**IEEE P802.15**

**Wireless Personal Area Networks**

|  |  |
| --- | --- |
| Project | IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs) |
| Title | TG4q Coexistence Assurance Document |
| Date Submitted | December 2014 |
| Source | Jinesh P Nair, Chandrashekhar Thejaswi PS, Kiran Bynam and Henk de Ruijter |
| Re: | IEEE 802.15.4q |
| Abstract | Analysis on coexistence of IEEE 802.15.4q with other IEEE 802 systems within the same frequency bands |
| Purpose | To address the coexistence capability of IEEE 802.15.4n to satisfy requirements of the IEEE 802.19 Work Group and IEEE 802 Executive Committee to determine if a proposed IEEE 802 standard has made a reasonable effort to be able to coexist with devices compliant to other IEEE 802 standards in their operating band. |
| Notice | This document has been prepared to assist IEEE P802.15 coexistence. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein. |
| Release | The contributor acknowledges and accepts that this contribution becomes the property of IEEE and may be made publicly available by P802.15. |
|  |  |

Table of Contents

[1 Introduction 1](#_Toc405976971)

[1.1 Scope 1](#_Toc405976972)

[2 Bibiography 1](#_Toc405976973)

[3 Acronyms and abbreviations 1](#_Toc405976974)

[4 Overview 2](#_Toc405976975)

[4.1 General 2](#_Toc405976976)

[4.2 Operating frequency bands 2](#_Toc405976977)

[4.3 MCS modes and parameters 3](#_Toc405976978)

[4.4 Coexistence mechanisms 4](#_Toc405976979)

[5 Other IEEE 802 systems coexisting in the same frequency bands 4](#_Toc405976980)

[5.1 Coexisting Systems in 169.400 – 169.475 MHz Band 4](#_Toc405976981)

[5.2 Coexisting Systems in 433.05 – 434.79 MHz Band 5](#_Toc405976982)

[5.3 Coexisting Systems in 470 – 510 MHz Band 5](#_Toc405976983)

[5.4 Coexisting Systems in 779 – 787 MHz Band 5](#_Toc405976984)

[5.5 Coexisting Systems in 863 – 870 MHz Band 5](#_Toc405976985)

[5.6 Coexisting Systems in 896 – 901 MHz Band 6](#_Toc405976986)

[5.7 Coexisting Systems in 902 – 928 MHz Band 6](#_Toc405976987)

[5.8 Coexisting Systems in 951 – 958 MHz Band 6](#_Toc405976988)

[5.9 Coexisting Systems in 2400 – 2483.5 MHz Band 6](#_Toc405976989)

[6 Coexistence scenarios and analysis 7](#_Toc405976990)

[6.1 PHY Modes in ULP-TASK PHY 7](#_Toc405976991)

[6.2 Parameters for ULP-TASK PHY modes 7](#_Toc405976992)

[6.3 BER/PER calculations for ULP-TASK PHY modes 7](#_Toc405976993)

[6.4 PHY Modes in ULP-GFSK PHY 8](#_Toc405976994)

[6.5 BER/PER calculations for ULP-GFSK PHY modes 9](#_Toc405976995)

[6.6 Interference modeling 9](#_Toc405976996)

[**6.7** **Coexistence performance in 433.05 – 434.79 MHz band** 10](#_Toc405976997)

[**6.7.1** **Parameters for coexistence quantification** 10](#_Toc405976999)

[**6.7.2** **Coexistence simulation results** 11](#_Toc405977001)

[**6.8** **Coexistence performance in 470 – 510 MHz band** 13](#_Toc405977002)

[**6.8.1** **Parameters for coexistence quantification** 13](#_Toc405977004)

[**6.8.2** **Coexistence simulation results** 15](#_Toc405977006)

[**6.9** **Coexistence performance in 779 – 787 MHz band** 17](#_Toc405977007)

[**6.9.1** **Parameters for coexistence quantification** 17](#_Toc405977009)

[**6.9.2** **Coexistence simulation results** 19](#_Toc405977011)

[**6.10** **Coexistence performance 863 – 870 MHz band** 21](#_Toc405977012)

[**6.10.1** **Parameters for coexistence quantification** 21](#_Toc405977014)

[**6.10.2** **Coexistence simulation results** 24](#_Toc405977016)

[**6.11** **Coexistence performance in 902 – 928 MHz band** 26](#_Toc405977017)

[**6.11.1** **Parameters for coexistence quantification** 26](#_Toc405977019)

[**6.11.2** **Coexistence simulation results** 29](#_Toc405977021)

[**6.12** **Coexistence performance in 951 – 958 MHz band** 30](#_Toc405977022)

[**6.12.1** **Parameters for Coexistence quantification** 30](#_Toc405977024)

[**6.12.2** **Coexistence simulation results** 32](#_Toc405977026)

[**6.13** **Coexistence performance 2400 – 2483.5 MHz band** 34](#_Toc405977027)

[**6.13.1** **Parameters for coexistence quantification** 34](#_Toc405977029)

[**6.13.2** **Coexistence simulation results** 36](#_Toc405977031)

[7 Interference avoidance and mitigation techniques 40](#_Toc405977032)

[8 Conclusions 40](#_Toc405977033)

# Introduction

## Scope

The IEEE 802.19 Work Group has mandated that new wireless standards developed under IEEE 802 be accompanied by a *Coexistence Assurance* document. Hence, this coexistence assurance document is provided by the IEEE 802.15.4q Task Group to satisfy the requirements of the IEEE 802.19 Work Group and IEEE 802 Executive Committee. A detailed discussion of coexistence and coexistence methods can be found in IEEE Standard 802.15.2-2003 [1]. In [2], guidelines are provided for how coexistence can be quantified based on predicted packet error rates among IEEE 802 wireless devices.

This document addresses the coexistence of the IEEE 802.15.4q systems with other IEEE 802 standards operating in the same frequency bands. It addresses the interference caused by IEEE 802.15.4q devices to these existing systems, and the interference from these existing standards with IEEE 802.15.4q.

# Bibiography

1. IEEE Std 802.15.2TM-2003, “Coexistence of Wireless Personal Area Networks with Other Wireless Devices Operating in Unlicensed Frequency Band”
2. S. Shellhammer, “Writing a Coexistence Assurance Document,” IEEE 802.19-09/0001r0, 2009.
3. Draft Part 15.4: LR-WPANs Amendment5: Amendment for an Ultra-low Power Physical Layer
4. IEEE Std. 802.15.4g TG4g Coexistence Assurance Document (IEEE 802.15-10-00668-05-004g)
5. IEEE Std 802.15.4TM-2011.
6. S. Shellhammer, “Estimating of Packet Error Rate Caused by Interference – A Coexistence Assurance Methodology,” IEEE 802.19-05/0028r2, 2005.
7. J .G. Proakis, Digital Communications 4th edition, 2000.
8. Doc 15-13-0313-03-4n-Chinese-Radio-Regulation-Discussion.doc
9. Doc 15-12-0471-04-4n-summary-of-interference-on-Chinese-Medical-bands.doc
10. IEEE Std. 802.15.4k TG4k Coexistence Assurance Document (IEEE 802.15-12-0314-01-004k)
11. IEEE 15-13-0329-00-004q Channel Models for IEEE 802.15.4q

# Acronyms and abbreviations

TASK ternary amplitude shift keying

BER bit error rate

PER packet error rate

IWN interfering wireless network

SIR signal to interference Ratio

DUR desired to undesired ratio

FSK frequency shift keying

GFSK Gaussian frequency shift keying

MCS modulation and coding schemes

DSSS direct sequence spread spectrum

OQPSK offset quadrature phase shift keying

ULP ultra-low power

MSK minimum shift keying

OFDM orthogonal frequency division multiplexing

CAD co-existence assurance document

# Overview

## General

The overview of IEEE 802.15.4q amendment is presented in [3]. Specifically, IEEE 802.154q has two PHYs: ULP-TASK PHY and ULP-GFSK PHY.

## Operating frequency bands

The following table provides the frequency bands of operation, and the occupancy of the band by each PHY.

Table 1 Frequency bands of operation for respective PHYs Specified in 802.15.4q

|  |  |  |
| --- | --- | --- |
| **Frequency Band (MHz)** | **IEEE 802.15.4q PHYs** | |
| **FSK** | **TASK** |
| 169.400-169.475 MHz (Europe) | X | - |
| 433.050-434.790 MHz (North America/Europe) | X | X |
| 470-510 MHz (China) | X | X |
| 779-787 MHz (China) | X | X |
| 863-876 MHz (Europe) | X | X |
| 896-901 MHz (USA) | X | - |
| 901-902 MHz (USA) | X | - |
| 902-928 MHz (USA) | X | X |
| 928-960 MHz (USA) | X | X |
| 2400-2483.5 MHz (Worldwide) | X | X |

## MCS modes and parameters

The IEEE 802.15.4q consists of two PHYs: ULP-TASK and ULP-GFSK. MCS and related parameters for both the PHYs are shown in Table 2-Table 4

Table 2: ULP-TASK PHY modulation and coding schemes and related parameters

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **MCS** | **Modulation format** | **Coding format** | **Bits per symbol** | **Chips per symbol** | **Code**  **rate** |
| 0 | 1/1-TASK | BCH | 1 | 1 | 51/63 |
| 1 | 2/4- TASK | BCH | 2 | 4 | 51/63 |
| 2 | 3/8- TASK | BCH | 3 | 8 | 51/63 |
| 3 | 5/32- TASK | BCH | 5 | 32 | 51/63 |
| 4  (Optional) | 1/1-TASK | BCH+ SiPC  concatenation | 1 | 1 | 408/567 |
| 5  (Optional) | 2/4- TASK | BCH+SiPC  concatenation | 2 | 4 | 408/567 |
| 6  (Optional) | 3/8- TASK | BCH+SiPC  concatenation | 3 | 8 | 408/567 |
| 7  (Optional) | 5/32- TASK | BCH+SiPC  concatenation | 5 | 32 | 408/567 |

Table 3: ULP-TASK PHY channel bandwidths in various frequency bands

|  |  |  |
| --- | --- | --- |
| **Frequency Band (MHz)** | **Chip rate**  **(kcps)** | **Channel bandwidth**  **(KHz)** |
| 433.050 – 434.790 | 250 | 400 |
| 470 – 510 | 250 | 800 |
| 779 – 787 | 600 | 2 |
| 863 – 876 | 600 | 2 |
| 902 – 928 | 600 | 2 |
| 928 – 960 | 600 | 2 |
| 2400 – 2483.5 | 1000 | 2 |

Table 4: ULP-GFSK PHY modulation and coding schemes and related parameters

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **ULP GFSK MCS Identifier** | **Data Rate [kbps]** | **Channel Spacing [kHz]** | **Mod index** | **Receiver BW**  **(kHz)** | **Average Transmit Power (dBm)** | **Receiver sensitivity (dBm)** | **Average Frame Lengths (Octets)** |
| 0 | 4.8 | 12.5 | 0.72 | 10 | 0 - 20 | -117 | 30 |
| 1 | 9.6 | 25 | 0.72 | 20 | 0 - 20 | -114 | 30 |
| 2 | 50 | 200 | 0.72 | 100 | 0 - 20 | -107 | 30 |
| 3 | 150 | 400 | 0.72 | 300 | 0 - 20 | -102 | 30 |
| 4 | 500 | 1000 | 0.72 | 1000 | 0 - 20 | -97 | 30 |
| 5 | 250 | 500 | 0.5 | 350 | 0 - 20 | -106 | 30 |
| 6 | 500 | 1000 | 0.5 | 700 | 0 - 20 | -103 | 30 |
| 7 | 1000 | 2000 | 0.5 | 1400 | 0 - 20 | -100 | 30 |
| 0a | 9.6 | 12.5 | 0.24 | 10 | 0 - 20 | -108 | 30 |
| 1a | 19.2 | 25 | 0.24 | 20 | 0 - 20 | -105 | 30 |
| 2a | 100 | 200 | 0.24 | 100 | 0 - 20 | -98 | 30 |
| 3a | 300 | 400 | 0.24 | 300 | 0 - 20 | -93 | 30 |
| 4a | 1000 | 1000 | 0.24 | 1000 | 0 - 20 | -88 | 30 |

## Coexistence mechanisms

The importance of coexistence mechanism in the IEEE 802.15.4q is two-fold.

Homogeneous coexistence: Internally, the two specified PHYs of IEEE 802.15.4q (ULP-TASK and ULP-GFSK) shall be able to coexist with each when they are co-located in the same frequency band. Heterogeneous coexistence: Externally, the IEEE 802.15.4q system shall be able to share multiple frequency bands with dissimilar 802 systems.

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

# Other IEEE 802 systems coexisting in the same frequency bands

The following sub-clauses present co-locating dissimilar systems with reference to the each of the frequency bands mentioned in Table 1.

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

1. Standard specification: the name of the 802 system with which 802.15.4g system is coexisting.
2. PHY specification: the PHY design of the above 802 system specification.
3. Receiver bandwidth: the receiver bandwidth of the above 802 system specification.
4. Transmit power: the transmit power of the above 802 system specification.
5. Receiver sensitivity: the receiver sensitivity of the above 802 system specification.
6. Involved 802.15.4q system: the particular PHY in 802.15.4g that is coexisting in the band.

## Coexisting Systems in 169.400 – 169.475 MHz Band

Table 5 shows the list of other 802 systems that share the169.400 – 169.475 MHz band with the ULP-GFSK PHY in 802.15.4q.

Table 5: Dissimilar systems co-existing with the 802.15.4q PHYs within the 169.400 – 169.475 MHz band

|  |  |  |
| --- | --- | --- |
| **Standard** | **Standard PHY Spec** | **Involved 802.15.4q PHY** |
| 802.15.4f | MSK | ULP-GFSK |
| 802.15.4k | FSK |

## Coexisting Systems in 433.05 – 434.79 MHz Band

Table 6 shows the list of other 802 systems that share the 433.05 – 434.79 MHz band with the PHYs in 802.15.4q.

Table 6: Dissimilar systems co-existing with the 802.15.4q PHYs within the 433.05 – 434.79 MHz band

|  |  |  |
| --- | --- | --- |
| **Standard** | **Standard PHY Spec** | **Involved 802.15.4q PHY** |
| 802.15.4f | MSK | ULP-TASK  ULP-GFSK |
| 802.15.4k | FSK |

## Coexisting Systems in 470 – 510 MHz Band

Table 7 shows the list of other 802 systems that share the 470 – 510 MHz band with the PHYs in 802.15.4q.

Table 7: Dissimilar systems co-existing with the 802.15.4q PHYs within the 470 – 510 MHz band

|  |  |  |
| --- | --- | --- |
| **Standard** | **Standard PHY Spec** | **Involved 802.15.4q PHY** |
| 802.15.4g | MR – FSK | ULP-TASK  ULP-GFSK |
| MR – OFDM |
| MR – OQPSK |
| 802.15.4k | DSSS O-QPSK |

## Coexisting Systems in 779 – 787 MHz Band

Table 8 shows the list of other 802 systems that share 779 – 787 MHz band with the PHYs in 802.15.4q.

Table 8: Dissimilar systems co-existing with the 802.15.4q PHYs within the 779 – 787 MHz band

|  |  |  |
| --- | --- | --- |
| **Standard** | **Standard PHY Spec** | **Inolved 802.15.4q PHY** |
| 802.15.4 | DSSS | ULP-TASK  ULP-GFSK |
| 802.15.4g | MR – FSK |
| MR – OFDM |
| MR – OQPSK |
| 802.15.4k | DSSS O-QPSK |

## Coexisting Systems in 863 – 870 MHz Band

Table 9 shows the list of other 802 systems that share 863 – 870 MHz band with the PHYs in 802.15.4q.

Table 9: Dissimilar systems co-existing with the 802.15.4q PHYs within the 863 – 870 MHz band

|  |  |  |
| --- | --- | --- |
| **Standard** | **Standard PHY Spec** | **Involved 802.15.4q PHY** |
| 802.15.4 | DSSS | ULP-TASK  ULP-GFSK |
| 802.15.4g | MR – FSK |
| MR – OFDM |
| MR – OQPSK |
| 802.15.4k | DSSS O-QPSK |

## Coexisting Systems in 896 – 901 MHz Band

Table 10 shows the list of other 802 systems that share 896 – 901 MHz band with the ULP-GFSK PHY in 802.15.4q.

Table 10: Dissimilar systems co-existing with the 802.15.4q PHYs within the in 896 – 901 MHz band

|  |  |  |
| --- | --- | --- |
| **Standard** | **Standard PHY Spec** | **Involved 802.15.4q PHY** |
| 802.15.4g | MR – FSK | ULP-GFSK |
| MR – OFDM |
| MR – OQPSK |
| 802.15.4k | DSSS O-QPSK |

## Coexisting Systems in 902 – 928 MHz Band

Table 11 shows the list of other 802 systems that share 902 – 928 MHz band with the PHYs in 802.15.4q.

Table 11: Dissimilar systems co-existing with the 802.15.4q PHYs within the in 902- 98.2 MHz band

|  |  |  |
| --- | --- | --- |
| **Standard** | **Standard PHY Spec** | **Involved 802.15.4q PHY** |
| 802.15.4 | DSSS | ULP-TASK  ULP-GFSK |
| 802.15.4g | MR – FSK |
| MR – OFDM |
| MR – OQPSK |
| 802.15.4k | DSSS O-QPSK |

## Coexisting Systems in 951 – 958 MHz Band

Table 12 shows the list of other 802 systems that share 951 – 958 MHz band with the PHYs in 802.15.4q.

Table 12: Dissimilar systems co-existing with the 802.15.4q PHYs within the in 951 – 958 MHz band

|  |  |  |
| --- | --- | --- |
| **Standard** | **Standard PHY Spec** | **Involved 802.15.4q PHY** |
| 802.15.4 | DSSS | ULP-TASK  ULP-GFSK |
| GFSK |
| 802.15.4g | MR – FSK |
| MR – OFDM |
| MR – OQPSK |

## Coexisting Systems in 2400 – 2483.5 MHz Band

Table 13 shows the list of other 802 systems that share 2400 – 2483.5 MHz band with the PHYs in 802.15.4q.

Table 13: Dissimilar systems co-existing with the 802.15.4q PHYs within the in 2400 – 2483.5 MHz band

|  |  |  |
| --- | --- | --- |
| **Standard** | **Standard PHY Spec** | **Involved 802.15.4q PHY** |
| **802.11b** | DSSS | ULP-TASK ULP-GFSK |
| **802.11g** | OFDM |
| **802.11n** | OFDM |
| **802.15.3** | FHSS |
| **802.15.4** | SC |
| DSSS |
| **802.15.4f** | MSK |
| **802.15.4g** | MR – FSK |
| MR – OFDM |
| MR – OQPSK |
| **802.15.4k** | FSK |
| DSSS |

# Coexistence scenarios and analysis

This clause presents the analysis of the interference caused by IEEE 802.15.4q devices to the IEEE 802 standard devices identified in 5, and vice versa. Note that the interferer parameters chosen in the following sub-clauses are chosen for the purpose of coexistence analysis in this CA document and are a sub-set of the available modes.

## PHY Modes in ULP-TASK PHY

Various MCS modes of ULP-TASK and the corresponding parameters for different frequency bands are provided in 4.3. For the sake of brevity, we here consider only two MCS modes across all frequency bands:

* **MCS-1** (2/4-TASK with BCH encoding and interleaving)
* **MCS-3** (5/32-TASK with BCH encoding and interleaving)

## Parameters for ULP-TASK PHY modes

The parameters for the MCS modes chosen for evaluation are given in Table 14.

Table 14: MCS modes in ULP-TASK selected for coexistence analysis

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **MCS** | **Transmit Power (dBm)** | **Receiver type** | **Receiver Sensitivity**  **(dBm)** | **Average Frame Lengths**  **(Octets)** |
| 2/4-TASK | 0 dBm | Non-coherent | -90 | 20 |
| 5/32-TASK | Non-coherent | -85 | 20 |

## BER/PER calculations for ULP-TASK PHY modes

The BER/PER calculations are similar to that mentioned in the TG4k and TG4g coexistence assurance documents [4], [10]. As defined in TG4g Coexistence Assurance Document section 4.1.2, the BER and PER are modeled in MATLAB with coded AWGN channel without interference for ULP-TASK PHY modes.

The BER and PER plots of the ULP-TASK PHY modes given in Table 14 for the 2.4 GHz band are illustrated in Figure 1. Since different band’s frequency contributes to different path loss which is reflected in the SNR value, the BER and FER vs. SNR performance curves in Figure 1 are also applicable to the 4q systems in other bands.



Figure 1: BER and PER vs. SNR for ULP-TASK PHY modes

## PHY Modes in ULP-GFSK PHY

Table 15: MCS modes in ULP-GFSK

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **ULP GFSK MCS Identifier** | **Data Rate [kbps]** | **Channel Spacing [kHz]** | **Mod index** | **Receiver BW**  **(kHz)** | **Average Transmit Power (dBm)** | **Receiver sensitivity (dBm)** | **Average Frame Lengths (Octets)** |
| 0 | 4.8 | 12.5 | 0.72 | 10 | 0 - 20 | -117 | 30 |
| 1 | 9.6 | 25 | 0.72 | 20 | 0 - 20 | -114 | 30 |
| 2 | 50 | 200 | 0.72 | 100 | 0 - 20 | -107 | 30 |
| 3 | 150 | 400 | 0.72 | 300 | 0 - 20 | -102 | 30 |
| 4 | 500 | 1000 | 0.72 | 1000 | 0 - 20 | -97 | 30 |
| 5 | 250 | 500 | 0.5 | 350 | 0 - 20 | -106 | 30 |
| 6 | 500 | 1000 | 0.5 | 700 | 0 - 20 | -103 | 30 |
| 7 | 1000 | 2000 | 0.5 | 1400 | 0 - 20 | -100 | 30 |
| 0a | 9.6 | 12.5 | 0.24 | 10 | 0 - 20 | -108 | 30 |
| 1a | 19.2 | 25 | 0.24 | 20 | 0 - 20 | -105 | 30 |
| 2a | 100 | 200 | 0.24 | 100 | 0 - 20 | -98 | 30 |
| 3a | 300 | 400 | 0.24 | 300 | 0 - 20 | -93 | 30 |
| 4a | 1000 | 1000 | 0.24 | 1000 | 0 - 20 | -88 | 30 |

## BER/PER calculations for ULP-GFSK PHY modes

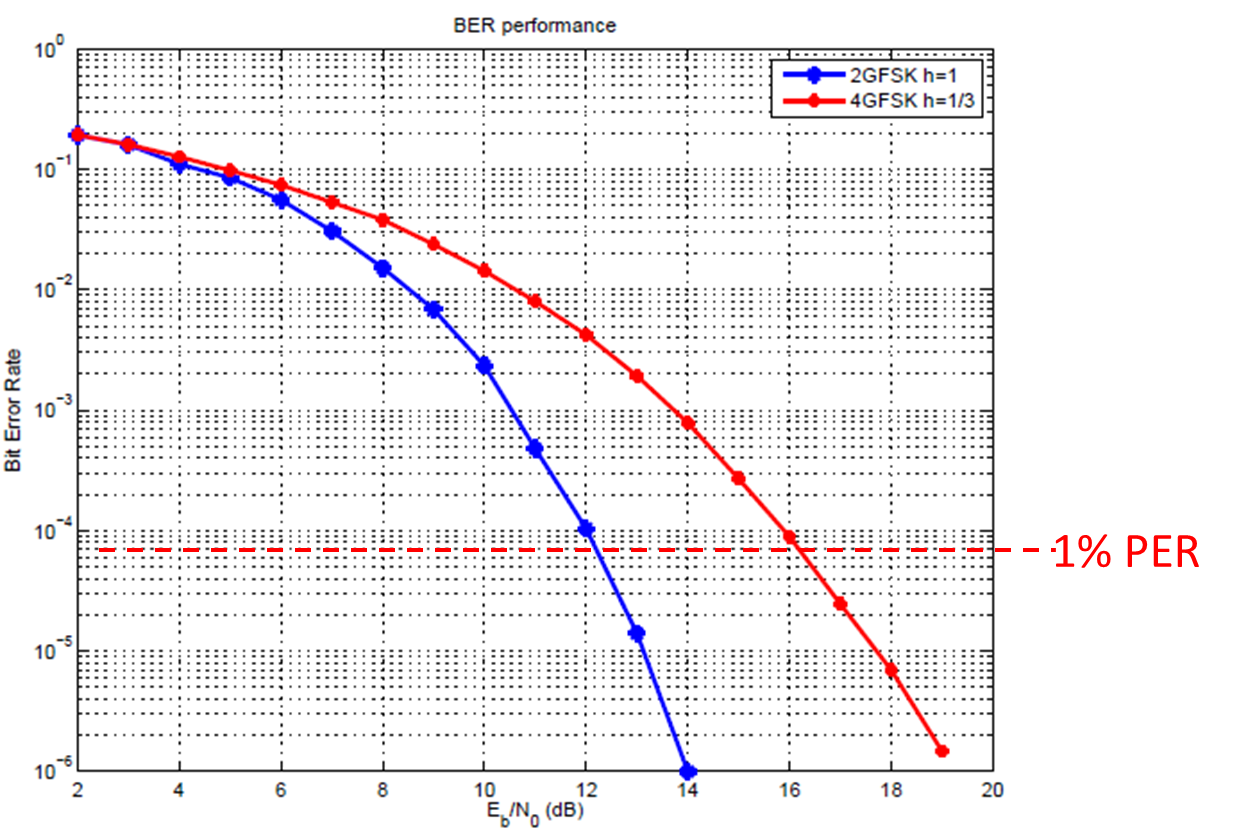


Figure 2: BER vs. Eb/No for the ULP-FSK PHY modes

## Interference modeling

The interference model is akin to that described in the coexistence analysis of IEEE802.15.4g [4].

* In the coexistence model, the transmitting power and the 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 vs. distance from the interferer’s transmitter to the victim’s receiver.
* The 802.15.4q indoor LOS channel model described in Sec. 2.2.1 in “15-13-0329-00-004q” is used here for the interference calculation. No AWGN noise is included in the channel. 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 centre frequency and the victim’s centre frequency in the spectrum.
* The antenna gains are assumed to be 0 dBi
* Unless otherwise mentioned, the transmitted power of 0 dBm is used for 802.15.4q as victim and interferer scenarios.
* The coexistence performance for the ULP-GFSK PHY is very similar to MR-FSK and the FSK PHY, see “15-10-0668-05-004g-tg4g-coexistence-assurance-document-first-draft” and “15-12-0314-01-004k-tg4k-coexistence-document.pdf”
  1. **Coexistence performance in 433.05 – 434.79 MHz band**

This sub-clause presents the coexistence performance of the systems coexisting in the in 433.05 – 434.79 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 802.15.4q systems and other 802 systems in the in 433.05 – 434.79 MHz band are set as the victim in a round-robin manner.

* + 1. **Parameters for coexistence quantification**

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

* + - 1. **PHY mode parameters of coexisting standards**

Table 16 shows the parameters for the PHY modes in each standard that is coexisting within the in 433.05 – 434.79 MHz band.

Table 16 : Major parameters of Systems in the in 433.05 – 434.79 MHz band

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| System | PHY Spec | PHY Mode | Channel Bandwidth (KHz) | Transmit Power  (dBm) | Receiver Sensitivity | Average Frame Length (Octets) |
| 802.15.4f | MSK | MSK-250 kbps | 580 | 0 |  | 250 |
| 802.15.4k | FSK | FSK-25 kbps | 200 | 0 | -90 | 250 |

* + - 1. **BER/PER for PHY modes of coexisting 802 Standards**

In this sub-clause, the BER / PER performance corresponding to SNR for the 802 standards within the frequency band is presented. The parameter SNR is defined as the ratio between the energy in each chip to the noise power spectral density in each chip.



Figure 3: Victim BER/PER vs. distance between interferer to 802.15.4q victim receiver in the 433.05-434.79 MHz band.

* + 1. **Coexistence simulation results**

#### 802.15.4q ULP-TASK as the victim receiver

Figure 4 shows the relationship between the PER performances of the 802.15.4q victim receiver corresponding to the distance between the victim receivers to the interferer. The list of interferers is given in Figure 4.



Figure 4: Victim PER vs. Distance between interferer to 802.15.4q ULP-TASK victim receiver in the 433.05-434.79 MHz band

#### Other 802.15 PHY Modes as Victim Receivers

This sub-clause presents the results setting other 802 systems as the victim and 802.15.4q as the interferer. Figure 5 shows the relationship between the PER performances of the 802.15 (including 802.15.4k and 802.15.4f) victim receivers corresponding to the distance between the victim receivers to the 802.15.4q interferers. The list of interferers is given in Figure 5.



Figure 5: Victim PER vs. Distance between interferer to other 802.15.4 victim receivers (802.15. 4k-QPSK and 802.15.4f-MSK) in the 433.05-434.79 MHz band.

* 1. **Coexistence performance in 470 – 510 MHz band**

This sub-clause presents the coexistence performance of the systems coexisting in the in 470 – 510 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 802.15.4q systems and other 802 systems in the 470 – 510 MHz band are set as the victim in a round-robin manner.

* + 1. **Parameters for coexistence quantification**

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

* + - 1. **PHY mode parameters of coexisting standards**

Table 17 shows the parameters for the PHY modes in each standard that is coexisting within the in 470 – 510 MHz band.

Table 17: Major parameters of systems in the 470 – 510 MHz band

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| System | PHY Spec | PHY Mode | Channel Bandwidth (KHz) | Transmit Power  (dBm) | Receiver Sensitivity | Average Frame Length (Octets) |
| 802.15.4g | MR – FSK | FSK 50 kbps, h = 1.0 | 200 | 0 | -91 | 250 |
| MR – OFDM | QPSK, 100 kbps, OFDM Option 4, MCS3 | 200 | 0 | -103 | 20 |
| MR – OQPSK | QPSK, 100 kcps,  Rate Mode 3 | 400 | 0 | -95 | 20 |
| 802.15.4k | DSSS O-QPSK | 100 Kcps | 200 | 0 | -90 | 20 |

* + - 1. **BER/PER for PHY modes of coexisting 802 Standards**

In this sub-clause, the BER / PER performance corresponding to SNR for the 802 standards within the frequency band is presented. The parameter SNR is defined as the ratio between the energy in each chip to the noise power spectral density in each chip.



Figure 6: BER vs. SNR for 802 systems in the 470 – 510 MHz band



Figure 7: PER vs. SNR for 802 systems in the 470 – 510 MHz band

* + 1. **Coexistence simulation results**

#### 802.15.4q ULP-TASK as the victim receiver

Figure 8 shows the relationship between the PER performances of the 802.15.4q victim receiver corresponding to the distance between the victim receivers to the interferer. The list of interferers is given in Figure 8.



Figure 8: Victim PER vs. Distance between interferer to 802.15.4q ULP-TASK victim receiver in the 470-510 MHz band

#### Other 802 PHY modes as the victim receivers

This sub-clause presents the results setting other 802 systems as the victim and 802.15.4q as the interferer. Figure 9 shows the relationship between the PER performances of the 802.15 victim receivers corresponding to the distance between the victim receivers to the 802.15.4q interferers. The list of interferers is given in Figure 9.



Figure 9: PER vs. Distance between 802.15.4q ULP-TASK interferer to other co-existing 802 systems as victim receivers in the 470-510 MHz band

* 1. **Coexistence performance in 779 – 787 MHz band**

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

* + 1. **Parameters for coexistence quantification**

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

* + - 1. **PHY mode parameters of coexisting standards**

Table 18 shows the parameters for the PHY modes in each standard that is coexisting within the in 470 – 510 MHz band.

Table 18: Major parameters of systems in the 779 – 787 MHz band

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| System | PHY Spec | PHY Mode | Channel Bandwidth (KHz) | Transmit Power  (dBm) | Receiver Sensitivity | Average Frame Length (Octets) |
| 802.15.4 | DSSS | OQPSK, 1000 kcps, 250 kbps | 2000 | 0 | -85 | 22 |
| 802.15.4g | MR – FSK | FSK 50 kbps, h = 1.0 | 200 | 0 | -91 | 250 |
| MR – OFDM | QPSK, 100 kbps, OFDM Option 4, MCS3 | 200 | 0 | -103 | 20 |
| MR – OQPSK | QPSK, 1000 kcps,  Rate Mode 3 | 2000 | 0 | -90 | 20 |
| 802.15.4k | DSSS O-QPSK | 1000 Kcps | 1000 | 0 | -90 | 20 |

* + - 1. **BER/PER for PHY modes of coexisting 802 standards**

In this sub-clause, the BER / PER performance corresponding to SNR for the 802 standards within the frequency band is presented. The parameter SNR is defined as the ratio between the energy in each chip to the noise power spectral density in each chip.



Figure 10: BER vs. SNR for 802 systems in the 779-787 MHz band



Figure 11: PER vs. SNR for 802 systems in the 779-787 MHz band

* + 1. **Coexistence simulation results**

#### 802.15.4q as the victim receiver

Figure 12 shows the relationship between the PER performances of the 802.15.4q victim receiver corresponding to the distance between the victim receivers to the interferer. The list of interferers is given in Figure 12.



Figure 12: PER vs. Distance between interferer to 802.15.4q ULP-TASK victim receiver in the 779-787 MHz band

#### Other 802 systems as victim receiver

This sub-clause presents the results setting other 802 systems as the victim and 802.15.4q as the interferer. Figure 13 shows the relationship between the PER performances of the 802.15 victim receivers corresponding to the distance between the victim receivers to the 802.15.4q interferers. The list of interferers is given in Figure 13.



Figure 13: PER vs. Distance between 802.15.4q ULP-TASK interferer to other co-existing 802 systems as victim receivers in the 779-787 MHz band

* 1. **Coexistence performance 863 – 870 MHz band**

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

* + 1. **Parameters for coexistence quantification**

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

* + - 1. **PHY mode parameters of coexisting standards**

Table 19 shows the parameters for the PHY modes in each standard that is coexisting within the in 863 – 870 MHz band.

Table 19: Major parameters of systems in the 863-870 MHz band

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| System | PHY Spec | PHY Mode | Channel Bandwidth (KHz) | Transmit Power  (dBm) | Receiver Sensitivity | Average Frame Length (Octets) |
| 802.15.4 | DSSS | BPSK, 300 kcps, 20 kbps | 600 | 0 | -85 | 22 |
| 802.15.4g | MR – FSK | FSK 50 kbps, h = 1.0 | 200 | 0 | -91 | 250 |
| MR – OFDM | QPSK, 100 kbps, OFDM Option 4, MCS3 | 200 | 0 | -103 | 20 |
| MR – OQPSK | QPSK, 100 kcps,  Rate Mode 3 | 600 | 0 | -90 | 20 |
| 802.15.4k | DSSS O-QPSK | 100 Kcps | 200 | 0 | -90 | 20 |

* + - 1. **BER/PER for PHY modes of coexisting 802 standards**

In this sub-clause, the BER / PER performance corresponding to SNR for the 802 standards within the frequency band is presented. The parameter SNR is defined as the ratio between the energy in each chip to the noise power spectral density in each chip.



Figure 14: BER vs. SNR for 802 systems in the 863-876 MHz band



Figure 15: PER vs. SNR for 802 systems in the 863-876 MHz band

* + 1. **Coexistence simulation results**

#### 802.15.4q TASK as the victim receiver



Figure 16: PER vs. Distance between interferer to 802.15.4q ULP-TASK victim receiver in the 863-876 MHz band

Figure 16 shows the relationship between the PER performances of the 802.15.4q victim receiver corresponding to the distance between the victim receivers to the interferer. The list of interferers is given in Figure 16.

#### Other 802 systems as victim receivers



Figure 17: PER vs. Distance between 802.15.4q ULP-TASK interferer to other co-existing 802 systems as victim receivers in the 863-876 MHz band

This sub-clause presents the results setting other 802 systems as the victim and 802.15.4q as the interferer. Figure 17 shows the relationship between the PER performances of the 802.15 victim receivers corresponding to the distance between the victim receivers to the 802.15.4q interferers. The list of interferers is given in Figure 17.

* 1. **Coexistence performance in 902 – 928 MHz band**

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

* + 1. **Parameters for coexistence quantification**

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

* + - 1. **PHY mode parameters of coexisting standards**

Table 20 shows the parameters for the PHY modes in each standard that is coexisting within the in 902-928 MHz band.

Table 20: Major parameters of systems in the 902-928 MHz band

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| System | PHY Spec | PHY Mode | Channel Bandwidth (KHz) | Transmit Power  (dBm) | Receiver Sensitivity | Average Frame Length (Octets) |
| 802.15.4 | DSSS | BPSK, 600 kcps, 40 kbps | 2000 | 0 | -85 | 22 |
| 802.15.4g | MR – FSK | FSK 50 kbps, h = 1.0 | 200 | 0 | -91 | 250 |
| MR – OFDM | QPSK, 100 kbps, OFDM Option 4, MCS3 | 200 | 0 | -103 | 20 |
| MR – OQPSK | QPSK, 1000 kcps,  Rate Mode 3 | 2000 | 0 | -90 | 20 |
| 802.15.4k | DSSS O-QPSK | 100 Kcps | 200 | 0 | -90 | 20 |

* + - 1. **BER/PER for PHY modes of coexisting 802 standards**

In this sub-clause, the BER / PER performance corresponding to SNR for the 802 standards within the frequency band is presented. The parameter SNR is defined as the ratio between the energy in each chip to the noise power spectral density in each chip.



Figure 18: BER vs. SNR for 802 systems in the 902-928 MHz band



Figure 19: BER vs. SNR for 802 systems in the 902-928 MHz band

* + 1. **Coexistence simulation results**

#### 802.15.4q TASK as the victim receiver



Figure 20: PER vs. Distance between interferer to 802.15.4q ULP-TASK victim receiver in the 902-928 MHz band

Figure 20 shows the relationship between the PER performances of the 802.15.4q victim receiver corresponding to the distance between the victim receivers to the interferer. The list of interferers is given in Figure 20.

#### Other 802 systems as victim receivers

This sub-clause presents the results setting other 802 systems as the victim and 802.15.4q as the interferer. Figure 21 shows the relationship between the PER performances of the 802.15 victim receivers corresponding to the distance between the victim receivers to the 802.15.4q interferers. The list of interferers is given in Figure 21.



Figure 21: PER vs. Distance between 802.15.4q ULP-TASK interferer to other co-existing 802 systems as victim receivers in the 902-928 MHz band

* 1. **Coexistence performance in 951 – 958 MHz band**

This sub-clause presents the coexistence performance of the systems coexisting in the in 951 – 958 MHz band. An involving system is set as the victim while all other systems are set as the interferer, in order to understand the impact of the generated interference. All systems including the 802.15.4q systems and other 802 systems in the in 951 – 958 MHz band are set as the victim in a round-robin manner.

* + 1. **Parameters for Coexistence quantification**

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

* + - 1. **PHY mode parameters of coexisting standards**

Table 21 shows the parameters for the PHY modes in each standard that is coexisting within the in 951-958 MHz band.

Table 21: Major parameters of systems in the 951-958 MHz

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| System | PHY Spec | PHY Mode | Channel Bandwidth (KHz) | Transmit Power  (dBm) | Receiver Sensitivity | Average Frame Length (Octets) |
| 802.15.4 | DSSS | BPSK, 300 kcps, 20 kbps | 2000 | 0 | -92 | 22 |
| GFSK | GFSK-100 kbps | 200 | 0 | -85 | 250 |
| 802.15.4g | MR – FSK | FSK 50 kbps, h = 1.0 | 200 | 0 | -91 | 250 |
| MR – OFDM | QPSK, 200 kbps, OFDM Option 2, MCS2 | 800 | 0 | -100 | 20 |
| MR – OQPSK | QPSK, 1000 kcps,  Rate Mode 3 | 2000 | 0 | -90 | 20 |

* + - 1. **BER/PER for PHY modes of coexisting 802 Standards**

In this sub-clause, the BER / PER performance corresponding to SNR for the 802 standards within the frequency band is presented. The parameter SNR is defined as the ratio between the energy in each chip to the noise power spectral density in each chip.



Figure 22: BER vs. SNR for 802 systems in the 951-958 MHz band



Figure 23: PER vs. SNR for 802 systems in the 951-958 MHz band

* + 1. **Coexistence simulation results**

#### 802.15.4q TASK as the victim receiver

Figure 24 shows the relationship between the PER performances of the 802.15.4q victim receiver corresponding to the distance between the victim receivers to the interferer. The list of interferers is given in Figure 24.



Figure 24: PER vs. Distance between interferer to 802.15.4q ULP-TASK victim receiver in the 951-958 MHz band

#### Other 802 systems as victim receivers

This sub-clause presents the results setting other 802 systems as the victim and 802.15.4q as the interferer. Figure 25 shows the relationship between the PER performances of the 802.15 victim receivers corresponding to the distance between the victim receivers to the 802.15.4q interferers. The list of interferers is given in Figure 25.



Figure 25: PER vs. Distance between 802.15.4q ULP-TASK interferer to other co-existing 802 systems as victim receivers in the 951-958 MHz band

* 1. **Coexistence performance 2400 – 2483.5 MHz band**

This sub-clause presents the coexistence performance of the systems coexisting in the in 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 802.15.4q systems and other 802 systems in the in 2400 – 2483.5 MHz band are set as the victim in a round-robin manner.

* + 1. **Parameters for coexistence quantification**

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

* + - 1. **PHY mode parameters of coexisting standards**

Table 22 shows the parameters for the PHY modes in each standard that is coexisting within the in 2400-2483.5 MHz band.

Table 22: Major parameters of the systems in the 2400-2483.5 MHz

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| System | PHY Spec | PHY Mode | Channel Bandwidth (KHz) | Transmit Power  (dBm) | Receiver Sensitivity | Average Frame Length (Octets) |
| 802.11b | DSSS | CCK, 11 Mbps | 22000 | 14 | -76 | 1024 |
| 802.11g | OFDM | BSPK, 6 Mbps | 22000 | 14 | -88 | 1000 |
| 802.11n | OFDM | QPSK, 18 Mbps | 22000 | 14 | -83 | 4096 |
| 802.15.1 | FHSS | GFSK, 1 Mbps | 1000 | 0 | -70 | 1024 |
| 802.15.4 | SC | DQPSK, 22 Mbps | 15000 | 8 | -75 | 1024 |
| DSSS | OQPSK, 2000 Kcps, 250 Kbps | 2000 | 0 | -85 | 22 |
| 802.15.4f | MSK | MSK, 250 Kbps | 580 | 0 | - | - |
| 802.15.4g | MR – FSK | FSK 50 Kbps, h = 1.0 | 200 | 0 | -91 | 250 |
| MR – OFDM | QPSK, 100 kbps, OFDM Option 4, MCS3 | 200 | 0 | -103 | 20 |
| MR – OQPSK | QPSK, 2000 kcps,  Rate Mode 3 | 5000 | 0 | -90 | 20 |
| 802.15.4k | FSK | FSK 25 Kbps, h = 1.0 | 200 | 0 | -91 | 250 |
| DSSS | O-QPSK, 1000 kbps, | 200 | 0 | -103 | 20 |

* + - 1. **BER/PER for PHY modes of coexisting 802 standards**

In this sub-clause, the BER / PER performance corresponding to SNR for the 802 standards within the frequency band is presented. The parameter SNR is defined as the ratio between the energy in each chip to the noise power spectral density in each chip.



Figure 26: BER vs. SNR for systems operating in the 2400-2483.5 MHz band



Figure 27: PER vs. SNR for systems operating in the 2400-2483.5 MHz band

* + 1. **Coexistence simulation results**

#### 802.15.4q TASK as the victim receiver

Figure 28 and Figure 29 shows the relationship between the PER performances of the 802.15.4q victim receiver corresponding to the distance between the victim receivers to the interferer. The list of interferers is given in Figure 28 and Figure 29 .



Figure 28: PER vs. Distance between interferer to 802.15.4q 2/4-TASK victim receiver for the 2400-2483.5 MHz band



Figure 29: PER vs. Distance between interferer to 802.15.4q 5/32-TASK victim receiver for the 2400-2483.5 MHz band

#### Coexistence with 802.11 systems as the victim

This sub-clause presents the results setting other 802.11 systems as the victim and 802.15.4q as the interferer. Figure 30 shows the relationship between the PER performances of the 802.11 victim receivers corresponding to the distance between the victim receivers to the 802.15.4q interferers. The list of interferers is given in Figure 30.



Figure 30: PER vs. Distance between 802.15.4q ULP-TASK interferer to other co-existing 802.11 systems as victim receivers in the 2400-2482.5 MHz band

#### Coexistence with other 802.15 systems as the victim

This sub-clause presents the results setting other 802.15 systems as the victim and 802.15.4q as the interferer. Figure 31 shows the relationship between the PER performances of the 802.15 victim receivers corresponding to the distance between the victim receivers to the 802.15.4q interferers. The list of interferers is given in Figure 31.



Figure 31: PER vs. Distance between 802.15.4q ULP-TASK interferer to other co-existing 802.15 systems as victim receivers in the 2400-2482.5 MHz band

1. **Interference avoidance and mitigation techniques**

The 802.15.4q adopts the interference avoidance and mitigation techniques outlined in and 802.15.4 802.15.4g coexistence assurance documents.

1. **Conclusions**

The coexistence studies that have been carried out have revealed that the BER/PER performance of the 802.15.4q PHYs are comparable with the performance of other 802 PHYs. The comparable performances are observed in both cases, i.e. when the 802.15.4q PHYs are victims and also when the 802.15.4q PHYs are the interferers.