IEEE P802.15

Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)	
Title	Coexistence Document for IEEE 802.15.4ab	
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Re:	Analyze the coexistence of 802.15.4ab and other 802 wireless systems	
Abstract	IEEE 802.15.4 Coexistence Document	
Purpose	Document coexistence analysis	
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1 Introduction

This document provides a summary of coexistence assessment which has been performed to evaluate the performance of systems using the 802.15.4 UWB (HRP, LRP and LE) PHYs as amended by P802.15.4ab with respect to other 802 wireless standards which may operate in the same band.

The PAR for P802.15.4ab may be found in [1] .

802 standards to consider:

- 802.11-2020 [6] and 802.11ax-2021 [7]
- Draft 802.11be
- 802.15.6ma [25]
- Legacy 802.15.4 UWB (HRP, LRP) [5]
- Draft 802.15.4ab NB and UWB [4]

1.1 Acronyms

ACK	acknowledgment
CCA	Channel clear assessment
cPSDU	compact PSDU
eDAA	enhanced detect-and-avoid
IR-UWB	Impulse Radio UWB
LBT	listen before talk
MAC	medium access control
MMS	multi-millisecond
NACK	negative acknowledgment
NB	narrow-band
NBA	narrow-band Assist
OFDM	orthogonal frequency division multiplexing
O-QPSK	offset quadrature phase-shift keying
PHY	physical layer
PSDU	PHY service data unit
UWB	ultra-wide band
WLAN	wireless local area network

1.2 Terminology

The following terms, when used in this document, have the following meaning:

“base standard” means 802.15.4-2024 [2] which includes amendment 802.15.4z-2020 [3].

“802.15.4” means the base standard.

“This amendment” means amendment P802.15.4ab [4]: Standard for Low-Rate Wireless Network Amendment: Enhanced Ultra Wide-Band (UWB) Physical Layers (PHYs) and Associated Medium Access and Control (MAC) sublayer Enhancements.

2 Overview

Project P802.15.4ab is the latest amendment to the UWB PHYs in IEEE Std 802.15.4. The first UWB PHY was introduced in amendment IEEE Std 802.15.4a-2007, which defined an impulse radio (IR) UWB PHY with low data rates. With the addition of a second UWB PHY optimized for low complexity RFID with amendment IEEE-Std 802.15.4f-2012, named Low Rate Pulse repetition frequency (LRP) PHY. In the subsequent revision, IEEE Std 802.15.4-2015, the original UWB PHY was renamed High Rate Pulse repetition frequency (HRP) PHY to differentiate. Subsequently, amendment 802.15.4z-2020 [3] was completed, which enhanced both LRP and HRP PHYs.

The HRP UWB PHY channel plan comprises three sub-bands: a sub-1GHz channel plan, a low band from 3.1 GHz to 4.8 GHz, and the high band from 6.0 to 10.6 GHz. The channel plan included nominally 500 MHz channelization and optional wider channels (from 1.1 to 1.4 GHz). The 500 MHz channels have proven most popular in implementations. The LRP UWB PHY introduced three channels from 6 GHz to 8.5 GHz, IEEE Std 802.15.4z added additional LRP channels from 8.5 to 10.6 GHz.

Project P802.15.4ab is enhancing the HRP UWB PHY based on growing use of UWB and new market needs.

Subsequent to the completion of IEEE Std 802.15.4z-2020, IEEE Std 802.11ax-2021 [7] was completed that included channelization in the 6 GHz to 7 GHz range, overlapping with both HRP and LRP UWB PHYs. This was considered in the coexistence assessment for project 802.15.4z in [8].

This coexistence assessment examines coexistence studies that are available, and evaluates the changes included in the P80215.4ab draft as they may potentially affect coexistence.

The relevant 802 standards that use bands overlapping those used by the current project are identified in 2.1.1 .

2.1 Overview of 802.15.4ab UWB

2.1.1 Frequency bands of interest

The defined channel plans of interest for UWB cover the frequency range from 3.1 GHz to 10.6 GHz. The actual spectrum used varies by region.

The 802.15.4 Narrow band channel plan defined in this amendment overlaps with the UWB channel plan in the frequency range from 5.725 to 5.850 GHz and 5.925 to 6.425 GHz.

The 802.11 OFDM channel plan overlaps the UWB channel plan in the frequency range 5.925 GHz to 7.125 GHz (802.11ax) or 7.250 GHz (P802.11be).

2.1.2 Relevant 802 Standards

Table 1 lists the other 802 standard that may operate in overlapping bands. This information was derived from Annex E of IEEE Std 802.11 [6], IEEE Std 802.15.4 [5] and Tables of frequency and wavelength ranges of IEEE 802 wireless standards [23].

Table 1: Other 802 Wireless Standards in the Subject Bands

Standard	Frequency Band (MHz)	PHY description
802.15.4	3244–4743	HRP UWB low band
802.15.4	5944–10 234	HRP UWB high band
802.15.4	6289.6–9185.6	LRP UWB
802.11-2020	3650–3700	10, 20, 40 MHz channel spacing
802.11-2020	4002.5	5 MHz channel spacing
802.11-2020	4940–4990	20 MHz channel spacing
802.11-2020 802.11ax-2021	5150–5895	10,20, 40, 80, 160 MHz channel spacing
802.11ax-2021	5945 - 7125	10,20, 40, 80, 160 MHz channel spacing
P802.11be (Draft)	5945-7250	10, 20, 40, 80, 160, 320 MHz channel spacing

The analysis referenced in this document considers channel spacing from 2.5 to 500 MHz.

2.1.3 Summary of Amendment

This amendment enhances the Ultra Wideband (UWB) physical layers (PHYs) medium access control (MAC) to address growing market needs. Areas of enhancement include:

- Coding, preamble and modulation schemes to support improved link budget and/or reduced air-time relative to IEEE Std 802.15.4 UWB;
- Additional channel plans;
- Interference mitigation techniques to support greater device density and higher traffic use cases relative to the IEEE Std 802.15.4 UWB;
- Improvements to accuracy, precision and reliability and interoperability for high-integrity ranging;
- Means to reduce complexity and energy consumption;
- Definitions for tightly coupled hybrid operation with narrowband signaling to assist UWB;
- Enhanced native discovery and connection setup mechanisms;
- Sensing capabilities to support presence detection and environment mapping;
- Mechanisms supporting ultra low-power low-latency data communication
- New data rates to support at least 50 Mb/s of throughput.

This amendment supports multiple topologies including peer-to-peer, peer-to-multi-peer, and station-to-infrastructure. This amendment considers compatibility with legacy 802.15.4 UWB devices and includes mechanisms to ensure backwards compatibility, and means to ensure compatibility between new higher throughput data use cases and low duty-cycle ranging use cases.

This amendment includes enhancements to the O-QPSK PHY to support the hybrid operation (UWB and coupled narrow band signaling), including extended channel plans.

This amendment builds upon existing mechanisms in the standard to support sharing of spectrum with overlapping services, and introduces several new mechanisms described in sections that follow.

2.2 Overview of Coexistence Mechanisms in 802.15.4

The base standard includes a variety of channel access mechanisms. The base standard includes listen before talk via a simple yet flexible version of CSMA-CA. The standard includes multiple clear channel assessment (CCA) modes to support a wide variety of uses with very diverse needs such as throughput, activity factor, and duty cycle. In many applications of 802.15.4, data volumes are very small and activity factors low. In such uses, support for CCA mode that reduces CSMA-CA to unslotted or slotted Aloha provides effective channel access. With UWB PHYs, detection of the transmitted signal is very challenging, and traditional channel sensing mechanisms are often ineffective. Likewise for very low data volume narrow band use cases, such as wide area sensor networks and smart city and smart utility networks, Aloha is the commonly used channel access mechanism. Other mechanisms to mitigate potential interference effects and achieve positive coexistence in the presence of many different wireless technologies are supported by the standard, including frequency diversity (channel hopping), which is often used (and in some regulatory domains required) with 802.15.4 narrow band PHYs.

The 802.15.4 standard includes several CCA modes including: energy detection, carrier detection, preamble detection and aloha. There are many (very) different PHYs defined in 802.15.4, with very different signal structures and preambles. Thus no single preamble detection mechanism can be effective in the typical shared spectrum environment where multiple PHYs may be in operation.

This amendment introduces a new mechanism for random channel access that relies on sensing the spectrum prior to transmission (listen before talk). Spectrum Sensing Based Deferral (SSBD) is similar to CSMA-CA, but uses linear backoff when sensing channel busy instead of an exponential backoff. SSBD includes a persistence mechanism. SSBD is optimized to bound channel access latency and provides finer control of channel access timing than CSMA-CA. SSBD may be used with any 802.15.4 PHY.

When operating the narrow band PHYs in certain channels, e.g. those channels corresponding to U-NII 5, regulations may require use of a contention based protocol. The standard provides multiple mechanisms employing LBT that can be used to satisfy contention based protocol requirements. For example, CSMA-CA defined in the IEEE Std 802.15.4, and SSBD as defined in P802.15.4ab, when using CCA mode 1 or mode 3a. Both channel access mechanisms can be beneficial, even in the absence of regulatory mandates. Use of one of these LBT mechanisms prior to narrowband (NB) transmissions with

CCA mode 1 or 3 (as described above) can detect presence of transmissions from non-802.15.4 systems, e.g. those using IEEE Std 802.11. Which can enable collision avoidance, improving reliability and coexistence performance.

Additionally, the based 802.15.4 standard includes passive scan, which can be used to identify spectrum where channel access using CCA mode 1 through 3 will have the highest probability of being idle.

Additionally, the MAC provides for coordinated channel access via several mechanisms that provide temporal and frequency separation. Examples include channel diversity (hopping), coordinated channel switching, and support for enhanced detect and avoid (eDAA).

2.3 Coexistence Analysis Methodology

This document follows the methodology described in [8].

3 Dissimilar Systems Sharing the Same Frequency Bands

This clause presents coexistence considerations with other 802 systems which are specified to operate in some of the same frequency bands. For the purpose of this clause, dissimilar is defined as other than Impulse Radio UWB (IR-UWB) operating according to the 802.15.4 UWB standard.

3.1 802.11 Coexistence

3.1.1 802.11 WLAN impact on 802.15.4 UWB

References [9],[10],[12],[12],[14] and [22] contain information, analysis and measurement based studies of coexistence between 802.15.4 UWB and 802.11 operating in overlapping channels. These show the potential for severe impacts on UWB operation from collocated 802.11 devices.

These studies show that physical separation is an effective mitigation technique. In some scenarios, separation of 100s of meters is required. In others, when used in conjunction with other coexistence mechanisms, separation on the order of 10 meters is sufficient. As a sole means of mitigating interference, physical separation is often not sufficient.

Due to the extreme difference in transmit power levels used by UWB and 802.11, the UWB signal at as little as 1m physical separation from the 802.11 device is below -90 dBm/MHz. This is substantially below any of the energy detect thresholds specified for 802.11 CCA. The 802.11 channel access will not detect and defer in the presence of a UWB signal. However, if the UWB transmission is substantially below 1ms in duration, the peak limit applies and the UWB peak may be -58 dBm at the receiver at 1m, and detection is possible.

In [9] and [10] offsetting in frequency by more than the UWB channel width is used, and can be effective in mitigating interference risk. However, it is shown that out of band emissions of the RLAN system complying with the 802.11 standard can cause impactful interference with the UWB signal. These studies show in-band 802.11 can have a measurable impact on UWB with as much as 946 meters of physical separation.

In [14] and [22], it is shown that partial frequency offset can improve coexistence (both ways) significantly. These studies included use of SSBD to improve coexistence. In this scenario, the UWB device is able to detect transmissions from the 802.11 device, while the 802.11 device does not detect and defer in the presence of UWB signals. This one-way LBT is shown to improve coexistence performance. These studies also used frequency diversity in the UWB system, operating over multiple UWB channels. This is shown to improve coexistence performance also.

Additional techniques which can be applied for narrow band interference mitigation are described in [12], [13],[15] and [17].

Further study of coexistence impacts is needed. In particular, the inability of 802.11 based devices to detect UWB creates an asymmetric situation, compromising simple techniques based on LBT. The results presented in the referenced studies suggest that effective coexistence is possible, with further study and development of new techniques holds promise.

3.1.2 802.15.4 UWB impact on 802.11 WLAN

3.1.2.1 802.15.4 LE UWB PHY impact on 802.11 WLAN

This amendment (4ab) introduces a new Low-Energy UWB PHY (LE UWB PHY) with PHY layer parameters defined for non-coherent data communications. The LE UWB PHY applies several coexistence strategies. This section describes the LE UWB PHY strategies for mitigation of impact on 802.11 WLAN and on other communications occupying the same bands.

The use of Energy Detection (ED) afforded by the non-coherent receiver of the LE UWB PHY allows for enhanced detection of non-UWB transmissions for enhanced mitigation of interference to other systems. Listen-before-talk is easily implemented. In fact, the LE UWB PHY is intended to be combined with the Spectrum Sensing Based Deferral (SSBD) mechanism as described in Clause 6. SSBD based CCA LBT provides the ability for the LE UWB PHY to detect concurrent networks transmission and to delay its own transmission or switch center frequency to avoid interfering. A practical demonstration of the effectiveness of SSBD is described in the “SSBD enabled UWB radio coexistence with Wi-Fi 6e demo” document [34].

In addition to SSBD, the LE UWB PHY utilizes shorter preamble sequences and has shorter airtime relative to previous PHYs, thus providing additional robustness and mitigation of interference.

The combination of the above-mentioned coexistence strategies used by the LE UWB PHY will mitigate interference to both similar and dissimilar systems.

3.1.2.2 802.15.4 HRP UWB PHY impact on 802.11 WLAN

HRP and LRP impact on 802.11 WLAN systems is described in [8]. The summary is that due to the extreme difference in transmit power, interference from UWB is very unlikely. With free space loss, a separation distance of 1m reduces the UWB power spectral density at the receiver to less than -80 dBm, which is below the energy detect thresholds specified in 802.11, and below the minimum receiver sensitivity for most modulation and coding schemes and channel widths specified for the overlapping bands. Additionally, typical uses of UWB employ duty cycle below 5% (often much below).

In addition to the prior analysis, [14] and [22] include measurement-based studies of UWB impact on 802.11 operation. In these studies, a very unrealistic scenario was required to measure any impact from UWB on the 802.11 devices. A collection of UWB devices (12) operating within 0.33 meters of the 802.11ax AP, operating in continuous transmission mode and at maximum power spectral density, centered on the 802.11 channel, in the lab environment, could show a performance impact on the 802.11 link (from zero to 60 % reduction in throughput). As explained in the reference the configuration to create measurable impact was very specific and difficult to achieve, and shows that physical separation of 0.33 meter or more mitigated all impacts. Reducing to a more realistic transmission duty cycle mitigated impact. These studies also showed that within the very small sphere of impact, mitigation techniques such as partial channel frequency offset and/or SSBD reduced the impact to unobservable.

3.1.3 802.15.4 NB impact on 802.11 WLAN

802.15.4 UWB ranging is duty-cycle constraint to 5% when regulatory and public safety requirements apply [19] [20]. 95% or greater of the available airtime is typically available to other radio technologies operating in the same frequency bands. When the NB O-QPSK channel is used in NB-MMS, it is used in ranging services and thus will fall within these airtime duty cycle conditions. See [19] [20] for background on these values.

To further improve on coexistence between the 802.15.4 NB OQPSK and 802.11 WLAN, shorter packet durations are attainable through newly introduced higher rate 500k/1M modulations and the introduction of the newly introduced compact PSDU format. For ranging distance measurements, NB airtime is reduced in comparison to the 802.15.4 NB OQPSK 250kbps by up to 38% [26], therefore reducing the chances of packet collisions with 802.11 WLAN operating in the same frequency band. Additionally, the spectral efficiency has been improved by reducing the NB channel bandwidth to 2.5 MHz in 5.725 to 5.850 GHz and 5.925 to 6.425 GHz, thereby doubling the channels per MHz in comparison to the NB channel allocation in 2.400 to 2.480 GHz where 5 MHz bandwidth per NB channel are used.

An improved channel switching mechanism with improved statistical properties is newly defined that distributes packet transmissions sequentially over the increased number of up to 250 NB channels. The likelihood of sequential NB packet collisions with 802.11 WLAN primary channels is therefore reduced by up to 6.25 fold over NB operation in the 2.4 GHz band [27]. Periodic NB packet transmissions on fixed channels such as background advertising and control traffic are allocated in 4ab in newly allocated spectrum outside of the channel map used by 802.11 WLAN such that no interference is cast [18].

To allow improved spectrum sensing and interference avoidance techniques such as eDAA [20], 4ab newly introduces explicit control over the channel map selection. Specifically, when the presence of other radio is attested by in-band or out-of-band methods, 4ab NB devices may exclude possibly conflicting channels in the shared spectrum from access, therefore enabling efficient spectrum sharing with 802.11 WLAN and other radio technologies [32].

In addition to spectrum sensing techniques for channel map selection, the NBA-MMS ranging protocol specifically suppresses unnecessary packet transmissions following unrecoverable collision events or channel busy assessments when using channel access with LBT/CCA [17]. Ranging exchanges eliminate the airtime overhead created by ACK/NACK control transmissions by disallowing retries of packet transmissions outside of the statically allocated packet slots. Instead all packet transmissions are cancelled following a non-recoverable packet error.

The strict adherence to statically scheduled traffic provides the ability for other radio technologies to sense the channel occupancy patterns and to avoid interference entirely by adapting an orthogonal schedule. Additionally, 4ab actively promotes coordination between radios by introducing periodic broadcast packet transmissions that can be used to reveal channel occupancy patterns and interference avoidance information to other radios without spectrum sensing abilities [21]. The presence of periodic activity enables various techniques to be used to detect the activity: compatible devices that are able to receive the PPDU are one example; devices capable of detecting preamble patterns need not be able to receive and process the entire PPDU; It is in some environments useful to use energy detection, without recognition of the signal structure, to detect activity. Which is most effective depends on the environment, application and implementation details. This enables 802.11 devices operating in the band to detect the predictable patterns as well as use the scanning features of 802.11 to identify channels and times where clear channel assessment is more likely to return clear.

Mutual coexistence is improved when all participating devices use means to mitigate interference risk to other devices.

The potential coexistence impacts are further discussed in [24], [26] and [27].

In some applications, airtime duty cycles may exceed the levels noted above. IEEE Std 802.15.4[2] and P802.15.4ab [4] include channel access using CSMA-CA and SSBD, which employ sensing the channel via CCA prior to deciding to transmit. It is recommended that CSMA-CA or SSBD be used, using CCA mode 1 (Energy above threshold) or CCA mode 3a (Carrier sense with energy above threshold) be used for narrow band access when airtime duty cycle is high and presence of 802.11 systems operating in proximity of the narrow band radio range is expected.

3.2 802.15.4 Coexisting Systems

As shown in Table 1, the 802.15.4 UWB channel plans avoid the bands used by legacy non-UWB PHYs defined by IEEE Std 802.15.4. Compatibility with legacy UWB systems is described in [4].

4 802.15.4 UWB systems

Coexistence with legacy 802.15.4 UWB systems is similar to that described in [8].

Several features of P802.15.4ab allow for reducing the on-air duty cycle, which further improves positive coexistence with legacy UWB. Addition of SSBD provides a new mechanism that can improve coexistence with legacy UWB by sensing and deferring when a signal is detected, specifically when a large number of UWB devices are in a small space.

5 802.15.6 UWB systems

Coexistence mechanisms available in IEEE Std 802.15.6-2012 and P802.15.6ma are discussed in [25].

The UWB PHY operate in the same frequency ranges. The channel BAN UWB channel plan is identical to the HRP UWB PHY channels as defined in IEEE Std 802.15.4-2024. The channel plan overlaps the LRP UWB PHY channel plan in the range 5624.32–10 435.2 MHz. P802.15.4ab does not introduce any changes to LRP.

The potential for interference between HRP, LRP and BAN UWB exists when operating in overlapping frequencies. Do to the extremely low transmit power of UWB, the likely of interference decreases rapidly with separation distance (e.g. approximately 48 dB at 1 meter of free space path loss). The basic operation of an IR-UWB radio is that it depends on specific preamble patterns to detect such low level signals. Each standard includes multiple preamble patterns designed to maximize separation between devices using

P802.15.4ab introduces optional channelization that covers the same frequency range as the current channel plan, providing partial channel offsets. As was demonstrated in [22], this can improve performance both ways when the UWB channel center frequency is offset by even a partial channel width. This provides an additional mechanism to use to improve coexistence in some conditions. The P802.5.4ab channel plans enable use of channel diversity as an interference mitigation technique. IEEE Std 802.15.4-2024 includes channel scanning capability which enables scanning for UWB activity. Because the signal structure of the BAN UWB PHY can use the same signal structure, preamble codes and packet structure as 802.15.4 HRP UWB, it is possible to use the MLME-SCAN primitive to detect the presence of a BAN UWB device(s) operating in reception range.

As noted in [25], P802.15.6ma includes some mechanisms to detect 802.15.4 HRP UWB systems operating in the same channel. This enables exchange between P802.15.6ma devices about other systems detected.

P802.15.4ma includes additions to the UWB PHY to enable packet level exchange with 802.15.4 HRP UWB devices. This makes possible coordinated coexistence via information exchange between the devices. P02.15.6ma provides a scan procedure that can detect beacons transmitted by 802.15.4 UWN devices. This mechanism relies on detecting beacon frames. Popular uses of 802.15.4 UWB do not use beacon frames. However, an 802.15.4 HRP UWB device may transmit beacon frames, which may make it detectable by a BAN UWB device doing a scan.

6 802.15.6 Narrow Band

Coexistence mechanisms available in IEEE Std 802.15.6-2012 and P802.15.6ma are discussed in [25]. The narrow band PHY operates in the following frequency bands:

- 402 MHz to 405 MHz
- 420 MHz to 450 MHz

- 863 MHz to 870 MHz
- 902 MHz to 928 MHz
- 950 MHz to 958 MHz
- 2360 MHz to 2400 MHz
- 2400 MHz to 2483.5 MHz

P802.15.4ab introduces no changes to the operation of IEEE Std 802.15.4 compliant devices in any of these frequency bands. There are no changes to coexistence characteristics for these bands introduced in the amendment for the IEEE Std 802.15.6-2012 narrow band PHY.

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