**IEEE P802.15**

**Wireless Personal Area Networks**

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| Abstract | Analysis on coexistence of 802.15.4w with other 802 systems within the same spectrum bands. |
| Purpose | To address the coexistence capability of 802.15.4w. |
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# Introduction

## Bibliography

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| [1]  | C.-S. Sum, "TG4g Coexistence Assurance Document," DCN 15-10/668r5, 2011. |
| [2]  | Q. Li and S. Jillings, "TG4k Coexistence Document," DCN 15-12/314r1, 2012. |
| [3]  | P. J. Nair, C. Thejaswi , K. Bynam and H. de Ruijter, "TG4q Coexistence Assurance Document," DCN 15-14/709r0, 2014. |

# Overview

## Overview of IEEE 802.15.4w

The IEEE 802.15.4 Task Group 4w defines a PHY amendment and related MAC extensions based on the 802.15.4k LECIM FSK PHY. The objective of the standard is to provide a global open standard for Low Power Wide Area Networks (LPWAN) in highly interfered license exempt frequency bands. Such LPWAN offer long-range transmissions over several kilometers with transmit powers of e.g. 14dBm or less.

The long-range capability with low transmit powers is achieved by very low payload bitrates in addition to strong forward error correction, which enables for sensitives required for error-free reception of -140dBm or less. In order to comply with FCC regulations that limit the dwell time to 400ms, frequency hopping spread spectrum (FHSS) is introduced. For this the payload data is split into at least 12 fragments, which are then transmitted on different frequencies at different points of time. However, unlike existing 802.15.4 fragmentation solutions, the re-assembly is not achieved by means of MAC signaling information, but using a well-known hopping pattern. First, this approach significantly reduces the signaling overhead. And second, because the forward error correction (FEC) is done before the fragmentation, a significant increase of robustness is achieved. In most cases interfering signals will only impair a limited number of the fragments, which can then be easily recovered by means of the FEC. Using the powerful convolutional code with rate 1/3 – or the even more powerful rate 1/4 Low Density Parity Check (LDPC) code – more than 50% of the fragments can be lost without any significant impact on the reception level.

Caused by the very low required reception levels classical co-existence techniques – such as listen before talk – do not work, as the co-existing system may not be able to detect the low signal levels. Thus, FHSS provides the required co-existence and interference robustness as requested in the PAR, and additionally, FHSS provides additional diversity in time and frequency selective channels.

The defined amendment is intended to cover larges cells with low payload bitrates, which gives the impression that the overall achievable system capacity is very limited. However, using FHSS with different frequency hopping sequences, many 4w systems can be operated in parallel using identical frequency resources. This leads to a very high system capacity in a given area by using many simultaneous transmissions, even if the bitrate of a single link seems highly limited.

## Regulatory Information

The allocated frequency bands for 802.15.4w are given below:

1. 169.4 – 169.475 MHz (Europe)
2. 262 – 262 MHz (Korea)
3. 433.05 – 434.79 MHz (North America, Europe)
4. 470 – 510 MHz (China)
5. 779 – 787 MHz (China)
6. 863 – 876 MHz (Europe)
7. 902 – 928 MHz (Americas)
8. 915 – 928 MHz (Australia)
9. 917 – 923 MHz (Korea)
10. 920.5 – 923.5 MHz (Japan)
11. 921 – 928 MHz (New Zealand)

## Changes to the 802.15.4k LECIM FSK PHY

The amendment defined by the 802.15.4 Task Group 4w enhances the performance of the existing 802.15.4k LECIM FSK PHY for highly interfered license-exempt frequency bands by defining lower bitrates and improved error correction capabilities.

For this purpose 802.15.4w uses existing LECIM FSK modulation schemes and only adds additional rates to cover the demands of LPWAN. Hence, no new PHY modulation scheme is introduced and 802.15.4w can be transmitted using most existing 802.15.4 chips that support FSK modulation.

An additional change to the 802.15.4k LECIM FSK PHY is the introduction of Frequency Hopping Spread Spectrum (FHSS). In order to meet the FCC requirement of a maximum dwell time of 400ms fragmentation and frequency hopping are introduced. Fragmentation was already defined for the 802.15.4k LECIM DSSS PHY, but was missing in case of the amended FSK PHY. However, for improved robustness 4w fragments the transmit data after the Forward Error Correction (FEC) encoding, which is required to achieve the required interference robustness as requested in the PAR. Furthermore, the re-assembly of the fragments in case of FHSS is done using well-known time and frequency positions, which reduces the overhead compared to existing fragmentation schemes for short fragments. As the FEC encoding uses convolutional codes already defined in 802.15.4, or Low Density Parity Check (LDPC) codes that can be implemented in software, existing 802.15.4 chips can be utilized to implement the features of 802.15.4w.

## Overview of Coexistence Mechanisms in 802.15.4w

The developed amendment follows the coexistence mechanisms defined for 802.15.4. In particular it uses the following techniques:

* Frequency Hopping Spread Spectrum (FHSS): In the FHSS mode the fragmented data is transmitted on at least 12 different frequencies. Hence, the available frequency spectrum is uniformly deployed, leading to less channel use for co-existing systems. Additionally, many different 802.15.4w systems can operate on the same frequency band without impairing each other band by using different hopping sequences.
* Forward Error Correction (FEC): The powerful FEC codes defined within 802.15.4w can recover a significant number of interfered symbols. Especially in the FHSS with robust FEC more than 50% of the fragments may be fully destroyed by interference of other systems without significant performance degradation.
* Listen Before Talk (LBT): 802.15.4w uses LBT to reduce its impairment onto co-existing systems. Consequently, the transmissions of detected co-existing systems are not impaired. In the FHSS mode LBT is used for each fragment. Occupied channels are left out and the resulting missing fragments are recovered using the FEC without any impact on the transmission latency.
* Narrow-band transmission: 802.15.w uses variants of frequency shift keying (FSK) with very low symbol rates that result in a very low overall system bandwidth. Consequently, this low system bandwidth significantly reduces the impairment of broadband signals with low power spectral density, e.g. 802.11ah. On the other hand, 802.15.4w will only affect few sub-carriers of broadband OFDM signals, which may be recovered using FEC.

# Dissimilar IEEE 802 Systems Sharing the Same Frequency Bands with 802.15.4w

TODO: List all systems using the same frequency band for the sub-GHz channels. These systems are 802.15.4 and 802.11ah. Most work (except 802.11ah) can potentially be done by referencing existing IEEE 802.15.4 coexistence documents.

## Coexisting Systems in 169.4 – 169.475 MHz Band

Table 1: Dissimilar systems co-existing with the 802.15.4w PHY within the 169.4-169.475 MHz Band

|  |  |
| --- | --- |
| **System** | **PHY Specification** |
| 802.15.4-2015 | SUN FSK |
| LECIM FSK |
| 802.15.4q | ULP-GFSK |

## Coexisting Systems in 433.05 – 434.79 MHz Band

|  |  |
| --- | --- |
| **System** | **PHY Specification** |
| 802.15.4-2015 | MSK |
| LECIM FSK |
| 802.15.4q | ULP-GFSK |
| ULP-TASK |

## Coexisting Systems in 470 – 510 MHz Band

|  |  |
| --- | --- |
| **System** | **PHY Specification** |
| 802.15.4-2015 | SUN FSK |
| SUN OFDM |
| SUN O-QPSK |
| LECIM DSSS |
| LECIM FSK |
| 802.15.4q | ULP-GFSK |
| ULP-TASK |

## Coexisting Systems in 779 – 787 MHz Band

|  |  |
| --- | --- |
| **System** | **PHY Specification** |
| 802.15.4-2015 | O-QPSK |
| SUN FSK |
| SUN OFDM |
| SUN O-QPSK |
| LECIM DSSS |
| LECIM FSK |
| 802.15.4q | ULP-GFSK |
| ULP-TASK |
| 802.11ah | S1G OFDM |

## Coexisting Systems in 863 – 870 MHz Band

|  |  |
| --- | --- |
| **System** | **PHY Specification** |
| 802.15.4-2015 | O-QPSK |
| BPSK |
| ASK |
| SUN FSK |
| SUN OFDM |
| SUN O-QPSK |
| LECIM DSSS |
| LECIM FSK |
| 802.15.4q | ULP-GFSK |
| ULP-TASK |
| 802.11ah | S1G OFDM |

## Coexisting Systems in 902 – 928 MHz Bands

|  |  |
| --- | --- |
| **System** | **PHY Specification** |
| 802.15.4-2015 | O-QPSK |
| BPSK |
| ASK |
| SUN FSK |
| SUN OFDM |
| SUN O-QPSK |
| LECIM DSSS |
| LECIM FSK |
| 802.15.4q | ULP-GFSK |
| ULP-TASK |
| 802.11ah | S1G OFDM |

# Coexistence Scenarios and Analysis

## PHY Modes in the 802.15.4w System

### Parameters of the 802.15.4w PHY Modes

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **System** | **PHY** | **PHY Mode** | **Transmit Power (dBm)** | **Average Frame Length (Octet)** |
| 802.15.4w | FSK (h=1) | 6.25kb/s, CR 1/2 | 14 | 37 |
| MSK FHSS | 2.38kb/s, CR 1/32.38kb/s, CR 1/42.38kb/s with SF=2, CR 1/3 | 14 | 37 |

TODO: Give a parameter overview of the used parameters.

### BER / FER Calculations for the 802.15.4w PHY Modes

TODO: Show simulation results for 802.15.4w in the AWGN and the defined interference channel. These simulations already exist from the call for proposals and can be copy paste.



Figure 1: Frame Error Rate vs. SNR for different forward error correction modes (SF=1, frame length 37 octets)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **System** | **PHY** | **PHY Mode** | **Coding** | **SNR for FER < 1%** | **Sensitivity** | **Eff. Bitrate\*)** |
| . | MSK, SF1 | 19.04kb/s | Conv. 1/2 | 0.3 dB | -131 dBm | 9.5kb/s |
| 19.04kb/s | Conv. 1/3 | -1.7 dB | -133 dBm | 6.3kb/s |
| 2.38kb/s | Conv. 1/3 | -1.7 dB | -142 dBm | 0.8kb/s |
| MSK, SF2 | 1.19kb/s | LDPC 1/4 | -7.5dB | -148 dBm | 0.3kb/s |

**\*) Note: The effective payload bitrate is only valid for one client. The channel may be used by multiple devices simultaneously, resulting in a significantly higher rate per network cell.**

Add figure showing theoretical results, e.g. sphere packing bound?

## Interference Modeling

802.15.4g’s interference model, described in section 4.2 of the TG4g Coexistence Assurance Document [1], is adopted for the 802.15.4w coexistence simulation modeling. This is also identical to the interference model used for the TG4k and TG4Qq Coexistence Assurance Documents [2] [3].

* In the coexistence model, the transmitting power and the distance between the victim transmitter and victim receiver are fixed. Within this document we assume a distance of $d\_{D}=10m$. Hence, the received signal strength of the victim signal at the receiver is fixed, too. In contrast, the distance $d\_{U}$ of the interfering transmitter to the victim receiver is modified, which allows different inference levels at the victim receiver.
* The Hata model (large scale urban) is used for the path-loss calculation for the interference calculation in case of 802.15.4 interference. For 802.11ah interference the 802.11ah indoor channel path-loss model is used instead ([4], Sec. 3.5, model A, no shadow fading), as most coexistence issues are expected for indoor applications.
* No AWGN is included to focus on the impacts of the interference only.
* All antenna gains are assumed to be 0dBi. The transmit power of the 802.15.4w system is set to 14dBm, which is the maximum allowed transmit power for most frequency bands in Europe. Higher transmit powers are very unlikely, as 802.15.4w is intended for operation with tiny batteries. In case of 802.15.4w as victim the interferer powers are set to 14dBm and 30dBm (high power use-cases).
* For 802.15.4w the maximum spreading factor used is SF=2, as higher values would result in very low effective bitrates.
* Ideal channel knowledge is assumed.

## 802.15.4 Coexistence Performance

TODO: Show the coexistence performance by referencing the coexistence assurance documents of 802.15.4g, k, and q. As we have not defined any new modulation scheme, we may just reference the existing results. (To be confirmed)

## 802.11ah Coexistence Performance

TODO: The existing 802.15.4 coexistence documents do not cover 802.11ah, which did not exist when the previous new PHY modes were defined. Hence, we have to show the impact of 802.15.4w on 802.11ah and vice versa. We will do this by assuming worst case conditions, e.g. maximum overlap between both systems. Following the discussions within the 802.19 GHz coexistence study group we would use the same MCS modes as defined there, i.e. MCS1, MCS3, and MCS7. We would limit our simulations to the PHY only. Within the TG4w we already discussed to use the MATLAB WiFi Toolbox for the simulations, which makes the simulation results reproducible to others.

### Victim 802.11ah

Full overlap between 802.15.4w and 802.11ah

802.15.4w acts like narrow-band carrier. Results in actual implemenations could provide much better results, as 802.11ah is operated in same bands as RFID 🡪 shaping





### Victim 802.15.4w

All results with realistic channel estimation





# Interference Mitigation and Avoidance Techniques

TODO: Mention techniques used by 802.15.4, e.g. LBT.

# Conclusions