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Wireless Personal Area Networks

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Re:	
Abstract	Analysis on coexistence of 802.15.4g with other 802 systems within the same spectrum bands
Purpose	To address the coexistence capability of 802.15.4g
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1. Introduction

1.1. Bibliography

[B1] IEEE Std. 802.15.1[TM] – 2005, IEEE Standard for Information Technology – Telecommunications and Information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 15.1: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless Personal Area Networks (WPANs).

[B2] IEEE Std. 802.15.2[TM] – 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.

[B3] IEEE Std. 802.15.3[TM] – 2003, IEEE Standard for Information Technology – Telecommunications and Information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs).

[B4] IEEE Std. 802.15.4[TM] – 2006, 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 (WPANs).

[B5] IEEE Std. 802.11[TM] – 2007, IEEE Standard for Information Technology –

Telecommunications and Information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.

[B6] IEEE Std. 802.15.4g /D1 – 2010, IEEE Draft 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 (WPANs) – Amendment 4: Physical Layer Specifications for Low Data Rate Wireless Smart Metering Utility Networks.

[B7] IEEE Std. 802.11n[TM], IEEE Standard for Information Technology - Telecommunications and Information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment 5: Enhancements for Higher Throughput.

1.2.   Acronyms

ASK	amplitude shift keying
AWGN	additive white Gaussian noise
BER	bit error rate
BPSK	binary phase shift keying
Coex-beacon	coexistence beacon
CA	coexistence assurance
CAP	contention access period
CCI	co-channel interference
CCK	complementary code keying
CFP	contention free period
CSM	common signaling mode
CSMA/CA	collision avoidance multiple access / collision avoidance
D-QPSK	differential quadrature phase shift keying
DSSS	direct sequence spread spectrum
DUR	desired to undesired ratio
ED	energy detection
FER	frame error rate
FFD	full function device
FHSS	frequency hopping spread spectrum

GFSK   Gaussian frequency shift keying

GTS   guaranteed time slot

LQI   link quality indicator

MAC   medium access control

MPM   multi-PHY management

MR-FSK   multi-rate and multi-regional frequency shift keying

MR-OFDM   multi-rate and multi-regional orthogonal frequency division multiplexing

MR-O-QPSK   multi-rate and multi-regional offset-quadrature phase shift keying

PAN   personal area network

PHY   physical

OFDM   orthogonal frequency division multiplexing

O-QPSK   offset-quadrature phase shift keying

PSSS   parallel sequence spread spectrum

QAM   quadrature amplitude modulation

RF   radio frequency

RFD   reduced function device

SC   single carrier

SFD   start frame delimiter

SHR   synchronization header

SINR   signal to interference and noise ratio

SIR   signal to noise ratio

SOI   sphere of influence

SUN   smart utility network

TDMA   time division multiple access

2.   Overview

2.1.   Overview of IEEE 802.15.4g

The IEEE 802.15 Task Group 4g defines PHY amendment and related MAC extensions based on 802.15.4 for wireless Smart Utility Networks (SUN). The objective of the standard is to provide a global standard that facilitates very large scale process control applications such as the utility smart-grid network capable of supporting large, geographically diverse networks with minimal infrastructure, with potentially millions of fixed endpoints.

An 802.15.4g network contains one centralized coordinator. The coordinator starts and manages the network to facilitate communications among network devices. A network consists of one coordinator and at least one network device. In the 802.15.4g, there are two types of devices, the FFD and the RFD. The FFD contains the complete set of MAC services and is capable of acting as either a coordinator or a network device. The RFD contains reduced set of MAC services and is only capable as a network device. For medium accessing, the devices employ CSMA/CA to avoid wasteful collisions. Alternatively, TDMA may also be employed for guaranteed transmissions.

This standard specifies a total of three PHYs, namely the MR-FSK, MR-OFDM and MR-O-QPSK. All the PHYs are specified to address different system demands and market segments. In order to avoid mutual interference caused by multiple PHYs operating in the same location, an MPM scheme is defined to coordinate among the potentially coexisting PHYs. Each PHY is specified to allocate a fraction of regulated spectrum bands out of the complete list shown in the following sub-clause.

2.2. Regulatory Information

The allocated frequency bands for the 802.15.4g are given as below:

(a) 2400-2483.5 MHz (Worldwide)

(b) 902-928 MHz (United States)

(c) 863-870 MHz (Europe)

(d) 950-958 MHz (Japan)

(e) 779-787 MHz (China)

(f) 1427-1518 MHz (United States, Canada)

(g) 450-470 MHz (United States)

(h) 896-901 MHz (United States)

(i) 901-902 MHz (United States)

(j) 928-960 MHz (United States)

(k) 470-510 MHz (China)

(l) 917-923.5 MHz (Korea)

Out of the list, bands (a)-(e) and (k) are occupied by more than one 802.15.4g PHY, while bands (f)-(j) and (l) are only occupied by a single PHY. The details are listed in the Table 1.

Table 1 Regulatory Domains for Respective PHYs Specified in 802.15.4g

Frequency Band	IEEE 802.15.4g PHYs		
	MR-FSK	MR-O-QPSK	MR-OFDM
2400-2483.5 MHz (Worldwide)	X	X	X
902-928 MHz (United States)	X	X	X
863-870 MHz (Europe)	X	X	X
950-958 MHz (Japan)	X	X	X
779-787 MHz (China)		X	X
1427-1518 MHz (United States, Canada)	X		
450-470 MHz (United States)	X		
896-901 MHz (United States)	X		
901-902 MHz (United States)	X		
928-960 MHz (United States)	X		
470-510 MHz (China)	X	X	X
917-923.5 MHz (Korea)			X

2.3.   Overview of Coexistence Mechanism in 802.15.4 and 802.15.4g

The importance of coexistence mechanism in the SUN is two-fold. Internally, the SUN specified three alternative PHYs and these PHYs shall be able to coexist with each other if operating co-locatedly in the same frequency band. Externally, the SUN has to share multiple frequency bands with dissimilar 802 systems.

The following sub-clauses describe the coexistence mechanism specified in the 802.15.4 and 802.15.4g, that facilitates both homogeneous (among different SUN PHYs) and heterogeneous (across other 802 systems) coexistence.

2.3.1. MPM scheme

The MPM scheme is a newly defined mechanism in the 802.15.4g. The motivation of defining the MPM is the specification of multiple alternative SUN PHYs potentially operating in the same frequency bands. The sole objective of MPM is to facilitate CCI avoidance when more than one PHY are occupying the same channel. The description

of MPM can be found in sub-clause 5.2b [B6].

To facilitate the MPM operation, a pre-defined common PHY mode known as the CSM, a new frame known as the coex-beacon, and several corresponding MAC functions are specified. Coordinators of all three PHYs that operate at duty cycle greater than 1% shall be able to transmit and receive the CSM. The basic operation of the MPM is to require the coordinators to scan for the coex-beacon in CSM. Upon receiving a coex-beacon, the incoming coordinator realizes that there is another network occupying the channel, and may take several measures to avoid CCI, such as trying another channel or achieving synchronization with the current network. On the other hand, while operating in a certain channel, a coordinator is also required to send out coex-beacon in CSM to alert possible incoming coordinators.

2.3.2. Common Signaling Mode (CSM)

The CSM is a pre-defined common PHY mode that has to be supported by all the specified PHYs in 802.15.4g. CSM is used to aid coexistence among the alternative SUN PHYs. The role of the CSM is coexistence is primarily two-fold: (a) to facilitate the MPM mechanism that targets interference avoidance among networks with different PHYs, and (b) to enable a more efficient detection scheme (*e.g.* scanning, CCA, and *etc.*) between networks with different PHY designs. The PHY layer specification of the CSM is given in 6.1a [B6].

2.3.3. Channel Scan

A channel scan is an act of a receiver to detect any signal present in the channel. The channel scan is the basic means for systems to coexist: enabling detection between networks. There are different types of channel scan that give different levels of accuracy and require different levels of radio resources. In the 802.15.4g, the specified channel scan types are ED channel scan, active channel scan, passive channel scan and enhanced CMS channel scan. The following sub-clauses provide the details of the available scan types in the 802.15.4 and 802.15.4g. The ED scan, active channel scan and passive channel scan are specified in 802.15.4, while the enhanced CMS channel scan is newly specified in 802.15.4g.

2.3.3.1. ED Channel Scan

The ED channel scan allows a device to obtain a measure of the peak energy of the RF signal on the channel it is operating. The ED scan could be used by a prospective PAN coordinator to select a channel on which to operate prior to starting a new PAN. Upon detecting an existing PAN in a specific channel, incoming PAN coordinator may avoid colliding with the existing network by switching to another channel, thus enabling coexistence. The details of ED channel scan are given in 7.5.2.1.1 [B4].

2.3.3.2. Enhanced CSM Channel Scan

The enhanced CSM channel scan is newly defined in 802.15.4g, where three alternative PHYs are specified. A common signaling format, namely the CSM, is a PHY mode that has to be supported by all coordinators. Besides the coordinators, all devices may also support the CSM. The enhanced CSM channel scan allows a device to perform the specific sequence detection of the CSM, which is significantly more accurate as compared to energy detection. In cases where a device, the same goes to any device in the other non-SUN systems, is capable of receiving the CSM, the enhanced CSM channel scan can be performed for a more efficient coexistence.

2.3.3.3. Active Channel Scan

An active scan allows a device to locate any coordinator transmitting beacon frames within its radio SOI. This could be used by a prospective PAN coordinator to select a PAN identifier prior to starting a new PAN, or it could be used by a device prior to association. In a logical channel, the device first sends a beacon request command to the possibly existing coordinator. If the coordinator exists, and is operating in a non-beacon-enabled mode, it will send the beacon in the using the CSMA protocol. If the coordinator is operating in a beacon-enabled mode, it will send the beacon in the next scheduled beacon interval. Besides the intended SUN devices, other non-SUN devices may also employ the active channel scan and ED scan in order to detect and avoid possible scenarios of interference. Additionally, if the CSM is supported, CSM scan can be performed for increased detection probability. The details of active channel scan are given in 7.5.2.1.2 [B4].

2.3.3.4. Passive Channel Scan

A passive scan, like an active scan, allows a device to locate any coordinator transmitting beacon frames within its radio SOI. One major difference in the passive channel scan is that the beacon request command is not transmitted by the devices. This scan is used to search for coordinators in the radio SOI, participating in the beacon-enabled mode. An existing coordinator, will send periodical beacons and incoming devices will be performing passive scan to receive the beacon. In a similar way, other non-SUN devices may also employ the passive channel scan and ED scan in order to detect and avoid possible scenarios of interference. Additionally, if the CSM is supported, CSM scan can be performed for increased detection probability. The details of passive channel scan are given in 7.5.2.1.3 [B4].

2.3.4. Clear Channel Assessment

For the non-beacon-enabled network and CAP in the beacon-enabled network, the CSMA/CA mechanism is specified for handling multiple channel access. In the CSMA/CA mechanism, before transmissions of frames, CCA has to be performed to determine the vacancy of the channel. At least one of the following three CCA methods has to be performed in the CCA: ED over a certain threshold, detection of an 802.15.4g signal (*e.g.* the CSM), or a combination of these methods. Non-SUN devices may participate in the CSMA/CA protocol in a SUN system if it supports any of the CCA methods, so to avoid CCI with co-locating devices. The details of CCA are given in 6.9.9 [B4].

2.3.5. LQI and ED

The LQI measurement is a characterization of the strength and/or quality of a received frame. The measurement may be one of the receiver ED, the SNR estimation, or a combination of both. An example of conducting an LQI evaluation is by using the ED and SNR measurements. Low ED and low SNR values indicate that the receive signal is weak, possibly due to a bad channel or obstruction. High ED and low SNR values indicate that interference in the channel is present. High ED and high SNR naturally mean that the channel is in good condition. By using the LQI-ED-duet, the factors causing a degraded performance can be determined, or at least estimated, with which, responsive actions can be taken to rectify the situation. The details on ED and LQI are given in 6.9.7 and 6.9.8 [B4].

2.3.6. Channel Switching

Channel switching can be performed by a coordinator to avoid a channel with degraded quality due to interference or other factors. Upon determining that the channel quality is degraded (*e.g.* through LQI measurement), a coordinator may cease current transmissions, perform channel scan to find another channel with better quality to be switched to. The capability of channel switching equips the SUN to be able to coexist with other system, even in cases where the signal characteristics of the co-located network cannot be recognized.

2.3.7. Neighbor Network Capability

Neighbor network capability is a scheme facilitating coexistence and interoperability among multiple PHYs in the SUN, as well as between the SUN and other dissimilar systems.

In the beacon-enabled network, GTS can be allocated by the coordinator to a particular device to perform guaranteed transmission within the CFP employing the TDMA protocol. Similarly, a device belonging to a dissimilar system that supports the GTS allocation and management protocol can request and obtain GTS in the CFP to perform local communications. In this manner, the dissimilar system is able to form a neighbor network that could achieve synchronization with the existing SUN. The GTS allocation and management protocol is detailed in 7.5.7 [B4].

Besides the CFP, inactive portion is also specified in a superframe for the purpose of power saving. The timing information of the active and inactive boundaries is given in the beacon frame. A dissimilar system can take advantage to occupy the inactive portions of the superframe for local communications. The condition for achieving this level of synchronization is the ability to receive and decode the information contained in the SUN beacon frame. The details of the active and inactive portions are given in 7.5.1.1 [B4].

2.3.8. Duty Cycle

Duty cycle is known as the proportion of the signal duration to the regular interval or period of time. A part of devices specified in 802.15.4g SUN, primarily the

battery-powered devices operate in a very low duty cycle. While typical network device may operate at duty cycle as low as below 1%, the coordinators may operate at duty cycle of around 10%, as described in E5.4 [B4]. These low duty cycle devices only transmit energy into the air in a short duration in a long interval, and are less likely to cause interference to other co-located networks.

2.3.9. SFD Detection

The SFD is a field indicating the end of the SHR and the start of the frame data. The function of SFD is to determine the timing boundary from which point the receiver extracts the data in the frame. In 802.15.4g, besides timing establishment, SFD is also designed to facilitate the devices to distinguish the standard specification to which the incoming signal is belonging. The SFD detection is employed for differentiating 802.15.4g frame from the 802.15.4d frame.

3. Dissimilar Systems Sharing the Same Frequency Bands with 802.15.4g

This clause presents an overview on other 802 systems which occupy the same frequency bands that are also specified for the 802.15.4g. The following sub-clauses present co-locating dissimilar systems with reference to respective frequency bands. The frequency bands of interest are the 2400-2483.5 MHz band, the 902-928 MHz band, the 863-870 MHz band, the 950-958 MHz band, the 779-787 MHz band and the 400-430 MHz band.

Each frequency band is discussed referring to a table listing all the coexisting systems from other standard specifications. The contents of the tables (in this and the next sub-clause) are formatted as below:

  (a) Standard specification: the name of the 802 system with which 802.15.4g system is coexisting
  (b) PHY specification: the PHY design of the above 802 system specification
  (c) Receiver bandwidth: the receiver bandwidth of the above 802 system specification
  (d) Transmit power: the transmit power of the above 802 system specification
  (e) Receiver sensitivity: the receiver sensitivity of the above 802 system specification.
  (f) Involved 802.15.4g system: the particular PHY in 802.15.4g that is coexisting

with the above 802 system specification

Note: The data rate modes including receiver bandwidth, transmit power and receiver sensitivity listed in the columns of the following tables are only a part of the complete list from the respective standard specifications. These data rate modes are chosen for the purpose of coexistence analysis in this CA document.

3.1. Coexisting Systems in 2400-2483.5 MHz Band (Worldwide)

Table 2 shows the list of other 802 systems that are sharing the 2400-2483.5 MHz band with the MR-FSK, MR-O-QPSK and MR-OFDM PHYs in 802.15.4g.

Table 2: Dissimilar Systems Coexisting with 802.15.4g Systems within the 2400-2483.5 MHz Band

System	PHY Specification	Involved 802.15.4g System
802.11b	DSSS CCK	MR-FSK, MR-O-QPSK, MR-OFDM
802.11g	OFDM BPSK	
802.11n	OFDM QPSK	
802.15.1	FHSS GFSK	
802.15.3	SC D-QPSK	
802.15.4	DSSS O-QPSK	

3.2.   Coexisting Systems in 902-928 MHz Band (United States)

Table 3 shows the list of other 802 systems that are sharing the 902-928 MHz band with the MR-FSK, MR-O-QPSK and MR-OFDM PHYs in 802.15.4g.

Table 3 : Dissimilar Systems Coexisting with 802.15.4g Systems within the 902-928 MHz Band

System	PHY Specification	Involved 802.15.4g System
802.15.4	DSSS BPSK	MR-FSK, MR-O-QPSK, MR-OFDM
	DSSS O-QPSK	
	PSSS ASK	
802.15.4c	DSSS BPSK	
802.11ah	Currently in progress, specification not available	

3.3.   Coexisting Systems in 863-870 MHz Band (Europe)

Table 4 shows the list of other 802 systems that are sharing the 863-870 MHz band with the MR-FSK, MR-O-QPSK and MR-OFDM PHYs in 802.15.4g.

Table 4: Dissimilar Systems Coexisting with 802.15.4g Systems within the 863-870 MHz Band

System	PHY Specification	Involved 802.15.4g System
802.15.4	DSSS BPSK	MR-FSK, MR-O-QPSK, MR-OFDM
	DSSS O-QPSK	
	PSSS ASK	
802.15.4c	DSSS BPSK	

3.4. Coexisting Systems in 950-958 MHz Band (Japan)

Table 5 shows the list of other 802 systems that are sharing the 950-958 MHz band with the MR-FSK PHY in 802.15.4g.

Table 5: Dissimilar Systems Coexisting with 802.15.4g Systems within the 950-958 MHz Band

System	PHY Specification	Involved 802.15.4g System
802.15.4d	DSSS GFSK	MR-FSK, MR-O-QPSK, MR-OFDM
	DSSS BPSK	

3.5. Coexisting Systems in 779-787 MHz Band (China)

Table 6 shows the list of other 802 systems that are sharing the 779-787 MHz band with the MR-O-QPSK and MR-OFDM PHYs in 802.15.4g.

Table 6: Dissimilar Systems Coexisting with 802.15.4g Systems within the 779-787 MHz Band

System	PHY Specification	Involved 802.15.4g System
802.15.4c	DSSS O-QPSK	MR-O-QPSK, MR-OFDM

4.   Coexistence Scenario and Analysis

4.1.   PHY Modes in the 802.15.4g System

4.1.1.   Parameters for 802.15.4g PHY Modes

Table 7 shows the PHY modes chosen from each of the MR-FSK, MR-OFDM and MR-O-QPSK PHYs and their corresponding parameters.

Table 7: Major Parameters of 802.15.4g PHY Modes

System	PHY Spec.	Receiver Bandwidth (kHz)	Transmit Power (dBm)	Receiver Sensitivity (dBm)	PHY Mode
802.15.4g	MR-FSK	200	0	-90	50kbps FSK
	MR-OFDM	200	0	-100	200kbps QPSK CC R_{FEC}=1/2
	MR-O-QPSK	2000	0	-90	500kbps O-QPSK CC R_{FEC}=1/2 (8,4) DSSS

4.1.2.   BER/FER Calculations for 802.15.4g PHY modes

In this sub-clause, the BER/FER performance corresponding to SINR for the 802.15.4g PHY modes in Table 7 are provided. The parameter SINR is defined as the ratio between the energy in each chip to the noise power spectral density in each chip. SINR (i.e. E_c/N_0) can be expressed as:

$$E_c/N_0 = E_b/N_0 + 10 \log(L_m) + 10 \log(R_{FEC}) - 10 \log(L_s) \qquad (1)$$

where,

E_c/N_0 is the chip energy for over noise power spectral density

E_b/N_0 is the bit energy for over noise power spectral density

L_m is the modulation level

R_{FEC} is the FEC coding rate

L_s is the spreading factor

The Matlab source codes for the BER/FER calculations are given in Annex A.
The Q function is defined in C.3.6.6 [B2].

FER for the 802.15.4g PHY modes can be calculated from the corresponding BER
through the relationship:

$$\text{FER} = \mathbf{1 - (1 - BER)}^{L} \tag{2}$$

where,

L	is the average frame size
L	is 250 octets for FSK 50kbps in this standard
L	is 20 octets for OFDM 200kbps in this standard
L	is 20 octets for O-QPSK 500kbps in this standard

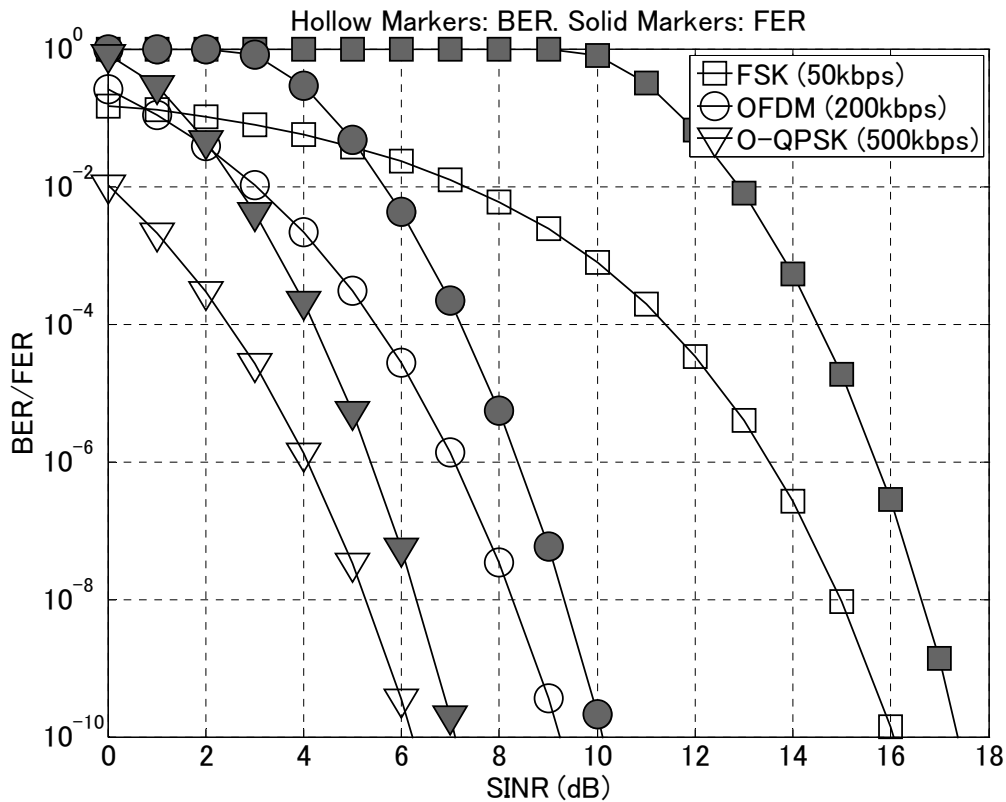The BER and FER of 802.15.4g PHY modes are given in Figure 1.

Figure 1 BER and FER vs. SINR for 802.15.4g PHY Modes

4.2.   Interference Modeling

4.2.1.   Interference Characteristics
The effect of the interfering signal on the desired signal is assumed to be averaged to the bandwidth of the victim system.

4.2.2.   Receiver-based Interference Model
As illustrated in Figure 2, victim receiver Rxv (with receive power P_{Rv} and antenna gain G_{Rv}) receives the desired signal from the victim transmitter Txv (with transmit power P_{Tv} and antenna gain G_{Tv}) located at distance d_D, while an interferer transmitter Txi (with transmit power P_{Ti} and antenna gain G_{Ti}) is located at distance d_U.

The ratio between the desired and undesired power present at the victim receiver will be used as the DUR *i.e.* SIR of the victim system.

At Rxv, the power received from Txv, known as P_{Rv} (in dB scale) is given as:

$$P_{Rv} = P_{Tv} + G_{Tv} + G_{Rv} - L_p(d_D)$$

On the other hand, the power received from Txi, known as P_{Rv}' (in dB scale) is given as:

$$P_{Rv}' = P_{Ti} + G_{Ti} + G_{Rv} - L_p(d_U)$$

Here, all antennas are assumed to be omni-directional, thus angle θ can be neglected. Therefore, the ratio between the desired signal power and the interference power is given as:
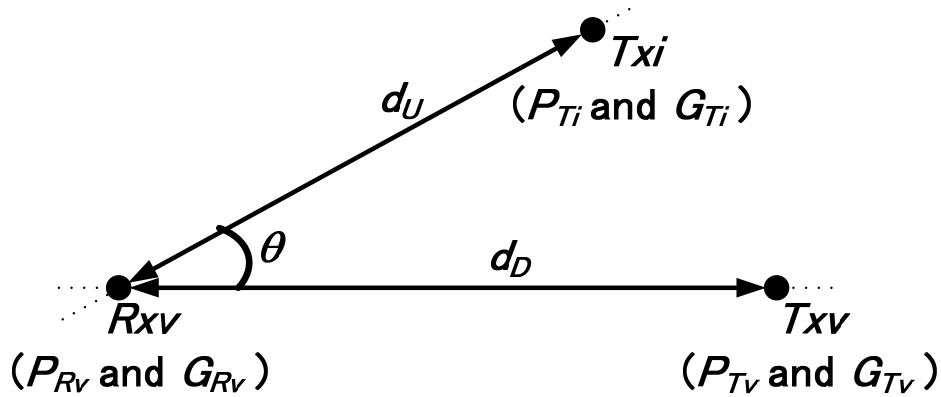
$$SIR = P_{Rv} / P_{Rv}'$$

Figure 2 Illustration for the Receiver-based Interference Model

4.2.3. Path Loss Model

The path loss model used in this document is the outdoor large-zone systems. The typical urban model is employed. The path loss can be expressed as:

$$L_p = 69.55 + 26.16 \log_{10} f_c + (44.9\text{-}6.55 \log_{10} h_b) \log_{10} d - 13.82 \log_{10} h_b - a(h_m)$$

where,

f_c	is the operating frequency
h_b	is the height of the coordinator in the network
h_m	is the height of the device
d	is the distance between coordinator and device, d can either be d_D or d_U

and $a(h_m)$ is the correction factor for the device antenna height given by:

$$a(h_m) = 3.2 \, [\log_{10} 11.75 \, h_m]^2 - 11.97$$

4.3. 2400-2483.5 MHz Band Coexistence Performance

This sub-clause presents the coexistence performance of the systems coexisting in the 2400-2483.5 MHz band. An involving system is set as the victim while all other systems are set as the interferer, in order to understand the impact of the generated interference. All systems including the 802.15.4g systems and other 802 systems in the 2400-2483.5 MHz band are set as the victim in a round-robin manner.

4.3.1. Parameters for Coexistence Quantification

The following sub-clauses present the parameters involved in quantification of coexistence analysis among the participating systems.

4.3.1.1. PHY Modes from Each Standard and Related Parameters

Table 8 shows the parameters for the PHY modes in each standard that is coexisting within the 2400-2583.5 MHz band.

Table 8: Major Parameters of Systems in the 2400-2483.5 MHz Band

System	PHY Spec.	Receiver Bandwidth (MHz)	Transmit Power (dBm)	Receiver Sensitivity (dBm)	PHY Mode
802.11b	DSSS	22	14	-76	CCK 11Mbps
802.11g	OFDM	22	14	-88	BPSK 6Mbps CC R_{FEC}=1/2
802.11n	OFDM	22	14	-83	QPSK 18Mbps CC R_{FEC}=3/4
802.15.1	FHSS	1	0	-70	GFSK 1Mbps
802.15.3	SC	15	8	-75	DQPSK 22Mbps
802.15.4	DSSS	2	0	-85	O-QPSK 250kbps

4.3.1.2. BER/FER for PHY Modes in Respective 802 Standards

In this sub-clause, the BER/FER performance corresponding to SINR for the all the 802 standards within the 2400-2583.5 MHz band are presented. The parameter SINR is defined as the ratio between the energy in each chip to the noise power spectral density in each chip. The SINR and FER can be derived using (1) and (2) respectively.

Here,

L is the average frame size

L is 1024 octets for 802.11b DSSS CCK 11Mbps

L   is 1000 octets for 802.11g OFDM 6Mbps

L   is 4096 octets for 802.11n OFDM 18Mbps

L   is 1024 octets for 802.15.1 FHSS 1Mbps

L   is 1024 octets for 802.15.3 SC DQPSK 22Mbps

L   is 22 octets for 802.15.4 O-QPSK 250kbps

BER for the 802.11b DSSS CCK 11Mbps, 802.15.1 FHSS 1Mbps, 802.15.3 SC DQPSK 22Mbps and 802.15.4 O-QPSK 250kbps are given in E.4.1.8 [B4].

BER calculations for the 802.11g OFDM 6Mbps and 802.11n OFDM 18Mbps are given in Matlab source codes in Annex A.

The Q function is defined in C.3.6.6 [B4].
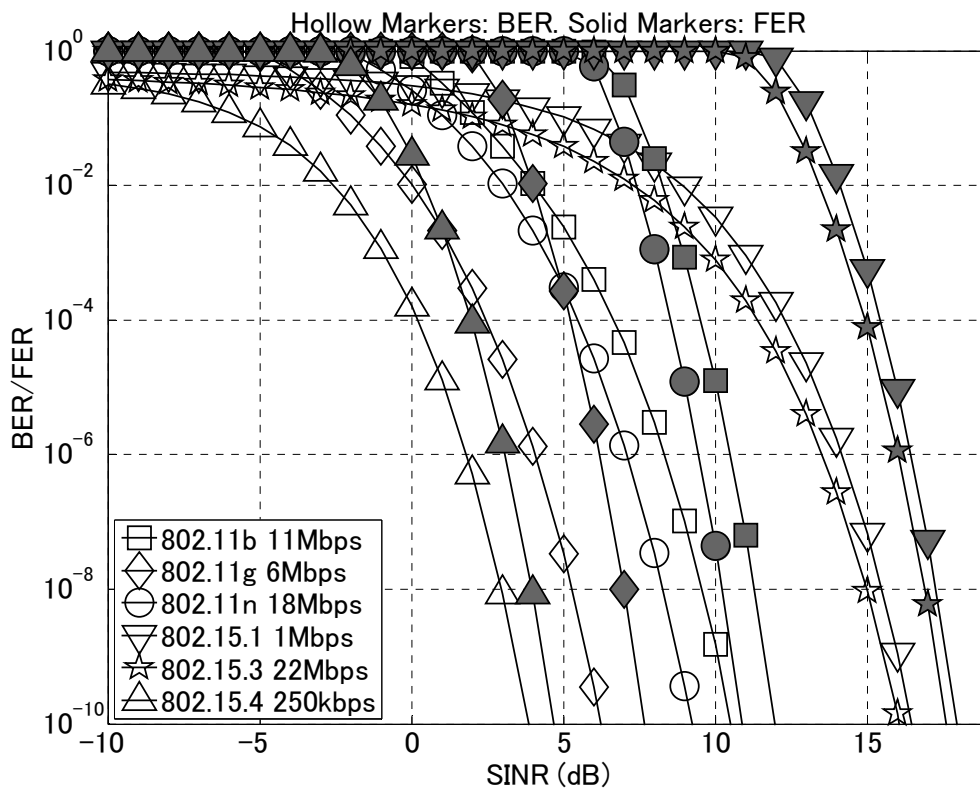

The BER and FER curves are given in Figure 3.

Figure 3 BER and FER vs. SINR for 802 Systems in the 2400-2483.5 MHz Band

4.3.2. Coexistence Simulation Results

4.3.2.1. 802.15.4g FSK 50kbps Mode as Victim Receiver

Figure 4 shows the relationship between the FER performance of the 802.15.4g FSK victim receiver corresponding to the distance between the victim receiver to the interferer. The list of interferers is given in Figure 4.
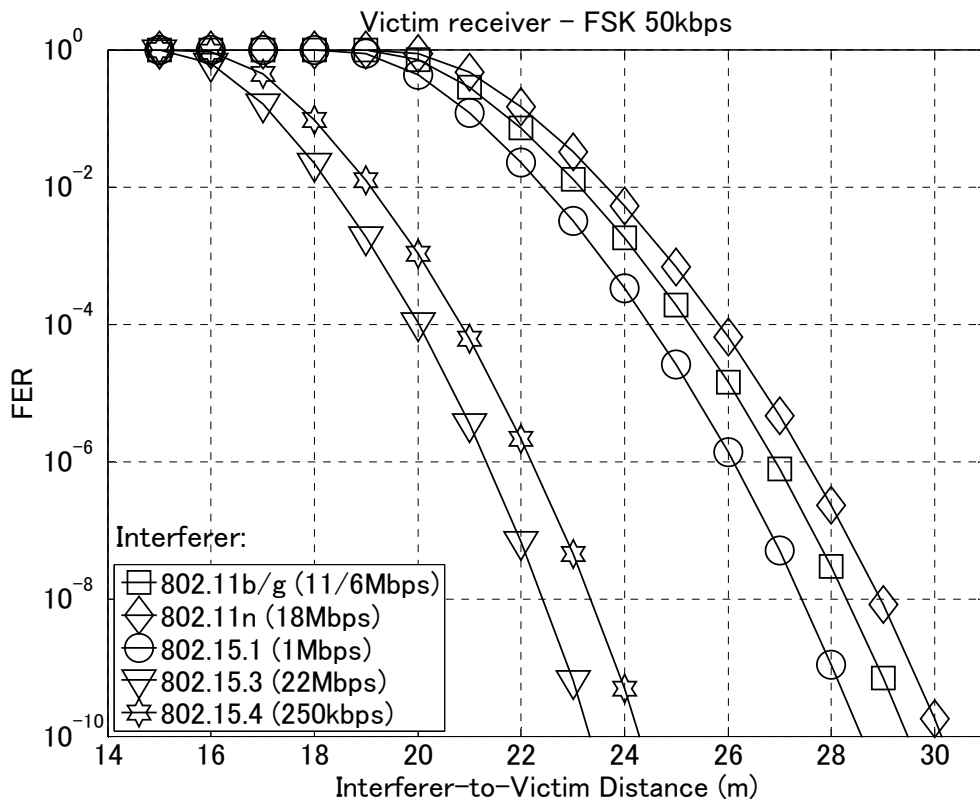
Figure 4 Victim FER vs. Distance between Interferer to 802.15.4g FSK Victim Receiver

4.3.2.2. 802.15.4g OFDM 200kbps Mode as Victim Receiver

Figure 5 shows the relationship between the FER performance of the 802.15.4g OFDM QPSK victim receiver corresponding to the distance between the victim receiver to the interferer. The list of interferers is given in Figure 5.
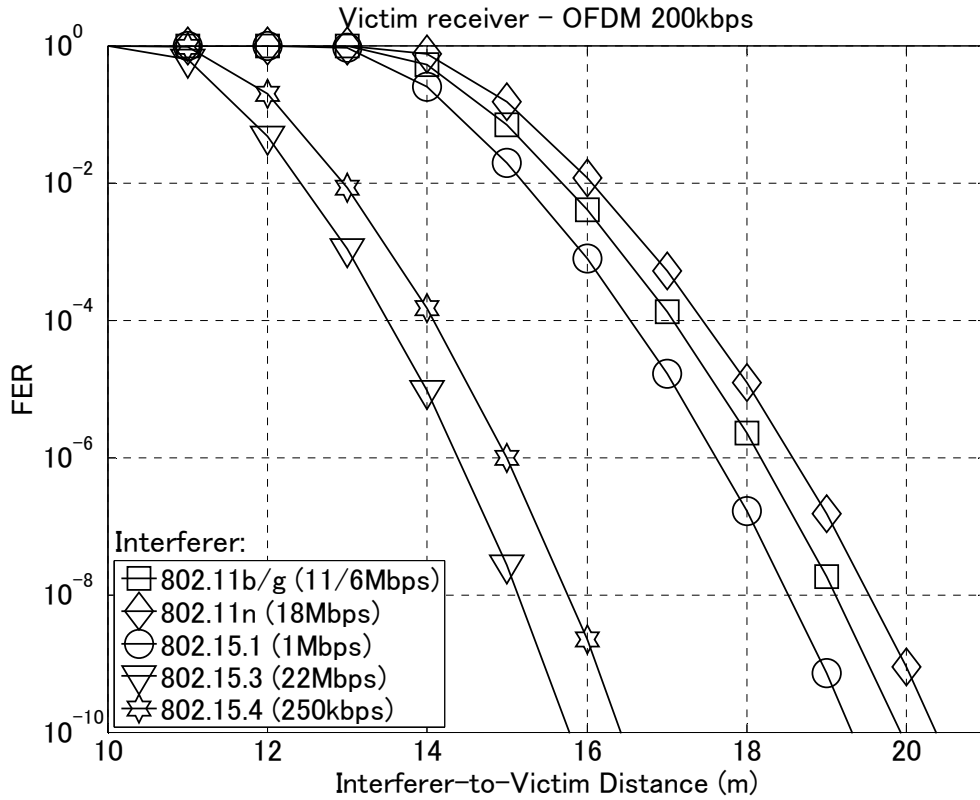

Figure 5 Victim FER vs. Distance between Interferer to 802.15.4g OFDM Victim Receiver

4.3.2.3. 802.15.4g O-QPSK 500kbps Mode as Victim Receiver

Figure 6 shows the relationship between the FER performance of the 802.15.4g DSSS O-QPSK victim receiver corresponding to the distance between the victim receiver to the interferer. The list of interferers is given in Figure 6.
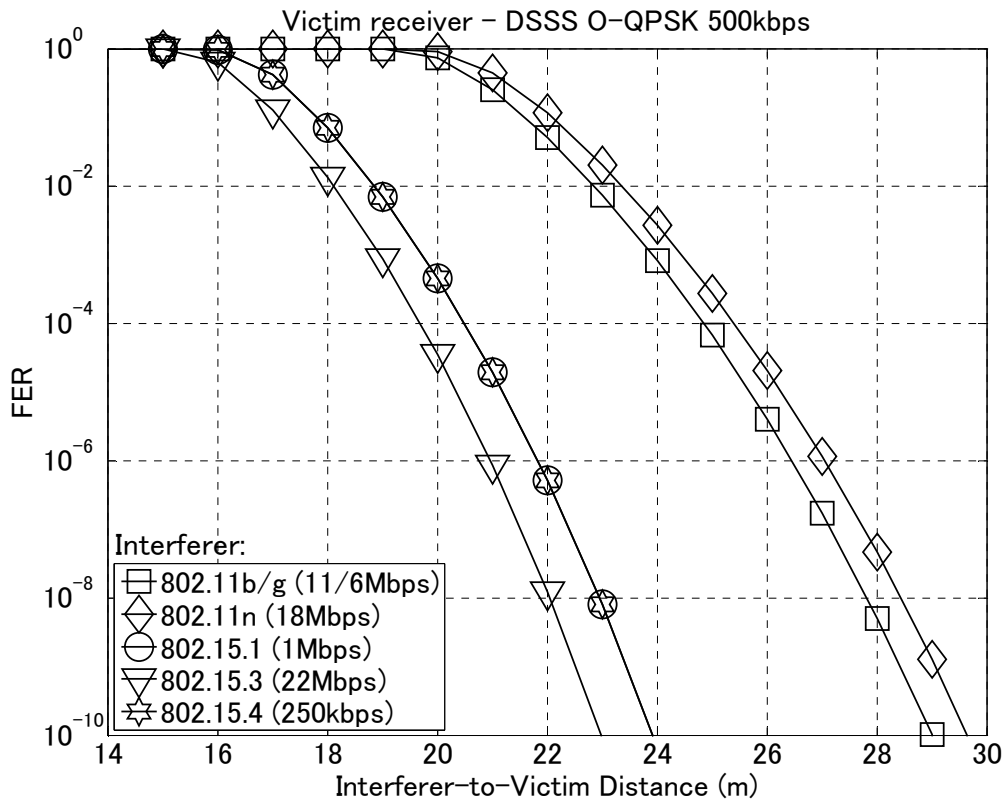

Figure 6 Victim FER vs. Distance between Interferer to 802.15.4g O-QPSK Victim Receiver

4.3.2.4. 802.11 PHY Modes as Victim Receivers

This sub-clause presents the results setting other 802 systems as the victim and 802.15.4g as the interferer. Figure 7 shows the relationship between the FER performances of the 802.11b/g/n victim receivers corresponding to the distance between the victim receivers to the 802.15.4g interferers.
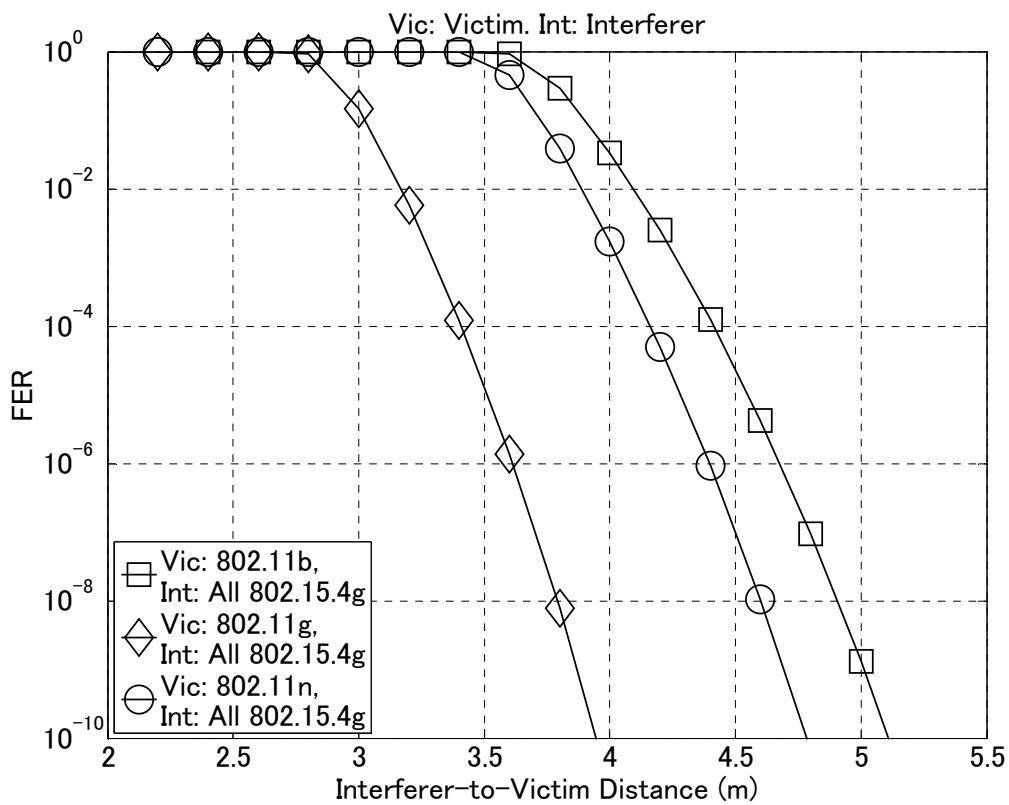

Figure 7 Victim FER vs. Distance between Interferer to 802.11 Victim Receivers. All 802.15.4g display nearly similar characteristics as interferers.

4.3.2.5. 802.15 PHY Modes as Victim Receivers

This sub-clause presents the results setting other 802 systems as the victim and 802.15.4g as the interferer. Figure 8 shows the relationship between the FER performances of the 802.15 (including 802.15.1, 802.15.3 and 802.15.4) victim receivers corresponding to the distance between the victim receivers to the 802.15.4g interferers. The list of interferers is given in Figure 8.
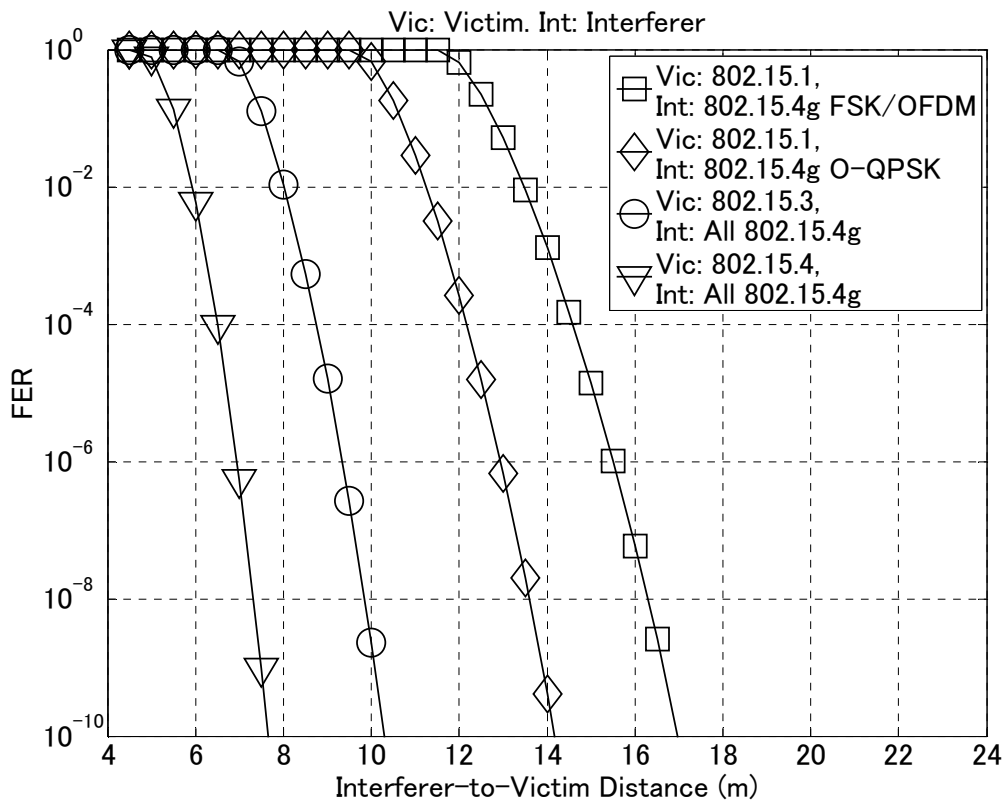

Figure 8 Victim FER vs. Distance between Interferer to 802.15 Victim Receivers. All 802.15.4g display nearly similar characteristics as interferers.

4.4.   902-928 MHz Band Coexistence Performance

This sub-clause presents the coexistence performance of the systems coexisting in the 902-928 MHz band. An involving system is set as the victim while all other systems are set as the interferer, in order to understand the impact of the generated interference. All systems including the 802.15.4g systems and other 802 systems in the 902-928 MHz band are set as the victim in a round-robin manner.

4.4.1.   Parameters for Coexistence Quantification

The following sub-clauses present the parameters involved in quantification of coexistence analysis among the participating systems.

4.4.1.1. PHY Modes from Each Standard and Related Parameters

Table 9 shows the parameters for the PHY modes in each standard that is coexisting within the 902-928 MHz band.

Table 9: Major Parameters of Systems in the 902-928 MHz Band

System	PHY Spec.	Receiver Bandwidth (MHz)	Transmit Power (dBm)	Receiver Sensitivity (dBm)	PHY Mode
802.15.4	DSSS BPSK	2	0	-92	BPSK 40kbps
	DSSS O-QPSK	2	0	-85	O-QPSK 250kbps
	PSSS ASK	2	0	-85	ASK 250kbps
802.15.4c	DSSS BPSK	2	0	-92	BPSK 40kbps
802.11*	Currently in progress, specification not available				

4.4.1.2. BER/FER for PHY Modes in Respective 802 Standards

In this sub-clause, the BER/FER performance corresponding to SINR for the all the 802 standards within the 902-928 MHz band are presented. The parameter SINR is defined as the ratio between the energy in each chip to the noise power spectral density in each chip. The SINR and FER can be derived using (1) and (2) respectively.

Here,

L	is the average frame size
L	is 22 octets for 802.15.4 DSSS BPSK 40kbps
L	is 22 octets for 802.15.4 O-QPSK 250kbps
L	is 22 octets for 802.15.4 PSSS ASK 250kbps

BER calculation for 802.15.4 DSSS BPSK 40kbps is given in E.5.5.1.1 [B4], with the modification of bit rate R_b from 20kbps to 40kbps.

BER calculation for 802.15.4 DSSS O-QPSK 250kbps is given in E.5.5.2.1 [B4].

BER calculation for 802.15.4 PSSS ASK 250kbps is given in E.5.5.3.1 [B4].

The BER and FER curves are given in Figure 9

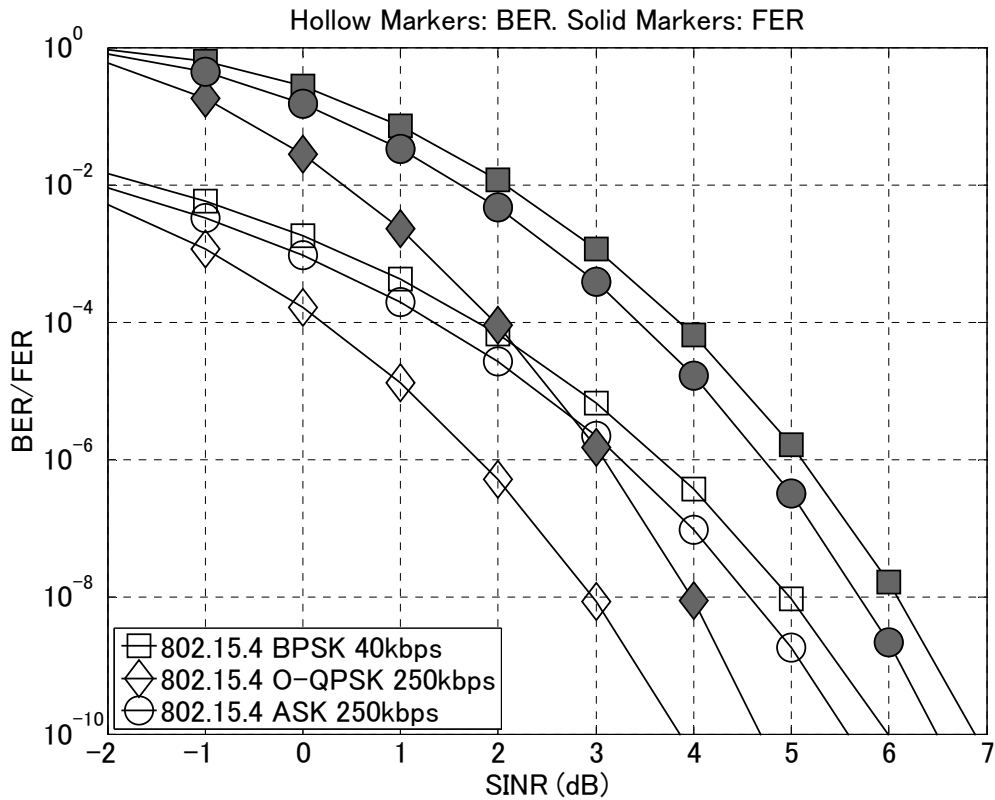**Figure 9 BER and FER vs. SINR for 802 Systems in the 902-928 MHz Band**

4.4.2. Coexistence Simulation Results

4.4.2.1. 802.15.4g PHY Modes as Victim Receivers

Figure 10 shows the relationship between the FER performance of the 802.15.4g FSK 50kbps, OFDM 200 kbps and O-QPSK 500kbps victim receivers corresponding to the distance between the victim receivers to the interferer. The list of interferers is given in Figure 10.

Figure 10 Victim FER vs. Distance between Interferer to all 802.15.4g Victim Receivers. All 802.15.4 PHY modes in Table 9 display nearly similar characteristics as interferers.

4.4.2.2. 802.15.4 PHY Modes as Victim Receivers

This sub-clause presents the results setting other 802 systems as the victim and 802.15.4g as the interferer. Figure 11 shows the relationship between the FER performances of the 802.15.4 (three different PHY modes) victim receivers corresponding to the distance between the victim receivers to the 802.15.4g interferers. The list of interferers is given in Figure 11.
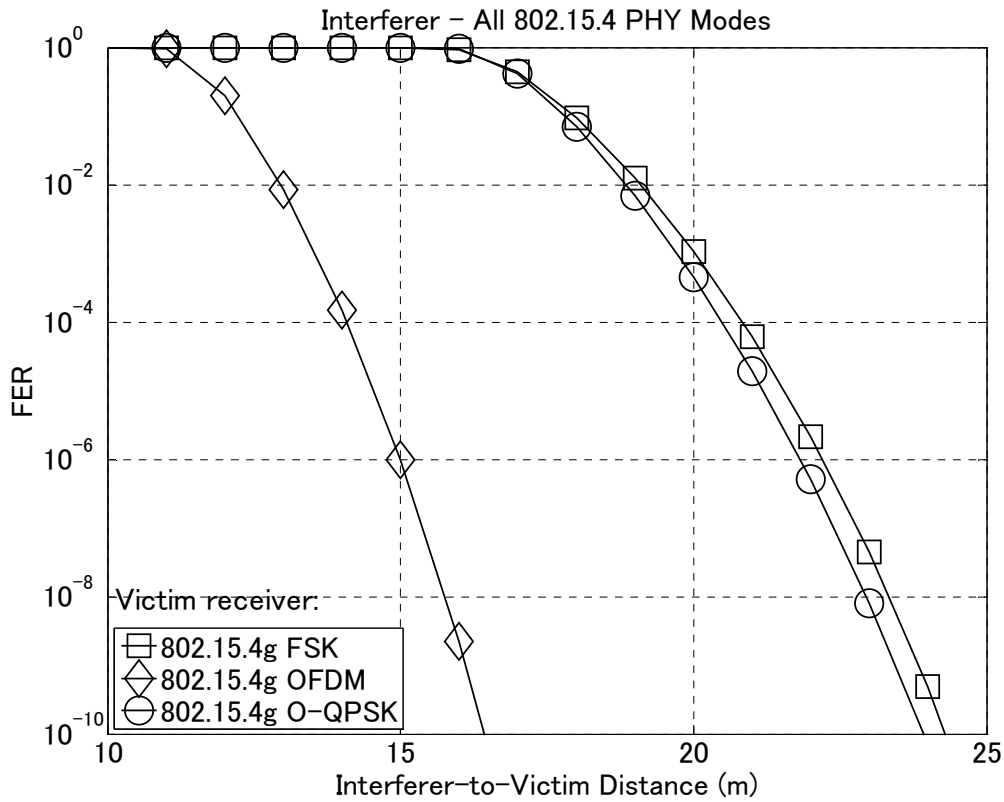
Figure 11 Victim FER vs. Distance between Interferer to all 802.15.4 Victim Receivers. All 802.15.4g PHY modes in Table 7 display nearly similar characteristics as interferers.

4.5.   863-870 MHz Band Coexistence Performance

This sub-clause presents the coexistence performance of the systems coexisting in the 863-870 MHz band. An involving system is set as the victim while all other systems are set as the interferer, in order to understand the impact of the generated interference. All systems including the 802.15.4g systems and other 802 systems in the 863-870 MHz band are set as the victim in a round-robin manner.

4.5.1.   Parameters for Coexistence Quantification

The following sub-clauses present the parameters involved in quantification of coexistence analysis among the participating systems.

4.5.1.1.   PHY Modes from Each Standard and Related Parameters

Table 10 shows the parameters for the PHY modes in each standard that is coexisting

within the 863-870 MHz band.

Table 10 : Major Parameters of Systems in the 863-870 MHz Band

System	PHY Spec.	Receiver Bandwidth (MHz)	Transmit Power (dBm)	Receiver Sensitivity (dBm)	PHY Mode
802.15.4	DSSS BPSK	2	0	-92	BPSK 20kbps
	DSSS O-QPSK	2	0	-85	O-QPSK 250kbps
	PSSS ASK	2	0	-85	ASK 250kbps
802.15.4c	DSSS BPSK	2	0	-92	BPSK 20kbps

4.5.1.2. BER/FER for PHY Modes in Respective 802 Standards

In this sub-clause, the BER/FER performance corresponding to SINR for the all the 802 standards within the 863-870 MHz band are presented. The parameter SINR is defined as the ratio between the energy in each chip to the noise power spectral density in each chip. The SINR and FER can be derived using (1) and (2) respectively. Note that the 802.15.4c DSSS BPSK has similar specifications with that in the 802.15.4 DSSS BPSK.

Here,

L is the average frame size

L is 22 octets for 802.15.4 DSSS BPSK 20kbps

L is 22 octets for 802.15.4 O-QPSK 250kbps

L is 22 octets for 802.15.4 PSSS ASK 250kbps

BER calculation for 802.15.4 DSSS BPSK 20kbps is given in E.5.5.1.1 [B4].

BER calculation for 802.15.4 DSSS O-QPSK 250kbps is given in E.5.5.2.1 [B4].

BER calculation for 802.15.4 PSSS ASK 250kbps is given in E.5.5.3.1 [B4].

The BER and FER curves are given in Figure 12.

Figure 12 BER and FER vs. SINR for 802 Systems in the 863-870 MHz Band

4.5.2. Coexistence Simulation Results

4.5.2.1. 802.15.4g PHY Modes as Victim Receivers

Figure 13 shows the relationship between the FER performance of the 802.15.4g FSK 50kbps, OFDM 200 kbps and O-QPSK 500kbps victim receivers corresponding to the distance between the victim receivers to the interferer. The list of interferers is given in Figure 13.
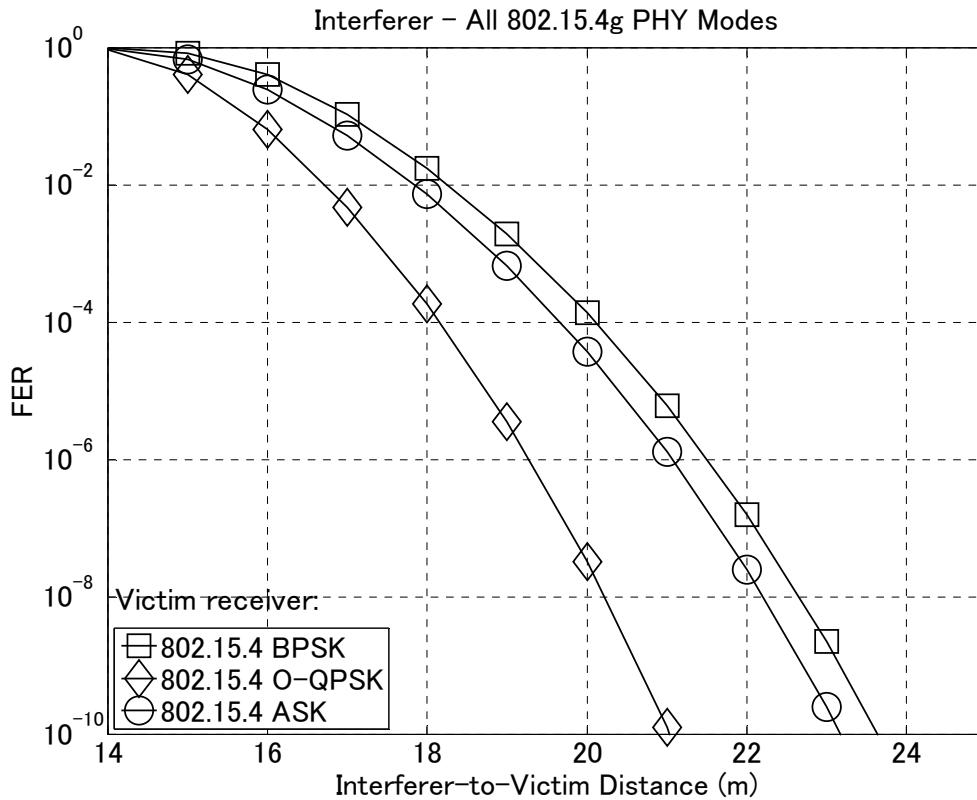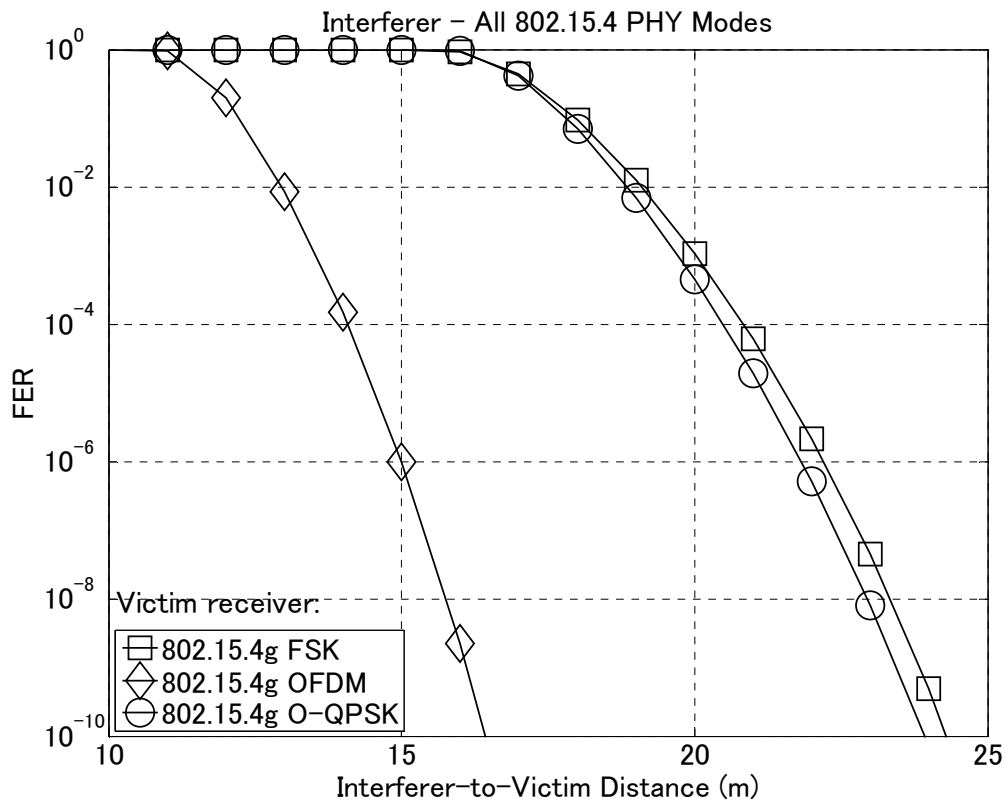

Figure 13 Victim FER vs. Distance between Interferer to all 802.15.4g Victim Receivers. All 802.15.4 PHY modes in Table 10 display nearly similar characteristics as interferers.

4.5.2.2. 802.15.4 PHY Modes as Victim Receivers

This sub-clause presents the results setting other 802 systems as the victim and 802.15.4g as the interferer. Figure 14 shows the relationship between the FER performances of the 802.15.4 (three different PHY modes) victim receivers corresponding to the distance between the victim receivers to the 802.15.4g interferers. The list of interferers is given in Figure 14.
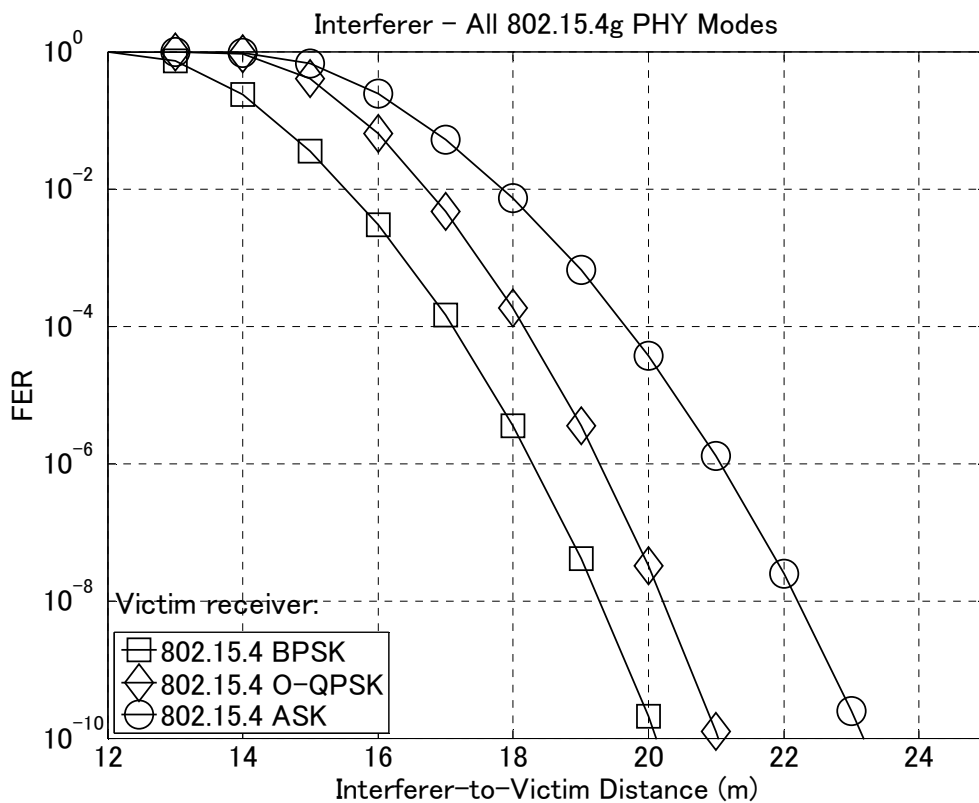
Figure 14 Victim FER vs. Distance between Interferer to all 802.15.4 Victim Receivers. All 802.15.4g PHY modes in Table 7 display nearly similar characteristics as interferers.

4.6.   950-958 MHz Band Coexistence Performance

This sub-clause presents the coexistence performance of the systems coexisting in the 950-958 MHz band. An involving system is set as the victim while all other systems are set as the interferer, in order to understand the impact of the generated interference. All systems including the 802.15.4g systems and other 802 systems in the 950-958 MHz band are set as the victim in a round-robin manner.

4.6.1.   Parameters for Coexistence Quantification

The following sub-clauses present the parameters involved in quantification of coexistence analysis among the participating systems.

4.6.1.1. PHY Modes from Each Standard and Related Parameters

Table 11 shows the parameters for the PHY modes in each standard that is coexisting within the 950-958 MHz band.

Table 11 : Major Parameters of Systems in the 950-958 MHz Band

System	PHY Spec.	Receiver Bandwidth (MHz)	Transmit Power (dBm)	Receiver Sensitivity (dBm)	PHY Mode
802.15.4d	GFSK	0.2	0	-85	GFSK 100kbps
	DSSS BPSK	2	0	-92	BPSK 20kbps

4.6.1.2. BER/FER for PHY Modes in Respective 802 Standards

In this sub-clause, the BER/FER performance corresponding to SINR for the all the 802 standards within the 950-958 MHz band are presented. The parameter SINR is defined as the ratio between the energy in each chip to the noise power spectral density in each chip. The SINR and FER can be derived using (1) and (2) respectively.

Here,

L is 250 octets for 802.15.4d DSSS GFSK 100kbps

L is 22 octets for 802.15.4d DSSS BPSK 20kbps

BER calculation for 802.15.4d DSSS GFSK 100kbps is Annex A.

BER calculation for 802.15.4d DSSS BPSK 20kbps is given in E.5.5.1.1 [B4].

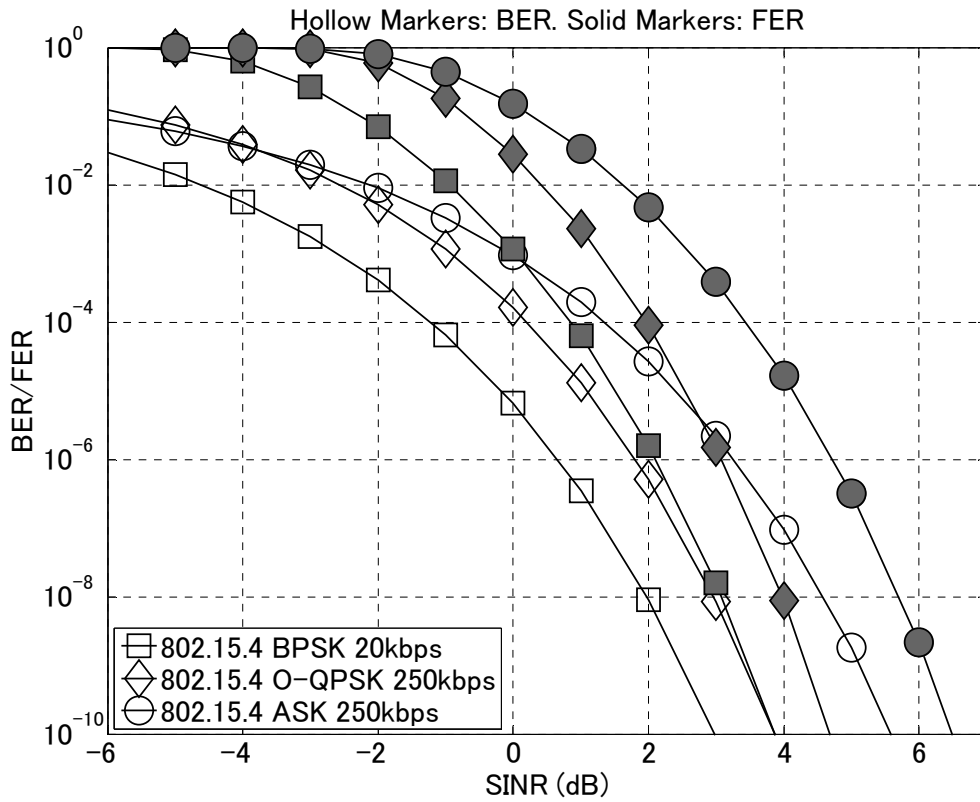The BER and FER curves are given in Figure 15.

Figure 15 BER and FER vs. SINR for 802 Systems in the 950-958 MHz Band

4.6.2. Coexistence Simulation Results

4.6.2.1. 802.15.4g PHY Modes as Victim Receivers

Figure 16 shows the relationship between the FER performance of the 802.15.4g FSK 50kbps, OFDM 200 kbps and O-QPSK 500kbps victim receivers corresponding to the distance between the victim receivers to the interferer. The list of interferers is given in Figure 16.

Figure 16 Victim FER vs. Distance between Interferer to all 802.15.4g Victim Receivers.

4.6.2.2. 802.15.4d PHY Modes as Victim Receivers

This sub-clause presents the results setting other 802 systems as the victim and 802.15.4g as the interferer. Figure 17 shows the relationship between the FER performances of the 802.15.4d (two different PHY modes) victim receivers corresponding to the distance between the victim receivers to the 802.15.4g interferers. The list of interferers is given in Figure 17.

Figure 17 Victim FER vs. Distance between Interferer to all 802.15.4d Victim Receivers. All 802.15.4g PHY modes in Table 11 display nearly similar characteristics as interferers.

4.7. 779-787 MHz Band Coexistence Performance

This sub-clause presents the coexistence performance of the systems coexisting in the 779-787 MHz band. An involving system is set as the victim while all other systems are set as the interferer, in order to understand the impact of the generated interference. All systems including the 802.15.4g systems and other 802 systems in the 779-787 MHz band are set as the victim in a round-robin manner.

4.7.1. Parameters for Coexistence Quantification

The following sub-clauses present the parameters involved in quantification of coexistence analysis among the participating systems.

4.7.1.1. PHY Modes from Each Standard and Related Parameters

Table 12 shows the parameters for the PHY modes in each standard that is coexisting within the 779-787 MHz band.

Table 12 : Major Parameters of Systems in the 779-787 MHz Band

System	PHY Spec.	Receiver Bandwidth (MHz)	Transmit Power (dBm)	Receiver Sensitivity (dBm)	PHY Mode
802.15.4c	DSSS O-QPSK	2	0	-85	O-QPSK 250kbps

4.7.1.2. BER/FER for PHY Modes in Respective 802 Standards

In this sub-clause, the BER/FER performance corresponding to SINR for the all the 802 standards within the 779-787 MHz band are presented. The parameter SINR is defined as the ratio between the energy in each chip to the noise power spectral density in each chip. The SINR and FER can be derived using (1) and (2) respectively.

Here,

L is 22 octets for 802.15.4c DSSS O-QPSK 250kbps

BER calculation for 802.15.4c O-QPSK 250kbps are given in E.4.1.8 [B4].

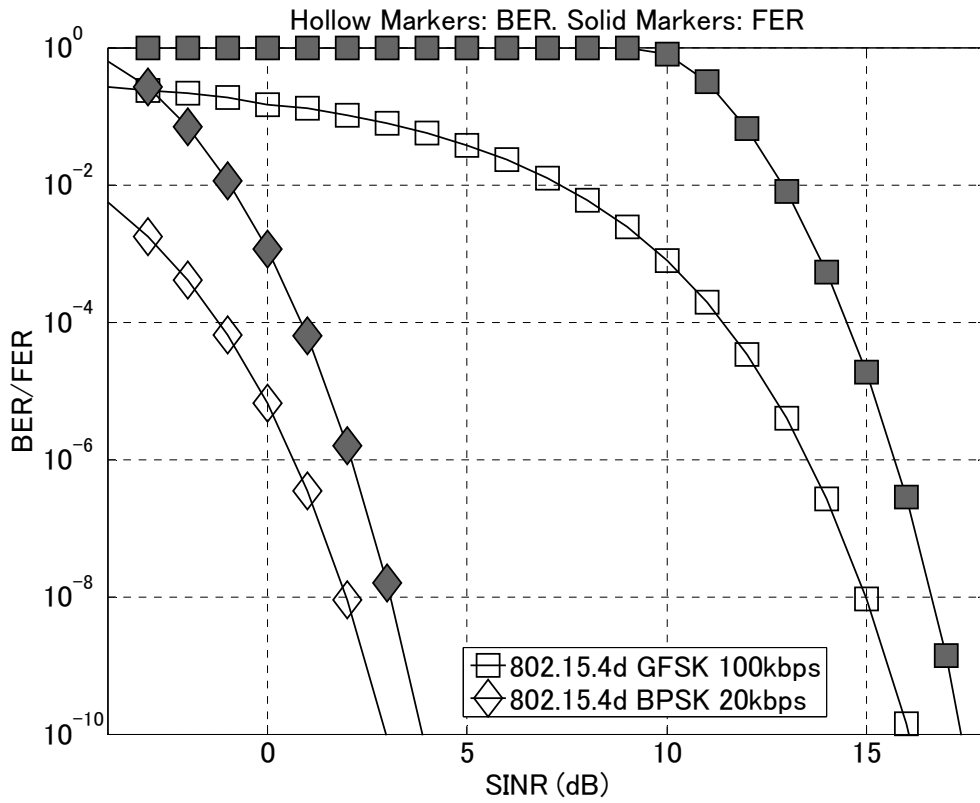The BER and FER curves are given in Figure 18.
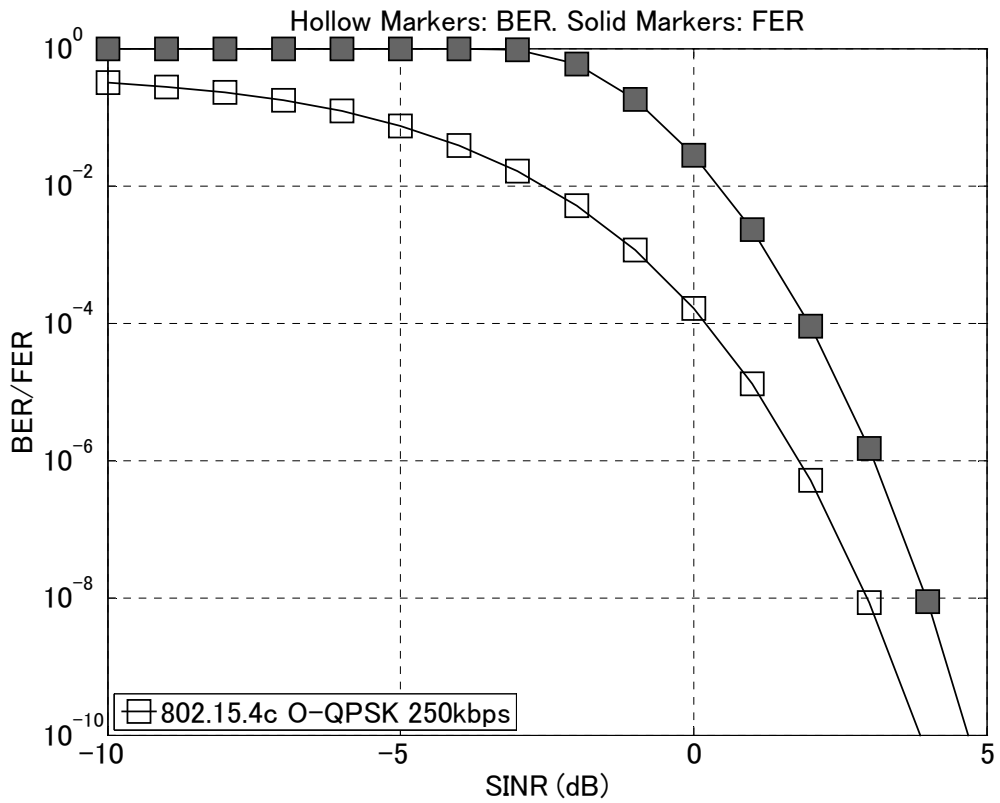
Figure 18 BER and FER vs. SINR for 802 Systems in the 779-787 MHz Band

4.7.2.   Coexistence Simulation Results

4.7.2.1. 802.15.4g PHY Modes as Victim Receivers

Figure 19 shows the relationship between the FER performance of the 802.15.4g FSK 50kbps, OFDM 200 kbps and O-QPSK 500kbps victim receivers corresponding to the distance between the victim receivers to the interferer. The list of interferers is given in Figure 19.
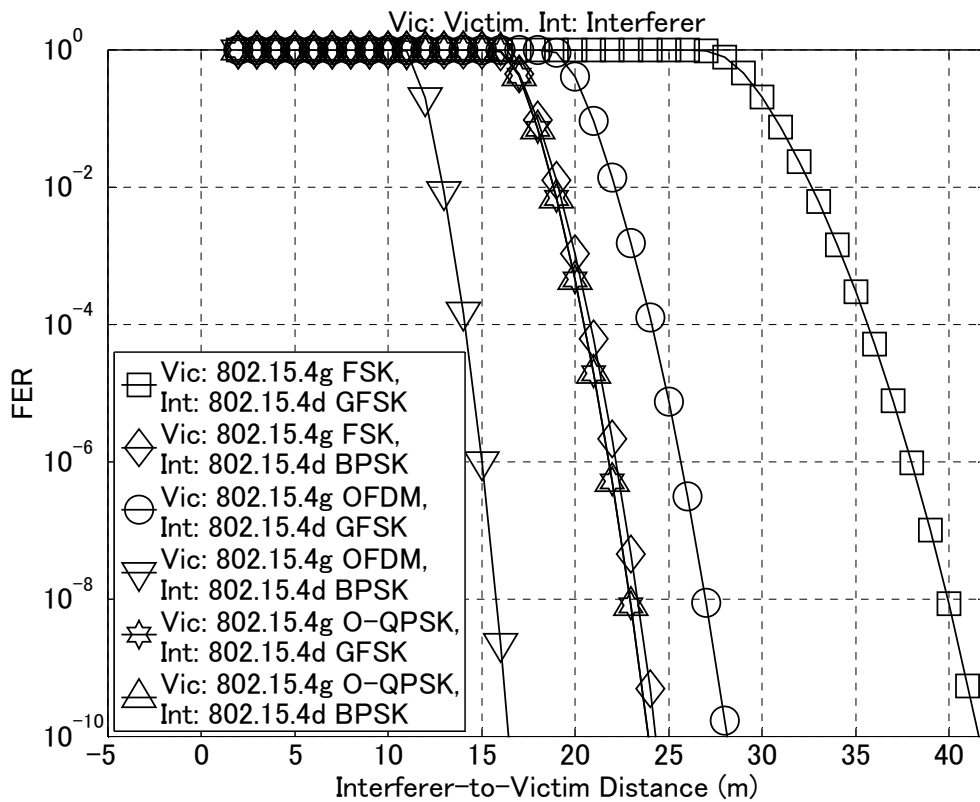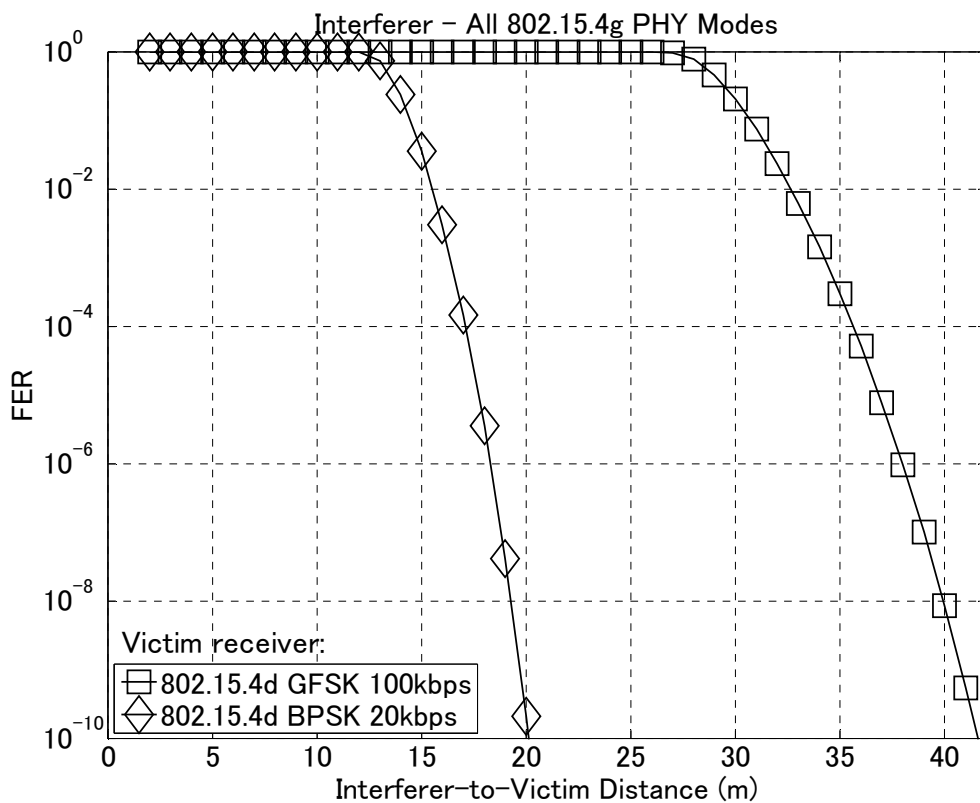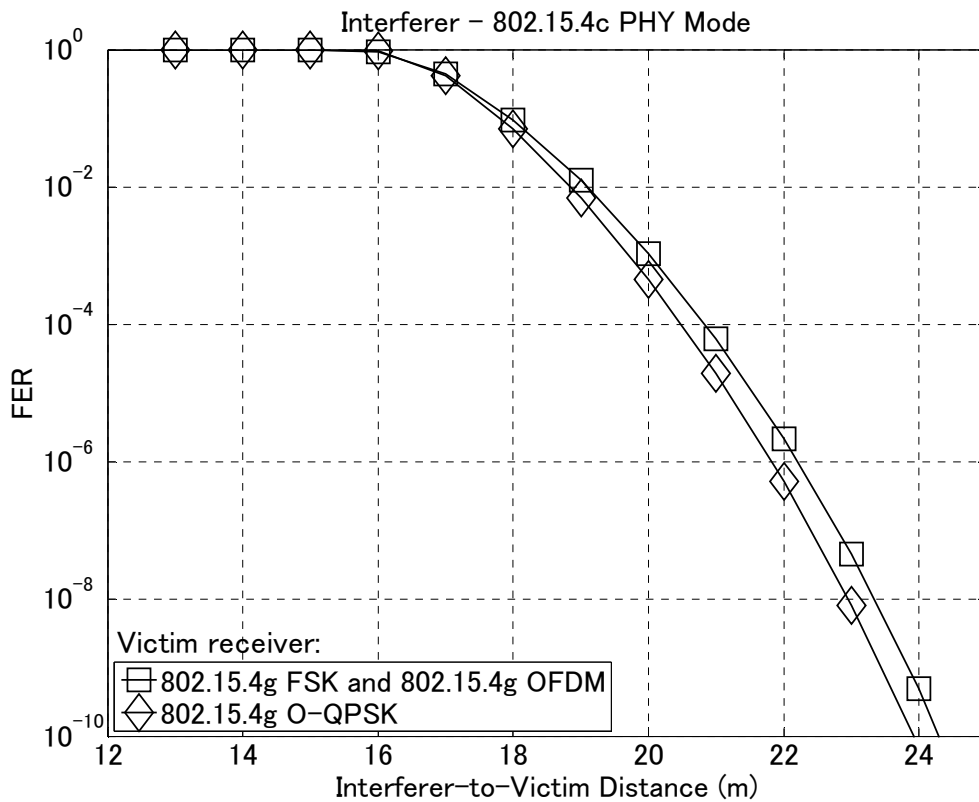

Figure 19 Victim FER vs. Distance between Interferer to all 802.15.4g Victim Receivers.

4.7.2.2. 802.15.4c PHY Modes as Victim Receivers

This sub-clause presents the results setting other 802 systems as the victim and 802.15.4g as the interferer. Figure 20 shows the relationship between the FER performances of the 802.15.4c (one PHY mode) victim receivers corresponding to the distance between the victim receivers to the 802.15.4g interferers. The list of interferers is given in the figure.
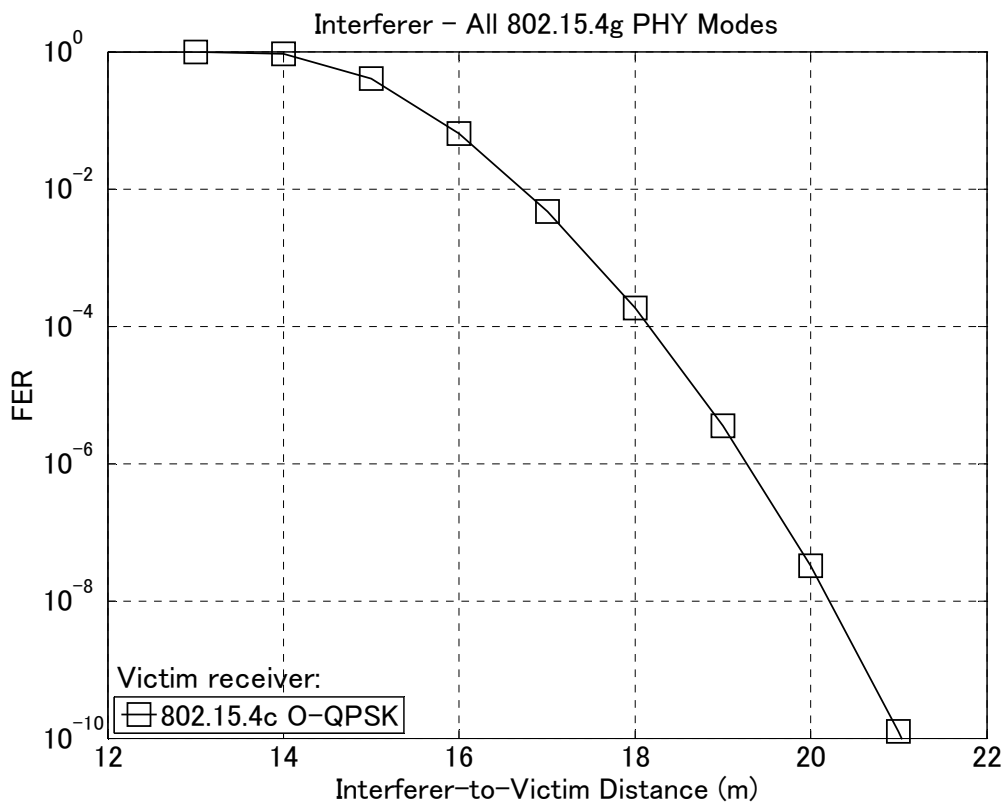
Figure 20 Victim FER vs. Distance between Interferer to 802.15.4c Victim Receiver. All 802.15.4g PHY modes in Table 12 display nearly similar characteristics as interferers.

5.   Detailed Coexistence Analysis and Interference Avoidance/Mitigation Techniques

5.1.   Channel Alignment

The channel alignment among 802.15.4g systems and other 802 systems are summarized in Table 13, Table 14, Table 15, Table 16 and Table 17 for respective bands within which multiple systems are coexisting. By knowing the locations of center frequencies and system bandwidth for different systems, it is possible to identify and occupy channels with the least likelihood to interfere or be interfered by other coexisting systems. The tables show the center frequencies for respective systems, while the system bandwidth can be obtained from Table 7, Table 8, Table 9, Table 10, Table 11 and Table 12.

5.1.1.   2400-2483.5 MHz (Worldwide)

Table 13 Channel Alignment for Systems in the 2400-2483.5 MHz Band

802.15.4g				802.11b	802.11g	802.11n	802.15.1	802.15.3	802.15.4
MR-FSK (200kHz)	MR-FSK (400kHz)	MR-O-QPSK	MR-OFDM	DSSS CCK	OFDM BPSK	OFDM QPSK	FHSS GFSK	SC D-QPSK	DSSS O-QPSK
2400.1									
	2400.2		2400.2						
2400.3									
2400.5									
	2400.6		2400.6						
2400.7									
2400.9									
...	2401		2401						
...	...		...						
...	...		...				2402		
...	...		...						
...	2403		2403				2403		
...	...		...						
...	...		...				2404		

...	...		...						
...	2405	2405	2405				2405		2405
...	...		...				...		
...	...	2410	...				2410		2410
...	...		...				...		
...	...		...	2412	2412	2412	2412	2412	
...	...		...				...		
...	2415	2415	2415				2415		2415
...	...		...				...		
...	2417		2417	2417	2417	2417	2417		
...	...		...				...		
...	...	2420	...				2420		2420
...	...	...	...				...		...
...	...	...	...	2422	2422	2422	2422		...
...	...	...	...	...	...	...	...		...
...	...	...	...	...	...	...	2428	2428	...
...	...	...	...	...	...	...	...	...	...
...	2437	...	2437	2437	2437	2437	2437	2437	...
...	...	...	...	...	...	...	...		...
...	2445	2445	2445	...	...	...	2445	2445	2445
...	...	...	...	...	...	...	...		...
...	...	...	...	2462	2462	2462	2462	2462	...
...	...	...	...	...	...	...	...		...
...	...	2480	...	...	...	...	2480		2480
...	...	...	...	...	...	...			
...	2483.4		2483.4	...	...	...			
2483.5				...	...	...			
				2484	2484	2484			

5.1.2. 902-928 MHz (United States)

Table 14 Channel Alignment for Systems in the 902-928 MHz Band

802.15.4g				802.15.4	
MR-FSK (200 kHz)	MR-FSK (400 kHz)	MR-O-QPSK	MR-OFDM	DSSS BPSK	DSSS O-QPSK
902.2					
902.4	902.4		902.4		
902.6					
902.8	902.8		902.8		
903					
903.2	903.2		903.2		
…	…		…		
904	904	904	904		
…	…		…		
906	906	906	906	906	906
…	…		…		
908	908	908	908	908	908
…	…		…		
910	910	910	910	910	910
…	…	…	…	…	…
922	922	922	922	922	922
…	…		…	…	…
924	924		924	924	924
…	…		…		
928	928		928		

5.1.3. 863-870 MHz (Europe)

Table 15 Channel Alignment for Systems in the 863-870 MHz Band

802.15.4g				802.15.4		
MR-FSK (200 kHz)	MR-FSK (400 kHz)	MR-O-QPSK	MR-OFDM	DSSS BPSK	PSSS ASK	DSSS O-QPSK
863.125						
	863.225		863.225			
863.325						
863.525						
	863.625		863.625			
863.725						
863.925						
	864.025		864.025			
…	…		…			
868.325		868.3		868.3	868.3	868.3
…	…	…	…			
	869.625	869.525	869.625			
869.725						

5.1.4. 950-958 MHz (Japan)

Table 16 Channel Alignment for Systems in the 950-958 MHz Band

802.15.4g					802.15.4d		
MR-FSK (200 kHz)	MR-FSK (400 kHz)	MR-FSK (600 kHz)	MR-O-QPSK	MR-OFDM	BPSK 1mW DSSS	BPSK 10mW DSSS	GFSK DSSS
	950.9		950.9	950.9			
951							
							951.1
951.2		951.2			951.2		
	951.3		951.3	951.3			
951.4							

							951.5
951.6							
	951.7		951.7	951.7			
951.8		951.8			951.8		
							951.9
952							
	952.1		952.1	952.1			
952.2	...		...	...			
	...		...	...			952.3
952.4	...	952.4	...	...	952.4		...
...	...	...	...	...	...		...
954.4	...	...	...	...	...	954.4	...
	954.5	...	954.5	954.5	...		...
954.6	...	...	...	...	...	954.6	...
...	...	...	...	...	...		...
955.4	...	955.4	...	...	955.4		...
...	...	...	...	...			955.5
...	...	...	...	...			
...	956.9	...	956.9	956.9			
957		...					
		...					
957.2		957.2					
957.4							
957.6							

5.1.5. 779-787 MHz (China)

Table 17 Channel Alignment for Systems in the 779-787 MHz Band

802.15.4g		802.15.4c	
MR- O-QPSK	MR- OFDM	O-QPSK DSSS	MPSK DSSS
	779.4		
	779.8		
780	...	780	780
	...		
782	...	782	782
	...		
784	...	784	784
	...		
786	...	786	786
	...		
	786.6		

5.2.   Coexistence with Transmit Power Control

The specifications of IEEE draft standard 802.15.4g addresses low data rate, wireless, smart metering utility networks with a key attribute of low power consumption. An effective control of transmit power not only reduces the power consumed for transmit operation by a SUN device but it also helps with coexistence of a SUN device with other devices sharing the same spectrum in conjuction with other key SUN device attributes such as an inherent low duty cycle of operation, possible minimization of air time by communicating only when a coordinated handshake has occurred.

Each SUN device can reduce the amount of interference it generates for the other coexisting devices by keeping its transmitted output power at the minimum level needed to achieve reliable communication. A SUN device can implement a simple mechanism of controlling its transmitted power using a measurement of the received coex-beacon power. The plot in Figure 21 shows using Hata's Model (see section 4.2.3) the path loss

and the received coex-beacon strength as a function of the distance between the coex beacon transmitting coordinator and a receiving SUN device.
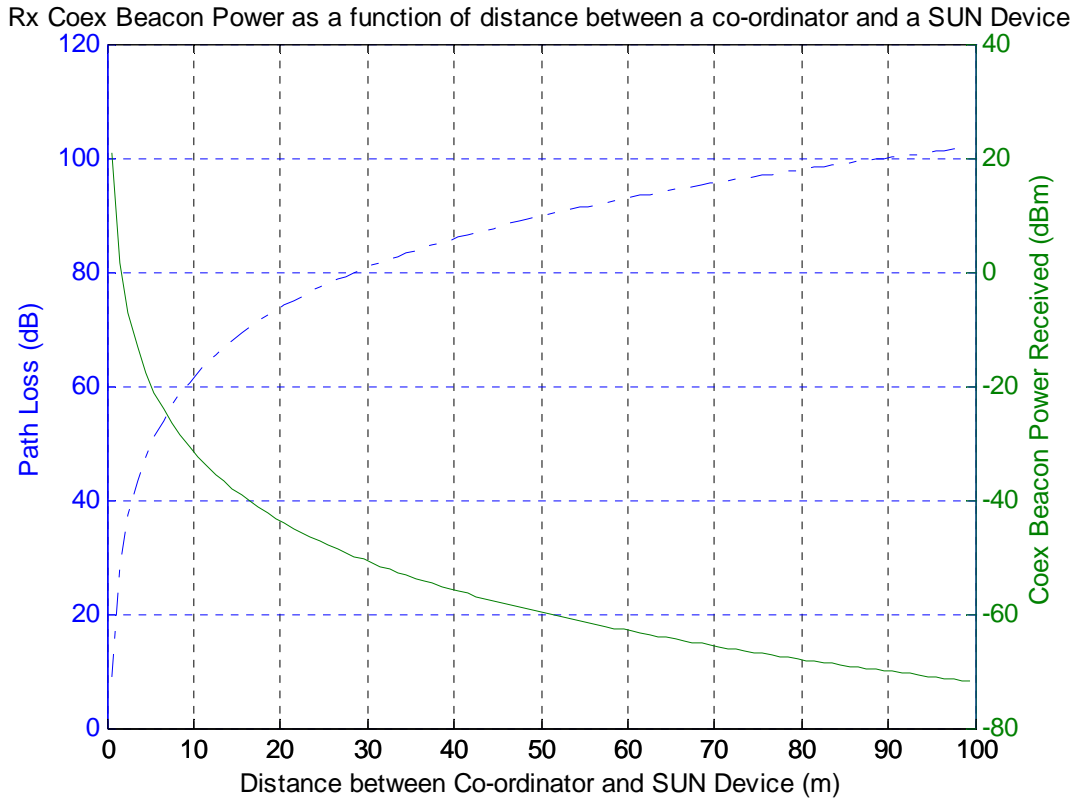
Rx Coex Beacon Power as a function of distance between a co-ordinator and a SUN Device

Figure 21 Coex-beacon signal power as a function of the path loss due to inter-device distance

The SUN device receiving the coex-beacon can make a measurement of the received coex-beacon signal strength, *e.g.*, using a mechanism such as received signal strength indictor (RSSI), which can also be used by the automatic gain control mechanism for the receiver chain, to estimate the strength of the incident coex-beacon signal say P_{beacon_rx}. The SUN device can then perform a simple calculation to determine the TX power that it should use to communicate with the coordinator transmitting the coex-beacon as follows:

Let

$P_{tx,max}$ Maximum allowable TX output power (dBm)

$P_{tx,min}$ Minimum allowable TX output power (dBm)

$P_{tx,step}$ TX power control step size (dB)

P_{beacon} Transmitted power of the beacon (assume 30 dBm)

$RX\_min\_sensitivity$ Minimum RX sensitivity of a SUN device (using -90 dBm)

RX_SNRmin Minimum SNR desired for transmission (assume 4 dB)

Then,

$$P_{tx} = \max(\min(P_{tx,max}, (P_{beacon} - P_{beacon\_rx}) + RX\_min\_sensitivity + RX\_SNRmin), Ptx\_min)$$

If the TX power is implemented with a gain step size of $P_{tx,step}$, the quantized TX power can be computed as:

$$P_{tx,\,quant} = \mathrm{round}(P_{tx}/\,P_{tx,step})*\,P_{tx,step}$$

An example calculation for the Transmitter power control for a distance of up to 250m around the co-ordinator using assumptions of $P_{tx,max}$ = 30dBm, $P_{tx,min}$ = -30dBm, $P_{tx,step}$ = 6dB, P_{beacon} = 30dBm, $RX\_min\_sensitivity$ = -90dBm, RX_SNRmin = 4dB is shown below:

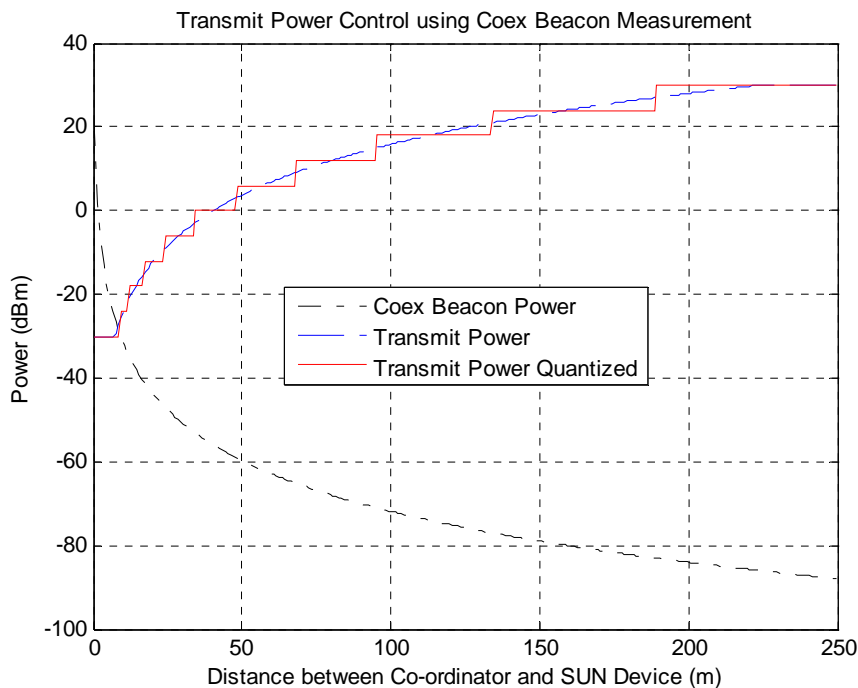**Figure 22 1W TX power control using coex-beacon signal power measurement**

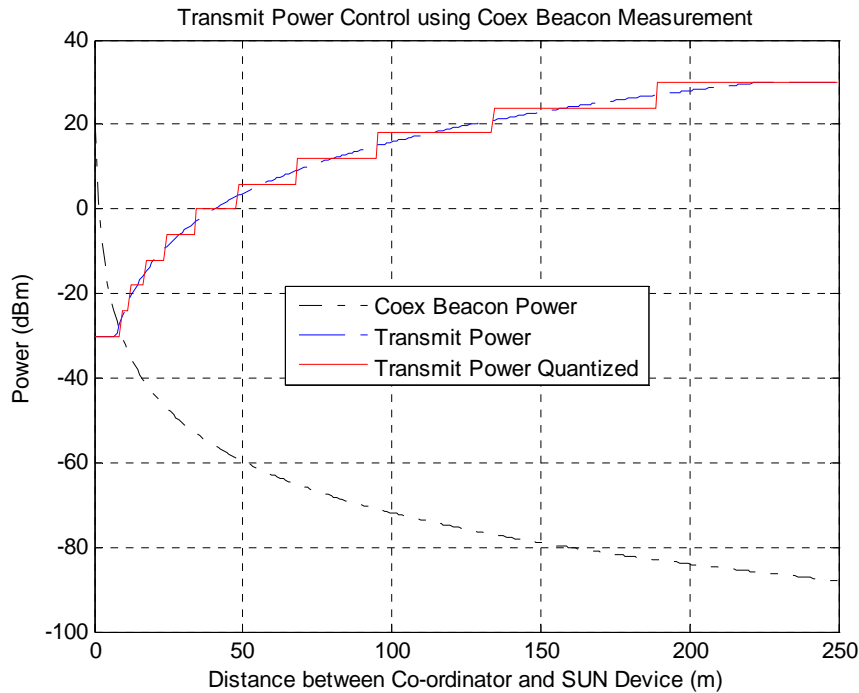Transmit Power Control using Coex Beacon Measurement

Figure 23 1mW TX power control using coex-beacon signal power measurement

It is evident using Figure 22 and Figure 23 that using the proposed scheme, the TX transmits at less than full power for 76% of the time. The power consumption in an efficient implementation of the TX heavily depends on the transmitted output power. Use of a power control mechanism, such as described can result in potentially a saving of 62% of average power consumed[1] in the TX operation by SUN devices assuming a uniformly distributed mesh of SUN devices around a centrally located coordinator.

For the frequency bands in which the TX output power is limited to 100μW (or $P_{tx,max}$ = 20 dBm), assuming that the minimum TX controllable power $P_{tx,min}$ = -22dBm, implementing a power control strategy as described above results in use of less than max transmit power for 42% of the time. Correspondingly, this results in a 16.4% saving in the power consumed by the transmit operation.

---

[1] The power savings have been computed using a TX power consumption profile of the form $+\beta \cdot e^{\gamma(P_{tx}-P_{tx,max})}$, where α is the power consumption of TX at $P_{tx,min}$, β is the power consumption difference between $P_{tx,max}$ and $P_{tx,min}$ and γ is an implementation dependant power scaling constant.

5.3.   Coexistence with Low Duty Cycle

Duty cycle is known as the proportion of the signal duration to the regular interval or period of time. A part of devices specified in 802.15.4g SUN, primarily the battery-powered devices, operate in a very low duty cycle. While typical network device may operate at duty cycle as low as below 1%, the coordinators may operate at duty cycle of around 10%, as described in E5.4 [B4]. These low duty cycle devices only transmit energy into the air for a short duration in a long interval, and are less likely to cause interference to other co-located networks. In fact, a combination of low transmission duty cycle, low transmit power and use of appropriate spacing for CCA greatly reduces the average probability of blocking/interference by a SUN device to its neighbors.

Figure 24 below shows the data throughput for a SUN device, which is being duty cycled. The plots assume a minimal communication overhead of 15% only. Accounting for the typical data throughput overhead due to coding, framing, redundancy and MAC; a more practical 60% overhead case is shown in Figure 25. The power consumption in a communication device is proportional to its active time. The data suggests that for a required set of data symbols to be transmitted, it is more power efficient if a higher data rate (if possible with comparable power consumption) is chosen and the active duty cycle of the SUN communication device is lowered.

Effective Data throughput of a SUN device operating at a low duty cycle with a 15% Overhead

Figure 24 SUN device throughput rate operating at a low duty cycle with a 15% throughput overhead for various PHY data rates.

Effective Data throughput of a SUN device operating at a low duty cycle with a 60% Overhead

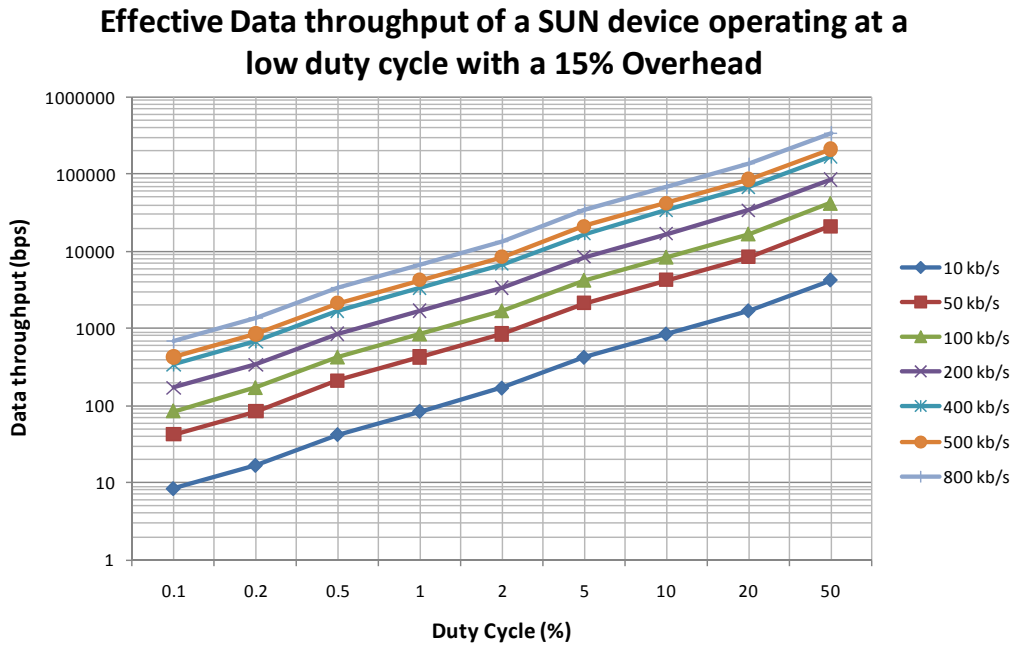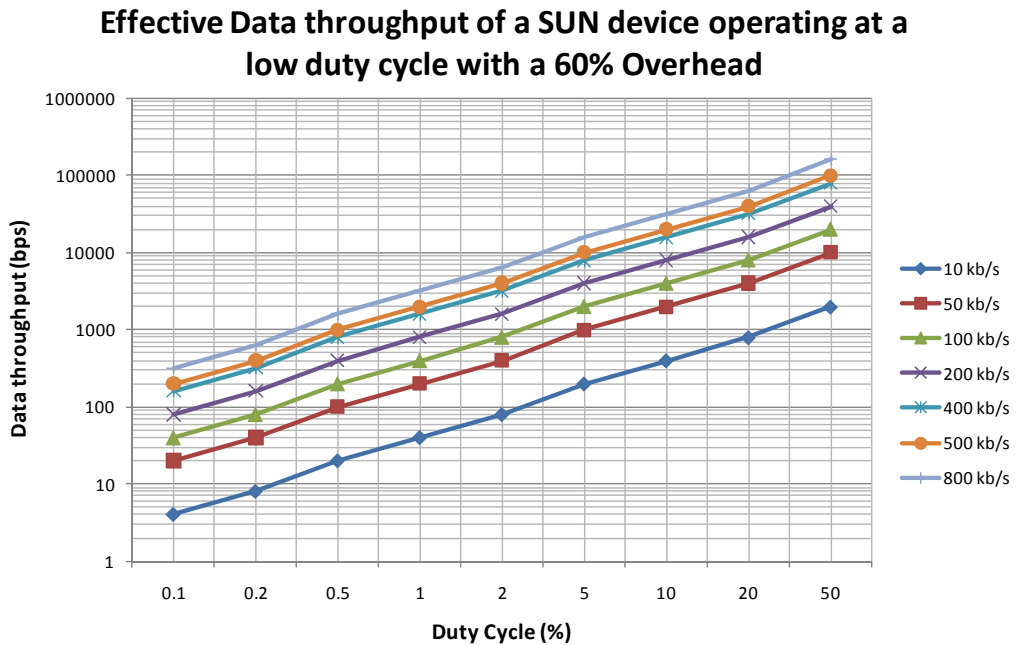**Figure 25 SUN device throughput rate operating at a low duty cycle with a 60% throughput overhead for various PHY data rates.**

5.4 Performance of CSM

MPM is an interference avoidance mechanism equipped with a common signaling known as CSM. CSM is a PHY mode employed for different PHYs within the 802.15.4g to negotiate among each other prior to starting respective networks. While the MPM protocols and the PHY specification of CSM are clearly outlined, the receiver design is implementation-dependent.

In this section, the performance of CSM is evaluated. The system model is constructed by an FSK transmitter, the 900MHz propagation channel (typically a two-path Rayleigh fading channel) and two different types of receivers, the correlator and the energy detector. In actual implementations, receiver design may choose either one to capture the CSM in order to detect the presence of an already existing system in the channel.

Figure 26 shows the performance for both the BER for the correlator and the mis-detection probability P_{md} for the energy detector. The results of the performance determine the likelihood of detecting presence/absence of the CSM, thus the effective ness of coexistence. It is observed that the correlator has an approximately 25dB improvement as compared to energy detector at FER=0.01, *i.e.* the required error criterion.
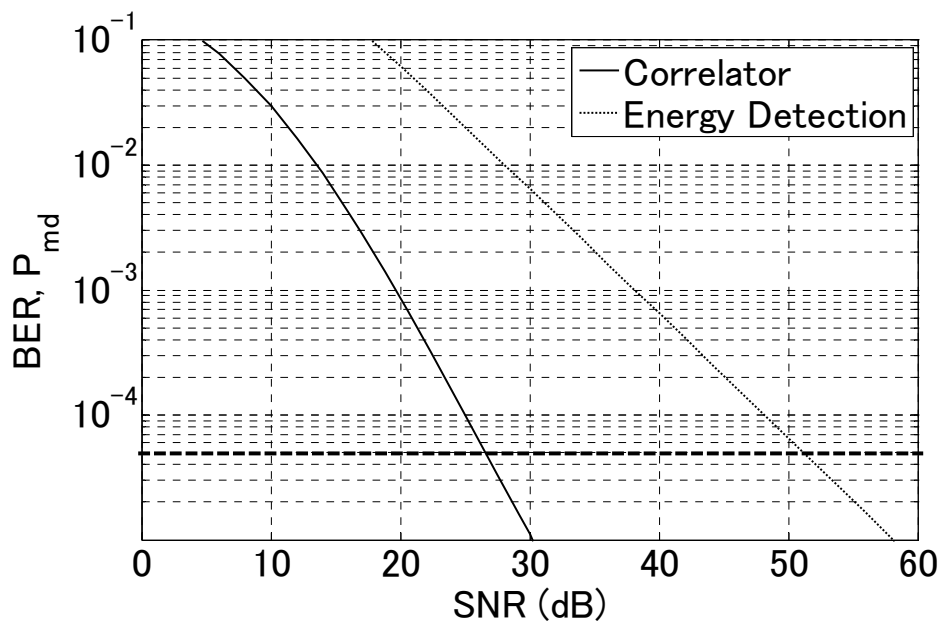

Figure 26 Performance comparison between CSM correlator and energy detector. Horizontal line across BER=5*10⁻⁵ is the equivalent BER for FER=0.01, as required in 802.15.4g.

6.   Discussions and Conclusion

This document has presented the overview of coexistence analysis for the IEEE 802.15.4g and other IEEE 802 systems. Firstly, the document listed all the involved homogeneous systems within the 802.15.4g and heterogeneous systems across other 802 systems. Secondly, an overview of all the available coexistence mechanisms applicable to 802.15.4g is given. Thirdly, analysis on performance due to coexisting/co-locating systems is presented considering no assistance from any coexistence mechanisms. Fourthly, mechanisms for the purpose of interference avoidance/mitigation for 802.15.4g are proposed and evaluated.

To comprehensively describe the findings of the coexistence evaluation, parameter d_{cri} is defined as the critical distance below where the interferer causes performance degradation greater than that required by respective standards. As an example, the required FER for 802.15.4g MR-FSK is 0.01, d_{cri} is the minimum distance between victim receiver and interferer transmitter that gives FER=0.01 along the MR-FSK FER curve. If the distance becomes smaller than d_{cri}, FER will be degraded beyond the required value of 0.01.

Table 18 summarizes the values of parameter d_{cri} for frequency bands with coexisting heterogeneous systems. It is observed that even without any coexistence mechanism, the 802.15.4g system are able to achieve the required FER given that an interferer is located as near as 12m away. Furthermore, with the employment of various coexistence mechanism listed in this document, a more harmonious radio environment can be achieved.

Table 18 Critical distance d_{cri} for 802.15.4g in different frequency bands.
Interferer: Other 802 systems. Victim: 802.15.4g systems.

Frequency Band	d_{cri}
2400-2483.5 MHz (Worldwide)	~12-25m
902-928 MHz band (United States)	~12-20m
863-870 MHz band (Europe)	~12-20m
950-958 MHz band (Japan)	~12-30m
779-787 MHz band (China)	~20m

Annex A

Matlab Program for Plotting BER/FER Curves for 802.15.4g PHY Modes

```matlab
%%%%%%%%%%%%%%%%%%% Parameter Settings %%%%%%%%%%%%%%%%%%%%%%%%%%%%

SINR = 0:20;                                    % SINR (Ec/N0) in dB

trellisOFDMOQPSK = poly2trellis(7,[133 171]);   % convolutional code generators for OFDM and DSSS QPSK

spectOFDMOQPSK = distspec(trellisOFDMOQPSK);

L_FSK50 = 250*8;                                % frame length for FSK 50kbps

L_OFDM200 = 20*8;                               % frame length for OFDM QPSK 200kbps

L_OQPSK500 = 20*8;                              % frame length for DSSS O-QPSK 500kbps


modlev_FSK50 = 1;                               % modulation level for FSK 50kbps

modlev_OFDM200 = 2;                             % modulation level for OFDM 200kbps

modlev_OQPSK500 = 2;                            % modulation level for OQPSK 500kbps


Rfec_FSK50 = 1;                                 % FEC coding rate for FSK 50kbps

Rfec_OFDM200 = 0.5;                             % FEC coding rate for OFDM 200kbps

Rfec_OQPSK500 = 0.5;                            % FEC coding rate for OQPSK 500kbps


SF_FSK50 = 1;                                   % spreading factor for FSK 50kbps

SF_OFDM200 = 1;                                 % spreading factor for OFDM 200kbps

SF_OQPSK500 = 2;                                % spreading factor for OQPSK 500kbps


%%%%%%%%%%%%%%%%%%%%% Per-bit Energy Calculations %%%%%%%%%%%%%%%%%%

EbN0_FSK50 = SINR - 10*log10(modlev_FSK50) - 10*log10(Rfec_FSK50) + 10*log10(SF_FSK50);

EbN0_OFDM200 = SINR - 10*log10(modlev_OFDM200) - 10*log10(Rfec_OFDM200) + 10*log10(SF_OFDM200);

EbN0_OQPSK500 = SINR - 10*log10(modlev_OQPSK500) - 10*log10(Rfec_OQPSK500) + 10*log10(SF_OQPSK500);

%%%%%%%%%%%%%%%%%%%%%% BER / FER Calculations %%%%%%%%%%%%%%%%%%%%%%

BER_FSK50 = berawgn(EbN0_FSK50,'fsk',2,'coherent');    % BER for FSK 50kbps

BER_OFDM200 = bercoding(EbN0_OFDM200,'conv','hard',0.5,spectOFDMOQPSK);

                                                % BER for OFDM QPSK 200kbps

BER_OQPSK500 = bercoding(EbN0_OQPSK500,'conv','hard',0.5,spectOFDMOQPSK);

                                                % BER for DSSS O-QPSK 500kbps

FER_FSK50 = 1-((1-BER_FSK50).^L_FSK50);         % FER for FSK 50kbps

FER_OFDM200 = 1-((1-BER_OFDM200).^L_OFDM200);   % FER for OFDM QPSK 200kbps

FER_OQPSK500 = 1-((1-BER_OQPSK500).^L_OQPSK500); % FER for DSSS O-QPSK 500kbps
```

Matlab Program for Plotting BER/FER Curves for Other 802.11/15 PHY Modes in the 2400-2483.5 MHz Band

```matlab
% BER and FER calculation for 802 systems in the 2.4GHz band


%%%%%%%%%%%%%%%%%%% Parameter Settings %%%%%%%%%%%%%%%%%%%%%%%%%%
SINR = -10:20;                              % SINR in dB
sinrp = 10.^(SINR./10);                     % SINR in linear power


trellisWLAN = poly2trellis(7,[133 171]);    % convolutional code generators for WLAN
spectWLAN = distspec(trellisWLAN);


L_11b = 1024*8;                             % frame length for 802.11b CCK 11Mbps
L_11g = 1000*8;                             % frame length for 802.11g OFDM 6Mbps
L_11n = 4096*8;                             % frame length for 802.11n OFDM 18Mbps
L_15_1 = 1024*8;                            % frame length for 802.15.1 FHSS 1Mbps
L_15_3 = 1024*8;                            % frame length for 802.15.3 SC 22Mbps
L_15_4 = 22*8;                              % frame length for 802.15.4 DSSS 250kbps


modlev_11g = 1;                             % modulation level for 802.11g OFDM 6Mbps
modlev_11n = 2;                             % modulation level for 802.11n OFDM 18Mbps


Rfec_11g = 0.5;                             % FEC coding rate for 802.11g OFDM 6Mbps
Rfec_11n = 3/4;                             % FEC coding rate for 802.11n OFDM 18Mbps


SF_11g = 1;                                 % spreading factor for 802.11g OFDM 6Mbps
SF_11n = 1;                                 % spreading factor for 802.11n OFDM 18Mbps


%%%%%%%%%%%%%%%%%%%%% Per-bit Energy Calculations %%%%%%%%%%%%%%%%%
EbN0_11g = SINR - 10*log10(modlev_11g) - 10*log10(Rfec_11g) + 10*log10(SF_11g);
EbN0_11n = SINR - 10*log10(modlev_11n) - 10*log10(Rfec_11n) + 10*log10(SF_11n);


%%%%%%%%%%%%%%%%%%%%% BER / FER Calculations %%%%%%%%%%%%%%%%%%%%%%%
BER_11b  =  (128/255)  *  24*Qfunct(sqrt(4*sinrp))  +  16*Qfunct(sqrt(6*sinrp))  +  174*Qfunct(sqrt(8*sinrp))  +
16*Qfunct(sqrt(10*sinrp)) + 24*Qfunct(sqrt(12*sinrp)) + Qfunct(sqrt(16*sinrp));

                                            % BER for 802.11b CCK 11Mbps
```

```matlab
BER_11g = bercoding(EbN0_11g,'conv','hard',0.5,spectWLAN);      % BER for 802.11g OFDM 6Mbps

BER_11n = bercoding(EbN0_11n,'conv','hard',3/4,spectWLAN);      % BER for 802.11n OFDM 18Mbps

BER_15_1 = berawgn(SINR,'fsk',2,'noncoherent');                % BER for 802.15.1 FHSS 1Mbps

BER_15_3 = Qfunct(sqrt(sinrp));                                % BER for 802.15.3 SC 22Mbps


for sinr_cnt=1:length(SINR)

    BER_15_4_temp =0;

    for k=2:16

        part_temp = (-1)^(k) * (factorial(16)/factorial(k)/factorial(16-k)) * exp(20*sinrp(sinr_cnt)*((1/k)-1));

        BER_15_4_temp = BER_15_4_temp + part_temp;            % BER for 802.15.4 DSSS 250kbps

    end

    BER_15_4(sinr_cnt) = (8/15) * (1/16) * BER_15_4_temp;

end



FER_11b = 1-((1-BER_11b).^L_11b);                             % FER for 802.11b CCK 11Mbps

FER_11g = 1-((1-BER_11g).^L_11g);                             % FER for 802.11g OFDM 6Mbps

FER_11n = 1-((1-BER_11n).^L_11n);                             % FER for 802.11n OFDM 18Mbps

FER_15_1 = 1-((1-BER_15_1).^L_15_1);                         % FER for 802.15.1 FHSS 1Mbps

FER_15_3 = 1-((1-BER_15_3).^L_15_3);                         % FER for 802.15.3 SC 22Mbps

FER_15_4 = 1-((1-BER_15_4).^L_15_4);                         % FER for 802.15.4 DSSS 250kbps
```

Matlab Program for Plotting FER Curves of the 802.15.4g FSK PHY Mode in response to Interference Generated by Other 802 Systems in the 2400-2483.5 MHz Band

*This program is used to analyze systems other than the 802.15.4g FSK as the victim receiver by replacing the relevant parameters.

*This program is also used to analyze frequency bands other than the 2400-2483.5 MHz band by replacing the relevant parameters.

```matlab
% 802.15.4g FSK as the victim receiver

% Txv and Rxv - 802.15.4g FSK 50kbps

% Txi - 802.11b CCK 11Mbps and 802.11g 6Mbps


% Interferer and Victim Parameters

IV_Para.P_Tv = 0;                              % victim TX transmit power in dBm

IV_Para.P_Ti = 14;                             % interferer TX transmit power in dBm

IV_Para.BW_Rv = 200e3;                         % bandwidth for victim receiver in Hz

IV_Para.BW_Ti = 22e6;                          % bandwidth for interferer in Hz

IV_Para.d_D = 0.01;                            % victim transmitter to victim receiver distance in km

IV_Para.d_U = [0.001:0.001:1];                 % interferer transmitter to victim receiver distance in km

IV_Para.fc = 2437;                             % center frequency in MHz


% Hata Path Loss Model Parameters

PL_Para.h_ap = 10;                             % access point height

PL_Para.h_dev = 2;                             % device height

PL_Para.cf = 3.2 * (log10(11.75*PL_Para.h_dev))^2 - 4.97;   % correction factor for device height

PL_Para.h_int = 2;                             % interferer height


% Calculation of SINR
for x=1:length(IV_Para.d_D)

    for y=1:length(IV_Para.d_U)

        DUR(x,y) = DUR_calculator(IV_Para,PL_Para,y);

    end

end


BER_FSK50 = berawgn(DUR,'fsk',2,'coherent');   % BER for victim

L_FSK50 = 250*8;                               % victim signal frame length

FER_FSK50 = 1-((1-BER_FSK50).^L_FSK50);        % FER for victim
```

Matlab Function Program for Calculating the DUR Corresponding to Path Loss

```matlab
% Function to calculate DUR or SINR

function DUR = DUR_calculator(IV_Para,PL_Para,y)


% for desired link

G_Tv = 0;                                    % victim transmitter antenna gain

G_Rv = 0;                                    % victim receiver antenna gain

PL_D = 69.55 + 26.16 * log10(IV_Para.fc) + (44.9-6.55 * log10(PL_Para.h_ap)) * log10(IV_Para.d_D) - 13.82 *

log10(PL_Para.h_dev) - PL_Para.cf;

                                              % path loss for desired link in dB

D = 10*log10 (dB2lin(IV_Para.P_Tv) .* dB2lin(G_Tv) .* dB2lin(G_Rv)) - PL_D;

                                              % victim receiver received power from victim transmitter


% for undesired link

G_Ti = 0;                                    % interferer transmitter antenna gain

PL_U = 69.55 + 26.16 * log10(IV_Para.fc) + (44.9-6.55 * log10(PL_Para.h_int)) * log10(IV_Para.d_U(y)) - 13.82 *

log10(PL_Para.h_dev) - PL_Para.cf;

                                              % path loss for undesired link in dB


if (IV_Para.BW_Rv < IV_Para.BW_Ti)

    U = 10*log10 (dB2lin(IV_Para.P_Ti) .* dB2lin(G_Ti) .* dB2lin(G_Rv) .* (IV_Para.BW_Rv/IV_Para.BW_Ti) ) - PL_U;

                                              % victim receiver received power from interferer transmitter

                                              % if victim bandwidth is smaller than interferer bandwidth

elseif (IV_Para.BW_Rv >= IV_Para.BW_Ti)

    U = 10*log10 (dB2lin(IV_Para.P_Ti) .* dB2lin(G_Ti) .* dB2lin(G_Rv) ) - PL_U;

                                              % victim receiver received power from interferer transmitter

                                              % if victim bandwidth is larger than interferer bandwidth

end


DUR = D-U;                                    % DUR or SINR
```