# IEEE P802.15

# Wireless Personal Area Networks

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| Re: | Task Group 15.4m Coexistence Assurance Document (CAD) to satisfy PAR and 5C |
| Abstract | [TG4m – to evaluate coexistence issues related to other existing TV white space systems and wireless systems sharing other frequency bands with 15.4m.] |
| Purpose | [Working document for the PAR and 5C to the P802.15 Working Group.] |
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# 802.15.4m Coexistence Assurance Document

**Doc# IEEE P802.15-13-0166-03-004m**

**May 2013**

# Contents

# 1. Introduction

At this time, there are two approved standards for operation in the TV white space bands: IEEE 802.22-2011 and IEEE 802.22.1-2010. This document investigates the coexistence impacts of the proposed 802.15.4m operation with respect to 802.22 and 802.22.1 devices by evaluating two types of performance analyses – one is the impact to 802.15.4m by 802.22 and 802.22.1 systems and the other is the impact to 802.22 and 802.22.1 systems by 802.15.4m.

Also the coexistence impacts of the proposed 802.15.4m operation with respect to 802.1 and 802.15 devices which share frequency bands with 802.15.4m are analyzed.

# Overview of 15.4m

The 802.15.4m is the amendment to IEEE Std 802.15.4-2011 which specifies alternate PHYs in addition to those of 802.15.4. In addition to the new PHYs, the amendment also defines those MAC modifications needed to support their implementation.

The alternate PHYs support principally outdoor, low-data-rate, wireless, TV White Space network (TVWS) applications under multiple regulatory domains. The three alternate TVWS PHYs for 802.15.4m are as follows:

- Frequency shift keying (TVWS-FSK) PHY
- Orthogonal frequency division multiplexing (TVWS-OFDM) PHY
- Narrow Band Orthogonal frequency division multiplexing (TVWS-NB-OFDM) PHY

The TVWS PHYs support multiple data rates in bands ranging from 54 MHz to 862 MHz.

Each of these PHY modes has key parameters shown in the following tables.

**Table 1: Key Parameters for 15.4m FSK PHY**

| Freq. Band | Parameter | Mode #1 | Mode #2 | Mode #3 | Mode #4 | Mode #5 |
|---|---|---|---|---|---|---|
| All available TVWS bands | Data rate (kbps) | 50 | 100 | 200 | 300 | 400 |
| | Modulation level | 2-level | 2-level | 2-level | 2-level | 4-level |
| | Modulation index h | 0.5 or 1.0 | 0.5 or 1.0 | 0.5 or 1.0 | 0.5 | 0.33 |
| | Channel spacing (kHz) | 100 if h=0.5<br>200 if h=1.0 | 200 if h=0.5<br>400 if h=1.0 | 400 if h=0.5<br>600 if h=1.0 | 600 | 600 |

**Table 2: Key Parameters for 15.4m FSK OFDM**

| Description | Mandatory mode | Optional mode<br>(4 times overclock mode) |
|---|---|---|
| Nominal bandwidth (kHz) | 1064.5 | 4258 |
| Channel spacing (kHz) | 1250 | 4*1250 |
| Subcarrier spacing (kHz) | 1250/128 | 4*1250/128 |
| DFT Size | 128 | 128 |
| Number of pilot tones | 8 | 8 |
| Number of data tones | 100 | 100 |
| BPSK ½ rate (kbps) | 390.625: MCS0 Mode | 1562.5: MCS3 Mode |
| QPSK ½ rate (kbps) | 781.250: MCS1 Mode | 3125: MCS4 Mode |
| 16-QAM ½ rate (kbps) | 1562.5: MCS2 Mode | 6250: MCS5 Mode |
| FEC coding | Convolutional coding with R = ½ and (7, [133,171]) | |

**Table 3: Key Parameters for 15.4m NB-OFDM PHY**

| Description | Mode #1, Mode #2 |
|---|---|
| Nominal bandwidth (kHz) | 389.95 |
| Subcarrier spacing (kHz) | 0.99206 (125kHz/126) |
| Number of subcarriers | 384 |
| Number of pilot tones | 32 |
| Number of data tones | 352 |
| Effective symbol duration (us) ($T_{FFT}$) | 1008 |
| Guard interval ($T_{GP}$) | 1/32 (31.5us) as mandatory<br>1/16 (63us) as optional<br>1/8 (126us) as optional |
| Symbol interval (us) | 1039.5 as mandatory<br>1071.0 as optional<br>1134.0 as optional ($T_{FFT}$+$T_{GP}$) |
| Modulation and coding | BPSK, QPSK, 16QAM, 64QAM<br>RS coding and convolutional coding with R = 1/2, 2/3, 3/4, 7/8. for R=1/2 (7, [133,171]) |

**Table 4: Data Rates for 15.4m NB-OFDM PHY**

| MCS Index | Modulation | CC coding rate | Data Rate (Kbps) | CC Coded bits per subcarrier ($N_{BPSC}$) | CC Coded bits per OFDM symbol ($N_{CPBS}$) | RS encoded Data bits per OFDM symbol ($N_{DBPS}$) |
|---|---|---|---|---|---|---|
| MCS0 | BPSK | 1/2 | 156 | 1 | 352 | 176 |
| MCS1 | BPSK | 3/4 | 234 | 1 | 352 | 264 |
| MCS2 | QPSK | 1/2 | 312 | 2 | 704 | 352 |
| MCS3 | QPSK | 3/4 | 468 | 2 | 704 | 528 |
| MCS4 | 16-QAM | 1/2 | 624 | 2 | 1408 | 704 |
| MCS5 | 16-QAM | 3/4 | 936 | 4 | 1408 | 1056 |
| MCS6 | 64-QAM | 1/2 | 1248 | 4 | 2112 | 1408 |
| MCS7 | 64-QAM | 3/4 | 1404 | 6 | 2112 | 1584 |
| MCS8 | 64-QAM | 7/8 | 1638 | 6 | 2112 | 1848 |

# Regulatory information of TV white space

Currently white space rules have been published in the United States, and other regions have rules pending. This analysis is based on the rules as published by the FCC. Current FCC rules (Part 15, subpart H) include the concept of a geo-location database containing availability of whitespace channels; 802.15.4m assumes some participating devices have access to the geo-location database. Regulatory work in other regions is ongoing.

Power limits defined by FCC regulations for whitespace devices are given in Table 5 and Figure 1. The maximum transmit power for fixed devices is limited to 1W transmit power in a TV channel; if occupied bandwidth of the signal is less than that for a TV channel, transmit power must be scaled down so that total power in the TV channel does not exceed 1W. Non-fixed devices are constrained to lower transmit power, with the same requirement to scale power relative to occupied bandwidth.

**Table 5: FCC Transmit Power Limitations**

| Type of TV bands device | Power limit (6 MHz) | PSD limit (100 kHz) | Adjacent channel limit (100 kHz) |
|---|---|---|---|
| Fixed | 30 dBm (1 Watt) | 12.6 dBm | -42.8 dBm |
| Personal/portable (adj. channel) | 16 dBm (40 mW) | -1.4 dBm | -56.8 dBm |
| Sensing only | 17 dBm (50 mW) | -0.4 dBm | -55.8 dBm |
| All other personal/portable | 20 dBm (100 mW) | 2.6 dBm | -52.8 dBm |

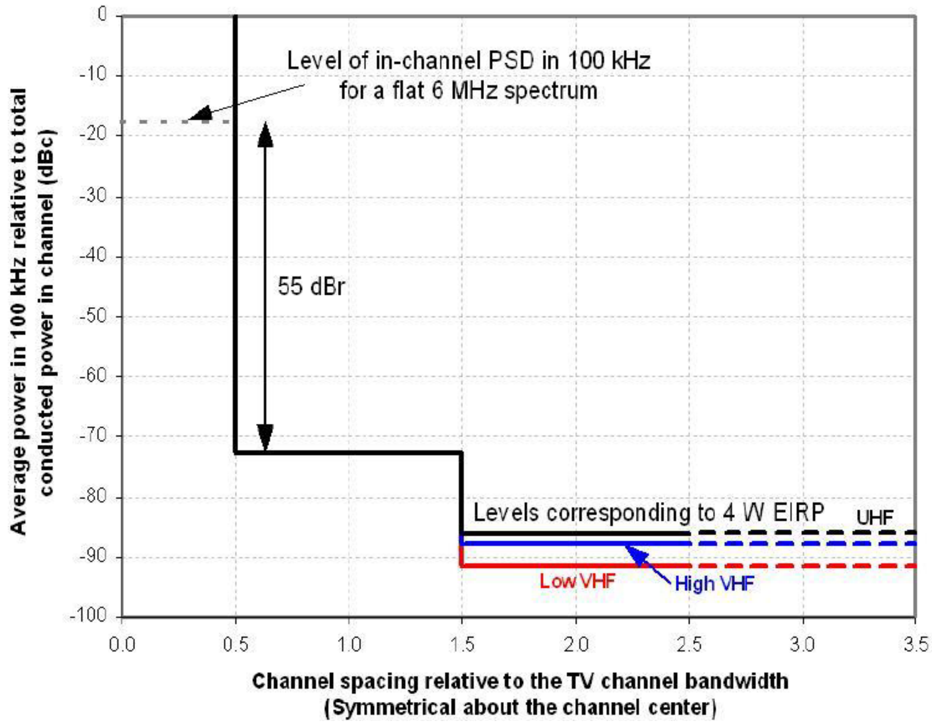



Figure 1: FCC Frequency Mask Requirements for TV white Space Bands

TVWS PHY transmit PSD masks from other local regulations should also be considered in the future for this analysis as they are finalized by regional regulatory bodies.

# Overview of Coexistence Mechanisms in 802.15.4 and 802.15.4m

The importance of coexistence mechanism in 802.15.4m is two-fold. 802.15.4m specifies three alternative PHYs that shall be able to coexist with each other if operating co-located in the same TV white space frequency band. 802.15.4m also has to coexist with other dissimilar 802 systems. So far two systems are identified in the TV white space bands – 802.22 and 802.22.1. Also in this document 802.11 and 802.15 systems which shares the frequency bands with 802.15.4m are considered.

The coexistence mechanisms specified in 802.15.4 and subsequent amendments are applicable to both homogeneous (among different 15.4m PHYs) and heterogeneous (across other 802 systems) coexistence.

## 2. Dissimilar Systems Sharing the Frequency Bands with 802.15.4m

This clause presents an overview on other 802 systems which are specified to operate in the TV white space bands and other frequency bands that are also specified for the 802.15.4m. The following sub-clauses present co-locating dissimilar systems with reference to respective TV white space bands and others frequency bands which are shared by dissimilar 802 systems.

The frequency bands of interest are
- the TV white space band between 300MHz and 700MHz and
- other bands including 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.

In this and following clauses, each coexisting system from other standard specifications is discussed regarding:

(a) Standard specification: the name of the 802 system with which 802.15.4m 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) Involved 802.15.4m system: the particular PHY in 802.15.4m that is coexisting with the above 802 system specification.

## Dissimilar Systems Sharing the TVWS Bands with 802.15.4m

Two dissimilar systems are identified which are operated in the TV white space bands – 802.22 and 802.22.1 as summarized as below.

### 802.22 System

Overview of the IEEE 802.22 Standard is as follows:

- Focus -Rural Broadband Wireless Access
- Core Technology -Cognitive radio technology based un-licensed use, primarily designed to operate in the TV Whitespaces from 54-862 MHz, on a non-interfering basis with the primary users (incumbents).
- CONOPS -VHF and UHF band operation allows long range propagation and cell radius of 17 –33 km. Approx 280 MHz of Bandwidth with 47 TV channels.
- PHY-Optimized for long channel response times and highly frequency selective fading channels.
- MAC–Provides compensation for long round trip delays
- Unique features introduced for Cognitive Radio based operation: spectrum sensing, spectrum management, intra-system co-existence, geo-location and security
- Mobility and Portability -Portability –IEEE 802.22 allows portability (nomadic use). In case the rules do change, IEEE 802.22 PHY is designed to support mobility of up to 114 km/hr (no hand-off is included in the current version).

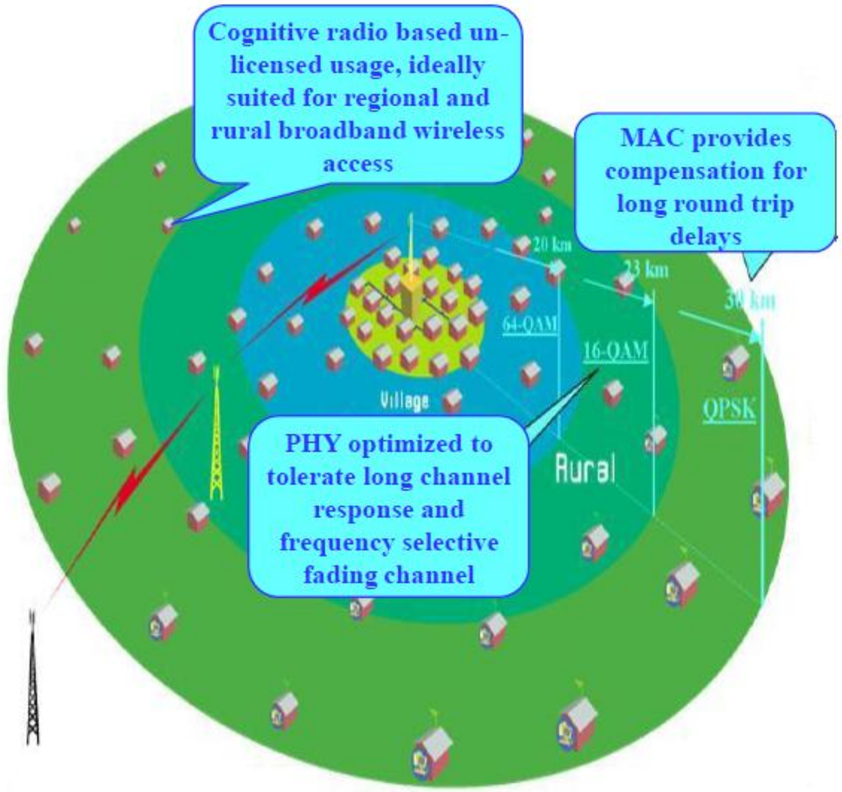



Figure 2: Operational Concept of 802.22

Major operational concepts for 802.22 can be described as follows:

- Operation in the VHF / UHF Bands. Frequency Allocation for the United States – 54 – 60, 76 – 88, 174 – 216, 470 - 608 and 614 – 698 MHz => Total of 282 MHz or 47 Channels
- Network Topology – Point-to-Multipoint (PMP)
- Max EIRP and Cell Radius – Fixed BS and Fixed Subscribers using 4W EIRP, Cell Radius 10 – 100 km. Portable Subscribers Station Supported. (Higher power BS allowed in other countries)
- Tx / Rx antenna – BS uses sectorized or omni-directional antenna. At the subscriber Tx /Rx antenna is directional with 14 dB of front-to-back lobe suppression,
- Sensing antenna - Requires horizontal and vertical polarization sensitivities to sense TV and microphone signals respectively, with omni-directional pattern.
- Geo-location - GPS based geo-location is mandatory, but terrestrial geo-location (triangulation) is supported.

Frame Structure of 802.22 has following features:

- 802.22 supports Time Division Duplex (TDD) frame structure
- Super-frame: 160 ms, Frame: 10 ms
- Each frame consists of downlink (DL) sub-frame, uplink (UL) sub-frame, and the Co-existence Beacon Protocol (CBP) burst
- Lengths of DL and UL sub-frames can be adjusted.

- Self Co-existence Window: BS commands subscribers to send out CBPs for 802.22
    - self co-existence –CBP bursts contain information about the backup channel sets and sensing times
    - terrestrial geo-location and
    - whitespace device identification as required by the regulatory domain rules.

Key PHY features of 802.22 are as follows:

- PHY Transport -802.22 uses Orthogonal Frequency Division Multiplexing (OFDM) as transport mechanism. Orthogonal Frequency Division Multiple Access (OFDMA) is used in the UL
- Coding–Convolutional Code is Mandatory. Turbo, LDPC or Shortened Block Turbo Code are Optional but recommended.
- Single PHY mode: OFDMA
    - Single FFT mode: 2048
    - Pilot Pattern -Each OFDM / OFDMA symbol is divided into sub-channels of 28 sub-carriers of which 4 are pilots. Pilot symbols are inserted once every 7 sub-carriers. Pilots cycle through all 7 sub-carriers over 7 symbol duration. No frequency domain interpolation is required.
    - TDD
- Net Spectral Efficiency -0.624 bits/s/Hz –3.12 bits/s/Hz
- Spectral Mask -802.22 has adopted the Spectral Mask requirements proposed by FCC. (200 tap FIR filter may be needed for implementation).
- OFDMA Design
    - symbol time: $1/\Delta f \sim 300$ μsec; CP ~ 75 μsec
    - Slow fading: $\Delta f \sim 3.3$ kHz (Robustness to ICI better than WiMax in 3.5 GHz)
- Throughput
    - Peak data rate per channel: 22.69 Mb/s (rate 5/6, 64-QAM)
- DS: little time diversity gain could be achieved across symbols due to channel changes slowly
- US: allocated across symbols to minimize the number of subchannels used by a CPE, hence reducing (EIRP) to mitigate potential interference to incumbent systems
- Adaptive Modulation and Coding
    - Four CP factors: 1/4, 1/8, 1/16, and 1/32
    - 3 modulations (QPSK, 16QAM, 64QAM) and 4 coding rates (1/2, 2/3, 3/4, 5/6)
    - Convolutional Code is Mandatory. Turbo, LDPC or Shortened Block Turbo Code are Optional but recommended
    - Turbo-block bit interleaver and subcarrier interleaver

**Table 6: Key PHY Parameters for 802.22**

| TV channel bandwidth (MHz) | 6 | 7 | 8 |
|---|---|---|---|
| Total number of subcarriers, $N_{FFT}$ | 2048 | | |
| Number of guard subcarriers, $N_G$ (L, DC, R) | 368 (184, 1, 183) | | |
| Number of used subcarriers, $N_T = N_D + N_P$ | 1680 | | |
| Number of data subcarriers, $N_D$ | 1440 | | |
| Number of pilot subcarriers, $N_P$ | 240 | | |
| Signal bandwidth (MHz) | 5.6240625 | 6.5625 | 7.494375 |

**Table 7: 802.22 PHY Data Rates**

**PHY capacity**

| Mod. | Rate | Mbit/s (CP= 1/8) | bit/(s*Hz) (CP= 1/8) |
|---|---|---|---|
| QPSK | 1/2 | 3.74 | 0.624 |
| | 2/3 | 4.99 | 0.832 |
| | 3/4 | 5.62 | 0.936 |
| | 5/6 | 6.24 | 1.04 |
| 16QAM | 1/2 | 7.49 | 1.248 |
| | 2/3 | 9.98 | 1.664 |
| | 3/4 | 11.23 | 1.872 |
| | 5/6 | 12.48 | 2.08 |
| 64QAM | 1/2 | 11.23 | 1.872 |
| | 2/3 | 14.98 | 2.496 |
| | 3/4 | 16.85 | 2.808 |
| | 5/6 | 18.72 | 3.12 |

**PHY performance: SNR (dB)**

| Mod. | Rate | SNR |
|---|---|---|
| QPSK | 1/2 | 4.3 |
| | 2/3 | 6.1 |
| | 3/4 | 7.1 |
| | 5/6 | 8.1 |
| 16QAM | 1/2 | 10.2 |
| | 2/3 | 12.4 |
| | 3/4 | 13.5 |
| | 5/6 | 14.8 |
| 64QAM | 1/2 | 15.6 |
| | 2/3 | 18.3 |
| | 3/4 | 19.7 |
| | 5/6 | 20.9 |

Note: includes phase noise: -80dBc/Hz at 1 kHz and 10 kHz and -105 dBc/Hz at 100 kHz

**Table 8: 802.22 Transmit power level by regulatory domain and classes**

| Regulatory domain | Regulatory class | Maximum BS EIR /Maximum antenna height | Maximum CPE EIRP/Maximum antenna height | Polarization |
|---|---|---|---|---|
| USA | Stationary fixed | 4 W / 30 m AGL, 76 m GHAAT | 4 W / 30 m AGL, 76 m GHAAT | Any |
| USA | Personal Portable (Modes I & II) | 100 mW / N/A | 100 mW / N/A | Any |
| CAN | Stationary fixed | 500 W / ≤ 60 m AHAAT<br>250 W / ≤ 90 m AHAAT<br>125 W / ≤ 120 m AHAAT<br>66 W / ≤ 180 m AHAAT<br>33 W / ≤ 240 m AHAAT<br>4 W / ≤ 500 m AHAAT | 4 W / 10 m AGL | Vertical |

Key MAC features of 802.22 are as follows:

- Connection-oriented MAC, establishes connection IDs and service flows which are dynamically created
- QoS – Various types of QoS services are supported (See below). ARQ supported. Uni-cast, Multi-cast and broadcast services are supported.
- Cognitive functionality –
    - Dynamic and adaptive scheduling of quiet periods to allow the system to balance QoS requirements of users with the need to quiet down the network to support spectrum sensing. Quiet periods range from 1 symbol (approx. 1/3 ms) to one super-frame
    - Subscribers can alert the BS, the presence of incumbents in a number of ways. Dedicated - Urgent Co-existence Situation (UCS) messages or low priority MAC messages
    - BS can ask one or more subscribers to move to another channel in a number of ways using Frame Control Header (FCH) or dedicated MAC messages

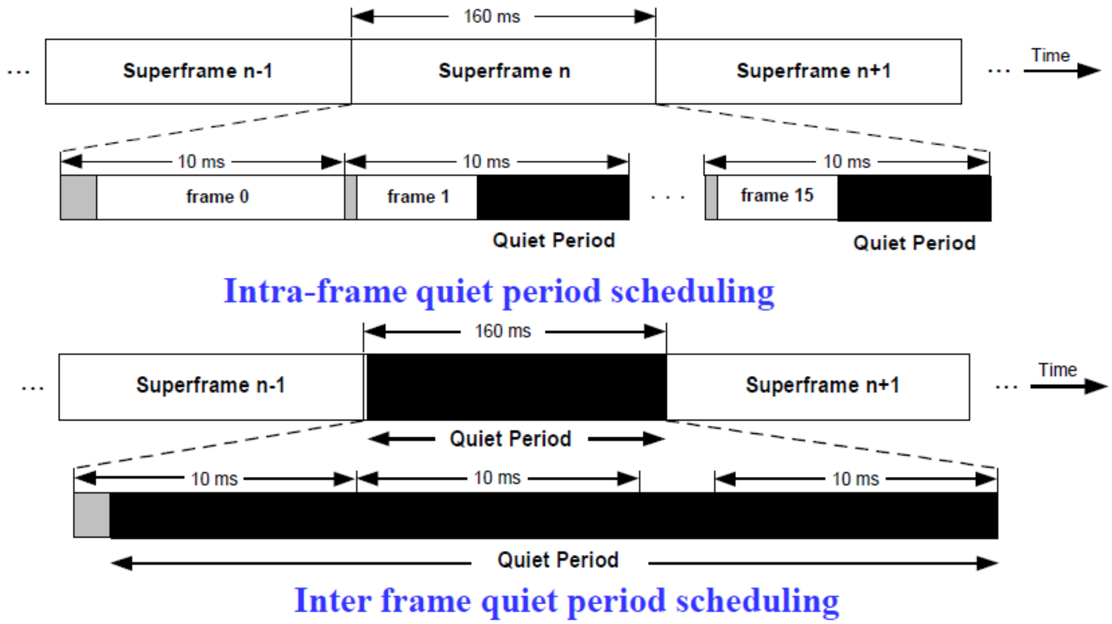



Figure 3: Superframe Structure of 802.22

## 802.22.1 System

Although the TV channels are not used for TV broadcasts, low-power, licensed devices, such as wireless microphones operated by broadcasters, do use these channels, and are entitled to protection by regulation to avoid disrupting incumbent services.

Furthermore, national regulators in many regions of the world are advancing regulations that allow license exempt devices to operate on a non-interfering basis within the portions of the TV spectrum that are not used for broadcasts or required to remain unused in order to protect broadcast stations from interference.

The 802.22.1 systems are the devices that serve as warning beacons to protect the operation of incumbent licensed low-power devices. The beacons should be installed by the operator of the licensed device at a location appropriate to afford protection to the protected service. The beacons transmit identifiable sync bursts as well as, optionally, information about locations and operational parameters of the protected devices. The unlicensed system should include an appropriate receiver to receive and decode the information and should have an operation policy that would avoid inflicting any interference to the protected device.

Wireless microphone beacon sensing has following features:

- Wireless microphones have a large signal level variability because of the way they operate
- Sensing wireless microphones would result in unreliable detection of their operation

- 802.22 developed a standard for the beacon to reliably signal the presence of wireless microphones:
  - Constant transmission power (250 mW at UHF)
  - Intelligent ad-hoc networking among beacons that results in only one active local beacon per TV channel
  - Beacon antenna normally located above the wireless microphone receivers (e.g., on top of ENG trucks) to maximize the bubble of protection from WRAN operation

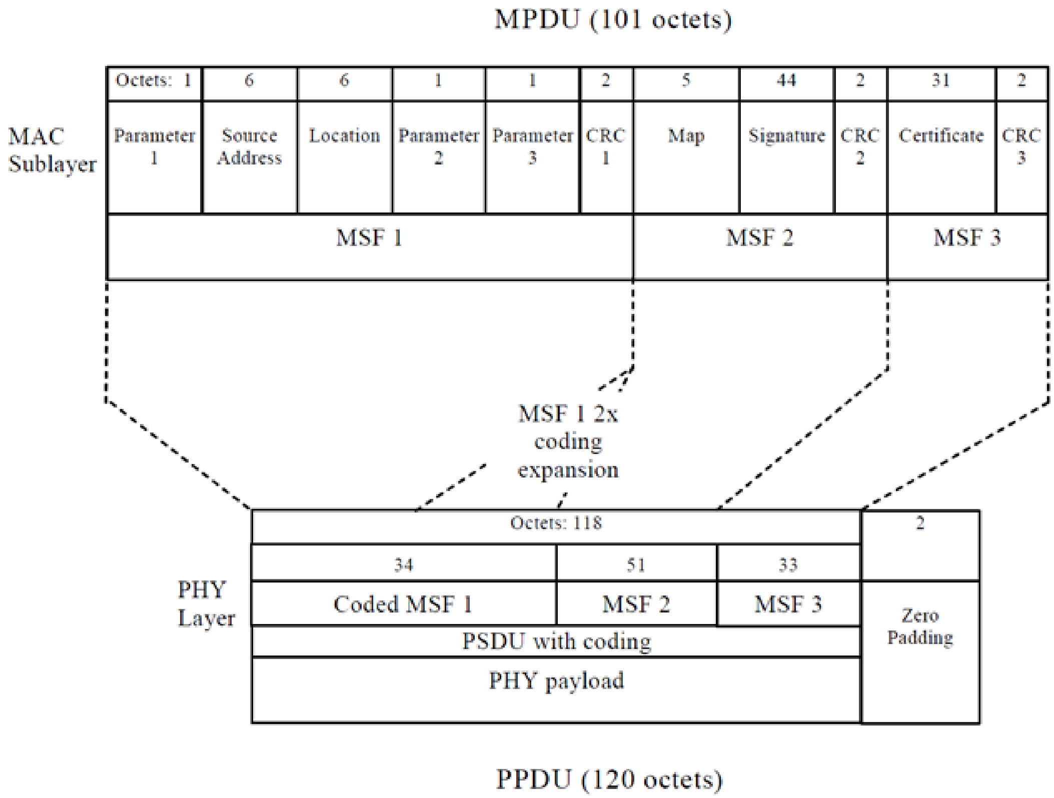
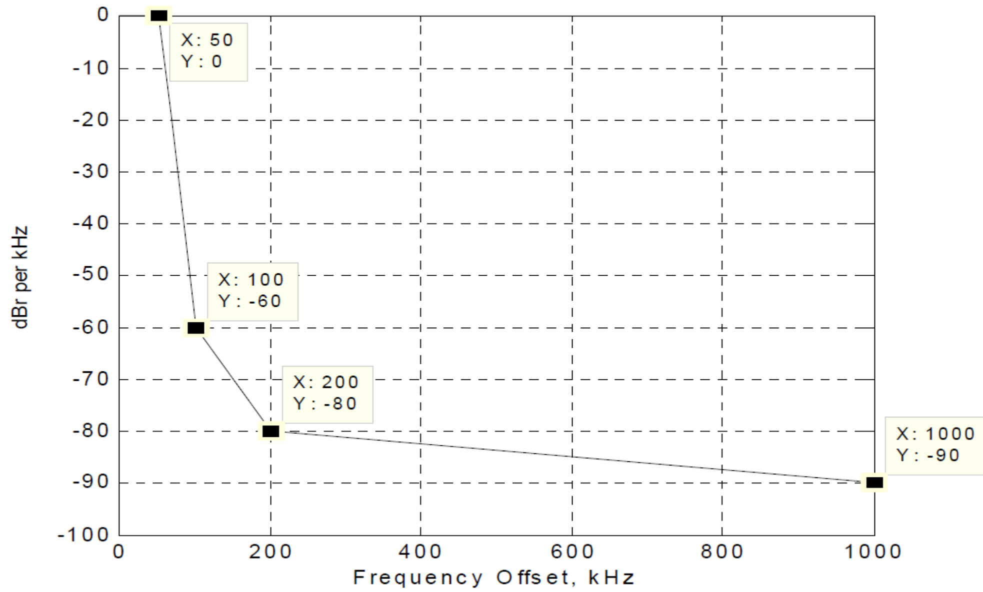



Figure 4: PHY Frame Structure of 802.22.1

**Table 9: Modulation Rates and Beacon Offset Location for ATSC DTV Regions**

| Offset from lower TV channel edge (kHz) | Chip rate (kchips/s) | Symbol rate (kBaud) |
|---|---|---|
| 309.4 | 76.873 | 9.6091 |




**Piece-wise linear transmit mask**

**[The mask is symmetric about the center frequency (0 kHz offset in this plot)]**

Figure 5: Transmit Mask of 802.22.1

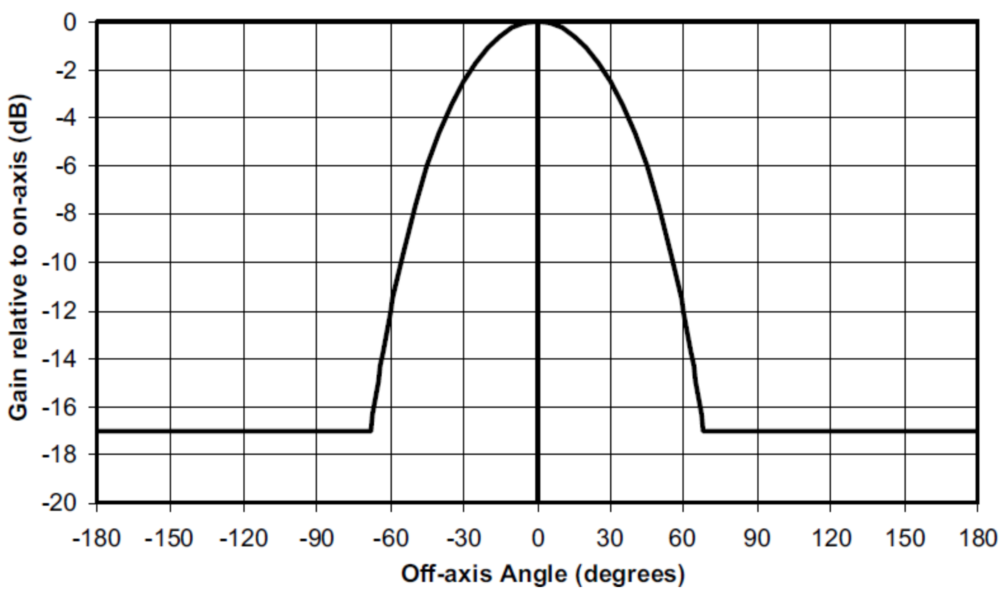



Figure 6: 802.22 Tx/Rx Reference Antenna Pattern

Practical limits to RF sensing can be summarized as follows:

- 802.22 Sensing threshold: -116 dBm
- Differential between beacon and microphone: 53 dB
- Required threshold to sense wireless microphone at the interference range: -116 -53 +6= -163 dBm (note that the 6 dB covering for frequency selective fading no longer applies when the actual microphone is detected.)
- For 100 mW portable devices, the interference range would be reduced: -163 + 10*log(4/0.1)= -147 dBm
- Since unlike in the case of DTV sensing, the azimuth of the W-microphone signal is the same as the signal transmitted, the same directional antenna could be used: -163+11 dBi = -152 dBm

# Dissimilar Systems Sharing Other Frequency Bands with 802.15.4m

The frequency bands of interest other than TV white space bands 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.

Coexisting systems in these bands are summarized in Table 10.

**Table 10: Dissimilar Systems Coexisting with 802.15.4m Systems within Non-TVWS Bands**

| Frequency band (MHz) | System | PHY specification |
|---|---|---|
| 2400-2483.5 (worldwide) | 802.11b | DSSS CCK |
| | 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 |
| 902-928 (United States) | 802.15.4 | DSSS BPSK |
| | | DSSS O-QPSK |
| | | PSSS ASK |
| | 802.15.4c | DSSS BPSK |
| 863-870 (Europe) | 802.15.4 | DSSS BPSK |
| | | DSSS O-QPSK |
| | | PSSS ASK |
| | 802.15.4c | DSSS BPSK |
| 950-958 (Japan) | 802.15.4d | DSSS GFSK |
| | | DSSS BPSK |
| 779-787 (China) | 802.15.4c | DSSS O-QPSK |

# 3. Coexistence Scenario and Analysis

## PHY Modes in the 802.15.4m System

As described in the above, three operational PHY modes are specified in the 802.15.4m standard. For each mode, relevant evaluation has been performed using the parameter values and methods described in the following sub-clauses.

### Parameters of the 802.15.4m PHY Modes used for coexistence evaluation

For the analyses in this document, the following parameters are used for 802.15.4m.

**Table 11: Major parameters of 802.15.4m PHY Modes used for analyses**

| Parameters and values | | FSK PHY | OFDM PHY | NB-OFDM PHY |
|---|---|---|---|---|
| Operation mode | | Mode #2 mod index 0.5 | MCS1 QPSK ½ | MCS2 QPSK 1/2 |
| Data rate (kbps) | | 100 | 781 | 312 |
| Modulation level | | 2 | 4 | 4 |
| Channel spacing or bandwidth (kHz) | | 200 | 1250 | 390 |
| Number of subcarriers | | n.a. | 128 | 384 |
| FEC coding | | Convolutional coding with R = ½ and (7, [133,171]) | Convolutional coding with R = ½ and (7, [133,171]) | Convolutional coding with R = ½ and (7, [133,171]) |
| Occupation factor in a TV channel (BW/6MHz) | | 0.2/6 = -14.8dB | 1.25/6 = -6.8 | 0.39/6 = -11.9 |
| Transmit power (dBm) | portable | 5.2 (20-14.8) | 13.2 (20-6.8) | 8.1 (20-11.9) |
| | fixed | 15.2 (30-14.8) | 23.2 (30-6.8) | 18.1 (30-11.9) |
| Length of a frame (bits) | | 2112 | 2896 | 2736 |
| Antenna height (m) | | Base station: 10 | CPE or other device: 2 | |
| Antenna gain (dB) | | 0 | | |

### BER / FER Calculations for 802.15.4m PHY Modes

In this sub-clause, the BER/FER performance corresponding to SNR for the 802.15.4m PHY modes listed in Table 11 are provided. The parameter SNR is defined as the ratio between the energy in each symbol to the noise power spectral density in each symbol. SNR can be expressed as:

$$E_b/N_o = SNR - 10\log(L_m) - 10\log(R_{FEC})$$

where $E_b/N_o$ is the bit energy for over noise power spectral density
$SNR$ is the symbol energy for over noise power spectral density
$L_m$ is the modulation level
$R_{FEC}$ is the FEC coding rate.

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

$$FER = 1 - (1-BER)^L$$

where $L$ is the average frame size.

The BER and FER are modeled in MatLab with uncoded AWGN channel without interference from outside for three 802.15.4m PHY modes – FSK PHY mode, OFDM PHY mode, and NB-OFDM PHY mode. The receiver bandwidth is assumed to be equal to the channel spacing of the PHY mode. The BER and FER plots of the 802.15.4m PHY modes are illustrated in Figure 7.

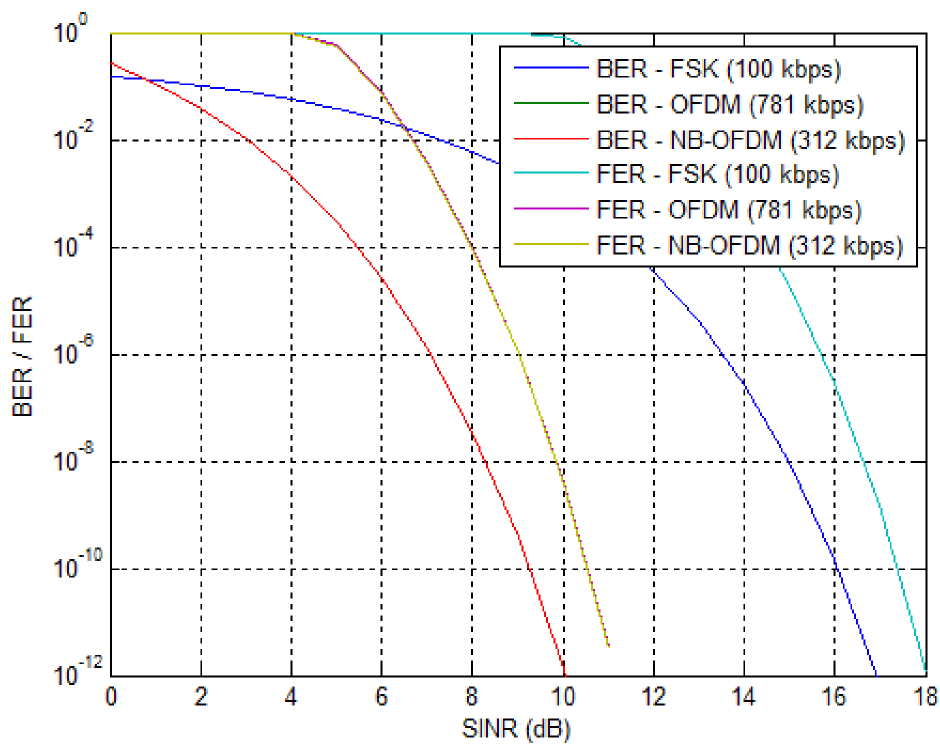



Figure 7: BER/FER vs. SNR for 802.15.4m PHYs
(OFDM PHY has the same BER and FER curves as NB-OFDM.)

# Interference Modeling

For 802.15.4m's coexistence simulation modeling, the following is adopted:

- In the coexistence model, the transmitting power and distance between the victim's transmitter and receiver are fixed, thus the received signal strength is fixed. The interference at the victim's receiver is injected accordingly versus the distance from the interferer's transmitter to the victim's receiver.
- Modified Hata Model for Propagation Prediction Used for ERC Report 68 defined in the 15.4m Technical Guidance Document (15-11-0684-12-004m-tg4m-technical-guidance-document) is used for the interference calculation. No AWGN noise is included in the channel to limit the factors affecting the system's performance to interference only. Therefore the coexistence performance analysis herein is mainly focused on the interference caused by the interferer's transmitter.
- There is no frequency offset between the interferer's center frequency and the victim's center frequency in the spectrum. This assumes worst case - center freq of 4m and co-existing PHYs are coincident.
- The victim's receiver bandwidth is assumed to be the same as the channel spacing, worse than the real implementation.
- Antenna gain is assumed 0dBi.
- Unless specifically mentioned, Tx power 20dBm is used for 802.15.4m both as victim and as interferer.

<u>Receiver-based Interference Model</u>

As illustrated in Figure 13, 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, the victim receiver antenna is 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:

$$\text{DUR} = P_{Rv} / P_{Rv}'$$

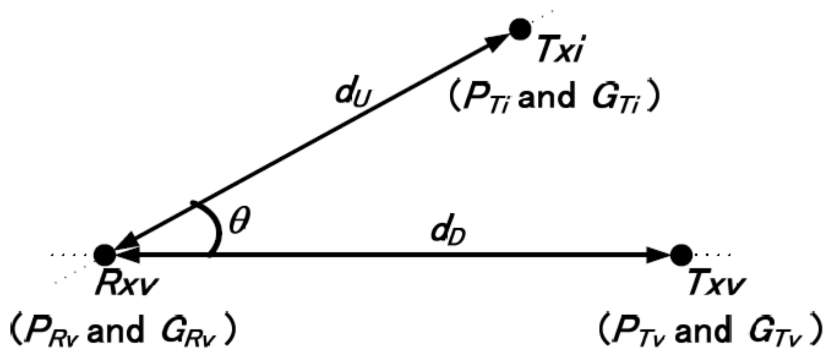



Figure 8: Illustration for the Receiver-based Interference Model

Path Loss Channel Models (for link budget calculation)

For the NLOS propagation model, modified Hata model from ERC Report 68 is chosen for evaluation of coexistence issues among the systems as suggested in the 802.15.4m Technical Guidance Document (TGD). [5]

## Coexistence Performance with 802.22

This sub-clause presents the coexistence performance of the systems coexisting in the TV white space band. In order to understand the impact of the generated interference, 802.15.4m systems and other coexisting 802 systems in this band are set as both the victim and interferer source.

As described in the above, two coexisting systems are so far identified: 802.22 and 802.22.1 systems in the white space bands.

### Parameters for Coexistence Quantification

The following sub-clauses present the parameters involved in quantification of coexistence analysis amongst the participating systems including BER and FER performance versus SNR.

## *PHY Parameters of Coexisting 802.22 Standards*

Table12 shows the PHY mode parameters of coexisting 802.22 standards.

**Table 12: Major Parameters of Coexisting 802.22 Systems used for analyses**

| **Parameters and values** | **802.22 PHY** | **802.22.1 PHY** |
|---|---|---|
| Operation mode | OFDM QPSK with 1/2 | DQPSK with 8-chip DSSS with ½ |
| Data rate (kbps) | 3740 | 19.2 |
| Modulation level | 4 | 4 |
| Channel spacing or bandwidth (kHz) | 5260 | 77 |
| No. of subcarriers | 2048 | |
| Spreading factor | n.a. | 8 |
| FEC coding | Convolutional coding with R = ½ and (7, [133,171]) | Convolutional coding with R = ½ and (7, [133,171]) |
| Occupation factor in a TV channel (BW/6MHz) | 5.26/6 = -0.3 | |
| Transmit power (dBm) | Base station: 29.7 (30-0.3)<br>CPE: 29.7 (20-0.3) | 24 |
| Transmit antenna gain (dB) | Base station: 6<br>CPE: 6 (in direction to BS) | 2 |
| Antenna height (m) | Base station: 30<br>CPE: 10 | 3 |
| Length of a frame (bits) | 2048 | 960 |

## *BER / FER for PHY Modes of Coexisting 802.22 Standards*

In this sub-clause, the BER / FER performance corresponding to SNR for all the 802.22 standards are presented. The parameter SNR is defined as the ratio between the energy in each symbol to the noise power spectral density in each symbol. The average frame size of 252 and 512 octets for 802.22 and 120 octets for 802.22.1 are used for FER calculation.

The BER and FER curves for 802.22 and 802.22.1 are illustrated in Figures 9 and 10 respectively.

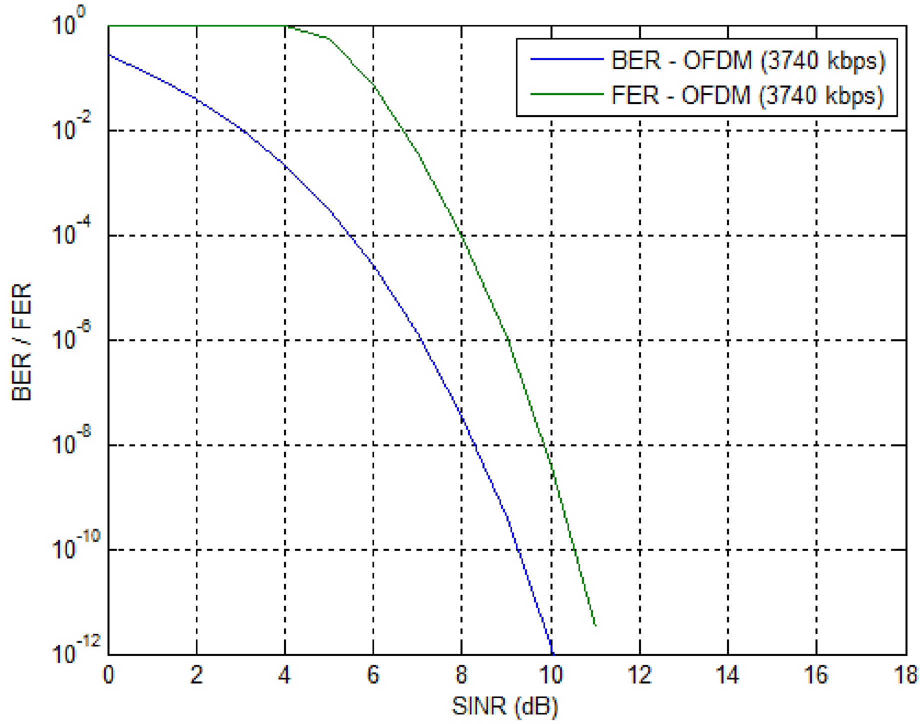



Figure 9-1: BER/FER vs. SNR for 802.22 (with frame size=2048 bits)

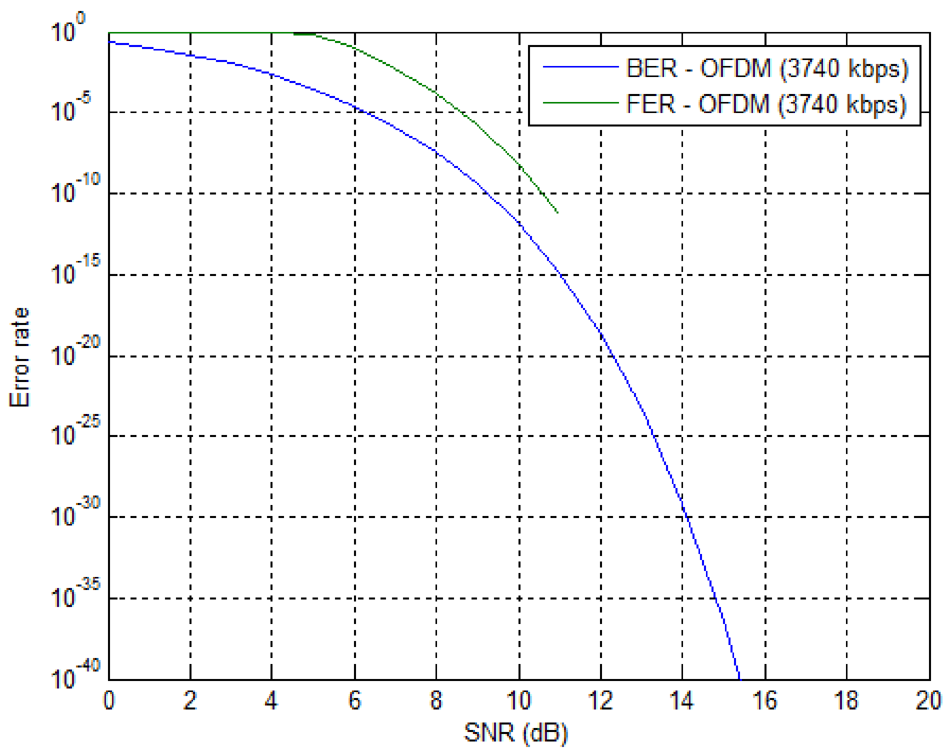



Figure 9-2: BER/FER vs. SNR for 802.22 (with frame size=4096 bits)

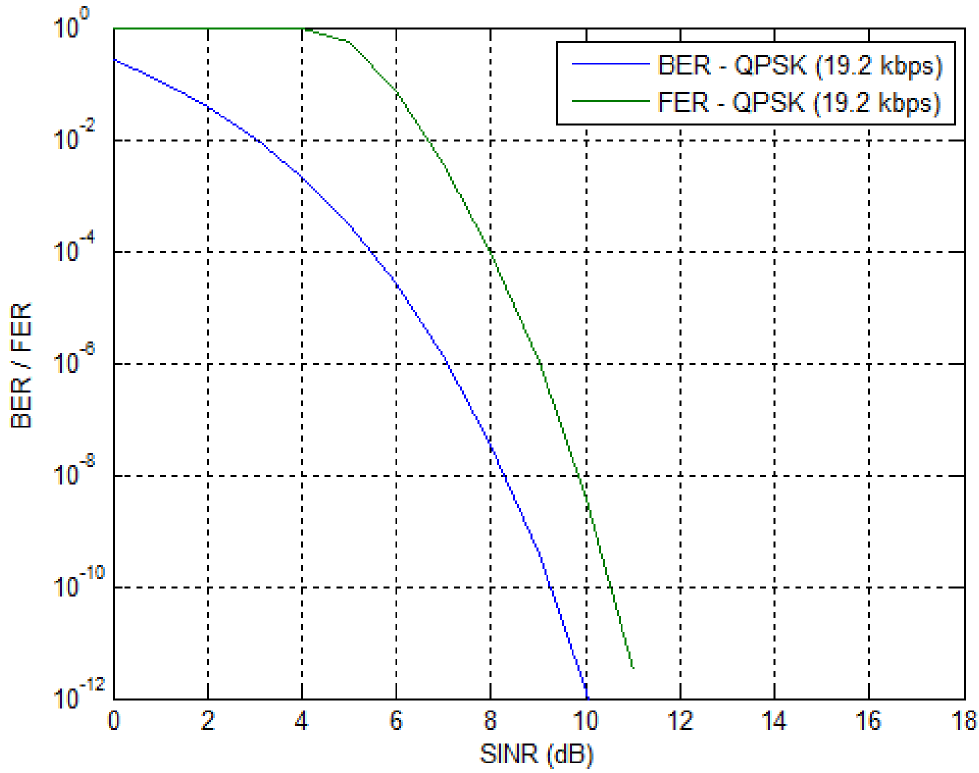



Figure 10: BER/FER vs. SNR for 802.22.1

## Coexistence Simulation Results

### *802.15.4m PHY Mode as Victim Receiver*

Figures 11, 12, and 13 show the BER/FER performance of the 802.15.4m FSK PHY mode, OFDM PHY mode, and NB-OFDM PHY mode victim receivers respectively, corresponding to the distance from the 802.22 interferer transmitter to the 802.15.4m victim receivers.

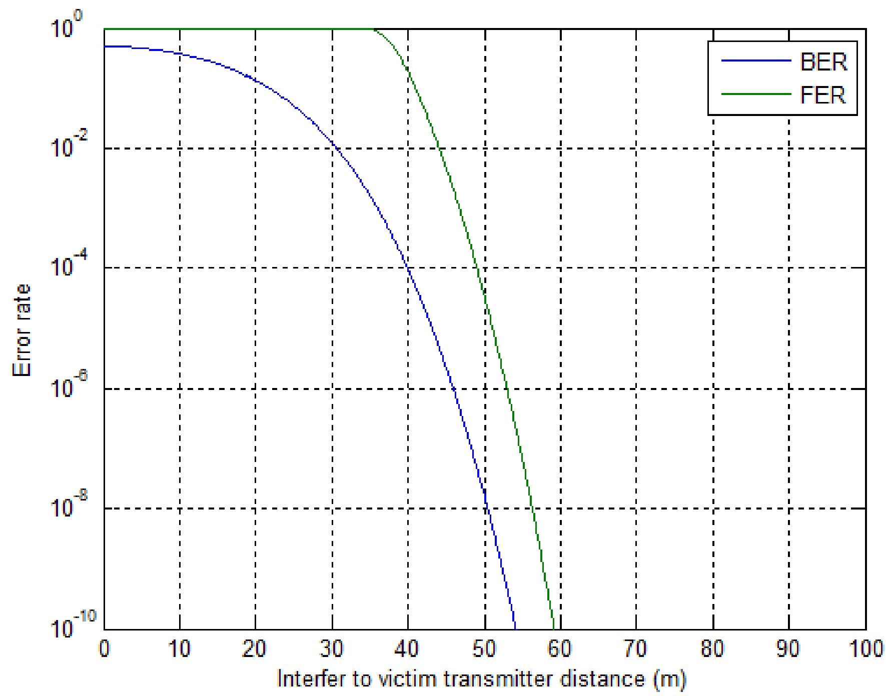



Figure 11-1: Victim BER/FER vs. Distance
from 802.22 BS Interferer Tx to 802.15.4m FSK PHY Portable Device Victim Rx
(victim TX pwr:5.2, interferer TX pwr:29.7, victim ant: 10/2/0/0, interf BS ant: 30/6)

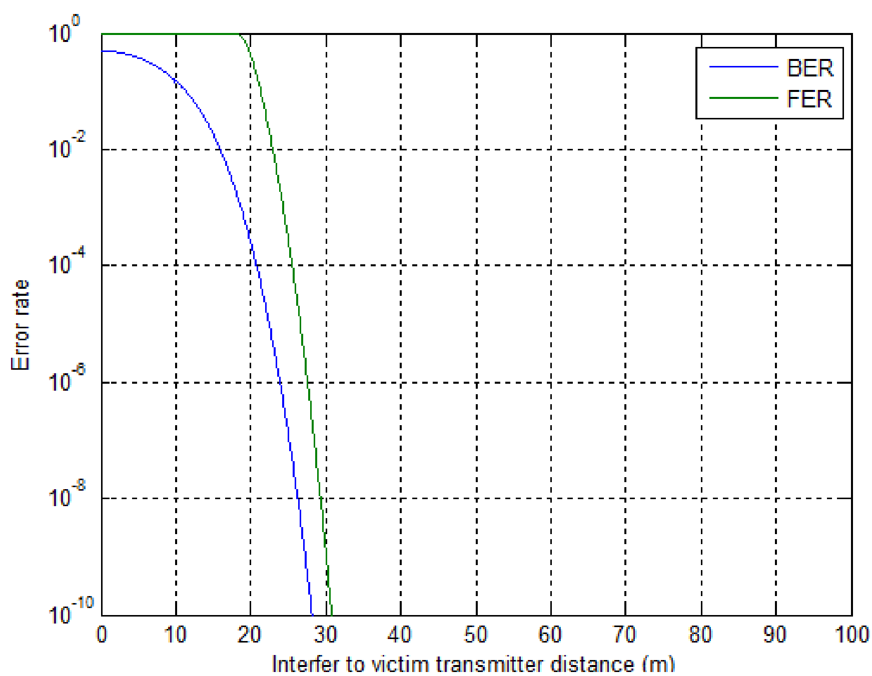



Figure 11-2: Victim BER/FER vs. Distance
from 802.22 BS Interferer Tx to 802.15.4m FSK PHY Fixed Device Victim Rx
(victim TX pwr:15.2, interferer TX pwr:29.7, victim ant: 10/2/0/0, interf BS ant: 30/6)

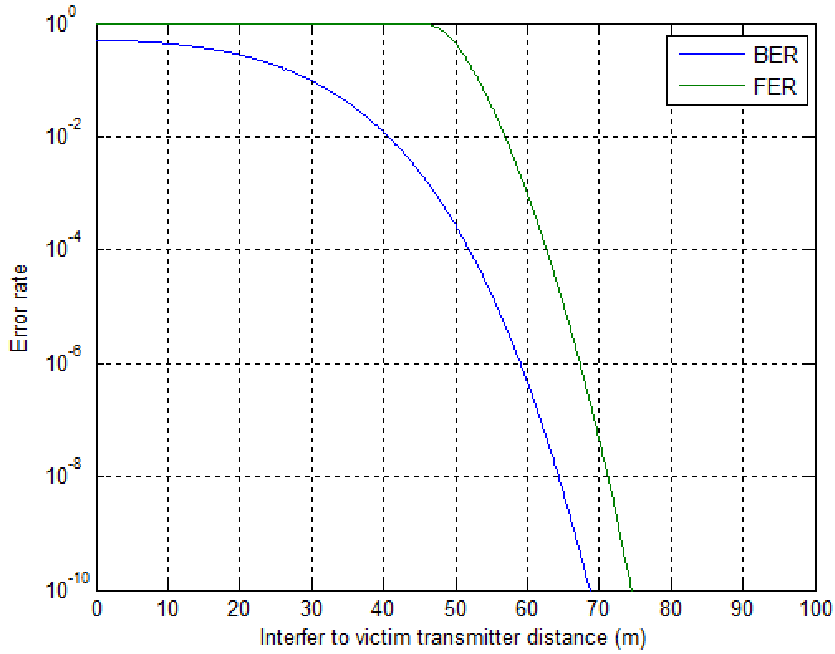



Figure 11-3: Victim BER/FER vs. Distance
from 802.22 CPE Interferer Tx to 802.15.4m FSK PHY Portable Device Victim Rx
(victim TX pwr:5.2, interferer TX pwr:29.7, victim ant: 10/2/0/0, interf CPE ant: 10/6)

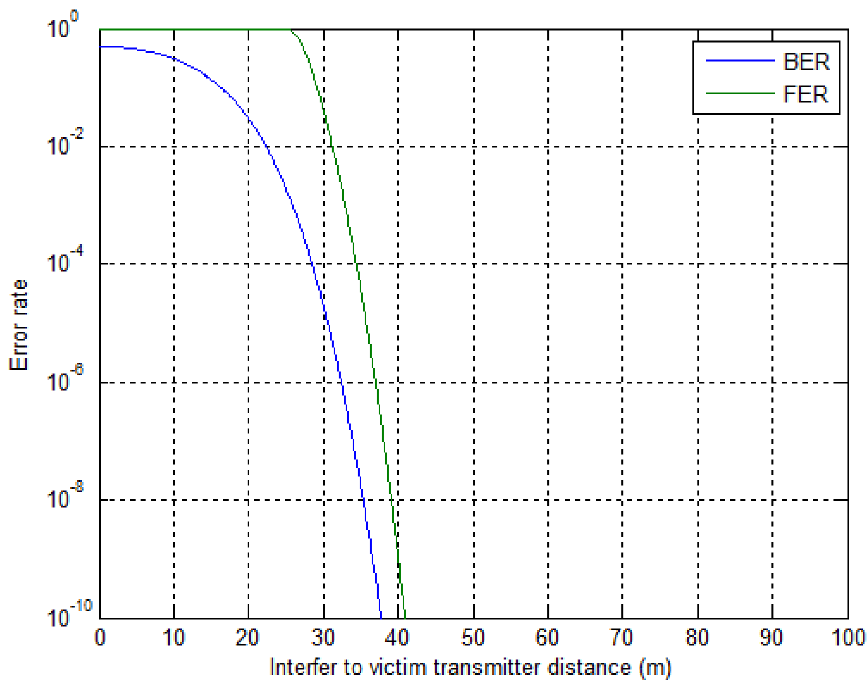



Figure 11-4: Victim BER/FER vs. Distance
from 802.22 CPE Interferer Tx to 802.15.4m FSK PHY Fixed Device Victim Rx
(victim TX pwr:15.2, interferer TX pwr:29.7, victim ant: 10/2/0/0, interf CPE ant: 10/6)

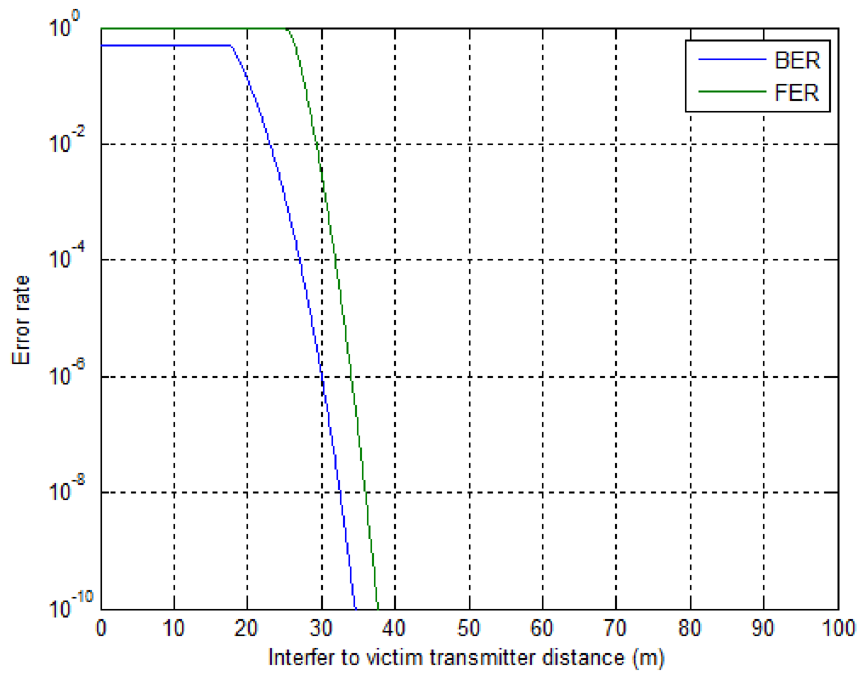



Figure 12-1: Victim BER/FER vs. Distance
from 802.22 BS Interferer Tx to 802.15.4m OFDM PHY Portable Device Victim Rx
(victim TX pwr:13.2, interferer TX pwr:29.7, victim ant: 10/2/0/0, interf BS ant: 30/6)

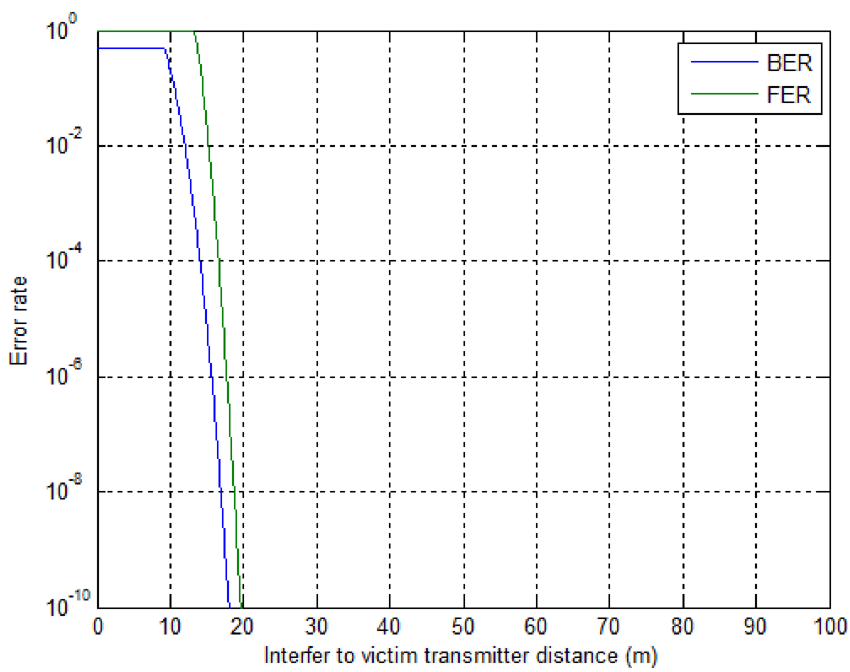



Figure 12-2: Victim BER/FER vs. Distance
from 802.22 BS Interferer Tx to 802.15.4m OFDM PHY Fixed Device Victim Rx
(victim TX pwr:23.2, interferer TX pwr:29.7, victim ant: 10/2/0/0, interf BS ant: 30/6)

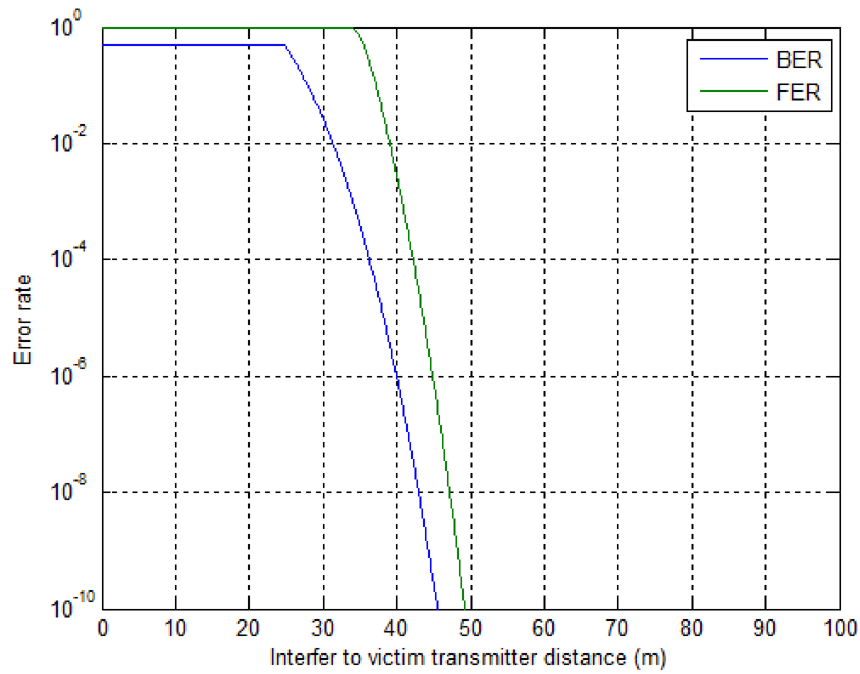



Figure 12-3: Victim BER/FER vs. Distance
from 802.22 CPE Interferer Tx to 802.15.4m OFDM PHY Portable Device Victim Rx
(victim TX pwr:13.2, interferer TX pwr:29.7, victim ant: 10/2/0/0, interf CPE ant: 10/6)

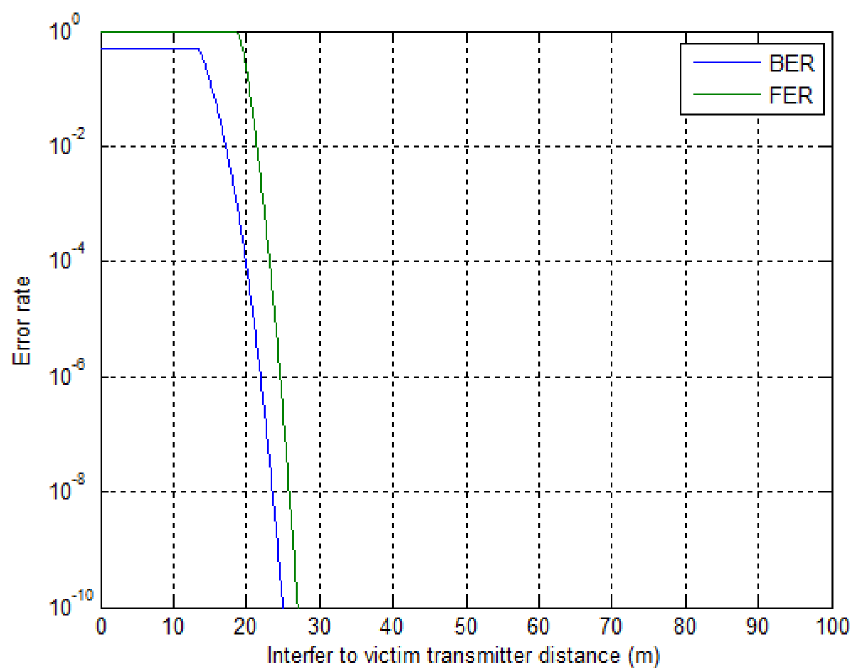



Figure 12-4: Victim BER/FER vs. Distance
from 802.22 CPE Interferer Tx to 802.15.4m OFDM PHY Fixed Device Victim Rx
(victim TX pwr:23.2, interferer TX pwr:29.7, victim ant: 10/2/0/0, interf CPE ant: 10/6)

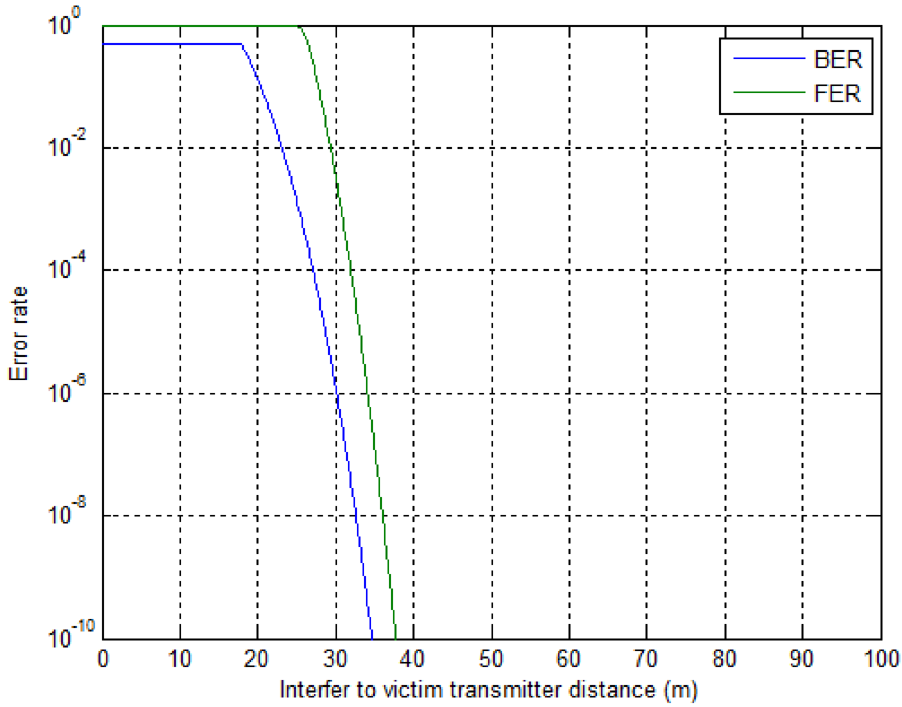



Figure 13-1: Victim BER/FER vs. Distance
from 802.22 BS Interferer Tx to 802.15.4m NB-OFDM PHY Portable Device Victim Rx
(victim TX pwr:8.1, interferer TX pwr:29.7, victim ant: 10/2/0/0, interf BS ant: 30/6)

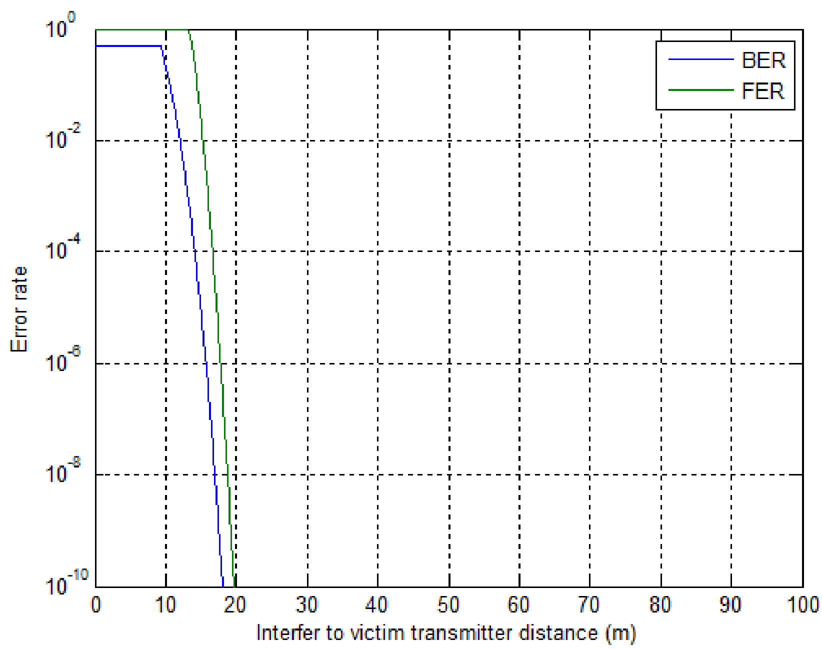



Figure 13-2: Victim BER/FER vs. Distance
from 802.22 BS Interferer Tx to 802.15.4m NB-OFDM PHY Fixed Device Victim Rx
(victim TX pwr:18.1, interferer TX pwr:29.7, victim ant: 10/2/0/0, interf BS ant: 30/6)

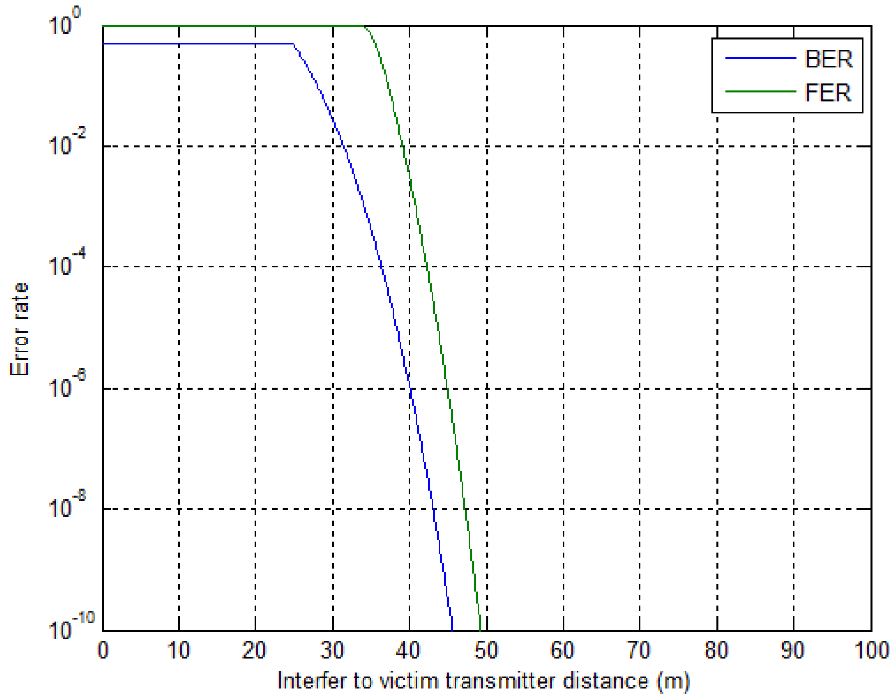



Figure 13-3: Victim BER/FER vs. Distance
from 802.22 CPE Interferer Tx to 802.15.4m NB-OFDM PHY Portable Device Victim Rx
(victim TX pwr:8.1, interferer TX pwr:29.7, victim ant: 10/2/0/0, interf CPE ant: 10/6)

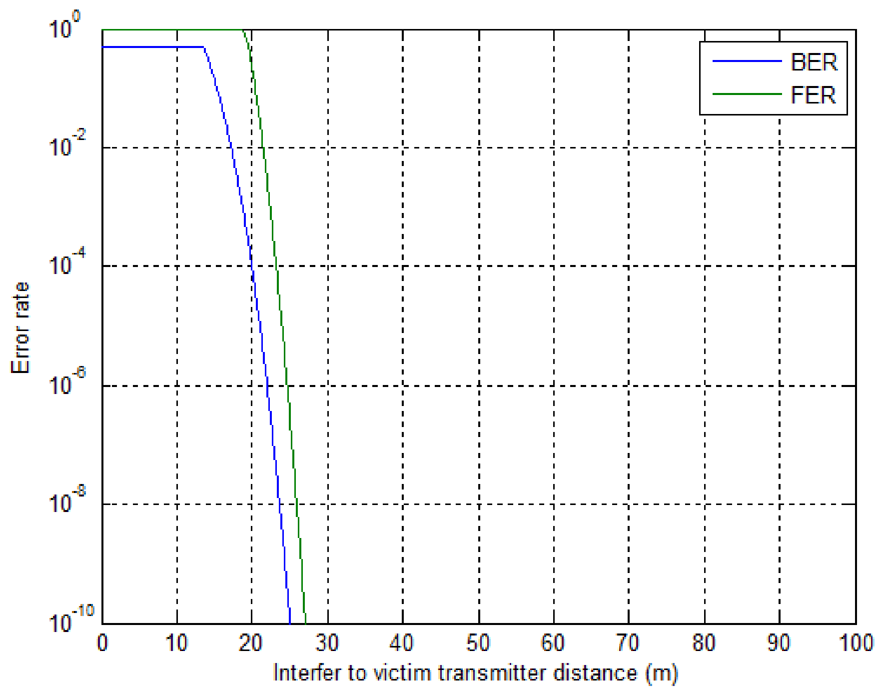



Figure 13-4: Victim BER/FER vs. Distance
from 802.22 CPE Interferer Tx to 802.15.4m NB-OFDM PHY Fixed Device Victim Rx
(victim TX pwr:18.1, interferer TX pwr:29.7, victim ant: 10/2/0/0, interf CPE ant: 10/6)

Figures 14, 15, and 16 show the BER/FER performance of the 802.15.4m FSK PHY mode, OFDM PHY mode, and NB-OFDM PHY mode victim receivers respectively, corresponding to the distance from the 802.22.1 interferer transmitter to the 802.15.4m victim receivers.

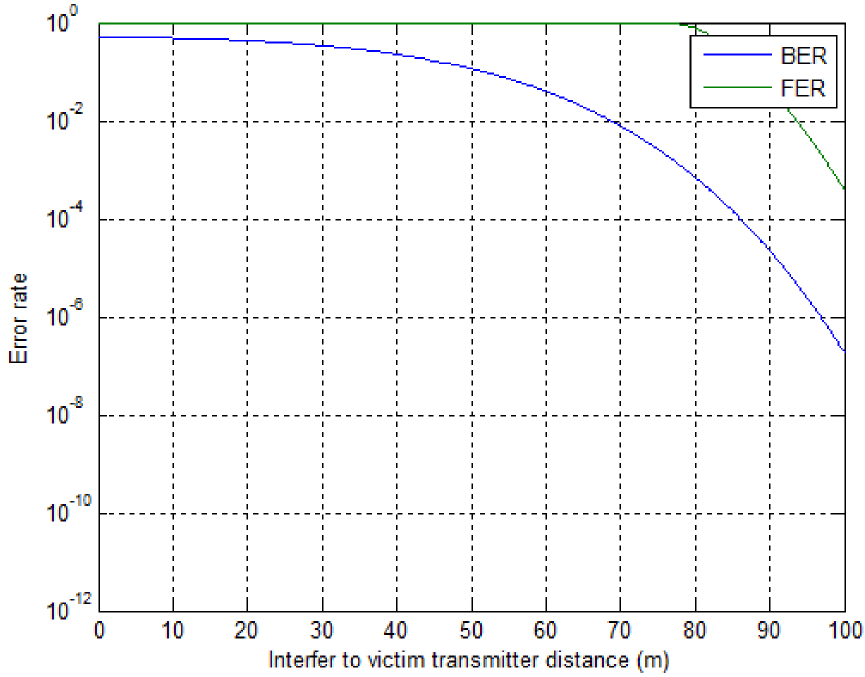



Figure 14-1: Victim BER/FER vs. Distance
from 802.22.1 Interferer Tx to 802.15.4m FSK PHY Portable Device Victim Rx
(victim TX pwr:5.2, interferer TX pwr:24, victim ant: 10/2/0/0, interf ant: 3/2)

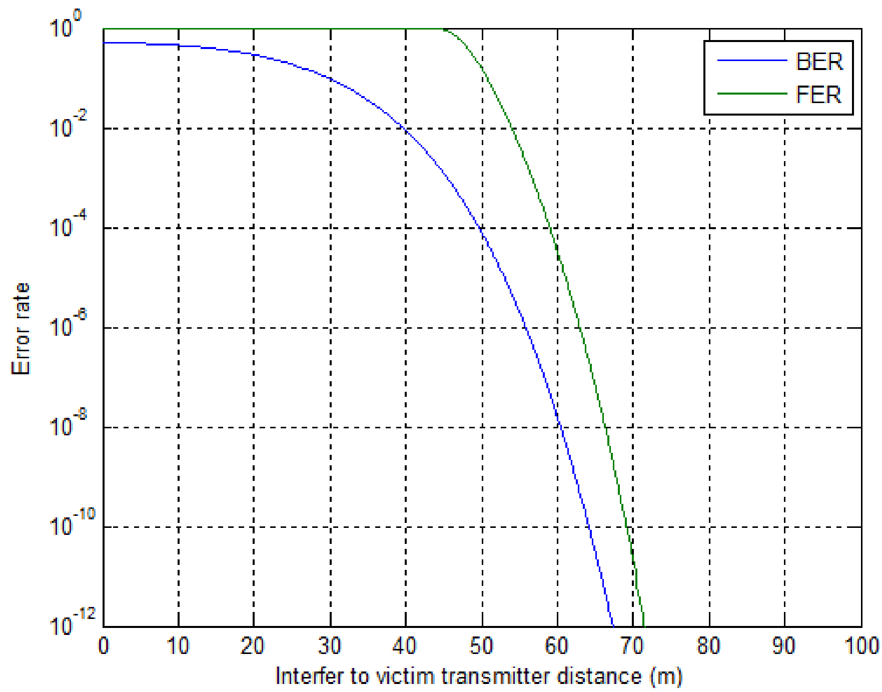



Figure 14-2: Victim BER/FER vs. Distance
from 802.22.1 Interferer Tx to 802.15.4m FSK PHY Fixed Device Victim Rx
(victim TX pwr:15.2, interferer TX pwr:24, victim ant: 10/2/0/0, interf ant: 3/2)

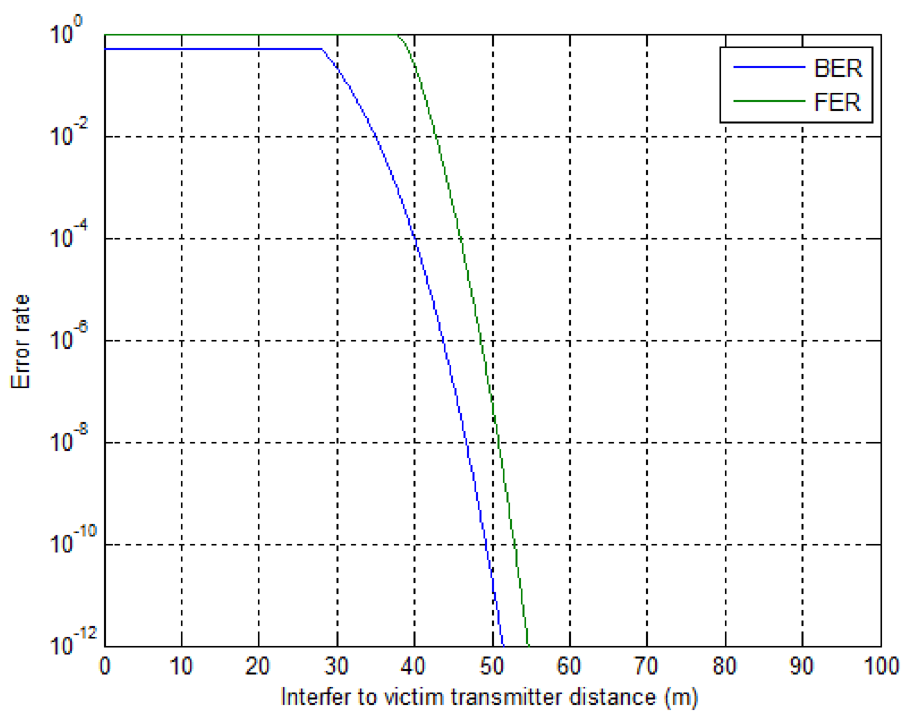



Figure 15-1: Victim BER/FER vs. Distance
from 802.22.1 Interferer Tx to 802.15.4m OFDM PHY Portable Device Victim Rx
(victim TX pwr:13.2, interferer TX pwr:24, victim ant: 10/2/0/0, interf ant: 3/2

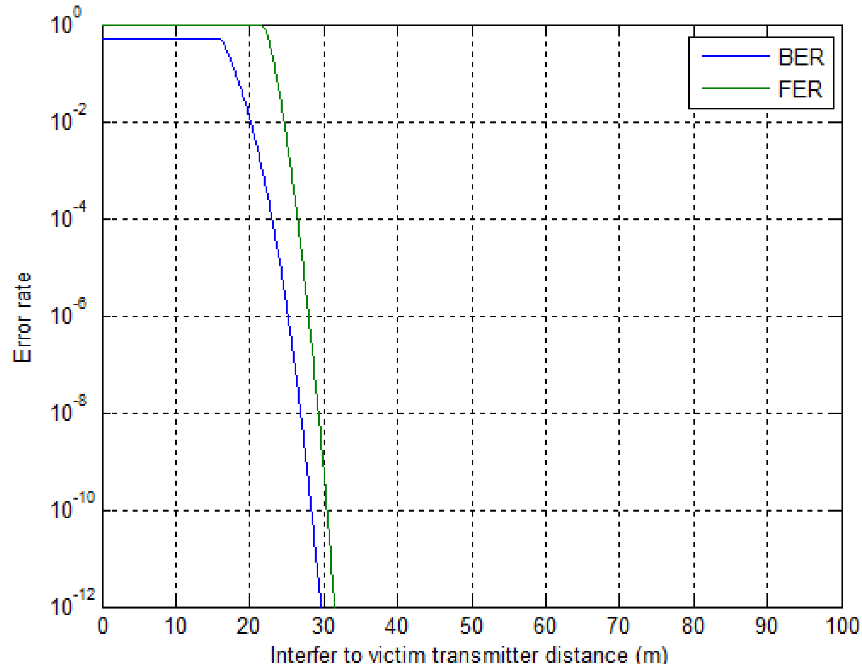



Figure 15-2: Victim BER/FER vs. Distance
from 802.22.1 Interferer Tx to 802.15.4m OFDM PHY Fixed Device Victim Rx
(victim TX pwr:23.2, interferer TX pwr:24, victim ant: 10/2/0/0, interf ant: 3/2)

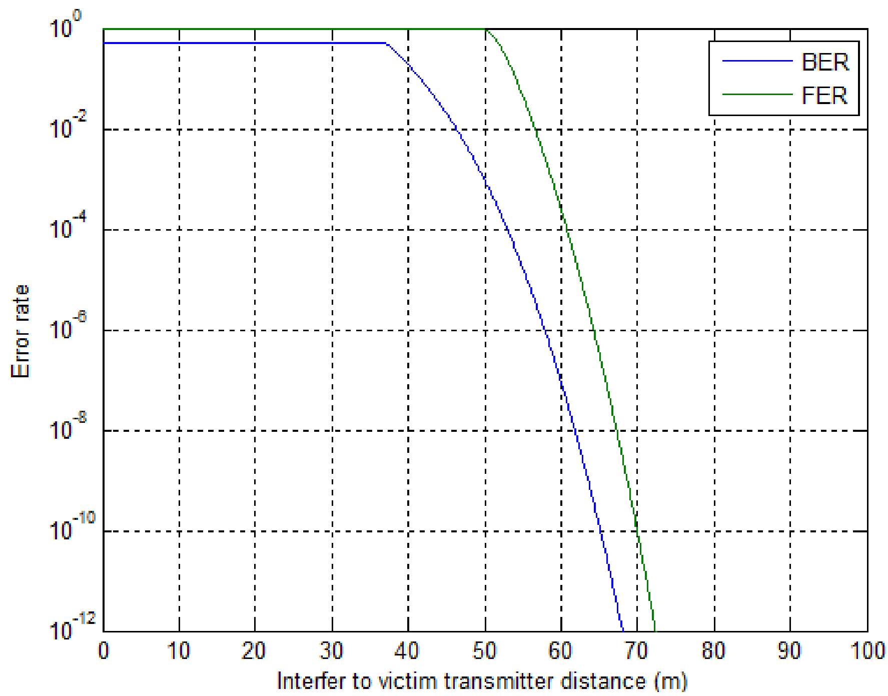



Figure 16-1: Victim BER/FER vs. Distance
from 802.22.1 Interferer Tx to 802.15.4m NB-OFDM PHY Portable Device Victim Rx
(victim TX pwr:8.1, interferer TX pwr:24, victim ant: 10/2/0/0, interf ant: 3/2)

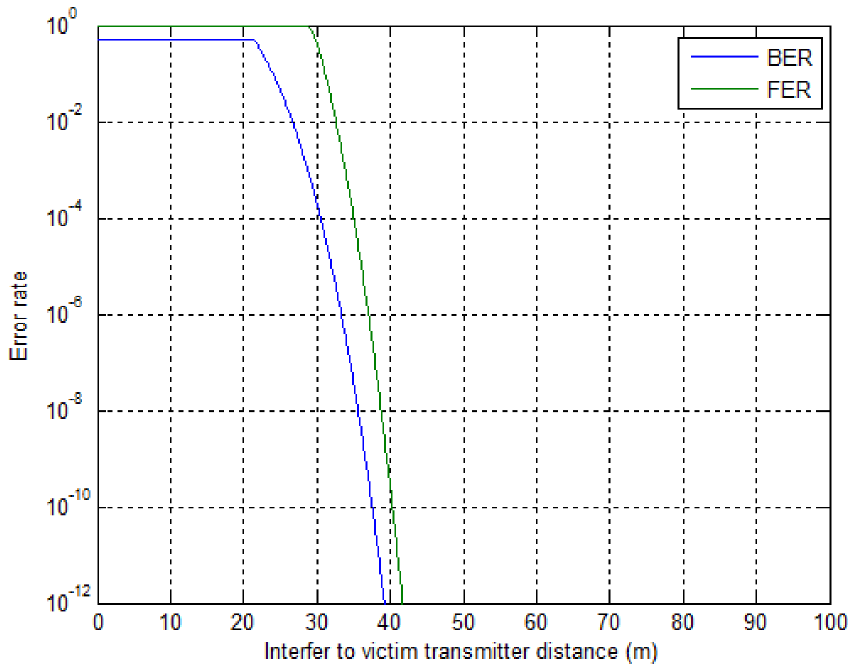



Figure 16-2: Victim BER/FER vs. Distance
from 802.22.1 Interferer Tx to 802.15.4m NB-OFDM PHY Fixed Device Victim Rx
(victim TX pwr:18.1, interferer TX pwr:24, victim ant: 10/2/0/0, interf ant: 3/2)

### *802.22 as Victim Receiver*

Figures 17, 18, and 19 show the BER/FER performances of the 802.22 victim receiver corresponding to the distance from the 802.15.4m FSK PHY mode, OFDM PHY mode, and NB-OFDM PHY mode interferer transmitters respectively to the 802.22 victim receiver with full interferer's transmitting power for the worst case scenario. 30dBm is applied as the maximum value for 802.22 device's (or base station's) transmitting power for the general case scenario.

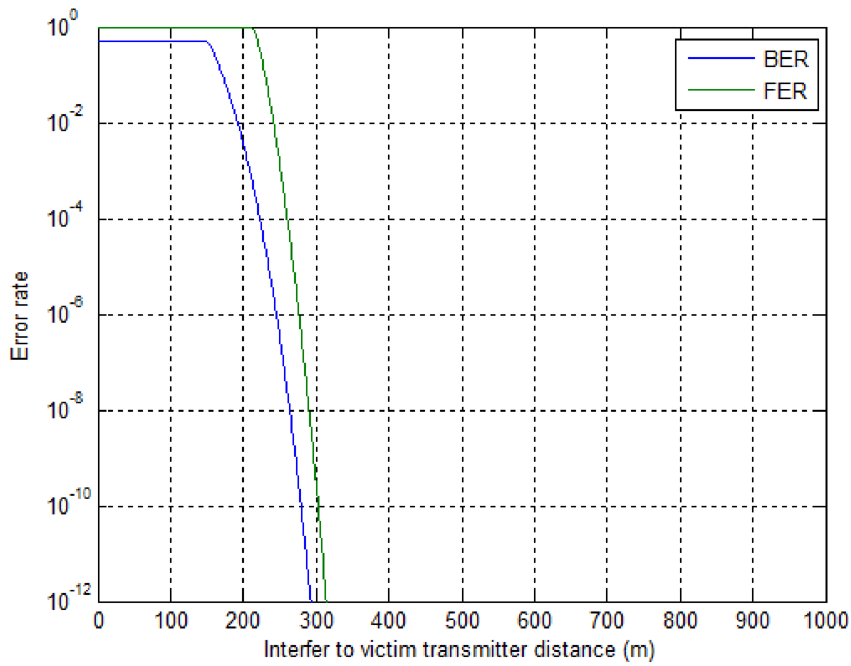



Figure 17-1: Victim BER/FER vs. Distance from 802.15.4m Portable Device FSK PHY Interferer Tx to 802.22 Victim Rx (with 1km between 802.22 Victim Tx and Rx)
(victim TX pwr:29.7, interferer TX pwr:5.2, victim ant: 30/10/6/6, interf ant: 10/0)

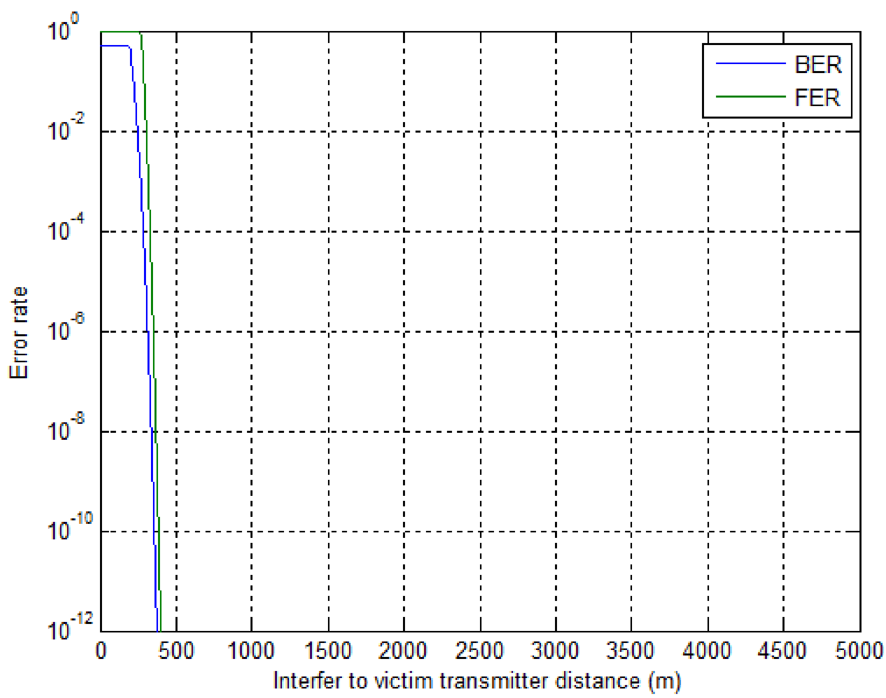



Figure 17-2: Victim BER/FER vs. Distance from 802.15.4m Fixed Device FSK PHY Interferer Tx to 802.22 Victim Rx (with 1km between 802.22 Victim Tx and Rx)
(victim TX pwr:29.7, interferer TX pwr:5.2, victim ant: 30/10/6/6, interf ant: 10/0)

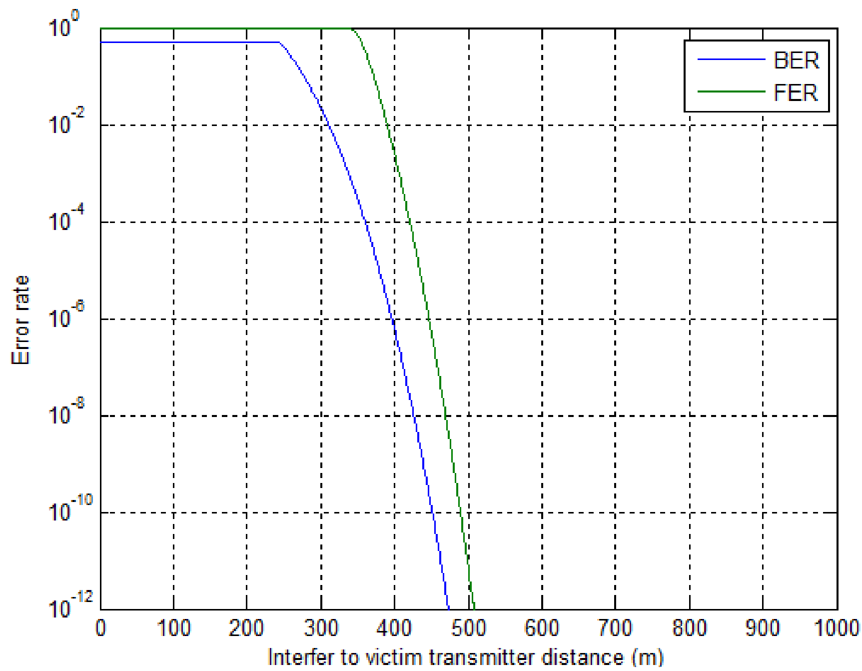



Figure 18-1: Victim BER/FER vs. Distance from 802.15.4m Portable Device OFDM PHY Interferer Tx to 802.22 Victim Rx (with 1km between 802.22 Victim Tx and Rx) (victim TX pwr:29.7, interferer TX pwr:13.2, victim ant: 30/10/6/6, interf ant: 10/0)

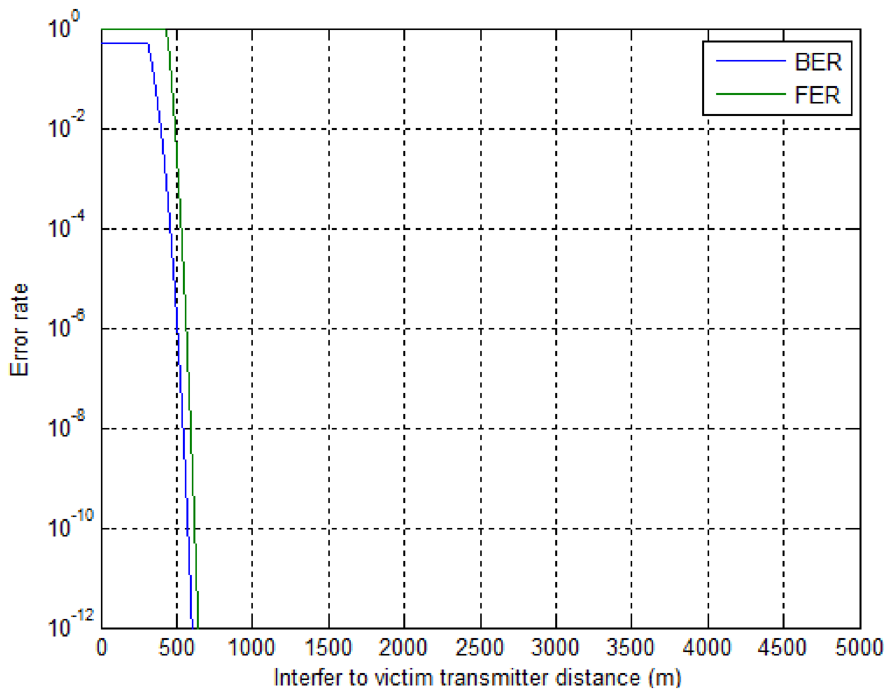



Figure 18-2: Victim BER/FER vs. Distance from 802.15.4m Fixed Device OFDM PHY Interferer Tx to 802.22 Victim Rx (with 1km between 802.22 Victim Tx and Rx) (victim TX pwr:29.7, interferer TX pwr:13.2, victim ant: 30/10/6/6, interf ant: 10/0)

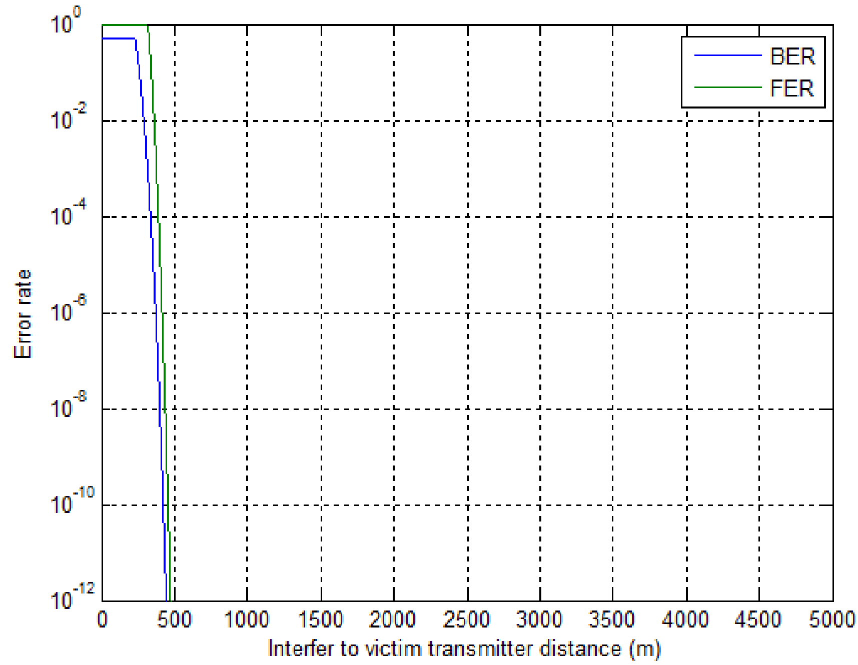



Figure 19-1: Victim BER/FER vs. Distance from 802.15.4m Portable Device NB-OFDM PHY Interferer Tx to 802.22 Victim Rx (with 1km between 802.22 Victim Tx and Rx)
(victim TX pwr:29.7, interferer TX pwr:8.1, victim ant: 30/10/6/6, interf ant: 10/0)

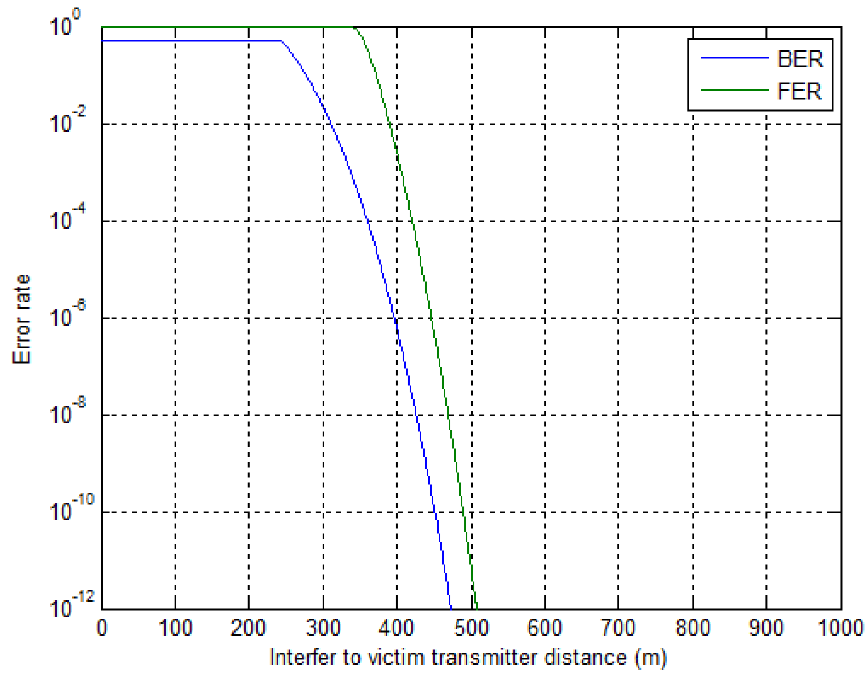



Figure 19-2: Victim BER/FER vs. Distance from 802.15.4m Portable Device NB-OFDM PHY Interferer Tx to 802.22 Victim Rx (with 1km between 802.22 Victim Tx and Rx)
(victim TX pwr:29.7, interferer TX pwr:8.1, victim ant: 30/10/6/6, interf ant: 10/0)

*802.22.1 as Victim Receiver*

Figures 20, 21, and 22 show the BER/FER performances of the 802.22.1 victim receiver corresponding to the distance from the 802.15.4m FSK PHY mode, OFDM PHY mode, and NB-OFDM PHY mode interferer transmitters respectively to the 802.22.1 victim receiver with full interferer's transmitting power for the worst case scenario. 24dBm is applied as the typical value for 802.22.1 device's transmitting power for the general case scenario.

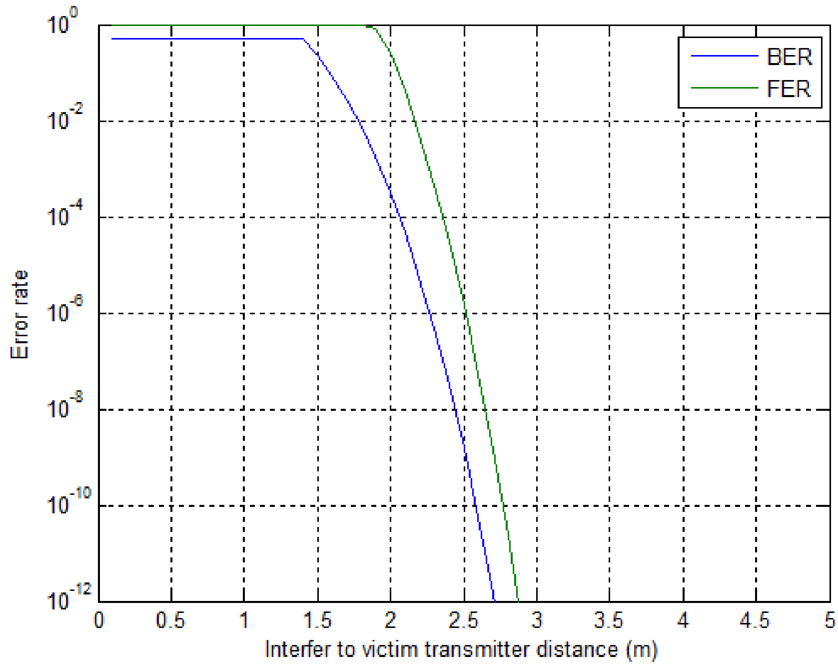



Figure 20-1: Victim BER/FER vs. Distance
from 802.15.4m FSK PHY Portable Device Interferer Tx to 802.22.1 Victim Rx
(victim TX pwr:20, interferer TX pwr:5.2, victim ant: 3/3/2/2, interf ant: 10/0)

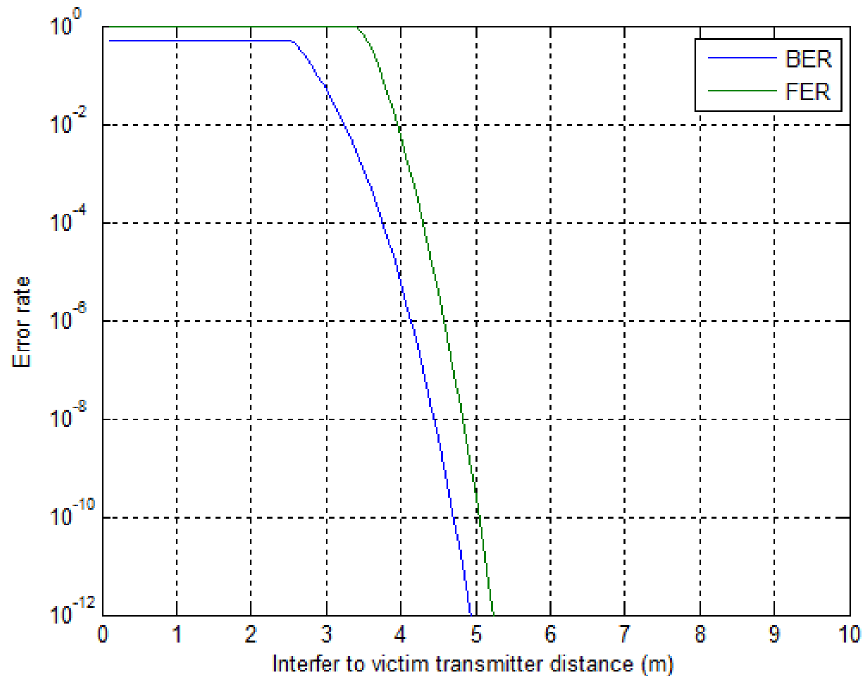



Figure 20-2: Victim BER/FER vs. Distance
from 802.15.4m FSK PHY Fixed Device Interferer Tx to 802.22.1 Victim Rx
(victim TX pwr:20, interferer TX pwr:15.2, victim ant: 3/3/2/2, interf ant: 10/0)

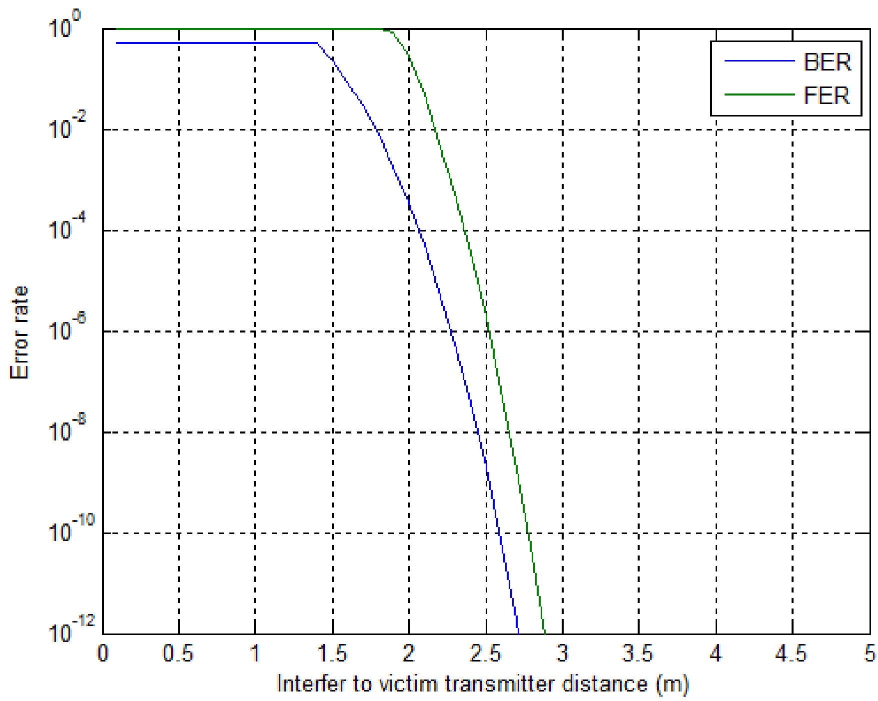



Figure 21-1: Victim BER/FER vs. Distance
from 802.15.4m OFDM PHY Portable Device Interferer Tx to 802.22.1 Victim Rx
(victim TX pwr:20, interferer TX pwr:13.2, victim ant: 3/3/2/2, interf ant: 10/0)

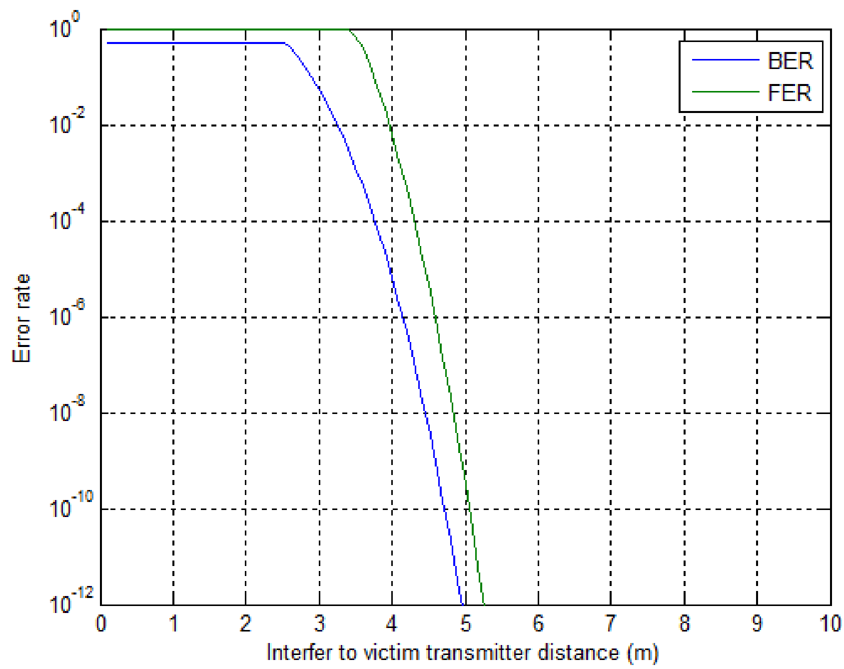



Figure 21-2: Victim BER/FER vs. Distance
from 802.15.4m OFDM PHY Fixed Device Interferer Tx to 802.22.1 Victim Rx
(victim TX pwr:20, interferer TX pwr:23.2, victim ant: 3/3/2/2, interf ant: 10/0)

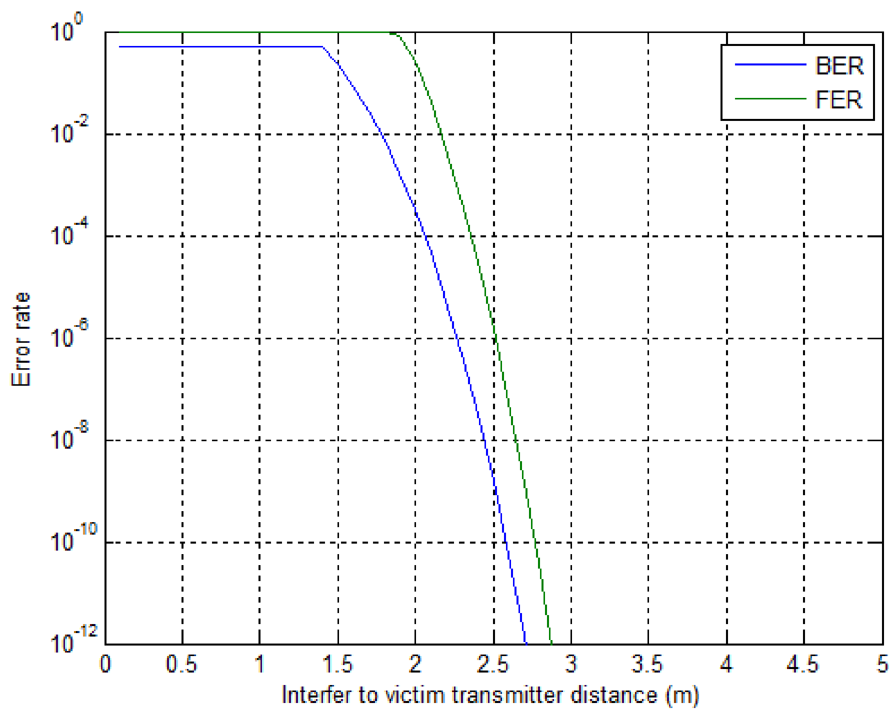



Figure 22-1: Victim BER/FER vs. Distance
from 802.15.4m NB-OFDM Portable Device PHY Interferer Tx to 802.22.1 Victim Rx
(victim TX pwr:20, interferer TX pwr:8.1, victim ant: 3/3/2/2, interf ant: 10/0)

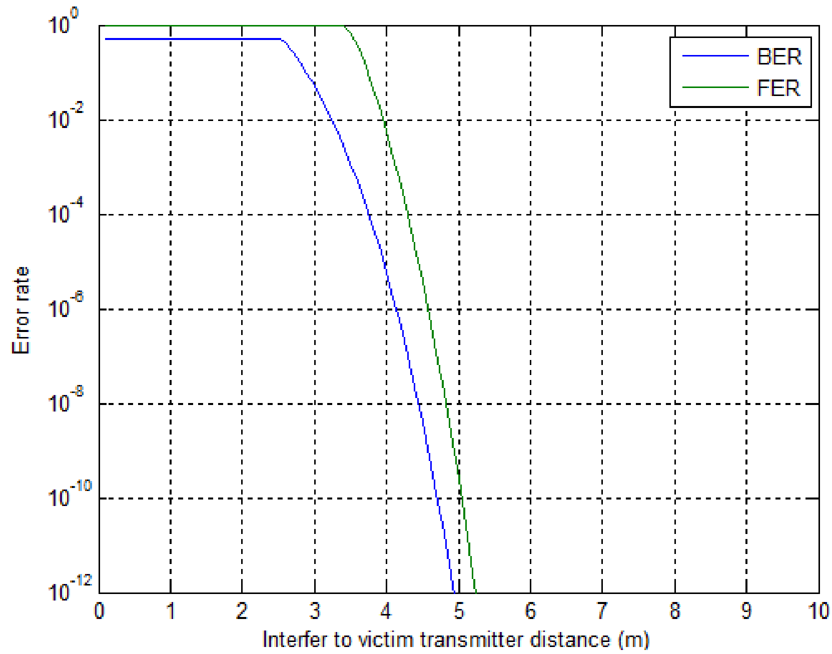



Figure 22-2: Victim BER/FER vs. Distance
from 802.15.4m NB-OFDM PHY Fixed Device Interferer Tx to 802.22.1 Victim Rx
(victim TX pwr:20, interferer TX pwr:18.1, victim ant: 3/3/2/2, interf ant: 10/0)

## Coexistence Performance with 802.11 and 802.15 Systems in Non-TVWS bands

This sub-clause presents the coexistence performance of the systems coexisting in the non-TV white space bands. In order to understand the impact of the generated interference, 802.15.4m systems and other coexisting 802 systems in these bands are set as both the victim and interferer source.

As described in the above, the frequency bands of interest other than TV white space bands 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 and eight coexisting systems are so far identified: 802.11b, 11g, 11n, 15.1, 15.3, 15.4, 15.4c, and 15.4d systems. (Refer to Tables 13 through 17.)

### Parameters for Coexistence Quantification

The following sub-clauses present the parameters involved in quantification of coexistence analysis amongst the participating systems including BER and FER performance versus SNR.

#### *PHY Parameters of Coexisting 802.11 and 802.15 Standards*

Tables 13 through 17 show the PHY mode parameters of coexisting 802.11b, 11g, 11n, 15.1, 15.3, 15.4, 15.4c, and 15.4d standards in each of the frequency band.

**Table 13: 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 |

**Table 14: 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 | | | | |

**Table 15: 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 |

**Table 16: 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 |

**Table 17: 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 |

## *BER / FER for PHY Modes of Coexisting 802.11 and 15 Standards*

In this sub-clause, the BER / FER performance corresponding to SNR for all the 802.11 and 802.15 standards are presented. The parameter SNR is defined as the ratio between the energy in each symbol to the noise power spectral density in each symbol.

The BER and FER curves for all 802.11 and 802.15 systems are illustrated in Figures 23 through 27.

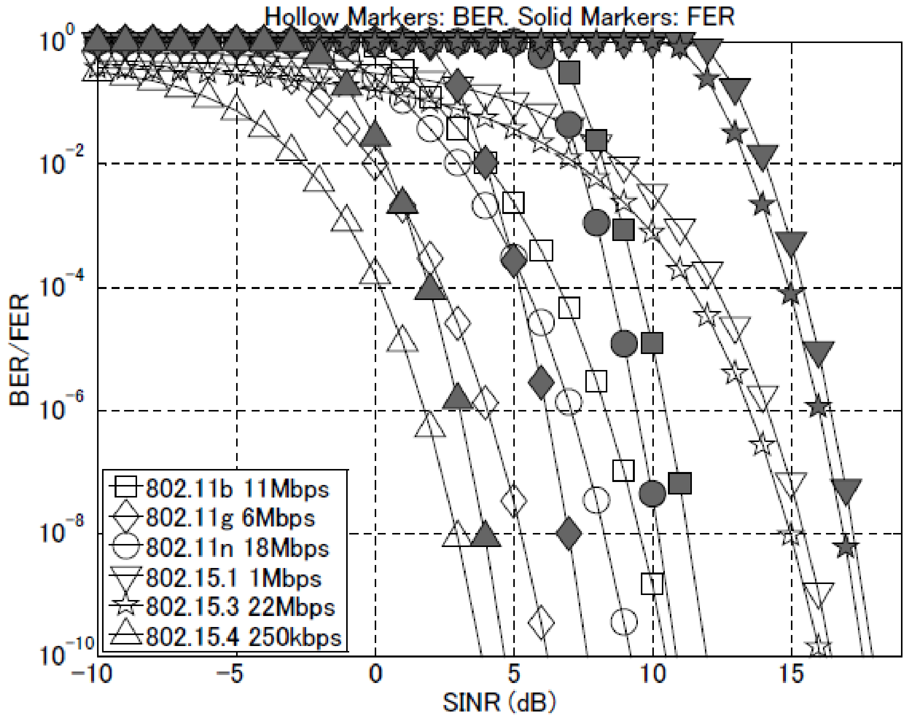



**Figure 23: BER and FER vs. SNR for 802 Systems in the 2400-2483.5 MHz Band (This figure is imported from IEEE802 15-10-0668-05.)**

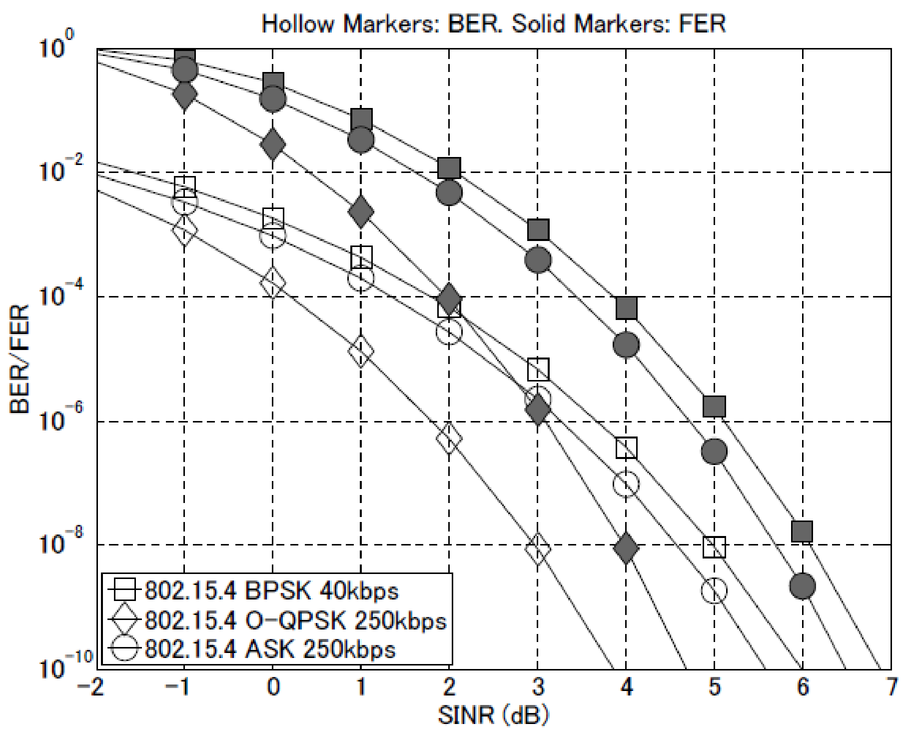



**Figure 24: BER and FER vs. SNR for 802 Systems in the 902-928 MHz Band (This figure is imported from IEEE802 15-10-0668-05.)**

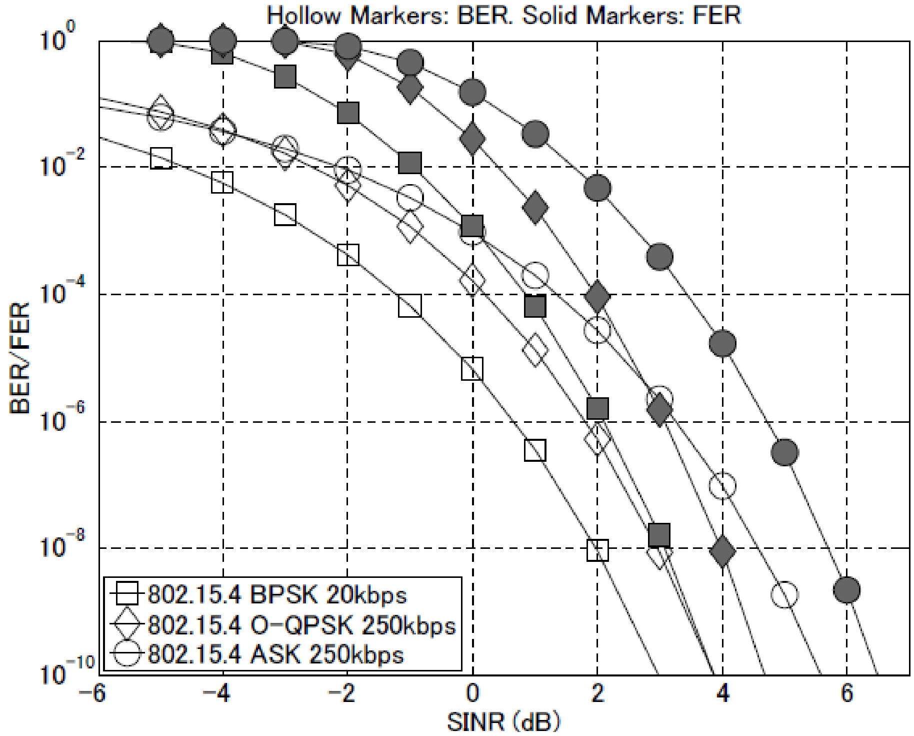



**Figure 25: BER and FER vs. SNR for 802 Systems in the 863-870 MHz Band (This figure is imported from IEEE802 15-10-0668-05.)**

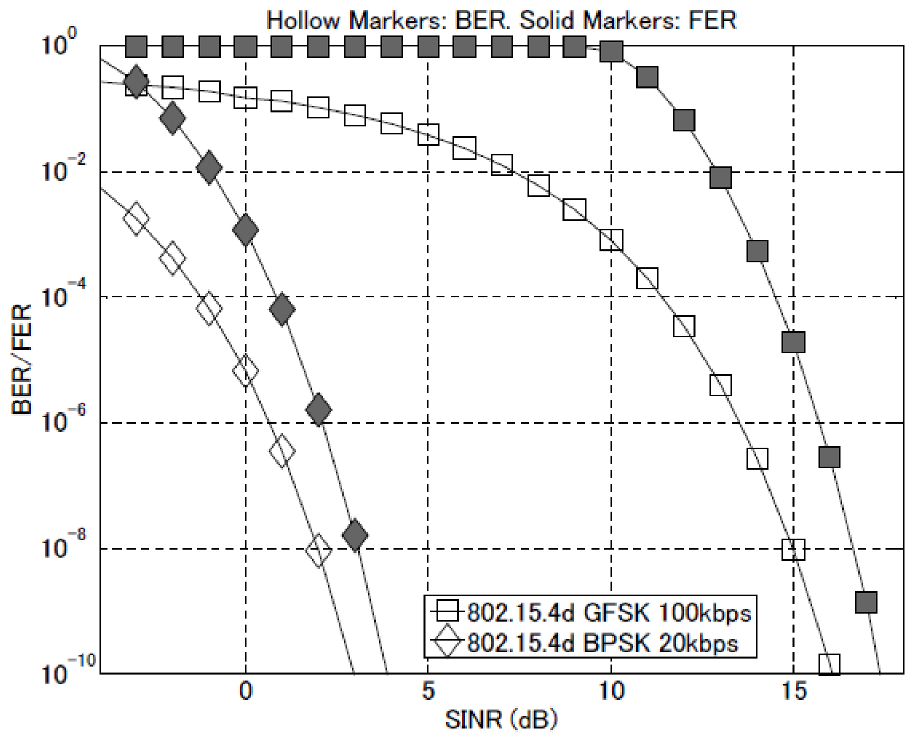



**Figure 26: BER and FER vs. SNR for 802 Systems in the 950-958 MHz Band (This figure is imported from IEEE802 15-10-0668-05.)**

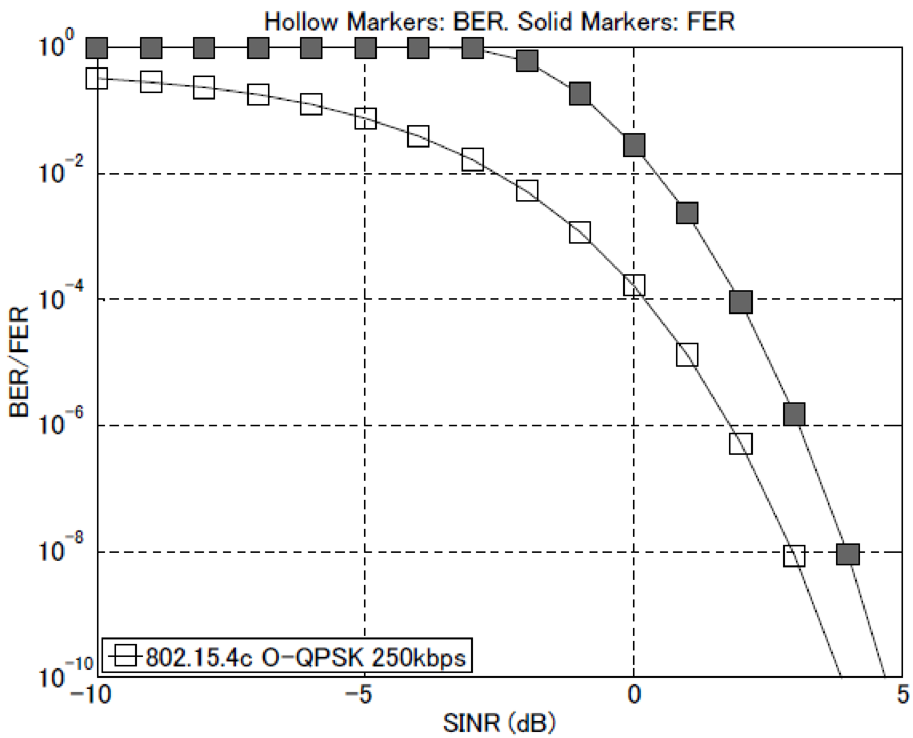



**Figure 27: BER and FER vs. SNR for 802 Systems in the 779-787 MHz Band**
**(This figure is imported from IEEE802 15-10-0668-05.)**

Coexistence analysis for 802.15.4m systems is to be done using the results for 802.15.4g (relevant document: IEEE802 15-10-0668-05). To do this, major parameters of these two systems are compared in Table 18.

**Table 18: Comparison of Major Parameters of 802.15.4m and 15.4g PHY Modes**

| System | PHY spec. | Receiver Bandwidth (kHz) | PHY Mode |
|---|---|---|---|
| 802.15.4m | FSK | 200 | 100kbps FSK |
| | OFDM | 1250 | 781kbps QPSK<br>CC *RFEC*=1/2 |
| | NB-OFDM | 390 | 312kbps QPSK<br>CC *RFEC*=1/2 |
| 802.15.4g | MR-FSK | 200 | 50kbps FSK |
| | MR-OFDM | 200 | 200kbps QPSK<br>CC *RFEC*=1/2 |
| | MR-O-QPSK | 2000 | 500kbps O-QPSK<br>CC *RFEC*=1/2<br>(8,4) DSSS |

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.

If the same transmit power for both 802.15.4m and 802.15.4g is considered, we have the same results from coexistence evaluation for the 802.15.4m as for the 802.15.4g suggested in doc. IEEE802 15-10-0668-05 as shown in Table 19.

**Table 19: Critical distance $d_{cri}$ for 10^-2 FER for 802.15.4m in different frequency bands. Interferer: Other 802 systems. Victim: 802.15.4m systems.**

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

# 4. Interference Avoidance and Mitigation Techniques

## Additional Interference Mitigation Mechanisms

Many mitigation techniques exist in the 802.15.4 for detection and avoidance of interference with both similar and dissimilar systems, including multiple CCA based on energy detection, CSMA, inherently low duty cycles, support for frequency hopping, and spread spectrum techniques. This standard supports as similar techniques as described in 802.11af Coexistence Assurance Document [1] for coexistence with in TVWS bands. Other examples may be found in [2].

These mitigation techniques existing in the 802.15.4 are explained in the 802.15.4g coexistence assurance document (IEEE802 15-10-0668-05).

# 5. Conclusions

In this document, three types of impacts related to 802.15.4m systems are analyzed:

- impact of 802.22 on 802.15.4m,
- impact of 802.15.4m on 802.22, and
- impact of other 802 systems which share frequency bands with 802.15.4m.

## Impact of 802.22 on 802.15.4m

Figure 28 shows the interference levels at a 802.15.4m receiver as a function of distance when using the power level of 1W as allowed by FCC (as in Table 5 and Figure 1) and for a wireless signals occupying the TV channel.

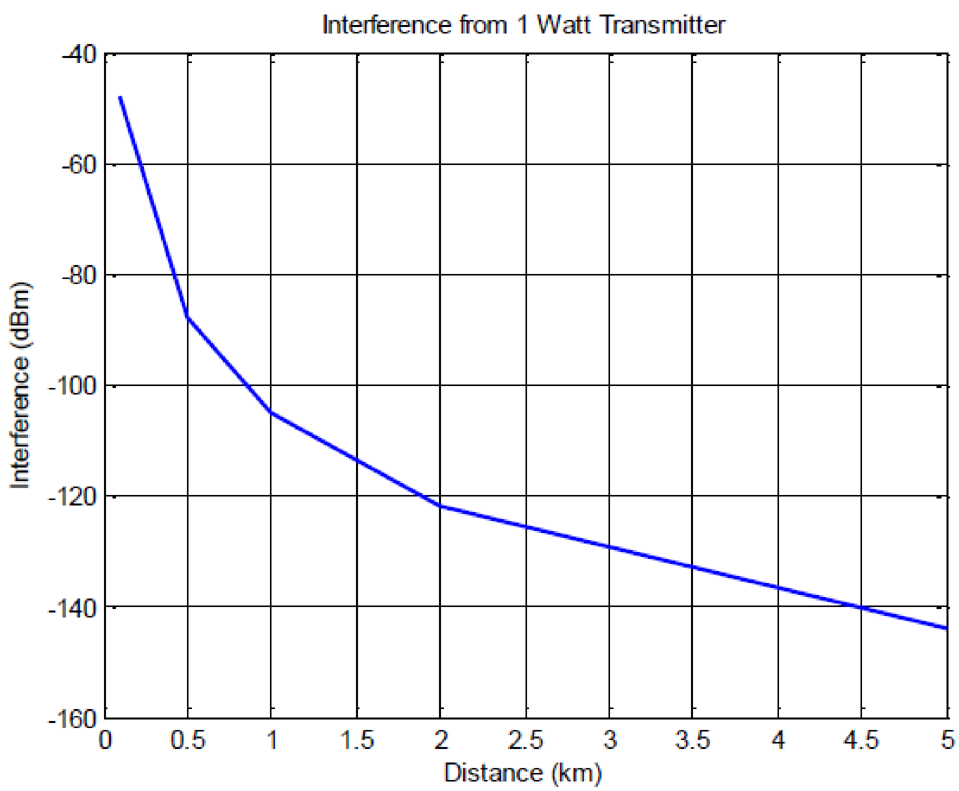



Figure 28: Interference Level vs. Distance between Transmitter and Receiver

With physical separation of 1 km or greater the inference footprint of the 802.22 system on the 802.15.4m is at or below typical expected noise levels. The narrower occupied bandwidth used in 802.22.1 the power scales down with bandwidth.

## Impact of 802.15.4m on 802.22 devices

Figure 29 shows that the received signal power at the 802.22 receiver decreases as the distance between 802.22 transmitter and receiver increases when there is no interference from other systems. From the results of this figure, the received signal power is below typical thermal noise floor level for distances larger than 10km, which means that we can only consider only the separation of 10 km or less between 802.22 transmitter and receiver for evaluation of interference from 802.15.4m.

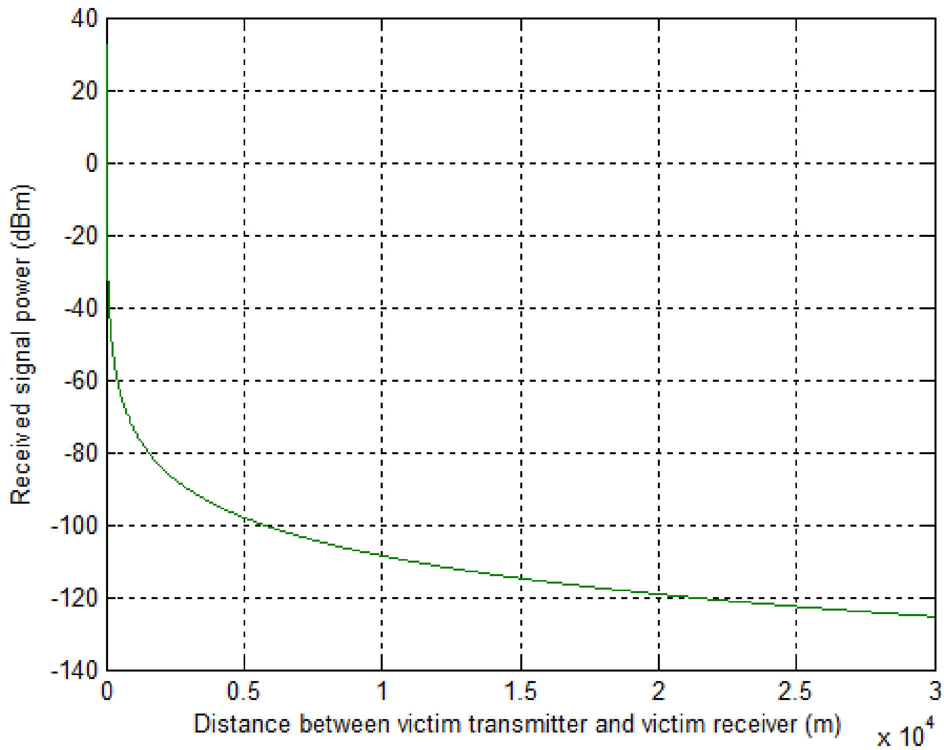



Figure 29: Received Signal Power vs. Distance between 802.22 Transmitter and Receiver When there is No Interference from Other Systems.

The impact of an 802.15.4m transmitter on 802.22 receivers will be similar to the case above. For the narrower channels used by 802.15.4m, transmit power and noise threshold scale together and it reduces to a symmetric impact and equivalent results are expected. In addition, channel estimation schemes can be used to mitigate against narrowband interferers for improved performance.

In this document, for the above two types of impacts numerous scenarios are considered extensively. For each scenario, error rate performance is evaluated for the worst case. The analysis results are summarized in Table 20.

**Table 20: Distances between Victim Receiver and Interferer for (BER=10^-6) and (FER=10^-2). (Unit: m)**

| | 15.4m | TX power:5.2, 13.2, 8.1 Ant: 10/2/0/0, Portable Device * | | TX power: 15.2, 23.2, 18.1 Ant: 10/2/0/0, Fixed Device * | |
|---|---|---|---|---|---|
| | 22 | BS TX power: 29.7, Ant: 30/6 ** | CPE TX power: 29.7, Ant: 10/6 ** | BS TX power: 29.7, ant: 30/6 ** | CPE TX power: 29.7, Ant: 10/6 ** |
| | | BS-CPE distance: 1km | | BS-CPE distance: 1km | |
| | 22.1 | TX power: 24 , Ant: 3/2 ** | | TX power: 24 , Ant: 3/2 ** | |
| 22 to 15.4m | FSK | 45/43 | 58/56 | 23/23 | 33/32 |
| | OFDM | 30/29 | 40/39 | 16/15 | 23/22 |
| | NB-OFDM | 30/29 | 40/39 | 7.5/7 | 22/21 |
| 22.1 to 15.4m | FSK | 97/94 | | 55/54 | |
| | OFDM | 43/43 | | 25/24 | |
| | NB-OFDM | 57/56 | | 33/32 | |
| 15.4m to 22 *** | FSK | 168/160 | | 190/182 | |
| | OFDM | 280/273 | | 350/343 | |
| | NB-OFDM | 210/205 | | 280/273 | |
| 15.4m to 22.1 | FSK | 2.3/2.2 | | 4.2/4 | |
| | OFDM | 2.3/2.2 | | 4.2/4 | |
| | NB-OFDM | 2.3/2.2 | | 4.2/4 | |

* Tx power for 15.4m is ones for FSK, OFDM, and NB-OFDM PHYs respectively and Ant: x/y/z/w means transmit and receive antenna heights x and y and transmit and receive antenna gains z and w.
** Ant: x/y for other systems means antenna height x and antenna gain y.
*** Antenna gain of 802.22 CPE in the direction to 15.4m is assumed to be 0 dB.

## Impact of 802.15.4m on Other 802 Systems Sharing Frequency Bands and Impact of Other 802 Systems on 802.15.4m

The impact of other 802 systems which share frequency bands with 802.15.4m on 802.15.4m is analyzed and summarized using the results for the 802.15.4g case in Table 21.

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, if the required FER for 802.15.4m FSK is 0.01, $d_{cri}$ is the minimum distance between victim receiver and interferer transmitter that gives FER=0.01

along the FSK FER curve. If the distance becomes smaller than $d_{cri}$, FER will be degraded beyond the required value of 0.01.

**Table 21: Critical Distance $d_{cri}$ for 802.15.4m in Different Frequency Bands. Interferer: Other 802 Systems. Victim: 802.15.4m Systems.**

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

The impact of 802.15.4m on other 802 systems is similar to the results for the 802.15.4g case if the same transmit power is considered for both 802.15.4m and 802.15.4g. (Refer to IEEE802 15-10-0668-05.) From these results, the critical distance, $d_{cri}$, is as small as 12m for all 802 systems considered in this document.

## Summary and Conclusions from Coexistence Analyses

This document listed all the involved homogeneous systems within the 802.15.4m and heterogeneous systems across other 802 systems. It also has presented the overview of coexistence analysis for the IEEE 802.15.4m and IEEE 802.22 and 22.1 systems which are operated in the TV white space bands and 802.11 and 802.15 systems in other frequency bands which share these frequency bands with 802.15.4m.

Analysis on performance due to coexisting/co-locating systems is presented considering no assistance from any coexistence mechanisms.

An overview of all the available coexistence mechanisms applicable to 802.15.4m is given. Mechanisms for the purpose of interference avoidance/mitigation for 802.15.4m are proposed and evaluated.

Tables 20 and 21 summarize the values of parameter $d_{cri}$, the critical distance below where the interferer causes performance degradation greater than FER of 0.01 for frequency bands with coexisting heterogeneous systems – with 802.22 and 22.1 systems in Table 20 and with other 802 systems in Table 21 - for the worst cases.

It is observed that even without any coexistence mechanism, the 802.15.4m system are able to achieve the required FER given that an interferer is located as near as 7m away although the 802.22 system are able to achieve the same FER with interference from the 802.15.4m system more distance away up to 350m. Furthermore, with the employment of various coexistence mechanisms listed in this document, a more harmonious radio environment can be achieved.

Other 802 systems can achieve almost the same performance with interference from an 802.15.4m system as with interference from an 802.15.4g, assuming the same transmit power is used for both 802.15.4m and 802.15.4g. 802.15.4m can also achieve almost the same performance as in the case of 802.15.4g when other 802 systems are operated in the same frequency bands.

# References

[1] Doc # 802.11-11/0177r1 "11af Coexistence Assurance Document"
[2] Doc # 802.15-12-0341-01 "TG4k Coexistence Document"
[3] Doc # 802.15-10-0668-05-004g-tg4g-coexistence-assurance-document-first-draft
[4] http://www.fcc.gov/Daily_Releases/Daily_Business/2010/db0923/FCC-10-174A1.pdf from 802.11af
[5] Doc # 15-11-0684-12-004m-tg4m-technical-guidance-document
[6] Doc # 22-04-0022-01-0000-draft-guide-coexistence-assurance-methodology, "Draft Guide for Methodology on Evaluating Coexistence"
[7] Doc # 22-10-0073-03-0000-802-22-overview-and-core-technologies
[8] Doc # 22-10-0106-00-0000-ieee-802-22-phy-overview
[9] Doc # 22-13-0010-00-0001-overview-of-the-ieee-802-22-1-standard
[10] IEEE 802.22.1, IEEE Standard for Information Technology—Telecommunications and information exchange between systems--Local and metropolitan area networks—Specific requirements, Part 22.1: Standard to Enhance Harmful Interference Protection for Low-Power Licensed Devices Operation in TV Broadcast Bands, 01 Nov. 2010

# Annex

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

```
%%%%%%%%%%%%%%%%%%% Parameter Settings %%%%%%%%%%%%%%%%%
SNR = 0:20;                                      % SNR (Ec/N0) in dB
trellisOFDM = poly2trellis(7,[133 171]);         % convolutional code generators for OFDM
spectOFDM = distspec(trellisOFDM);
trellisNBOFDM = poly2trellis(7,[133 171]);       % convolutional code generators for NB-OFDM
spectNBOFDM = distspec(trellisNBOFDM);           % RS coding needed for NB-OFDM before convolutional coding (?)
L_FSK100 = 2112;                                 % frame length for FSK 100kbps
L_OFDM781 = 2896;                                % frame length for OFDM 781kbps
L_NBOFDM312 = 2736;                              % frame length for NB-OFDM 312kbps
modlev_FSK100 = 1;                               % modulation level for FSK 100kbps
modlev_OFDM781 = 2;                              % modulation level for OFDM 781kbps
modlev_NBOFDM312 = 2;                            % modulation level for NB-OFDM 312kbps
Rfec_FSK100 = 1;                                 % FEC coding rate for FSK 100kbps
Rfec_OFDM781 = 0.5;                              % FEC coding rate for OFDM 781kbps
Rfec_NBOFDM312 = 0.5;                            % FEC coding rate for NB-OFDM 312kbps

%%%%%%%%%%%%%%%%%%%% Per-bit Energy Calculations %%%%%%%%%%%%%%%%%%%
EbN0_FSK100 = SNR - 10*log10(modlev_FSK100) - 10*log10(Rfec_FSK100);
EbN0_OFDM781 = SNR - 10*log10(modlev_OFDM781) - 10*log10(Rfec_OFDM781);
EbN0_NBOFDM312 = SNR - 10*log10(modlev_NBOFDM312) - 10*log10(Rfec_NBOFDM312);
%%%%%%%%%%%%%%%%%% BER / FER Calculations %%%%%%%%%%%%%%%%%%%
BER_FSK100 = berawgn(EbN0_FSK100,'fsk',2,'coherent');          % BER for FSK 100kbps
BER_OFDM781 = bercoding(EbN0_OFDM781,'conv','hard',0.5,spectOFDM);
                                                               % BER for OFDM 781kbps
BER_NBOFDM312 = bercoding(EbN0_ NBOFDM312,'conv','hard',0.5,spect NBOFDM);
                                                               % BER for NB-OFDM 312kbps
FER_FSK100 = 1-((1-BER_FSK100).^L_FSK100);                     % FER for FSK 100kbps
FER_OFDM781 = 1-((1-BER_OFDM781).^L_OFDM781);                  % FER for OFDM 781kbps
FER_NBOFDM312 = 1-((1-BER_ NBOFDM312).^L_ NBOFDM312);          % FER for NB-OFDM 312kbp
```

## Matlab Program for Plotting BER/FER Curves for 802.22 PHY Mode

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

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

trellis22OFDM = poly2trellis(7,[133 171]);           % convolutional code generators for 22OFDM

spect22OFDM = distspec(trellis22OFDM);

L_OFDM3740 = 4098;                                   % frame length for OFDM  3740kbps

modlev_OFDM3740 = 2;                                 % modulation level for OFDM 3740kbps

Rfec_OFDM3740 = 0.5;                                 % FEC coding rate for OFDM 3740kbps


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

EbN0_OFDM3740 = SNR - 10*log10(modlev_OFDM3740) - 10*log10(Rfec_OFDM3740);


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

BER_OFDM3740 = bercoding(EbN0_OFDM3740,'conv','hard',0.5,spect22OFDM);

                                                     % BER for OFDM 3740kbps

FER_OFDM3740 = 1-((1-BER_OFDM3740).^L_OFDM3740);     % FER for OFDM QPSK 3740kbps
```

## Matlab Program for Plotting BER/FER Curves for 802.22.1 PHY Mode

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

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

trellis221QPSK = poly2trellis(7,[133 171]);          % convolutional code generators for 22.1

spect221QPSK = distspec(trellis221QPSK);

L_QPSK19 = 960;                                      % frame length for QPSK  19.2kbps

modlev_QPSK19 = 2;                                   % modulation level for QPSK  19.2kbps

Rfec_QPSK19 = 0.5;                                   % FEC coding rate for QPSK  19.2kbps

SF_QPSK19 = 8;                                       % spreading factor for OQPSK 500kbps


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

EbN0_QPSK19 = SNR - 10*log10(modlev_QPSK19) - 10*log10(Rfec_QPSK19) + 10*log10(SF_QPSK19);


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

BER_QPSK19 = bercoding(EbN0_QPSK19,'conv','hard',0.5,spect221QPSK);

                                                     % BER for QPSK  19.2kbps

FER_QPSK19 = 1-((1-BER_QPSK19).^L_QPSK19);           % FER for QPSK  19.2kbps
```

## Matlab Program for Plotting BER/FER Curves of the 802.15.4m FSK PHY Mode in response to Interference Generated by 802.22 Systems

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

```
% 802.15.4m FSK as the victim receiver                     % Txv and Rxv - 802.15.4m FSK 100kbps
% Txi - 802.22 3740 kbps

% Interferer and Victim Parameters
IV_Para.P_Tv = 5.2;                                        % victim TX transmit power in dBm (20dBm-14.8dB)
IV_Para.P_Ti = 29.7;                                       % interferer TX transmit power in dBm
IV_Para.BW_Rv = 200e3;                                     % bandwidth for victim receiver in Hz (6M/200k=14.8dB)
IV_Para.BW_Ti = 56e5;                                      % bandwidth for interferer in Hz (6/5.6=0.03dB)
IV_Para.d_D = 0.01;                                        % victim transmitter to victim receiver distance in km
IV_Para.d_U = [0.01:0.01:10];                              % interferer transmitter to victim receiver distance in km
IV_Para.fc = 400;                                          % center frequency in MHz

% Modified Hata Path Loss Model Parameters
PL_Para.h_ap = 10;                                         % base station 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 = 10;                                        % interferer height (only consider 22 CPE)

% Calculation of SNR
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);              % this can be performed using a function, DUR
end
end

BER_FSK100 = berawgn(DUR,'fsk',2,'coherent');              % BER for victim
L_FSK100 = 2112;                                           % victim signal frame length
FER_FSK100 = 1-((1-BER_FSK100).^L_FSK100);                 % FER for victim
```

## Matlab Program for Plotting BER/FER Curves of the 802.15.4m OFDM PHY Mode in response to Interference Generated by 802.22 Systems

```
% 802.15.4m OFDM as the victim receiver                      % Txv and Rxv - 802.15.4m OFDM 781kbps
% Txi - 802.22 3740 kbps

% Interferer and Victim Parameters
IV_Para.P_Tv = 13.2;                                         % victim TX transmit power in dBm
IV_Para.P_Ti = 29.7;                                         % interferer TX transmit power in dBm
IV_Para.BW_Rv = 1250e3;                                      % bandwidth for victim receiver in Hz
IV_Para.BW_Ti = 56e5;                                        % bandwidth for interferer in Hz
IV_Para.d_D = 0.01;                                          % victim transmitter to victim receiver distance in km
IV_Para.d_U = [0.01:0.01:10];                                % interferer transmitter to victim receiver distance in km
IV_Para.fc = 400;                                            % center frequency in MHz

% Modified Hata Path Loss Model Parameters
PL_Para.h_ap = 10;                                           % base station 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 = 10;                                          % interferer height

% Calculation of SNR
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);                % this can be performed using a function, DUR
end
end

trellisOFDM = poly2trellis(7,[133 171]);                     % convolutional code generators for 15.4m OFDM
spectOFDM = distspec(trellisOFDM);

BER_OFDM781 = bercoding(DUR,'conv','hard',0.5,spectOFDM);    % BER for victim
L_OFDM781 = 2896;                                            % victim signal frame length
FER_OFDM781 = 1-((1-BER_OFDM781).^L_OFDM781);                % FER for victim
```

## Matlab Program for Plotting BER/FER Curves of the 802.15.4m NB-OFDM PHY Mode in response to Interference Generated by 802.22 Systems

```
% 802.15.4m NB-OFDM as the victim receiver              % Txv and Rxv - 802.15.4m NB-OFDM 312kbps
% Txi - 802.22 3740 kbps

% Interferer and Victim Parameters
IV_Para.P_Tv = 8.1;                  % victim TX transmit power in dBm
IV_Para.P_Ti = 29.7;                 % interferer TX transmit power in dBm
IV_Para.BW_Rv = 390e3;               % bandwidth for victim receiver in Hz
IV_Para.BW_Ti = 56e5;                % bandwidth for interferer in Hz
IV_Para.d_D = 0.01;                  % victim transmitter to victim receiver distance in km
IV_Para.d_U = [0.01:0.01:10];        % interferer transmitter to victim receiver distance in km
IV_Para.fc = 400;                    % center frequency in MHz

% Modified Hata Path Loss Model Parameters
PL_Para.h_ap = 10;                   % base station 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 = 10;                  % interferer height

% Calculation of SNR
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);     % this can be performed using a function, DUR
end
end

trellisNBOFDM = poly2trellis(7,[133 171]);        % convolutional code generators for 15.4m NB-OFDM
spectNBOFDM = distspec(trellisNBOFDM);

BER_NBOFDM312 = bercoding(DUR,'conv','hard',0.5,spectNBOFDM);     % BER for victim
L_NBOFDM312 = 2736;                                               % victim signal frame length
FER_NBOFDM312 = 1-((1-BER_NBOFDM312).^L_NBOFDM312);               % FER for victim
```

Matlab Function Program for Calculating the DUR Corresponding to Path Loss

```
% Function to calculate DUR or SNR

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;

                                                   % received power by victim receiver from victim transmitter

% for undesired link

G_Ti = 6;                                          % 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;

                                                   % received power by victim receiver 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;

                                                   % received power by victim receiver from interferer transmitter
                                                   % if victim bandwidth is larger than interferer bandwidth

end

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

(Antenna gains applied in the above function vary according to the types of the victim transmitter, the receiver and the interferer.)