

**IEEE P802.15**  
**Wireless Personal Area Networks**

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)	
Title	TG4g Coexistence Assurance Document	
Date Submitted	Sept. 2010	
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Re:		
Abstract	Analysis on coexistence of 802.15.4g with other systems in the same spectrum band	
Purpose	To address the coexistence capability of 802.15.4g	
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Release	The contributor acknowledges and accepts that this contribution becomes the property of IEEE and may be made publicly available by P802.15.	

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## 1. Introduction

### 1.1. Bibliography

[B1] IEEE Std. 802.15.1<sup>TM</sup> – 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<sup>TM</sup> – 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<sup>TM</sup> – 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<sup>TM</sup> – 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<sup>TM</sup> – 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<sup>TM</sup> /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.

## 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
CFP	contention free period
CSM	common signaling mode
CSMA/CA	collision avoidance multiple access / collision avoidance
DSSS	direct sequence spread spectrum
DUR	desired to undesired ratio
ED	energy detection
FER	frame error rate
FFD	full function device
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
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
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 a PHY specification 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 of one centralized network coordinator, called the network 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, OFDM and 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) 950-956 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) 400-430 MHz (Japan)
- (l) 470-510 MHz (China)
- (m) 922 MHz (Korea)

Out of the list, bands (a)-(e) are occupied by more than one 802.15.4g PHY, while bands (f)-(m) 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	O-QPSK	OFDM
2400-2483.5 MHz (Worldwide)	X	X	X
902-928 MHz (United States)	X	X	X
863-870 MHz (Europe)	X	X	X
950-955 MHz (Japan)	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		
400-430 MHz (Japan)	X		
470-510 MHz (China)	X		X
922 MHz (Korea)			

### 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.

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 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 the possible incoming coordinators. Note that support of the CSM is not mandatory for normal devices. The devices are under control of the coordinators, and will not commence communication before the coordinator has indicated the channel clear.

The details of the MPM and CSM are given in sub-clause 5.

### 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.

### 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 will 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.

#### 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 network 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.

#### 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.



#### 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 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 network 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.

#### 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-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.

#### 2.3.6. Channel Alignment

#### 2.3.7. 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 seize current transmissions, perform channel scan to find another channel with better quality, and occupy the channel. 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.

#### 2.3.8. 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 (*e.g.* one of other 802 systems) 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.

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.

#### 2.3.9. 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%. 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.

#### 2.3.10. Low Transmit Power

### 2.3.11. 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.

## 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 950-956 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 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 nominal 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, O-QPSK and 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	MR-FSK, O-QPSK, OFDM
802.11g	OFDM	
802.11n	OFDM	
802.15.1	FHSS	
802.15.3	SC	
802.15.4	DSSS	

## 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, O-QPSK and 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, O-QPSK, OFDM
	PSSS ASK	
	DSSS O-QPSK	
802.15.4c	DSSS BPSK	
802.11 SIG*	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, O-QPSK and 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, O-QPSK, OFDM
	PSSS ASK	
	DSSS O-QPSK	
802.15.4c	DSSS BPSK	

### 3.4. Coexisting Systems in 950-956 MHz Band (Japan)

Table 5 shows the list of other 802 systems that are sharing the 950-956 MHz band with the MR-FSK PHY in 802.15.4g.

**Table 5: Dissimilar Systems Coexisting with 802.15.4g Systems within the 950-956 MHz Band**

System	PHY Specification	Involved 802.15.4g System
802.15.4d	DSSS GFSK	MR-FSK
	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 O-QPSK and 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	O-QPSK, 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 the each of the MR-FSK, OFDM and 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
	OFDM	200	0	--	200kbps QPSK CC $R_{FEC}=1/2$
	O-QPSK	2000	0	-100	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 8 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:

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

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.

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

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

where,

$L$  is the average frame size

$L$  is 250 octets for MR-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.

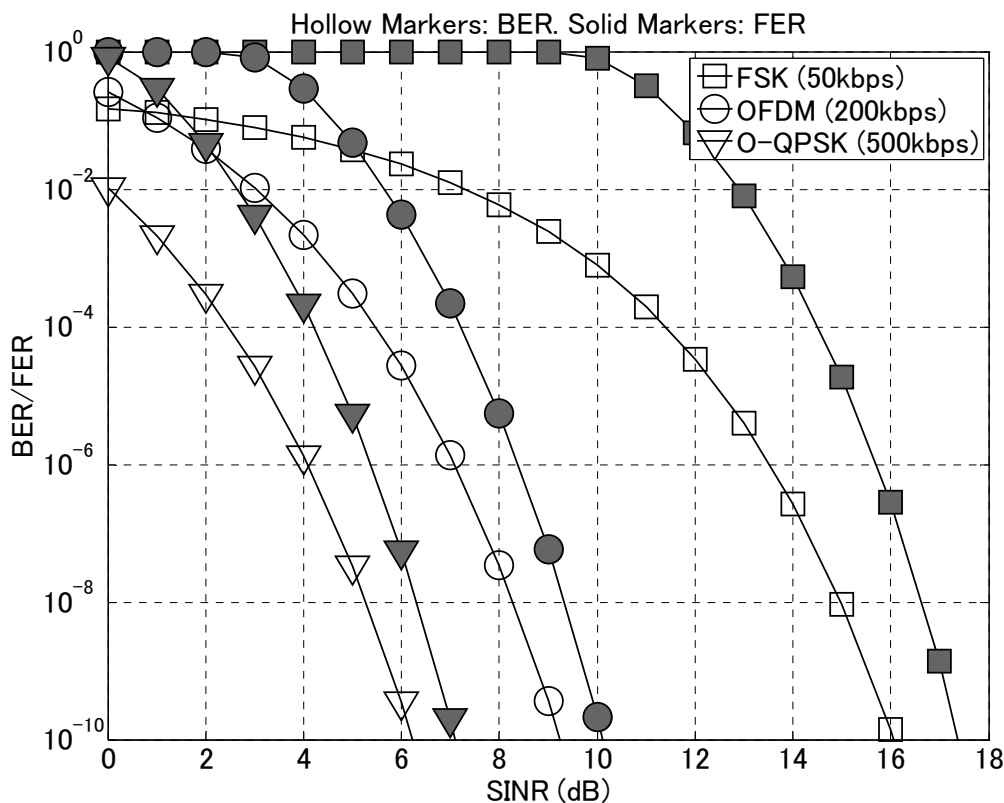


Figure 1 BER and FER vs. SINR for 802.15.4g PHY Modes

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  $R_{xv}$  (with receive power  $P_{Rv}$  and antenna gain  $G_{Rv}$ ) receives the desired signal from the victim transmitter  $T_{xv}$  (with transmit power  $P_{Tv}$  and antenna gain  $G_{Tv}$ ) located at distance  $d_D$ , while an interferer transmitter  $T_{xi}$  (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  $R_{XV}$ , the power received from  $T_{XV}$ , known as  $P_{R_V}$  (in dB scale) is given as:

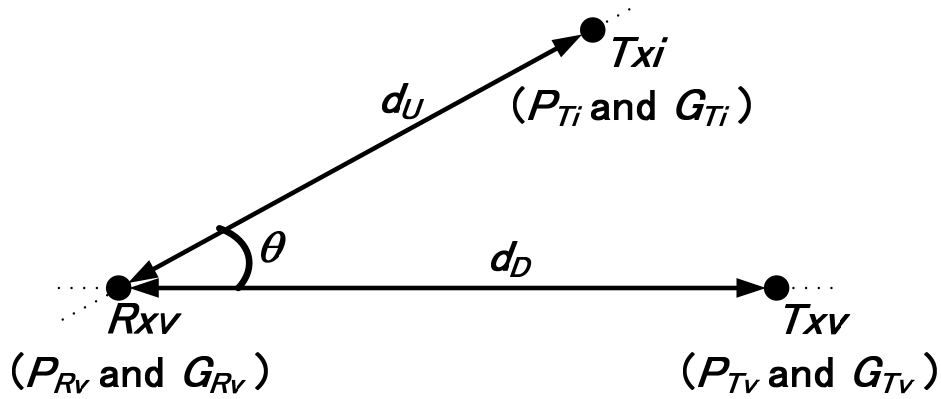
$$P_{R_V} = P_{T_V} + G_{T_V} + G_{R_V} - L_p(d_D)$$

On the other hand, the power received from  $T_{Xi}$ , known as  $P_{R_V}'$  (in dB scale) is given as:

$$P_{R_V}' = P_{T_i} + G_{T_i} + G_{R_V} - L_p(d_U)$$

Here, all antennas are assumed to be omni-directional, thus angle  $\theta$  can be neglected. Therefore, the ratio between the desired signal power and the interference power is given as:

$$\text{SIR} = P_{R_V} / P_{R_V}'$$



**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:

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

where,

- $f_c$  is the operating frequency
- $h_b$  is the height of the network coordinator
- $h_m$  is the height of the device

$d$  is the distance between network 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 9 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	11Mbps CCK
802.11g	OFDM	22	14	-88	6Mbps BPSK CC $R_{FEC}=1/2$
802.11n	OFDM	22	14	-83	18Mbps QPSK CC $R_{FEC}=3/4$
802.15.1	FHSS	1	0	-70	1Mbps GFSK

802.15.3	SC	15	8	-75	22Mbps DQPSK
802.15.4	DSSS	2	0	-85	250kbps O-QPSK

#### 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

The Matlab source codes for the BER/FER calculations are given in [Annex A](#).

The Q function is defined in C.3.6.6.

The BER and FER curves are given in Figure 2.

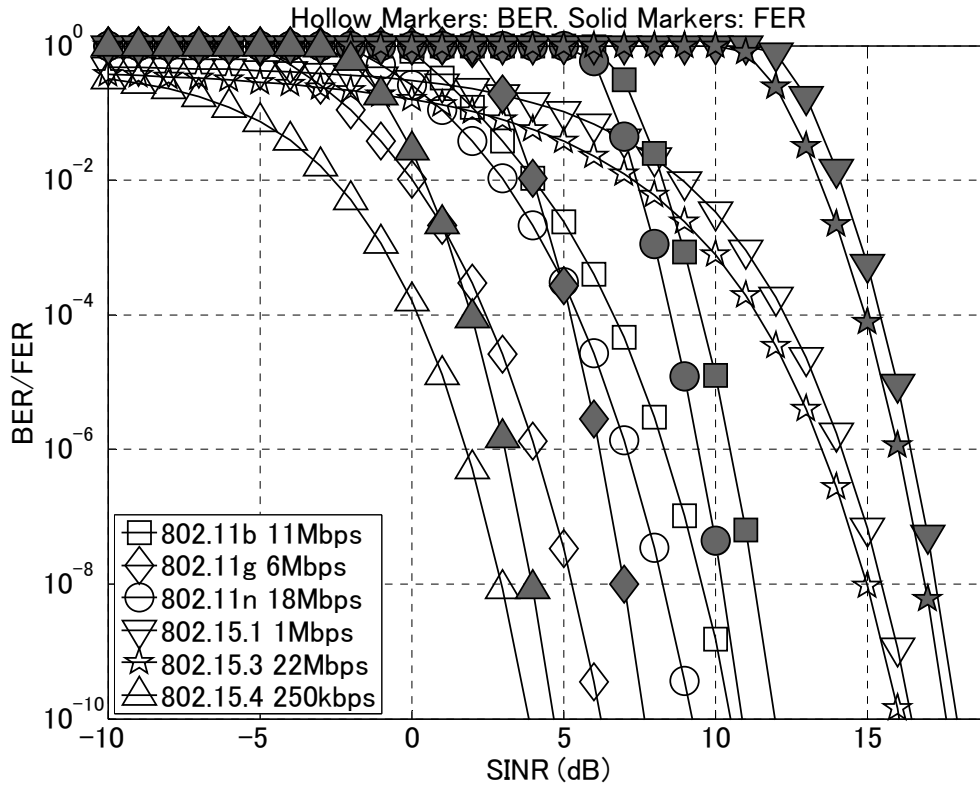


Figure 3 BER and FER vs. SINR for 802 Systems in the 2400-2483.5 MHz Band

4.3.2. Coexistence Simulation Results

4.3.2.1. 802.15.4g FSK 50kbps Mode as Victim Receiver

Figure 3 shows the relationship between the FER performance of the 802.15.4g MR-FSK victim receiver corresponding to the distance between the victim receiver to the interferer. The list of interferers is given in the figure.

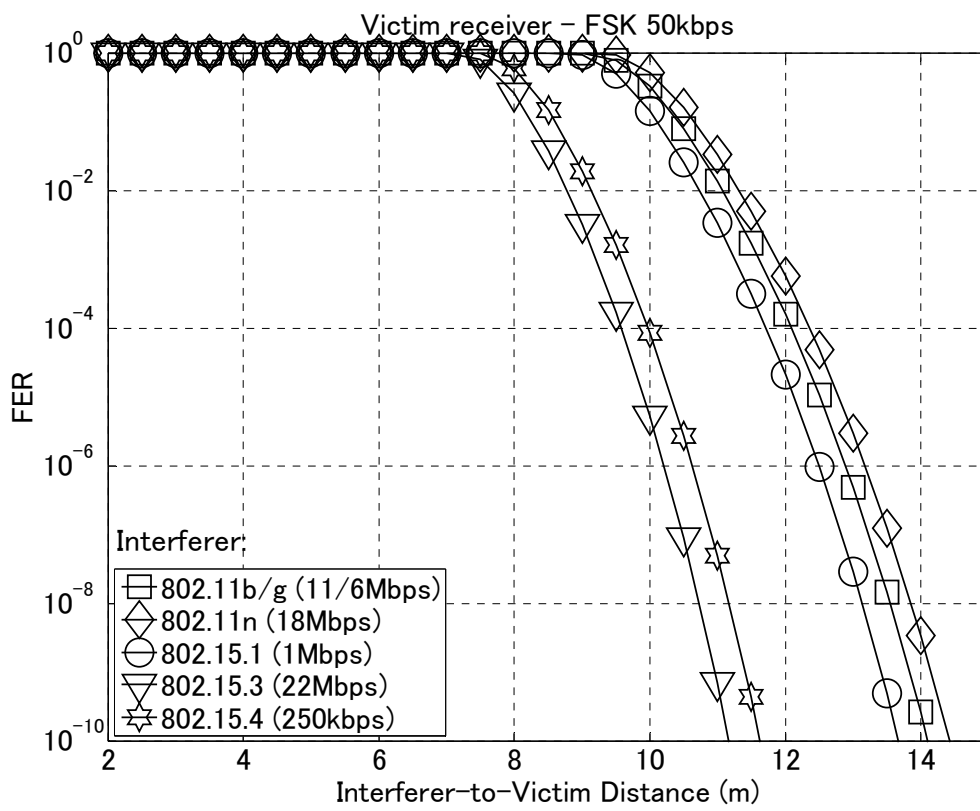


Figure 4 FER vs. Distance between Interferer to 802.15.4g MR-FSK Victim Receiver

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 the figure.

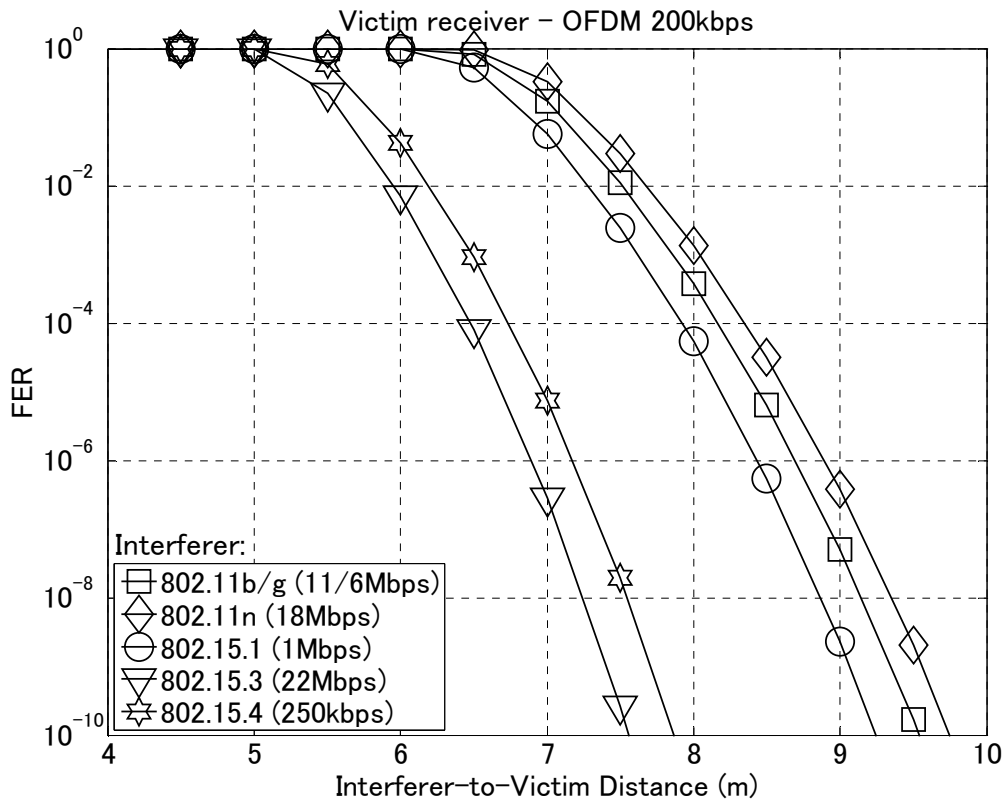


Figure 5 FER vs. Distance between Interferer to 802.15.4g OFDM Victim Receiver

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 the figure.

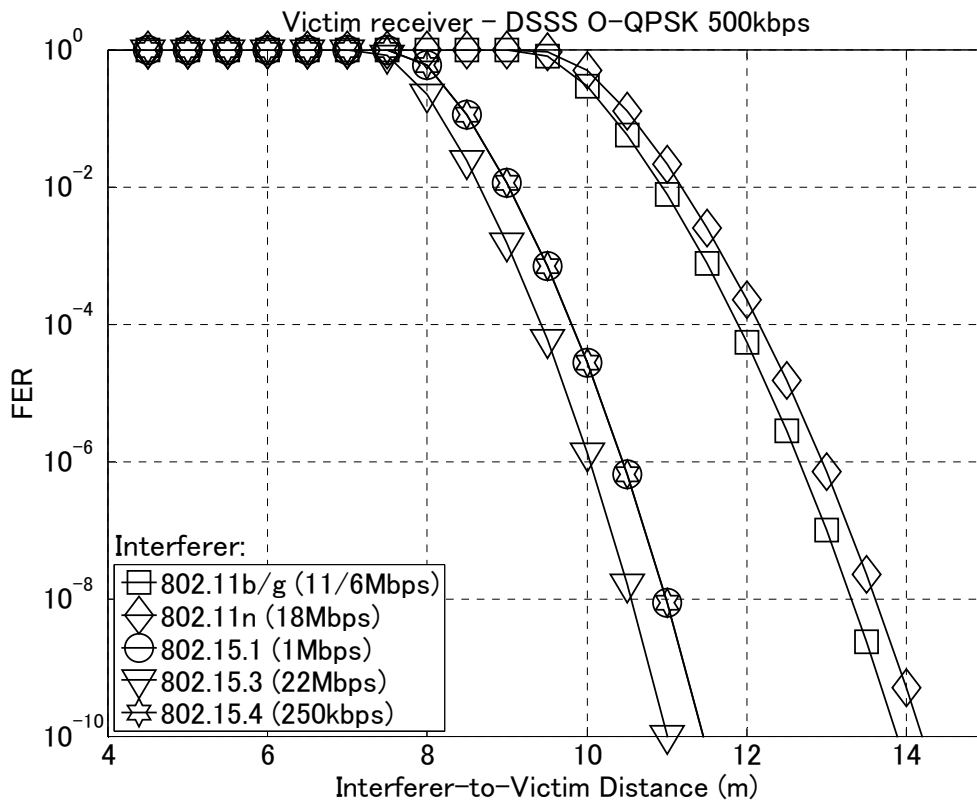


Figure 6 FER vs. Distance between Interferer to 802.15.4g O-QPSK Victim Receiver

4.3.2.4. 802.11 Systems 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. The list of interferers is given in the figure.

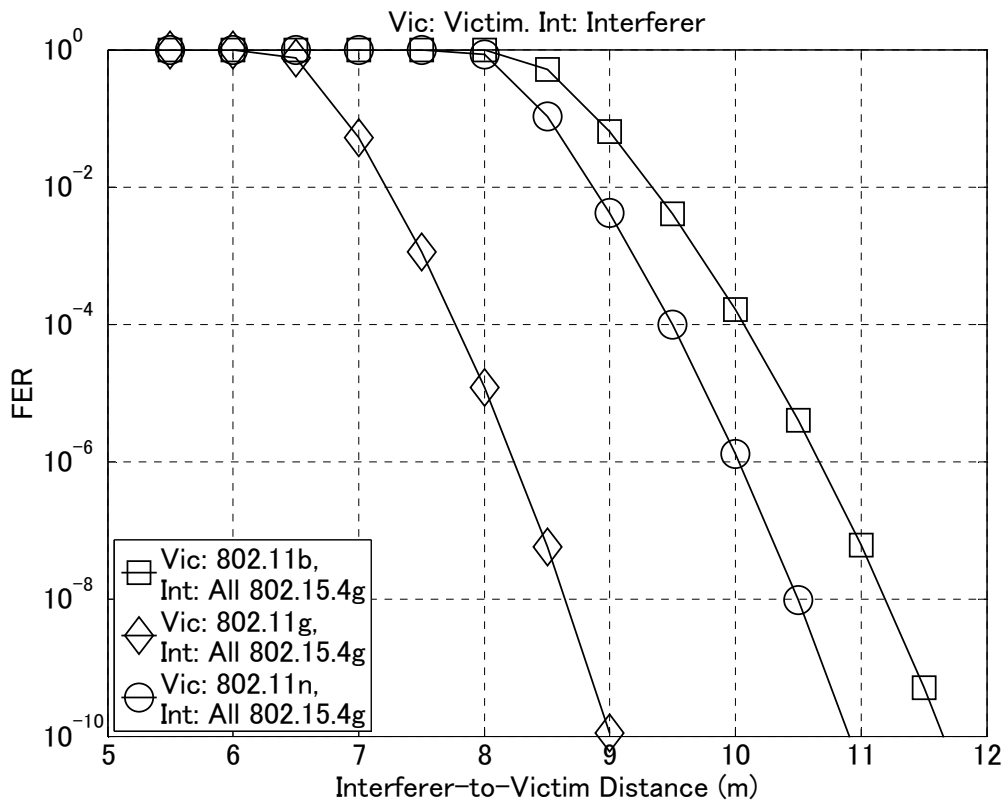


Figure 7 FER vs. Distance between Interferer to 802.11 Victim Receivers. All 802.15.4g display nearly similar characteristics as interferers.



4.3.2.5. 802.15 Systems 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 the figure.

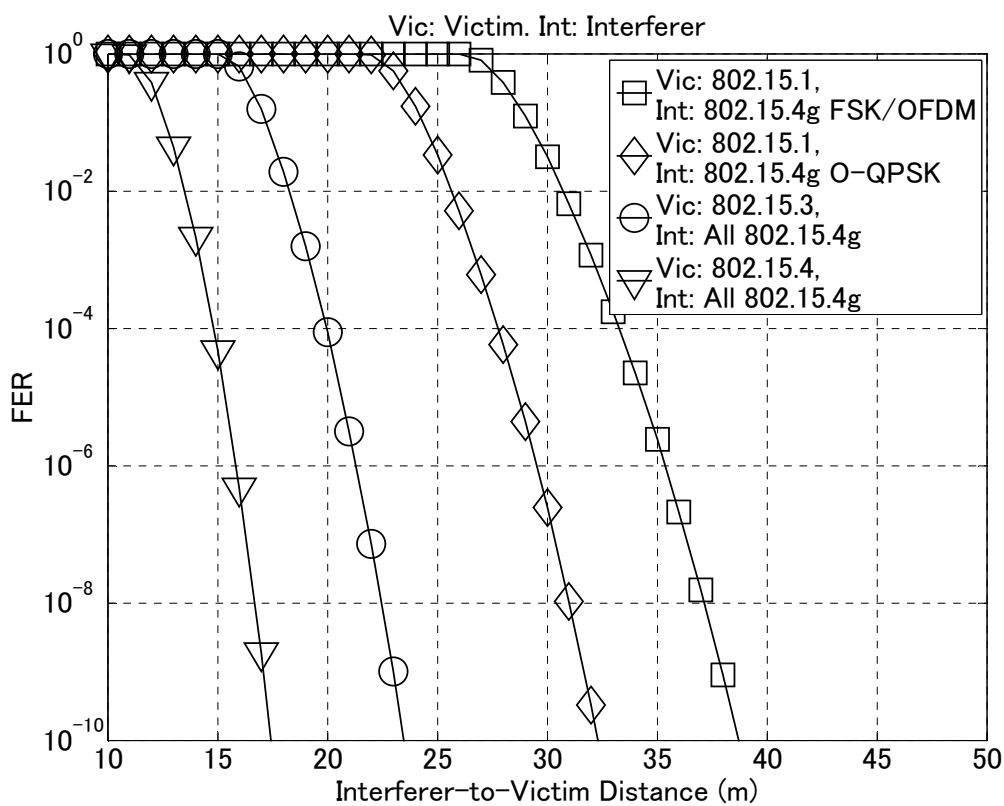


Figure 8 FER vs. Distance between Interferer to 802.15 Victim Receivers. All 802.15.4g display nearly similar characteristics as interferers.

## 4.4. 902-928 MHz Band Coexistence Performance

: 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	40kbps BPSK
	PSSS ASK	2	0	-85	250kbps ASK
	DSSS O-QPSK	2	0	-85	250kbps O-QPSK
802.15.4c	DSSS BPSK	2	0	-92	40kbps BPSK
802.11*	Currently in progress, specification not available				

## 4.5. 863-870 MHz Band Coexistence Performance

: 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	20kbps BPSK
	PSSS ASK	2	0	-85	250kbps ASK
	DSSS O-QPSK	2	0	-85	250kbps O-QPSK
802.15.4c	DSSS BPSK	2	0	-92	20kbps BPSK

## 4.6. 950-956 MHz Band Coexistence Performance

**: Major Parameters of Systems in the 950-956 MHz Band**

<b>System</b>	<b>PHY Spec.</b>	<b>Receiver Bandwidth (MHz)</b>	<b>Transmit Power (dBm)</b>	<b>Receiver Sensitivity (dBm)</b>	<b>PHY Mode</b>
802.15.4d	DSSS GFSK	0.2 (non-DSSS) 0.6 (DSSS)	0	-85	100kbps GFSK
	DSSS BPSK	2	0 (also 10)	-92	20kbps BPSK

## 4.7. 779-787 MHz Band Coexistence Performance

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

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

## 5. Specification Details of 802.15.4g Coexistence Mechanism for Multiple PHYs

## Annex A

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

%%%%%%%%%% Parameter Settings %%%%%%%%%%

```
SINR = 0:20; % SINR (Ec/N0) in dB
trellisOFDMQPSK = poly2trellis(7,[133 171]); % convolutional code generators for OFDM and DSSS QPSK
spectOFDMQPSK = distspec(trellisOFDMQPSK);
```

```
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,spectOFDMQPSK);
% BER for OFDM QPSK 200kbps
BER_OQPSK500 = bercoding(EbN0_OQPSK500,'conv','hard',0.5,spectOFDMQPSK);
```

```

% 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

% 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

```
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 MR-FSK PHY Mode in response to Interference Generated by Other 802 Systems

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

```

% 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 = 10; % victim transmitter to victim receiver distance in meter
IV_Para.d_U = [2:0.5:20]; % interferer transmitter to victim receiver distance in meter
IV_Para.fc = 2437e6; % center frequency

% 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

```

