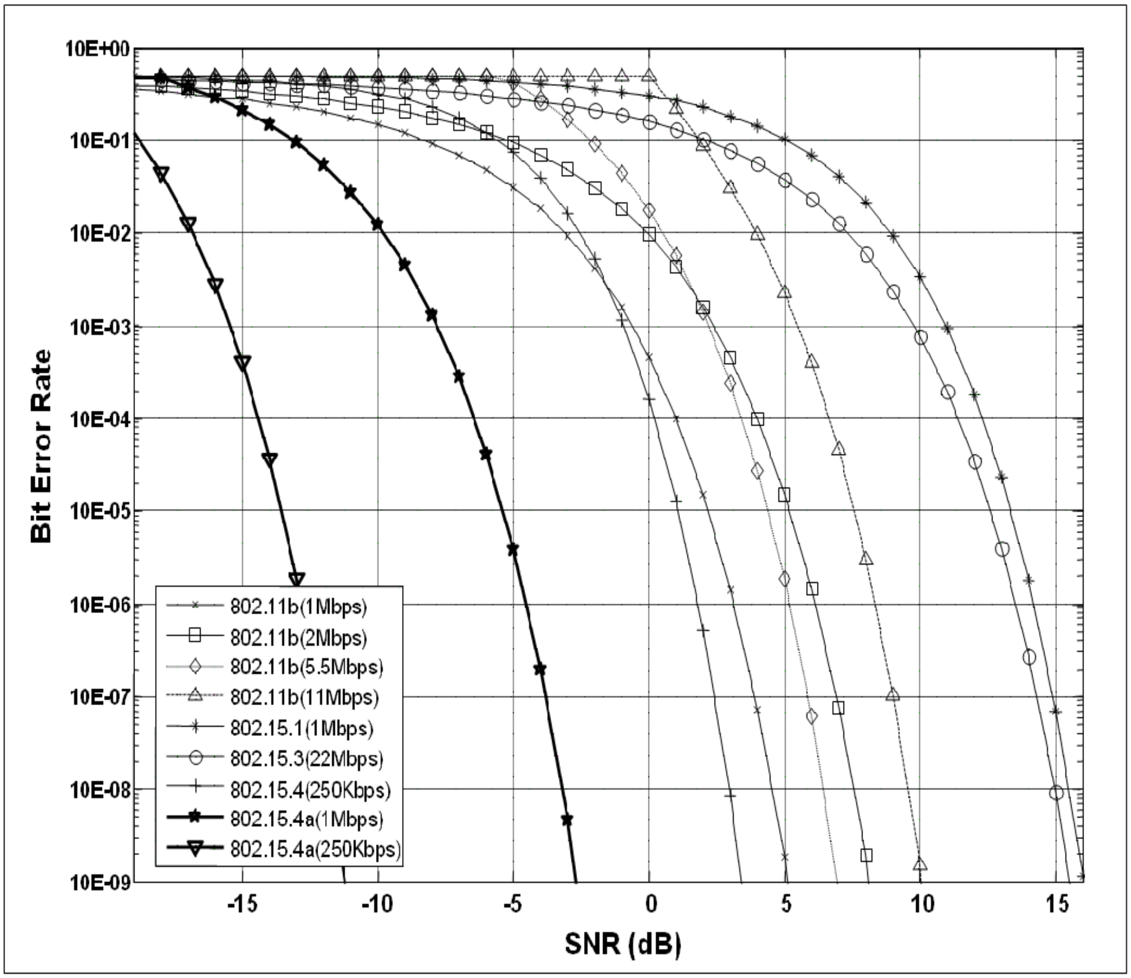

Figure E9—BER Results of IEEE 802.11b, IEEE 802.15.1, IEEE 802.15.3, IEEE 802.15.4 (2400 MHz PHY) and IEEE P802.15.4a CSS

E.6.2 Coexistence simulation results

The shapes of the assumed transmit spectra and receive filter shapes are defined in Table E1

E.6.3 Low duty cycle assumption

In general 15.4 and 15.4a devices address low duty cycle applications. The assumption of 1 % duty cycle for 15.4 devices was introduced in 15.4-2003, E.2.4. Under the assumption that 4a devices are battery powered and have a life time 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 15.4 device operating at 2.4 GHz has a Tx current of 30 mA. If the device only transmits during its entire life time the result would be 30/1800=60h of operation. Over a life time of one year =365*24h=8760h 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 15.4 devices. In

Table E1—Transmit spectra and receiving filter shapes

IEEE802	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
11b	0	0	0	0
	4	0	4	0
	6	10	6	10
	9	30	9	30
	15	50	15	50
	20	55	20	55
11g	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 E1—Transmit spectra and receiving filter shapes *(continued)*

IEEE802	Transmit		Receive	
	Frequency offset (MHz)	Attenuation (dB)	Frequency offset (MHz)	Attenuation (dB)
15.4	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
15.4a - CSS	0	0	0	0
	6	0	6	0
	12	32	12	32
	15	55	15	55

some rare cases traffic might aggregate in proximity of coordinator nodes. Thus an aggregated duty cycle of up to 10% can be assumed in rare cases.

E.6.4 Impact of increased data rate

It should be noted that 15.4 and 15.4a devices will serve applications with similar low required data traffic. Since 4a devices offer a significantly increased data rate (1 Mb/s vs 250b/s) the duty cycle of 4a devices can be expected to be significantly below the duty cycle of 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.

E.6.5 Cochannel 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 behaviour of both sytstems. Applying the duty cycle assumptions on 15.4a devices as stated above will result in reasonable performance. However it is recommended to avoid this situation by using another nonoverlapping band. If this is not possible an overlapping band in between two nonoverlapping bands used for example by 802.11 networks the center frequency of CSS should be selected such that the spatially closer 802.11 network has a frequency offset of 15 MHz.

Add the following figures :

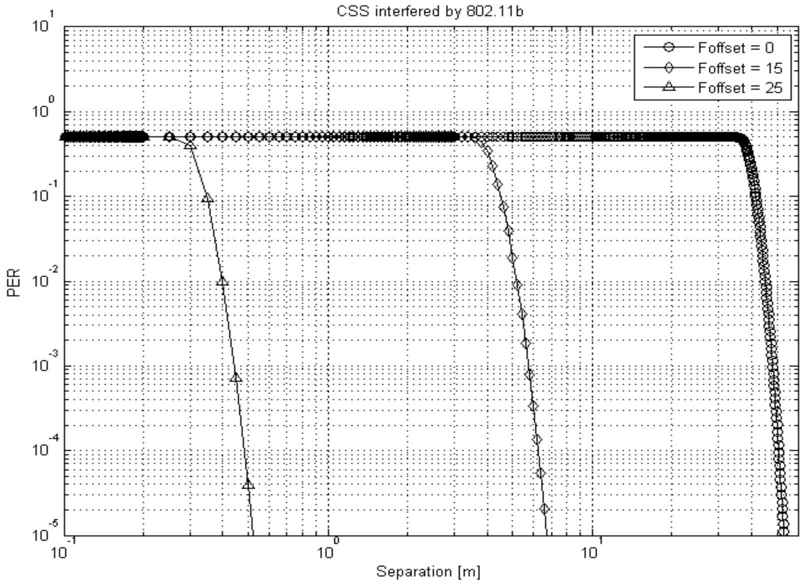

Figure E10—IEEE P802.15.4a CSS receiver, IEEE 802.11b interferer

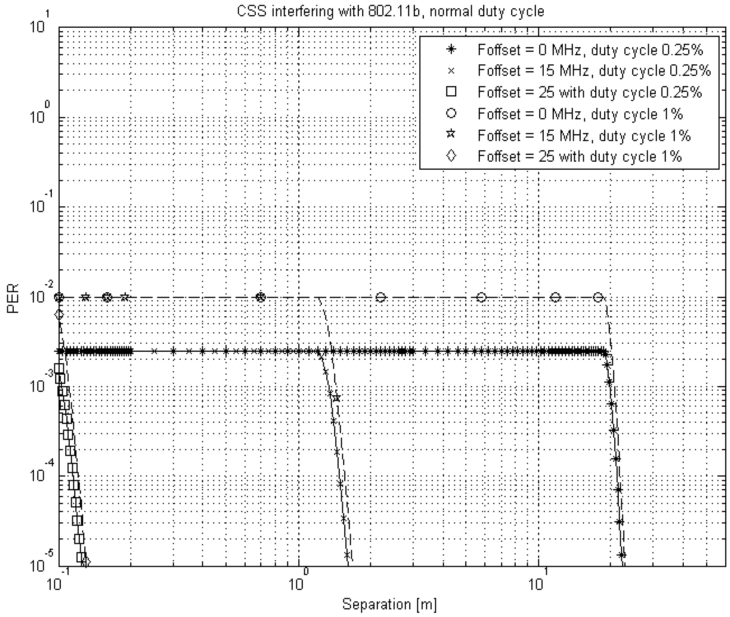

Figure E11—IEEE 802.11b receiver, IEEE P802.15.4a CSS interferer with normal duty cycle

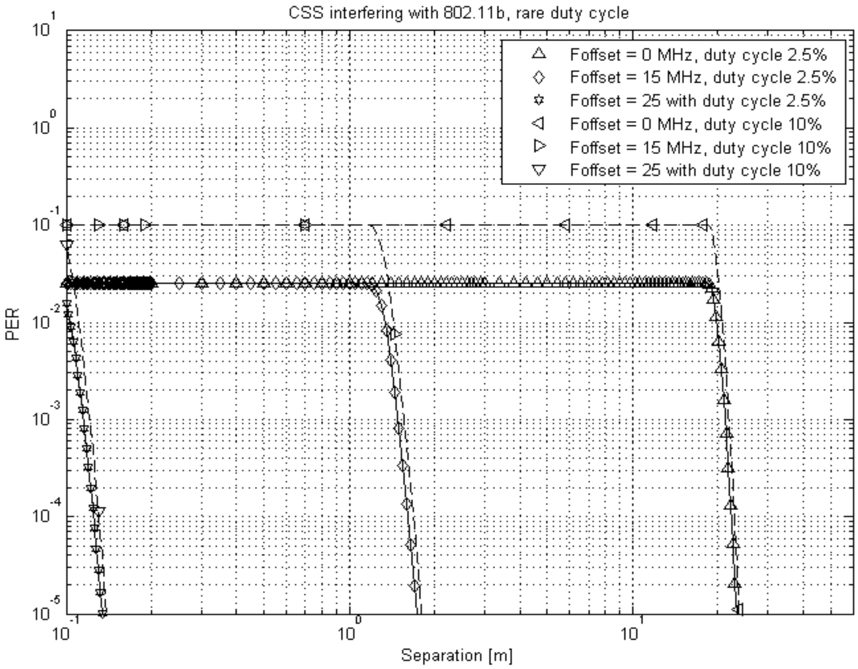

Figure E12—IEEE 802.11b receiver, IEEE P802.15.4a CSS interferer with rare duty cycle

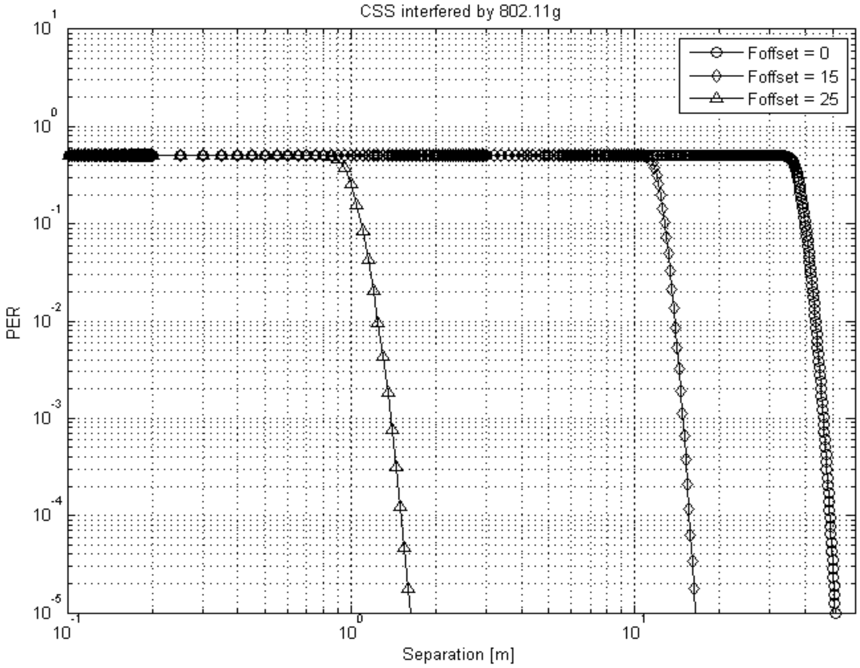

Figure E13—IEEE 802.15.4a CSS receiver, IEEE P802.11g interferer

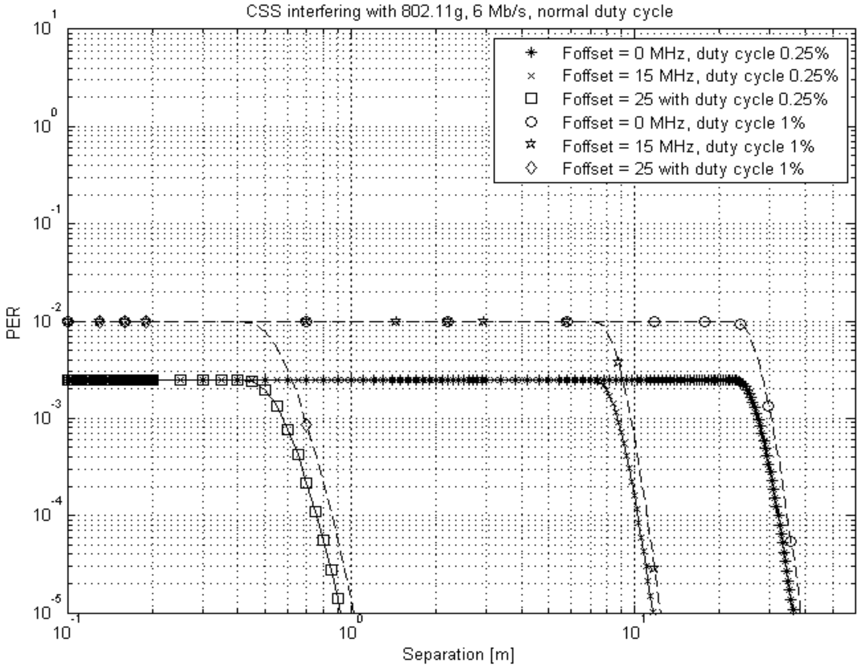

Figure E14—IEEE 802.11g receiver, 6Mb/s, IEEE P802.15.4a CSS interferer, normal duty cycle

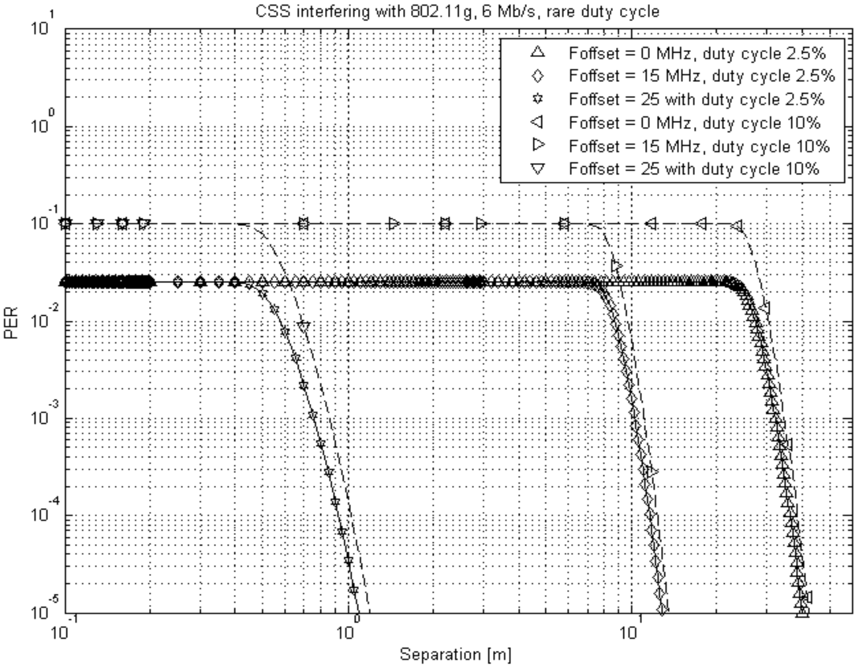

Figure E15—IEEE 802.11g receiver, 6Mb/s, IEEE P802.15.4a CSS interferer, rare duty cycle

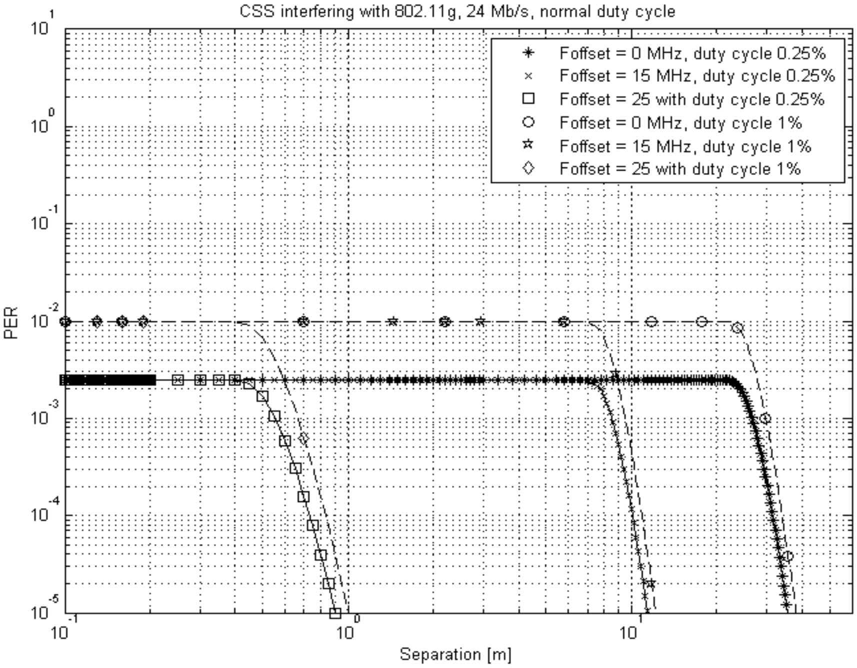

Figure E16—IEEE 802.11g receiver, 24Mb/s, IEEE P802.15.4a CSS interferer, normal duty cycle

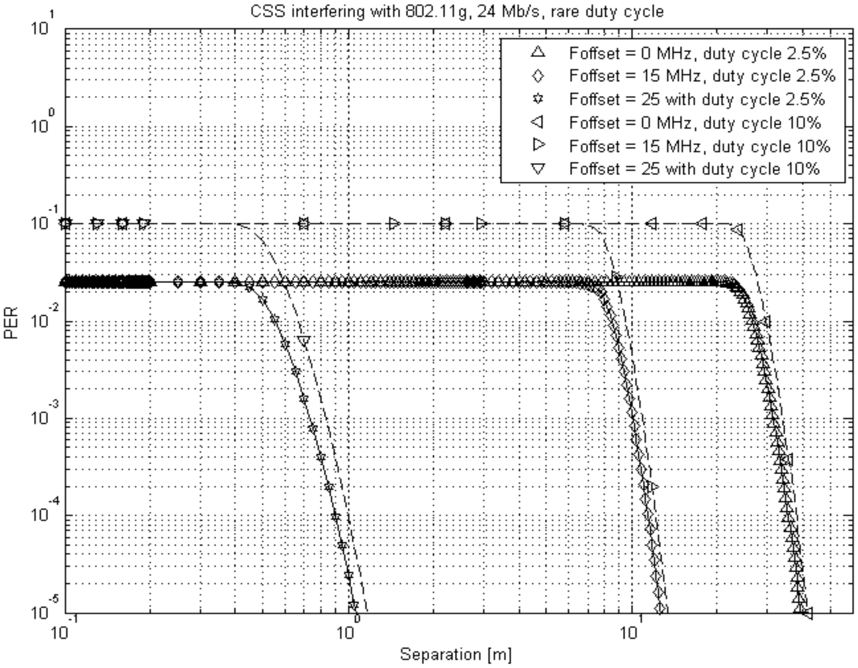

Figure E17—IEEE 802.11g receiver, 24Mb/s, IEEE P802.15.4a CSS interferer, rare duty cycle

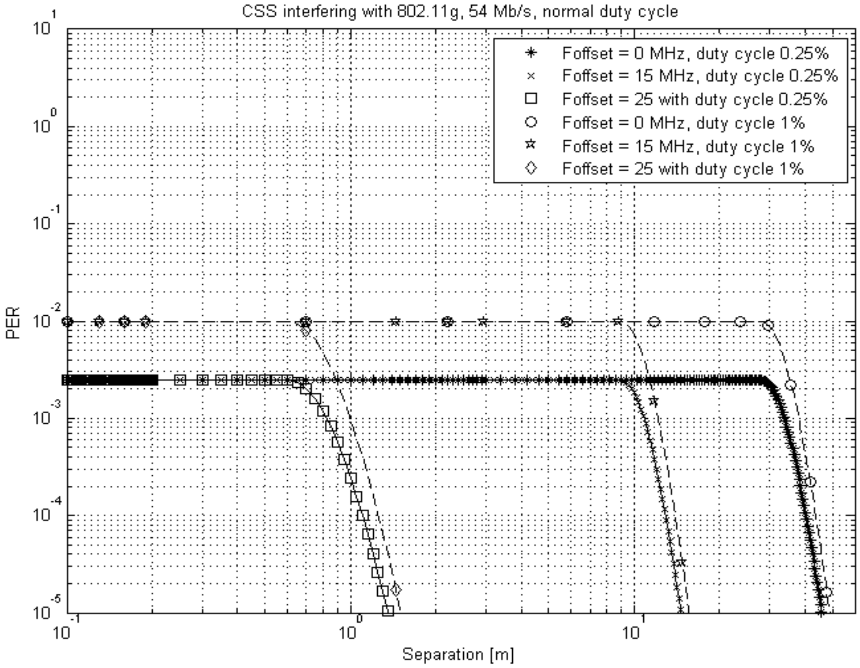

Figure E18—IEEE 802.11g receiver, 54Mb/s, IEEE P802.15.4a CSS interferer, normal duty cycle

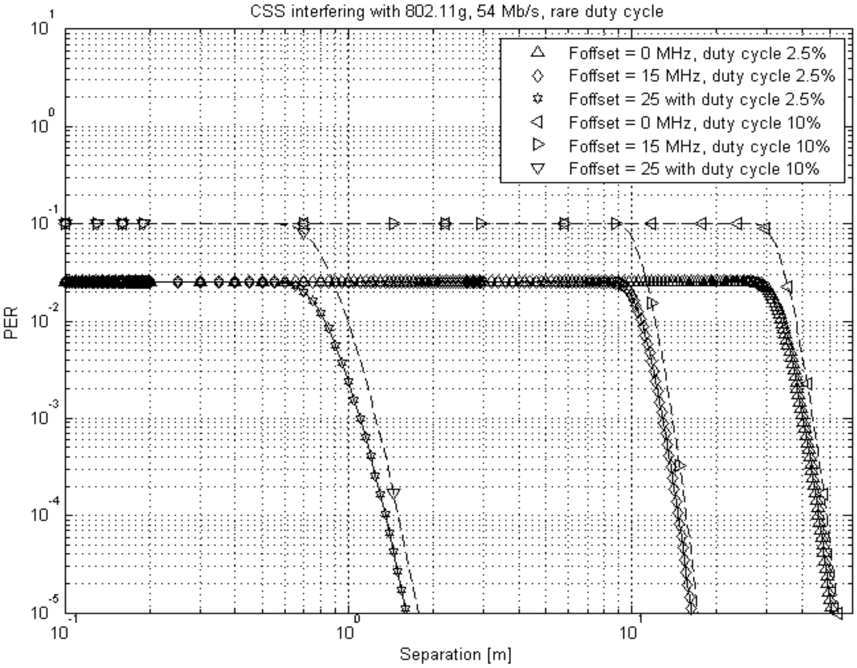

Figure E19—IEEE 802.11g receiver, 54Mb/s, IEEE P802.15.4a CSS interferer,

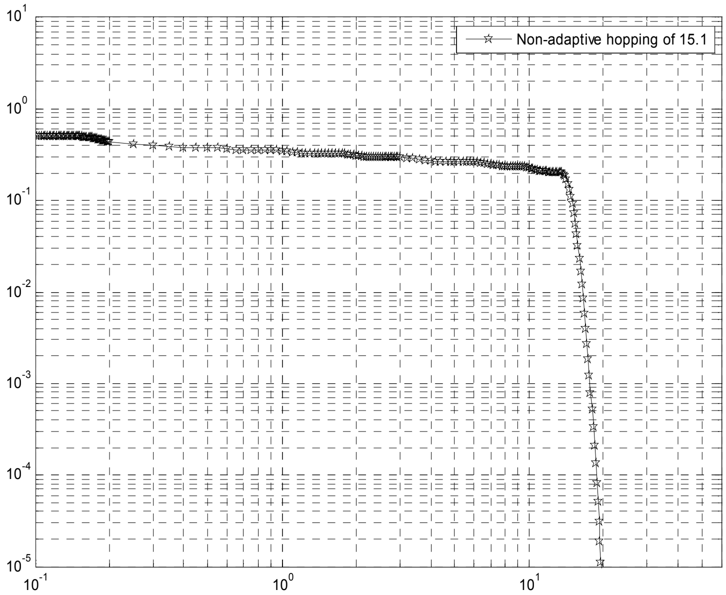

Figure E20—IEEE P802.15.4a CSS receiver, IEEE 802.15.1 interferer

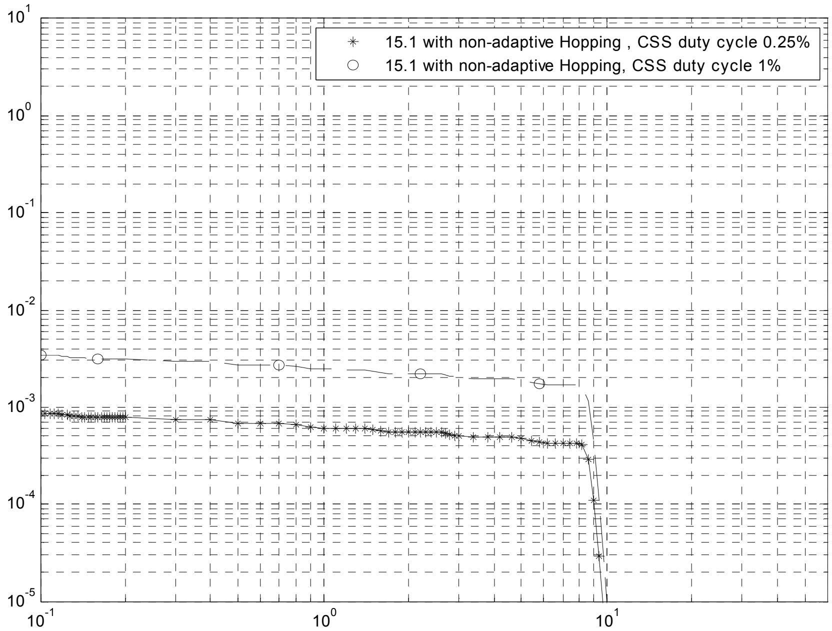

Figure E21—IEEE 802.15.1 receiver, IEEE P802.15.4a CSS interferer with normal duty cycle

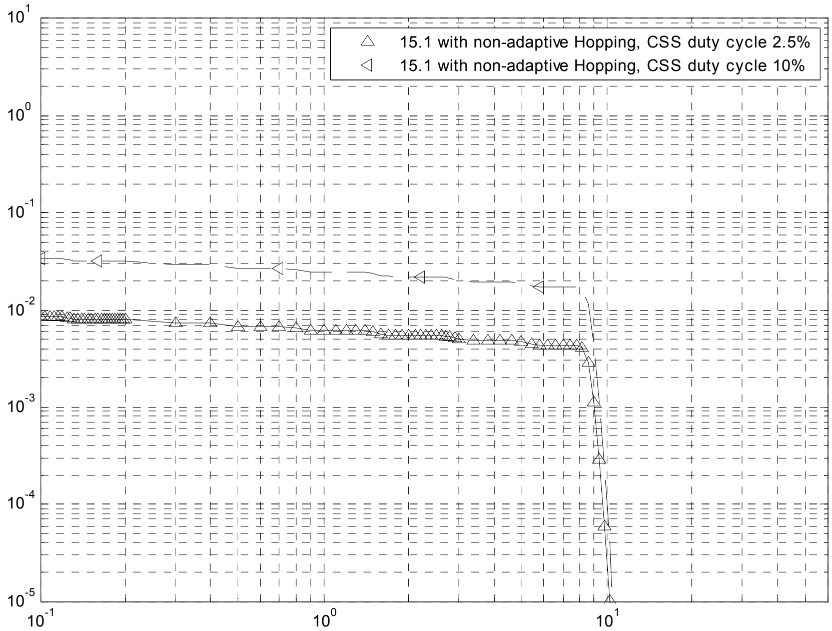

Figure E22—IEEE 802.15.1 receiver, IEEE P802.15.4a CSS interferer with rare duty cycle

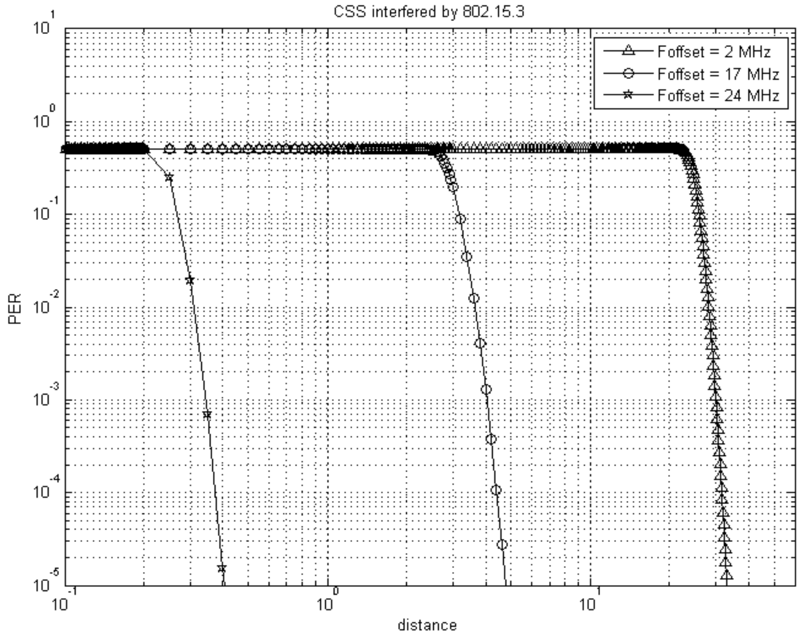

Figure E23—IEEE P802.15.4a CSS receiver, IEEE 802.15.3 interferer

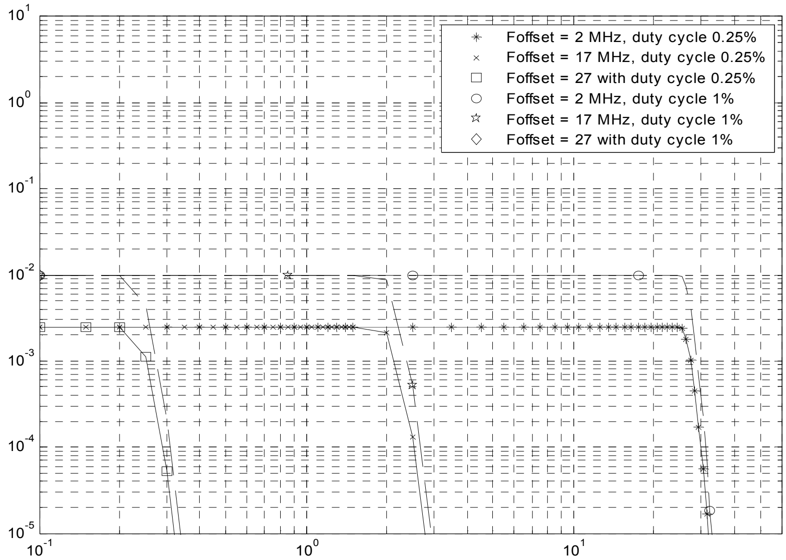

Figure E24—IEEE 802.15.3 receiver, IEEE P802.15.4a CSS interferer with normal duty cycle

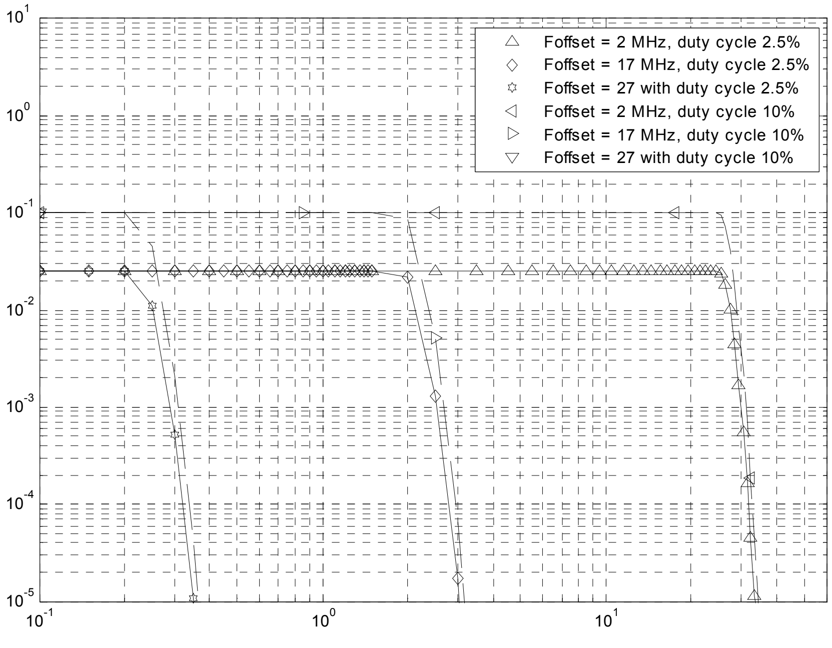

Figure E25—IEEE 802.15.3 receiver, IEEE P802.15.4a CSS interferer with rare duty cycle

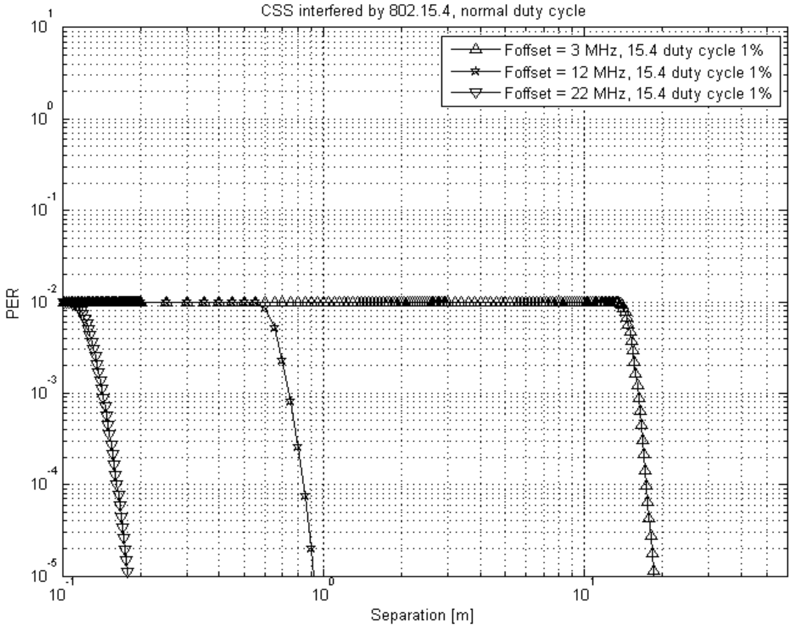

Figure E26—IEEE P802.15.4a CSS receiver, IEEE 802.15.4 interferer with normal duty cycle

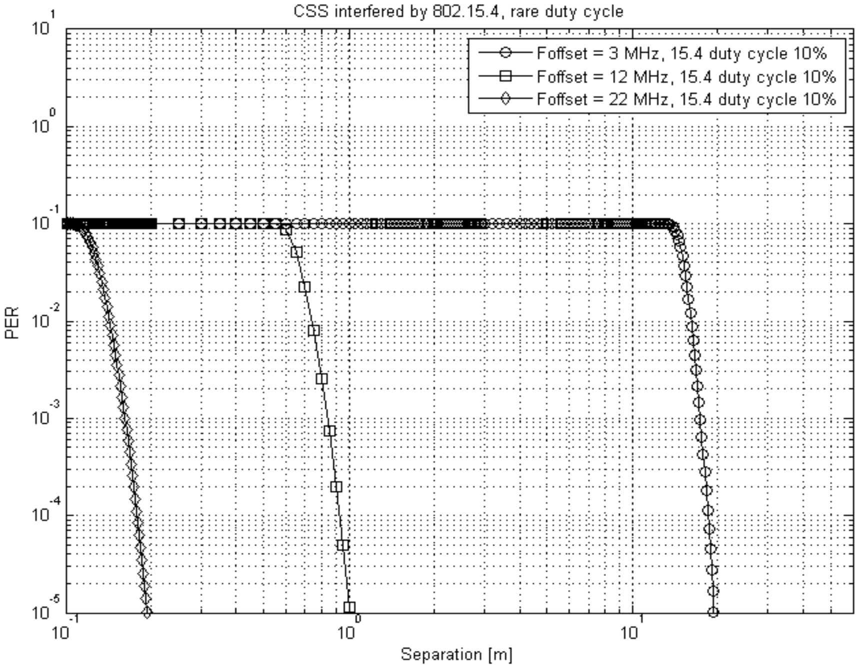

Figure E27—IEEE P802.15.4a CSS receiver, IEEE 802.15.4 interferer with rare duty cycl

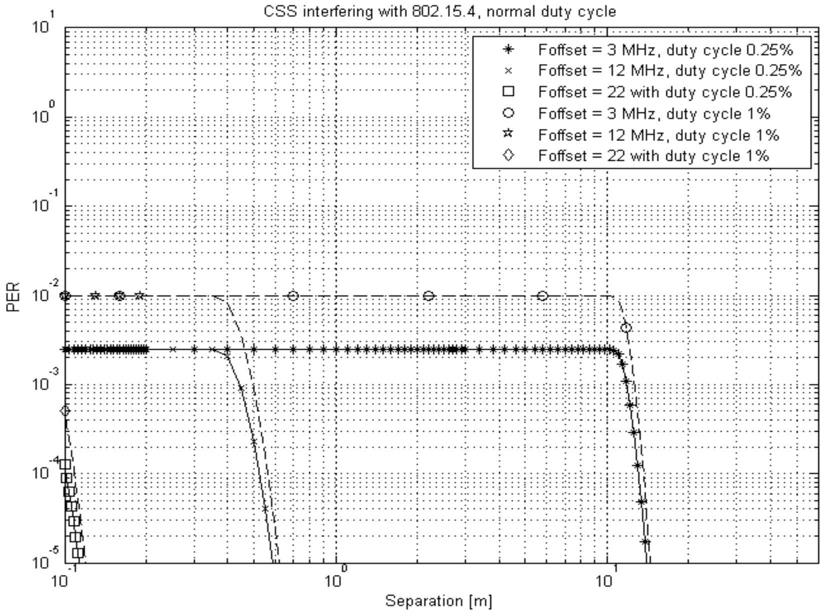

Figure E28—IEEE 802.15.4 receiver, IEEE P802.15.4a CSS interferer with normal duty cycle

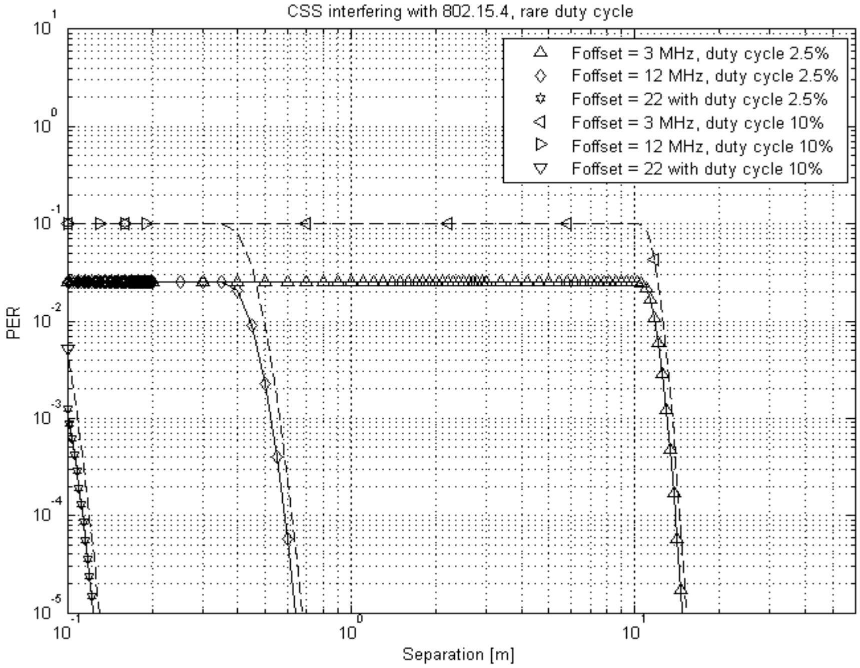

Figure E29—IEEE 802.15.4 receiver, IEEE P802.15.4a CSS interferer with rare duty cycle

E.7 UWB coexistence performance

E.7.1 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, 802.16 systems below 10 GHz. Cognizant of the potential for coexistence issues, regulators in those parts of the world where 802.16 systems (such as WiMAX) 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 in the EU, regulators are creating rules for unlicensed UWB operation that will require specific active mitigation mechanisms to ensure peaceful coexistence with 802.16 systems or other similar systems used for fixed or mobile wireless access.

Additionally, a proposed IEEE standard, 802.22, 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) 35dB lower compared the limits for the 3.1 to 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 U.S, it can be observed that coexistence with the proposed 802.22 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.

E.7.2 Mitigation of interference from UWB devices using low piconet duty cycles

One proposal made to the TG4a is to use a lower duty cycle within a UWB piconet to reduce potential interference effects. Low duty cycle piconet scenarios could be used where:

- "IEEE 802.15.4a devices are deployed in high density in a limited area, e.g., hot-spot deployment scenarios; or
- "UWB victim systems cover much larger area than the cover range of a typical IEEE 802.15.4a piconet.

In these 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 IEEE 802.15.4a devices to detect victim system reliably. The aggregate interference from the piconet increases with increment in number of piconet members. The interference to victim systems could be limited by controlling duty cycle of the piconet through general active/inactive period. The UWB traffic can only occur 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.

E.7.3 Coexistence Assurance: Methodology and Assumptions

In order to quantify the coexistence performance of the 802.14.4a UWB PHY, we have adapted the techniques described in [1], "Estimating Packet Error Rate Caused by Interference - A Coexistence Assurance Methodology".

The Coexistence Assurance Methodology predicts the Packet Error Rate (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 bit error rate 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 Signal to Interference Ratio (SIR) of AWN devices .
- "Temporal model for AWN packets and IWN "pulses" (interfering packets)

The following sub-sections describe the general assumptions made across all of the PHYs covered under this document.

E.7.4 UWB PHY Coexistence

E.7.4.1 Victims and Assailants

At present, the TG4a draft standard for a UWB system described in this document is the only wireless networking standard in the UWB band groups bands covered under IEEE 802. The only other IEEE wireless standard waveforms that overlap this same spectrum are 802.16 systems occupying 3400 to 3800 MHz licensed frequency bands in some regions (parts of Europe and Asia). In addition, the proposed IEEE 802.22 standard would occupy parts of the band between 150 to 650 MHz.

In addition to IEEE standardized wireless systems, another UWB standard produced by ECMA is specified in ECMA 368. We also provide a limited analysis of the coexistence between this system and the TG4a draft standard waveform.

In our analysis, we assume that the PHYs will serve as both 'victims' (participants in Affected Wireless Networks) and as 'assailants' (participants in Interfering Wireless Networks).

E.7.4.2 Bandwidth for UWB systems

The TG4a UWB PHYs that operate in any of the three UWB band groups 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 802.16 PHYs that operate in the 2-10 GHz band have multiple defined channels, each 20 MHz wide or less. The proposed 802.22 standard would have multiple defined channels, each 6 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 (so BUWB >> BNB).

E.7.5 Path Loss Model

The Coexistence Methodology uses a variant of the path loss model described [3], 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 formula given in [3] is:

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

The constants in this formula are based on a 2.4GHz center frequency. To adapt the model to a typical center frequency in the 3100 to 4800 MHz frequency band, we can generalize this as:

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

where pl(1) is the path loss at one meter (in dB) , 1 is the path loss exponent at 1 meter (2.0), and 8 is the path loss exponent at 8 meters (3.3). We compute the initial condition of pl(1) as:

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

With 1=2.0, f=3400MHz, and C=speed of light=299792458 ms-1, we can compute pl(1)=43.08 and pl(8)=61.14. The path loss function modified for 3400MHz is therefore:

$$pl(d) = \begin{cases} 43.03 + 20Log_{10}(d) & d \le 8m \\ 61.09 + 33Log_{10}\left(\frac{d}{8}\right) & d > 8m \end{cases}$$

With f=400MHz for the sub-GHz UWB band, we can compute pl(1)=24.49 and pl(8)=78.75. The path loss function for 400MHz center frequency is the same as for 3400MHz with the substitution of these constants:

$$pl(d) = \begin{cases} 24.49 + 20Log_{10}(d) & d \le 8m \\ 78.75 + 33Log_{10}\left(\frac{d}{8}\right) & d > 8m \end{cases}$$

A plot of the path loss as a function of device separation distance follows.

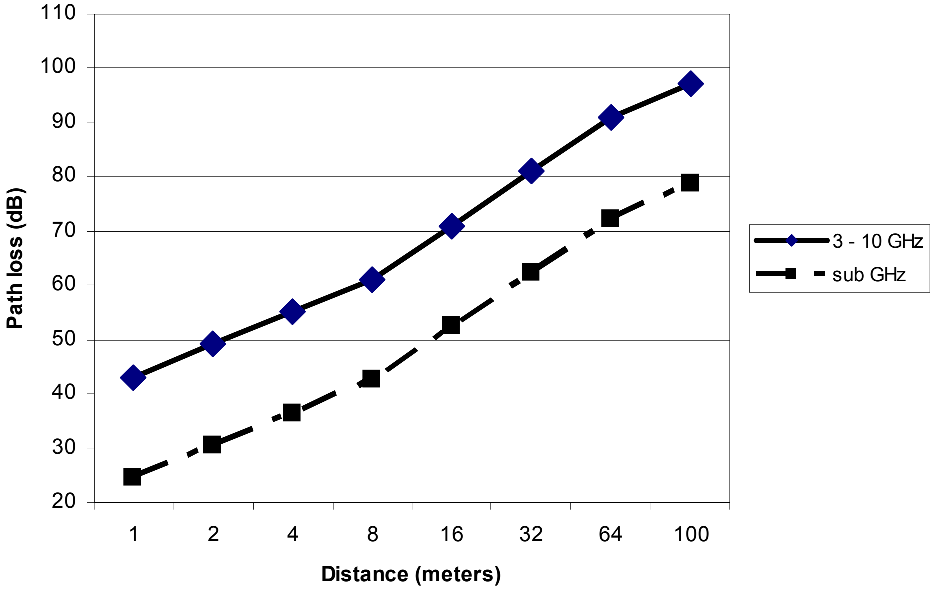

Figure E30—Path loss function

E.7.6 BER as a function of SIR

For the PHY specifications analyzed in this document, there are not any analytic expressions for the BER or SER of the signal due to the use of forward error correction methods to improve reliability. Additionally,

In this analysis, we will use a method that is equivalent to using interpolation of table values. In order to simplify the calculations and still provide meaningful results, we will approximate the relationship 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 (10x) 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 802.16 (Reed-Solomon block code), for ECMA-368, the proposed 802.22 and the TG4a draft standard (convolutional coding).

For each of the systems, we will characterize the effect of the IWN on the AWN 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 an operating margin to account for other real-world effects such as multipath propagation effects and co-channel or adjacent channel interference). This approach will allow us to characterize 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.

E.7.7 Temporal Model

In IEEE 802.15.4a, packet overhead is kept to minimum. The maximum PSDU size is 128 bytes, and a typical packet may be only 32 bytes, including PSDU and synchronization bytes. For our coexistence methodology, we assume all packets, whether belonging to the AWN or IWN, to be 32 bytes.

Although there is no duty-cycle limitation in the authorized UWB bands at this point, many 802.15.4a-based networks are expected to operate at well under 5% duty cycle, particularly those 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 as well. In addition, the TG4a draft standard is based on the use of 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 TG4a piconets used for many applications will operate at duty cycles as high as 10%. For purposes of modeling coexistence, we assume that all UWB band 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 (802.16, 802.22, and ECMA-368), anticipated applications are focused higher bandwidth connectivity over wide areas for 802.16 and 802.22 and over short WPAN ranges for ECMA-368. Because these systems are not deployed in great numbers, it is not possible to qualify typical operating duty cycle. For this analysis, we therefore initially assume a very conservative continuous operation as a baseline worst-case scenario.

E.7.8 Coexistence Analysis

In this section, we detail the assumptions for the coexistence analysis an present the results for each of the cases analyzed.

E.7.8.1 Impact of TG4a devices on 802.16 networks

Assumptions:

- The 802.16 receiver is the victim (AWN) and is an indoor fixed or nomadic client node of the network. We assume that the base station node will not be susceptible to TG4a UWB interference due to site positioning. The AWN operates in 3.4 to 3.8 GHz licensed bands (available in most of world except the United States).
- We assume the 802.16 receiver is operating in a real-world environment in the presence of multipath fading and interference and assume 3 to 10 dB margin above sensitivity to function well. We assume a baseline PER of 1e-6 at 3 dB above sensitivity in the absence of any UWB device effects and a 6 dB receiver NF.
- UWB interference is wideband uncorrelated noise since the bandwidth is much wider than victim receiver. We assume a 10 dB difference in antenna gains since the indoor or outdoor 802.16 antenna will have gain in the direction of the desired base station downlink signal and we assume the UWB device will not directly block the LOS.

E.7.8.1.1 Coexistence Methodology Results

Table E2 shows the calculation of the allowable path loss that would result in a TG4a UWB emission level at the AWN equal to the effective operating noise floor. Base on this path loss, we compute the effect on AWN PER as a function of separation distance, shown in Figure E31.

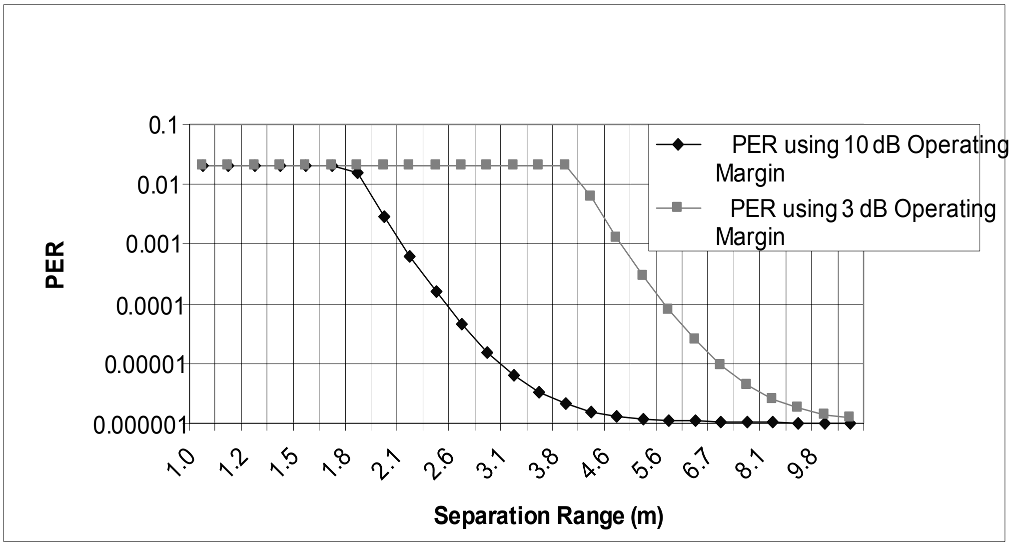

Figure E31—Effect on 802.16 AWN as a function of separation distance from TG4a UWB

E.7.8.2 Impact of an 802.16 devices on TG4a UWB networks

Assumptions:

- The TG4a UWB device is the affected device (AWN) and the 802.16 device is the interferer (IWN) and is an indoor fixed or nomadic client node of the network. We assume that the base station node will have less interference effects on TG4a UWB devices due to UWB device deployment much closer to subscriber or mobile 802.16 devices. The IWN operates in 3.4 to 3.8 GHz licensed bands (available in most of world except the United States). For this analysis, we assume the IWB operates at a conservative 50% duty cycle (802.16 subscriber uplink)
- We assume the TG4a UWB receiver is operating in a real-world environment in the presence of multipath fading and interference and assume 3 dB margin above sensitivity during operation. We assume a baseline PER of 1e-7 at 3 dB above sensitivity in the absence of any UWB device effects and a 10 dB receiver NF.
- UWB interference is wideband uncorrelated noise since the bandwidth is much wider than victim receiver. We assume a 10 dB difference in antenna gains since the indoor or outdoor 802.16 antenna will have gain in the direction of the desired base station downlink signal and we assume the UWB device will not directly block the LOS.

E.7.8.3 Coexistence Methodology Results

Table E2—Computation of the acceptable levels of TG4a device emissions for an operating 802.16 client node

Quantity	Value	Units	Notes
UWB Transmit PSD Limit (PLIM)	-41.3	dBm/MHz	Set by regulatory authority
Average margin to limit (MBO)	1.7	dB	Transmit power backoff due to spectral ripple (0.5+ dB) and ~1 dB margin for manufacturing tolerance, etc.
Average UWB antenna gain (GUWB)	-2	dBi	Average gain from small, low cost UWB antenna to arbitrary victim receiver over 360
Average emissions PSD (PLIM -MBO+GUWB) seen by 802.16 device receiver	-45	dBm/MHz	Average PSD seen in direction of arbitrary victim receiver

Table E2—Computation of the acceptable levels of TG4a device emissions for an operating 802.16 client node *(continued)*

Quantity	**Value**	**Units**	**Notes**
802.16 Thermal noise floor (kTB)	-114	dBm/MHz	Thermal noise floor (room temperature)
802.16 NF	6	dB	Noise figure for indoor 802.16 terminal
Average 802.16 Antenna gain in direction of interfering UWB	-4	dBi	Gain of 802.16 antenna in main beam (to desired 802.16 base station) is 6-7 dBi and to nearby UWB interferer (not blocking antenna main beam) -4 dBi
802.16 operating margin (M16)	3-10	dB	Operating margin for acceptable performance in presence of multipath fading and adjacent cell/channel interference
802.16 Effective operating noise floor for UWB interference susceptibility: (kTB + NF16 - G16 + MOP)	-101 to -94	dBm/MHz	This is the effective operating noise floor level for the 802.16 operating receiver
Level of wideband TG4a UWB interference that result in a 3 dB rise in 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 802.16 node receiver
Path loss (range) from UWB to 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 802.16 node receiver

Table E2—Computation of the acceptable levels of TG4a device emissions for an operating 802.16 client node *(continued)*

Quantity	Value	Units	Notes
Path loss (range) from UWB to 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 inband must be 6 dB below effective operating noise floor for indoor 802.16 node receiver

Table E3 shows the calculation of the allowable path loss that would result in a TG4a UWB emission level at the AWN equal to the effective operating noise floor. Base on this path loss, we compute the effect on AWN PER as a function of separation distance, shown in Figure E32.

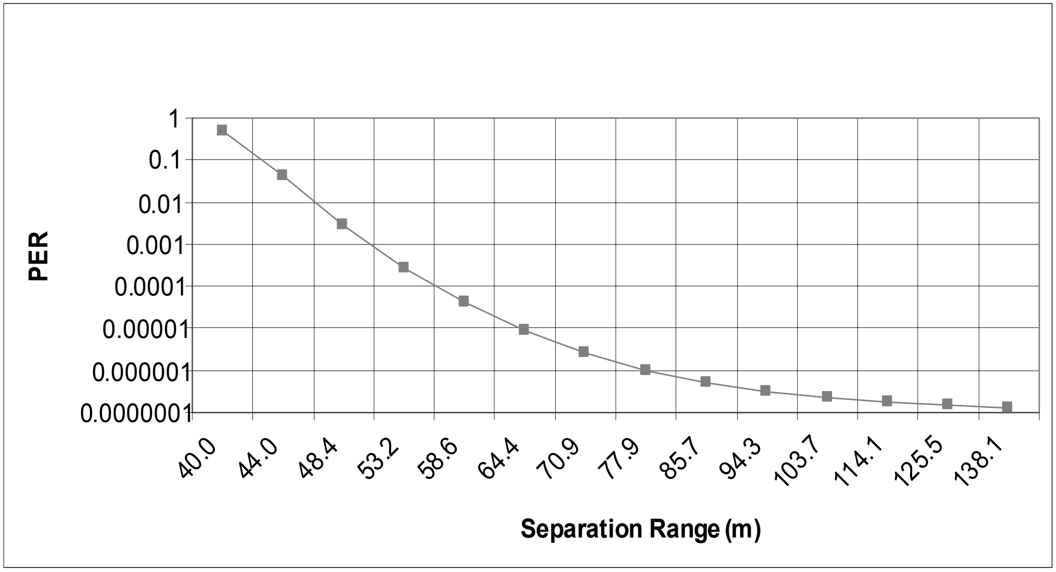

Figure E32—Effect on TG4a UWB AWN as a function of separation distance from 802.16 IWN device

E.7.9 Impact of TG4a devices on ECMA-368 networks

Assumptions:

- The ECMA-368 receiver is the victim (AWN). The AWN operates using frequency hopping in bands across the 3.1 to 4.8 GHz unlicensed UWB bands (available only in the United States at this time), but the TG4a device operates only in band 3 (mandatory).
- We assume the ECMA-368 receiver is operating in a real-world environment in the presence of multipath fading and interference and assume a 5 dB margin above sensitivity to function well. We assume a baseline PER of 8e-2 at sensitivity (8e-7 at 3 dB above sensitivity) in the absence of any UWB device effects and a 6 dB receiver NF.
- UWB interference is wideband uncorrelated noise since the bandwidth is much wider than victim receiver. We assume a 10 dB difference in antenna gains since the indoor or outdoor 802.16 antenna

Table E3—Computation of the acceptable levels of TG4a device emissions for an operating 802.16 client node

Quantity	Value	Units	Notes
802.16 client device transmit power (P16)	17	dBm	Assumes subscriber station in small cell
802.16 client device bandwidth	5	MHz	
TG4a UWB device bandwidth	500	MHz	
Average 802.16 antenna gain (G16)	-2	dBi	Average gain from antenna to arbitrary victim receiver over 360 (IWN typically not in main beam)

Table E3—Computation of the acceptable levels of TG4a device emissions for an operating 802.16 client node *(continued)*

Quantity	Value	Units	Notes
Average emissions PSD (P16+G16 - 10Log(BU-WB) seen by TG4a UWB device receiver	-12	dBm/MHz	Average PSD seen in direction of arbitrary victim receiver (assumes that UWB receiver can spread interference epower into receiver bandwidth)
TG4a UWB Thermal noise floor (kTB)	-114	dBm/MHz	Thermal noise floor (room temperature)
TG4a UWB NF	10	dB	Noise figure for low cost TG4a device
TG4a UWB operating margin (MUWB)	3	dB	Operating margin for acceptable performance in presence of multipath fading (assumes no interference other than IWN)
TG4a UWB effective operating noise floor for UWB interference susceptibility: (kTB + NFUWB + MUWB)	-101	dBm/MHz	This is the effective operating noise floor level for the TG4a operating receiver
Level of interference power density to achieve a 3 dB rise in TG4a UWB effective operating noise floor	-101	dBm/MHz	For 3 dB rise, 802.16 power emissions inband can be at the same level as effective operating noise floor for UWB receiver
Path loss (range) from 802.16 to UWB receiver (average case) for 3 dB rise in effective operating noise floor	89 (48)	dB (m)	For 3 dB rise, 802.16 power emissions inband can be at the same level as effective operating noise floor for UWB receiver
Path loss (range) from 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 inband must be 6 dB below effective operating noise floor for indoor 802.16 node receiver

will have gain in the direction of the desired base station downlink signal and we assume the UWB device will not directly block the LOS.

E.7.9.1 Coexistence Methodology Results

Table E4 shows the calculation of the allowable path loss that would result in a TG4a UWB emission level at the AWN equal to the effective operating noise floor. Base on this path loss, we compute the effect on AWN PER as a function of separation distance, shown in Figure E33.

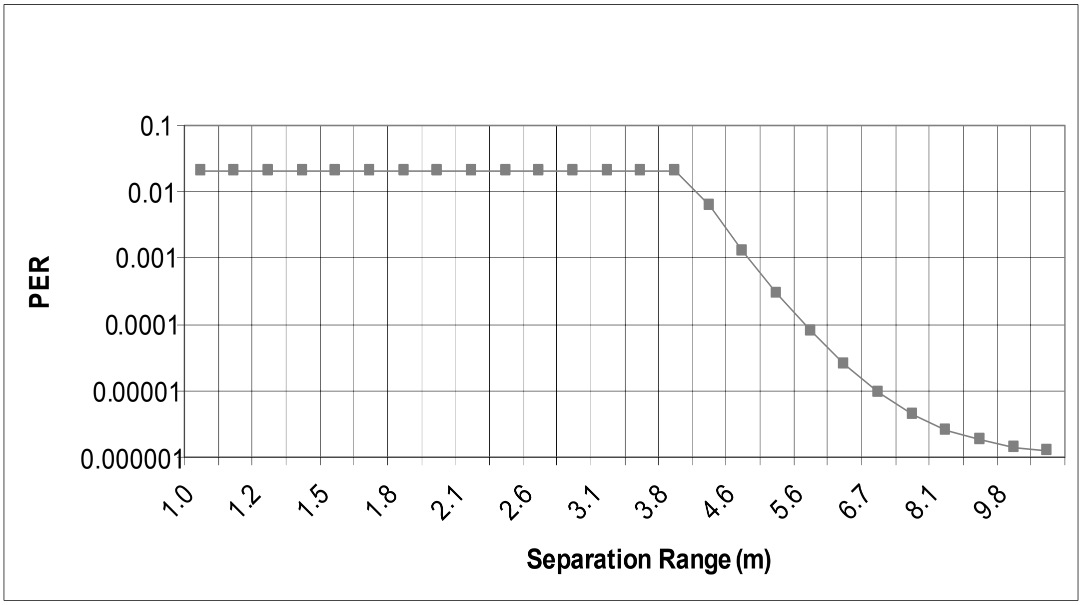

Figure E33—Effect on ECMA-368 AWN as a function of separation distance from TG4a UWB device

E.7.10 Impact of TG4a devices on 802.22 networks

Based on the currently available draft 802.22, the operating conditions are generally similar to 802.16. The primary operating considerations include:

- The 802.22 is a fixed point to multi-point network, operating in narrow band (6-8MHz) widely spaced between 54MHz and 862 MHz; the fixed node will not be susceptible to TG4a interference due to positioning;
- The UWB PHY channel at 150-650MHz is operating, on average, at least -75dBm (set by regulation, using current FCC limits), which is at approximately 34dB lower power than the higher band UWB PHY (-41.3dBm).
- UWB interference is wideband uncorrelated noise since the bandwidth is much wider than victim receiver. We assume a 10 dB difference in antenna in anticipation that 802.22 antenna will require gain in the direction of the desired fixed node (base station) downlink signal and we assume the UWB device will not directly block the LOS.

E.7.10.1 Coexistence Methodology Results

At the time of this analysis, the characteristics of the 802.22 AWN are not completely defined. Assuming similar characteristics as an 802.16 with the operating frequencies specified above, we note that the UWB

Table E4—Computation of the acceptable levels of TG4a device emissions for an operating ECMA-368 device

Quantity	Value	Units	Notes
UWB Transmit PSD Limit (PLIM)	-41.3	dBm/MHz	Set by regulatory authority
Average margin to limit (MBO)	1.7	dB	Due to spectral ripple (0.5+ dB) and ~1 dB margin for manufacturing tolerance, etc.
Average UWB antenna gain (GUWB)	-2	dBi	Average gain from small, low cost UWB antenna to arbitrary victim receiver over 360
Average emissions PSD (PLIM-MBO+GUWB)	-45	dBm/MHz	Average PSD seen in direction of arbitrary victim receiver

Table E4—Computation of the acceptable levels of TG4a device emissions for an operating ECMA-368 device *(continued)*

Quantity	Value	Units	Notes
UWB victim Thermal noise floor (kTB)	-114	dBm/MHz	Thermal noise floor (room temperature)
UWB victim NF	6	dB	Noise figure for the ECMA-368 receiver
UWB victim frequency diversity	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 (MECMA)	5	dB	Operating margin for acceptable performance in presence of multipath fading and RF interference
802.16 Effective operating noise floor for UWB interference susceptibility: (kTB + NFECMA368 + DFD + MOP)	-100	dBm/MHz	This is the effective allowable interference power level for the ECMA-368 operating receiver
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, TG4a 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 802.16 node receiver

PHY at 150-650MHz has a similar path loss curve as the 3100-4800MHz UWB PHY with the noted 6 to 8 dB difference along the curve, noting further that the maximum radiated power is 34dB lower, the effective interference seen by the AWN will be lower than shown for the 802.16 case.

E.7.11 Conclusions

These analyses characterize the expected coexistence behavior between TG4a UWB devices and 802.16 devices. Also described are the expected effects of a TG4a device on an ECMA-368 receiver and the proposed 802.22 devices. One conclusion that can be drawn is that the relative effects of the TG4a device and 802.16 device to each other are quite different. The TG4a device is impacted by the 802.16 device at much longer range than vice versa. The implication is that the TG4a device would not be able to operate at all at ranges where its emissions would impact the 802.16 device because of the large asymmetry in the transmit power levels (+17 dB for 802.16 versus -15 dBm for the TG4a device). In such case, the TG4a device would either 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 802.22 devices; there is an even greater asymitry in power levels, as the sub-GHz band is operated at a substantially lower levels 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-GHz UWB band has greatest advantage and is therefore most likely to be used, the operation of 802.22 deviecs in near proximity is unlikely. In application scenarios where it is expected TG4a sub-GHz devices may operate in proximity of 802.22 devices, the TG4a dvices may need to employ some other forms of interference mitigation. Aditional mitigation is available to the 802.22 device noting that a great number of potential channels are available above 650MHz, providing the option of the 802.22 device to change to a channel outside the operating range of the sub-GHz UWB.

E.7.12 References

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

[2] S. J. Shellhammer, Estimation of Packet Error Rate Caused by Interference using Analytic Techniques - A Coexistence Assurance Methodology, IEEE 802.19-05/0028r0, September 14, 2005.

[3] IEEE Std 802.15.2-2003, IEEE Recommended Practice for Information technology -Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements. Part 15.2: Coexistence of Wireless Personal Area Networks with Other Wireless Devices Operating in Unlicensed Frequency Bands, August 28, 2003.

[4] IEEE LAN/MAN Standards Committee, IEEE Std 802.15.4™-2003, IEEE Standard for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), IEEE, New York, NY, October 1, 2003.

[5] Sklar, Bernard, Digital Communications, Fundamentals and Applications (2nd Edition), Prentice Hall PTR, January 11 2001.

[6] 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.

[7] CHARACTERISTICS OF IEEE 802.16 SYSTEMS IN 2500-2690 MHz, Submission to ITU-R by IEEE802.16 WG, Document number: IEEE L802.16-04/42r3

change the heading number as follows

E.~~6~~ 8 Notes on the calculations