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IEEE Recommended Practice for Local and Metropolitan Area Networks— Part 19: Coexistence Methods for IEEE 802.11 and IEEE 802.15.4 Based Systems Operating in the Sub-1 GHz Frequency Bands

IEEE Computer Society

Developed by the
LAN/MAN Standards Committee

IEEE Std 802.19.3™-2021

IEEE

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IEEE SA Standards Board

Abstract: Millions of IEEE Std 802.15.4g™ based devices are currently operating in sub-1 GHz frequency bands to provide the low to moderate data rate capabilities. IEEE Std 802.11ah™ may operate in the same sub-1 GHz frequency bands and provides higher data rate capabilities. This recommended practice enables IEEE Std 802.15.4g and IEEE Std 802.11ah to effectively operate in license exempt sub-1 GHz frequency bands, by providing best practices and coexistence methods.

Keywords: coexistence, CSMA/CA, energy detection, FSK, IEEE 802.11ah™, IEEE 802.15.4g™, interference, OFDM, receiver sensitivity, sub-1 GHz frequency bands, Wi-Fi HaLow™, Wi-SUN®

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When the IEEE SA Standards Board approved this recommended practice on 25 March 2021, it had the following membership:

Introduction

This introduction is not part of IEEE Std 802.19.3-2021, IEEE Recommended Practice for Local and Metropolitan Area Networks—Part 19: Coexistence Methods for IEEE 802.11 and IEEE 802.15.4 Based Systems Operating in the Sub-1 GHz Frequency Bands.

Many millions of devices based on IEEE Std 802.15.4™ are currently operating in sub-1 GHz frequency bands, and the field is expanding rapidly. Critical applications, such as grid modernization (smart grid) and Internet of Things (IoT), are using the low to moderate data rate capabilities of IEEE Std 802.15.4. IEEE Std 802.11ah™ may operate in the same sub-1 GHz frequency bands and provides higher data rate capabilities than IEEE Std 802.15.4. For example, Japan formed the 802.11ah Promotion Council (AHPC) to promote the widespread use of IEEE Std 802.11ah technology in areas such as home, office, industry, infrastructure, and mobility. In consideration of the current usage, as well as anticipation of as yet unforeseen usage models enabled by the standards within the scope of this recommended practice, and to fully realize the opportunity for successful deployment of products sharing the spectrum, strategies and tactics to achieve good coexistence performance are critical.

This recommended practice enables IEEE Std 802.15.4 and IEEE Std 802.11ah to effectively operate in license exempt sub-1 GHz frequency bands by providing best practices and coexistence methods. This recommended practice uses existing features of the referenced standards and provides guidance to implementers and users of IEEE 802® wireless standards.

Contents

IEEE Recommended Practice for Local and Metropolitan Area Networks— Part 19: Coexistence Methods for IEEE 802.11 and IEEE 802.15.4 Based Systems Operating in the Sub-1 GHz Frequency Bands

1. Overview

1.1 Scope

This recommended practice provides guidance on the implementation, configuration, and commissioning of systems sharing spectrum between IEEE Std 802.11ah™-2016 and IEEE Std 802.15.4™ smart utility networking (SUN) frequency shift keying (FSK) physical layer (PHY) operating in sub-1 GHz frequency bands.

1.2 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).[1,2]

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

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[1] The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

[2] The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 802.11™-2016, IEEE Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.[3, 4]

IEEE Std 802.11ah™-2016, IEEE Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment 2: Sub 1 GHz License Exempt Operation.

IEEE Std 802.15.4™-2011, IEEE Standard for Low-Rate Wireless Networks.

IEEE Std 802.15.4™-2015, IEEE Standard for Low-Rate Wireless Networks.

IEEE Std 802.15.4™-2020, IEEE Standard for Low-Rate Wireless Networks.

IEEE Std 802.15.4g™-2012, IEEE Standard for Local and metropolitan area networks—Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)—Amendment 3: Physical Layer (PHY) Specifications for Low-Data-Rate, Wireless, Smart Metering Utility Networks.

IEEE Std 802.15.4s™-2018, IEEE Standard for Low-Rate Wireless Networks—Amendment 6: Enabling Spectrum Resource Measurement Capability.

IEEE Std 802.15.4x™-2019, IEEE Standard for Low-Rate Wireless Networks—Amendment 7: Defining Enhancements to the Smart Utility Network (SUN) Physical Layers (PHYs) Supporting up to 2.4 Mb/s Data Rates.

IEEE Std 802.15.4w™-2020, IEEE Standard for Low-Rate Wireless Networks—Amendment 2: Low Power Wide Area Network (LPWAN) Extension to the Low-Energy Critical Infrastructure Monitoring (LECIM) Physical Layer (PHY).

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[5]

[3] IEEE publications are available from The Institute of Electrical and Electronics Engineers (https://standards.ieee.org/).

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[5] *IEEE Standards Dictionary Online* is available at: http://dictionary.ieee.org. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

beamforming: A spatial filtering mechanism used at a transmitter to improve the received signal power or signal-to-noise ratio (SNR) at an intended receiver.

coexistence: The ability of multiple systems to perform tasks in a given shared environment, at the same time, in the same physical space, and within the same frequency band or overlapping frequency bands, where such systems may or may not be using the same set of rules.

coexistence mechanism: A means to improve performance, resilience, and reliability of systems operating simultaneously in a given shared environment, at the same time, in the same physical space, and within the same frequency band or overlapping frequency bands.

common signaling mode: A common physical layer (PHY) mode used between smart utility network (SUN) devices implementing the multi-PHY management (MPM) scheme.

duty cycle: The ratio of the sum of the durations of all transmissions in a given period of continuous operation, to the duration of the given period of continuous operation.

interference: In a communication system, power entering or induced in a channel from natural or man-made sources that might disrupt reception of desired signals or the disturbance caused by the undesired power.

restricted access window: A medium access interval for a group of stations (STAs) during which a STA in the restricted access window (RAW) group indicated by the RAW parameter set (RPS) element is allowed to contend for access to the medium.

smart utility network: A principally outdoor, low data rate wireless network that supports two-way communications among sensing, measurement, and control devices in the smart grid.

smart utility network (SUN) device: A device that uses the MAC sublayer and one or more of the SUN PHYs defined in IEEE Std 802.15.4.

target wake time: A specific time or set of times for individual stations (STAs) to wake in order to exchange frames with other STAs.

3.2 Acronyms and abbreviations

ACK	acknowledgment
AHPC	802.11ah Promotion Council
AID	association identifier
AMI	advanced metering infrastructure
AP	access point
BC	backoff counter
BDT	bidirectional TXOP
BPSK	binary phase-shift keying
CAP	contention access period
CCA	clear channel assessment
CFP	contention free period
CSMA/CA	carrier sense multiple access with collision avoidance

CSM	common signaling mode
CSS	chirp spread spectrum
CS	carrier sense
CW	contention window
DD-UNB	Dynamic Downlink Ultra Narrow Band
EB	enhanced beacon
ED	energy detection
ERP	effective radiated power
FCC	Federal Communications Commission
FEC	forward error correction
FER	frame error ratio
FSK	frequency shift keying
GMSK	Gaussian-filtered minimum shift keying
IoT	Internet of Things
ITS	intelligent transportation system
LDPC	low density parity check
LECIM	low-energy critical infrastructure monitoring
LPWAN	low power wide area network
MAC	medium access control
MCL	maximum coupling loss
MPM	multi-PHY management
OFDM	orthogonal frequency division multiplexing
PAN	personal area network
PANC	personal area network coordinator
PHY	physical layer
PPDU	PHY protocol data unit
QPSK	quadrature phase-shift keying
RAW	restricted access window
RFID	radio-frequency identification
RPS	RAW parameter set
RX	receive or receiver
S1G	sub-1 GHz
SDR	software defined radio
SRD	short range devices
SST	subchannel selective transmission
STA	station
SUN	smart utility network

SUN-FSK	smart utility network frequency shift keying
SUN-OFDM	smart utility network orthogonal frequency division multiplexing
SUN-O-QPSK	smart utility network offset quadrature phase-shift keying
TDMA	time division multiple access
TSCH	timeslotted channel hopping
TS-UNB	telegram splitting ultra narrow band
TXOP	transmission opportunity
TWT	target wake time
TX	transmit or transmitter

4. Overview of the sub-1 GHz frequency band systems

4.1 Introduction

The focus of this recommended practice is coexistence between IEEE Std 802.11ah and IEEE Std 802.15.4g based systems. A characteristic of licensed exempt operation around the world is that there can be many different radio systems operating in the same or overlapping bands without coordination. This subclause also describes other systems such as LoRa® [6] and Sigfox™ [7] likely to be found in the same bands to provide a coexistence “big picture” to aid understanding the coexistence challenges in licensed exempt sub-1 GHz bands.

Many Internet of Things (IoT) applications require low bandwidth communications over a long distance at low power. IEEE Std 802.11ah, IEEE Std 802.15.4g, IEEE Std 802.15.4w, LoRa, and Sigfox are the emerging technologies that fulfill these requirements by using the sub-1 GHz (S1G) frequency bands. These technologies support different topologies and use different terms for the network coordination device: Access point (AP) for IEEE Std 802.11ah, personal area network (PAN) coordinator (PANC) for IEEE Std 802.15.4g and IEEE Std 802.15.4w, gateway for LoRa and base station for Sigfox. Using these technologies, a network can support thousands of connected devices.

IEEE Std 802.11ah and IEEE Std 802.15.4g specify a communication range of up to 1 km. IEEE Std 802.15.4w, LoRa, and Sigfox are low power wide area network (LPWAN) technologies and they have a communication range up to 15 km. Many systems based on IEEE Std 802.15.4g use techniques such as mesh topologies with lowered power levels to achieve wider network range with less radio interference per device.

4.2 IEEE Std 802.11ah

Basic features of IEEE Std 802.11ah, which is marketed as Wi-Fi HaLow™ [8], are summarized in Guo, et al. [B23]. This is a wireless communication physical layer (PHY) and medium access control (MAC) layer standard that operates in the unlicensed sub-1 GHz frequency bands. IEEE Std 802.11ah defines an orthogonal frequency division multiplexing (OFDM) PHY with a minimum 1 MHz channel spacing. This allows channelization of the sub-1 GHz bands in many regions and makes it suitable for IoT applications.

[6] LoRa is a registered trademark of Semtech Corporation.
[7] Sigfox is a trademark of SIGFOX Société Anonyme.
[8] Wi-Fi HaLow is a trademark of Wi-Fi Alliance Corporation.

Frequency band allocation is region dependent, for example, 902–928 MHz band in the United States and 863–868 MHz band in Europe. At the time of publication of this recommended practice, 915–928 MHz band has been identified for use in Japan, but the specific regulations have not been finalized.

IEEE Std 802.11ah specifies the same data rate for uplink traffic and downlink traffic. With 1 spatial stream, IEEE Std 802.11ah enables a data rate up to 86.6667 Mb/s at short ranges and 150 kb/s up to 1 km. With 4 spatial streams, IEEE Std 802.11ah enables a data rate up to 346.6667 Mb/s at short ranges. Support for 1 MHz channel and 2 MHz channel with 1 spatial stream is mandatory. Support for 1 MHz channel and 2 MHz channel with 2, 3, or 4 spatial streams is optional. Support for 4 MHz channel, 8 MHz channel, and 16 MHz channel with 1, 2, 3, or 4 spatial streams is also optional.

The maximum allowed transmission power is region dependent and ranges from 3 mW to 1000 mW. Some regional examples include 1000 mW in the United States, 250 mW in Japan, and 25.12 mW in Europe.

In order to support large numbers of stations, IEEE Std 802.11ah extends the range of the association identifier (AID), and thus the number of associated stations, from 2007 up to 8191 per AP, and can organize stations in a four-level hierarchical structure to improve station management scalability. Stations are grouped together based on their similarities. Each station is assigned a four-level AID structure encompassing page, block, sub-blocks, and station fields.

In terms of channel access, IEEE Std 802.11ah typically applies carrier sense multiple access with collision avoidance (CSMA/CA) specified via the enhanced distributed channel access (EDCA) function, which implements service differentiation by classifying the traffic into four different access categories with different priorities. As such, a different backoff parameter set is specified for each access category (AC).

In addition, IEEE Std 802.11ah includes several features for spectrum efficiency and power efficiency. Restricted access window (RAW) and subchannel selective transmission (SST) are two of these features that can be applied to improve coexistence performance.

The RAW mechanism reduces contention by clustering stations into RAW groups and slots, only allowing the stations in one group to contend for the channel at any time slot. As such, it effectively combines CSMA/CA and time division multiple access (TDMA) into a dynamically adaptable MAC scheduler.

The sub-1 GHz stations that are associated with a sub-1 GHz AP transmit and receive on the channel or channels that are indicated by the AP as the enabled operating channels for the basic service set (BSS). The SST mechanism allows stations to rapidly select and switch to different channels between transmissions to counter fading over narrow subchannels. This feature can also help adjust to interference.

4.3 IEEE Std 802.15.4g

Guo, et al. [B23] overviews basic features of IEEE Std 802.15.4g, which was developed to address applications in a smart utility network (SUN) with modest data volume requirements, high tolerance to latency, and a requirement for ubiquitous and reliable delivery (eventually). Since publication in 2012, the standard has found application in many areas of IoT with similar performance requirements to SUN such as smart cities and environmental monitoring. IEEE Std 802.15.4g is a PHY amendment to the IEEE Std 802.15.4-2011, now included in IEEE Std 802.15.4-2020. IEEE Std 802.15.4g is designed to enable longer range than IEEE Std 802.15.4-2011 PHYs and great flexibility in channelization for a wide variety of bands, with very narrow channel spacing. The flexibility in particular of the FSK PHY has made it a very popular network solution for IoT applications. The standard includes channel plans to operate in many sub-1 GHz frequency bands as well as the globally available 2.4 GHz frequency bands.

IEEE Std 802.15.4g specifies three alternate PHYs in addition to those of IEEE Std 802.15.4-2011. The alternate PHYs support principally outdoor wireless SUN (Wi-SUN® [9]) applications under multiple regulatory domains. Three SUN PHYs are defined as follows:

— Multi-rate and multi-regional frequency shift keying (MR-FSK) PHY
— Multi-rate and multi-regional orthogonal frequency division multiplexing (MR-OFDM) PHY
— Multi-rate and multi-regional offset quadrature phase-shift keying (MR-O-QPSK) PHY

These were renamed in IEEE Std 802.15.4-2015 and subsequent revisions as shown in Table 1.

Table 1—SUN PHYs

IEEE Std 802.15.4g	IEEE Std 802.15.4-2015
MR-FSK	SUN-FSK
MR-OFDM	SUN-OFDM
MR-QPSK	SUN-QPSK

In addition to the new PHYs, the amendment also specifies MAC modifications to support new PHY uses. IEEE Std 802.15.4e™ [B26] introduces extensions to the IEEE Std 802.15.4-2011 MAC, several of which are commonly used in applications employing these PHYs. The CSMA/CA algorithm is the main channel access mechanism specified in IEEE Std 802.15.4. There are two forms of CSMA/CA, slotted and unslotted, which is used depends on whether the PAN is a beacon-enabled network or non-beacon-enabled network. In a beacon-enabled PAN a superframe structure is used that supports both TDMA and slotted CSMA/CA channel access. The superframe is composed of active and inactive periods. The active period of each superframe is composed of a contention access period (CAP) and a contention free period (CFP). Slotted CSMA/CA is used in the CAP of the superframe. TDMA-based channel access is provided in the CFP, which is composed of one or more guaranteed time slots (GTSs). In non-beacon-enabled networks, unslotted CSMA/CA based channel access is employed.

In addition to the basic superframe, there are alternate superframe structures defined in IEEE Std 802.15.4-2020, which use the same concepts of active, inactive, CAP, and CFP. Some forms add additional periods for specific applications.

IEEE Std 802.15.4e [B26] is an amendment to the MAC protocol defined by IEEE Std 802.15.4-2011, which adds many optional features to the MAC. IEEE Std 802.15.4e [B26] is included in IEEE Std 802.15.4-2020. One set of features added is timeslotted channel hopping (TSCH), which is a time-synchronized channel access scheme intended to provide deterministic performance, support ultra-low power consumption, and provide improved reliability. TSCH provides channel hopping to reduce interference potential. In TSCH mode, the basic timing structure is referred to as a slotframe, which replaces the concept of the superframe. In TSCH, beacons are used for advertising and joining a PAN. Beacon transmission is not necessarily periodic in a TSCH PAN. TSCH depends on a globally shared notion of time, termed the absolute slot number (ASN). Information contained in the beacon (using the "Enhanced Beacon" format) allows for initial synchronization to the PAN and distribution of synchronization information throughout the PAN. Each device in a TSCH PAN may propagate PAN information by transmitting Enhanced Beacons. Following synchronization, all devices communicate by the TSCH schedule. Synchronization is maintained by including timing information in data and acknowledgement exchanges with time source neighbors.

The star topology and mesh topology are typical network architectures for IEEE Std 802.15.4g network organization.

[9] Wi-SUN is a registered trademark of Wi-SUN Alliance, Inc.

The maximum transmission power is region dependent, for example, 1000 mW in the United States, 25 mW in Europe, and 250 mW in Japan. The transmission range is typically around 1 km. Multihop topologies give the ability to extend network range beyond the range of the radio without increasing the interference exposure.

The frequency band allocation is region dependent. Examples of sub-1 GHz bands include the 902–928 MHz band in the United States, 169 MHz and 863–870 MHz bands in Europe and the 920–928 MHz band in Japan. The narrow channels allow use of many regional bands.

Depending on the PHY configuration, the typical bandwidth of channels ranges from 200 kHz to 1200 kHz, though channel plans provide channel spacing down to 12.5 kHz. IEEE Std 802.15.4g specifies the same data rate for uplink traffic and downlink traffic. The data rate ranges from 6.25 kb/s to 800 kb/s. The maximum data rate was subsequently increased to 2.4 Mb/s in amendment IEEE Std 802.15.4x.

A number of amendments to IEEE Std 802.15.4-2015, subsequently included in IEEE Std 802.15.4-2020, have added band plans for a large number of regional sub-1 GHz bands and data rate enhancement.

IEEE Std 802.15.4u [B27] defines a PHY layer enabling the use of the 865 MHz to 867 MHz band in India. The supported data rate should be at least 40 kb/s and the typical line-of-sight range should be of the order of 5 km using an omnidirectional antenna. Included are any channel access and/or timing changes in the medium access control necessary to support this PHY layer.

IEEE Std 802.15.4v [B28] is an amendment to enable/update the use of regional sub-1 GHz bands. The smart utility network (SUN) physical layers (PHYs) in IEEE Std 802.15.4-2015 are changed by this amendment to enable the use of the 870–876 MHz and 915–921 MHz bands in Europe, the 902–928 MHz band in Mexico, the 902–907.5 MHz and 915–928 MHz bands in Brazil, and the 915–928 MHz band in Australia and New Zealand. Additional Asian regional frequency bands are also specified in this amendment. Furthermore, the amendment changes the channel parameters listed for the SUN PHYs, the low-energy critical infrastructure monitoring (LECIM) PHY, and the television white space (TVWS) PHY for the 470–510 MHz band in China and the 863–870 MHz band in Europe and aligns these channel parameters with regional requirements. The amendment includes channel access and/or timing changes to the MAC necessary for conformance to regional requirements for these bands.

IEEE Std 802.15.4x defines enhancements to the smart utility network (SUN) physical layers (PHYs) supporting up to 2.4 Mb/s data rates. Enhancements to the IEEE Std 802.15.4-2015 smart utility network (SUN) orthogonal frequency division multiplexing (OFDM) physical layers (PHYs) are defined by this amendment to IEEE Std 802.15.4-2015. This amendment also defines additional channel plans, as needed, to support emerging applications.

4.4 IEEE Std 802.15.4w

A summary of IEEE Std 802.15.4w is presented in Robert's "802.15.4w Overview and Status" [B36]. IEEE Std 802.15.4w has defined an LPWAN extension to the IEEE Std 802.15.4 LECIM PHY layer. This extension is intended to cover network cell radii of typically 10 km to 15 km in rural areas and deep in-building penetration in urban areas. It uses the LECIM FSK PHY modulation schemes with extensions to lower bitrates, for example payload bitrate typically <30 kb/s. It extends the frequency bands to additional sub-1 GHz unlicensed and licensed frequency bands to cover the market demand. For improved robustness in channels with high levels of interference, it defines mechanisms for the fragmented transmission of forward error correction (FEC) code-words, as well as time and frequency patterns for the transmission of the fragments. Furthermore, it defines lower code rates for the FEC in addition to the K=7 R=1/2 convolutional code.

IEEE 802.15.4w signal bandwidth ranges from approximately 2.3 kHz to 19 kHz using Gaussian-filtered minimum shift keying (GMSK) modulation, while the instantaneous PHY data rate ranges between 600 b/s and 9 kb/s. Using coding and fragmentation, the effective data rate is only from 60 b/s to 900 b/s, which is required to achieve the required long-range transmission with transmit powers of a few milliwatts only. Furthermore, multiple devices can access identical frequency resources at the same time.

The frequency band allocation is region dependent and supports most license-exempt sub-1 GHz bands, for example, 902–928 MHz band in the United States, 169 MHz and 863–870 MHz bands in Europe, and 920–928 MHz band in Japan. The maximum transmit power is also region dependent (e.g., up to 500 mW in Europe). However, the typical transmission for LPWAN is 10 mW.

IEEE Std 802.15.4w can use either TDMA or ALOHA for the channel access. An IEEE 802.15.4w network can have star or mesh topology.

IEEE Std 802.15.4w specifies active and passive coexistence methods with other IEEE 802.15.4 systems and IEEE 802.11ah systems.

4.5 LoRa

Guo, et al. [B24] summarizes the LoRa (Long Range modulation technique), which is a proprietary physical layer technology for creating long range communication links. Details of the PHY are not disclosed. LoRa uses a modulation based on chirp spread spectrum (CSS). This modulation has the benefit that it solves the problem of oscillator frequency offsets in the case of very low data bit-rates. In the mainly addressed 900 MHz bands such frequency offsets—caused by imperfect oscillators in the transmitters and receivers—may easily reach values of 50 kHz, which can be much higher than the actual signal bandwidth. Using CSS highly simplifies the receiver design in such cases. The information is encoded in the start position of a linearly increasing frequency ramp: the chirp. The possible parameter configuration for the chirp bandwidth lies between 62.5 kHz and 500 kHz, which is therefore much higher than the expected frequency offset. Consequently, a frequency shift has only small impact on the decoder. However, a drawback of this modulation technique is the very low bandwidth efficiency and the very high spectral footprint compared to the actual payload bit-rate, which can be less than 10 kb/s.

LoRa is typically operated in the license exempt frequency bands around 900 MHz. The maximum transmit power is also region dependent and can reach up to 1000 mW in the United States and 500 mW in Europe. The typical transmit power is 25 mW. Furthermore, other restrictions may also apply, for example, a 0.1% or 1% maximum duty cycle for most bands in Europe and 10% maximum duty cycle in Japan. In the United States, the maximum data length and the useable transmission parameters are limited by the maximum channel occupancy of 0.4 seconds in a 20 second period.

The Long Range Network protocol (LoRaWAN® [10]) defines the communication MAC protocol and system architecture for the network on top of the LoRa PHY layer. In contrast to the PHY, LoRaWAN is maintained by the LoRa Alliance® [10] and the specification is the publicly available LoRaWAN specification.

It is designed to allow low power devices to communicate with Internet connected applications over long range wireless connections. LoRaWAN can be mapped to the second and third layer of the OSI model. It is implemented on top of the LoRa PHY for lower bit-rates and FSK for higher bit-rates.

LoRaWAN defines three devices classes: Class A, Class B, and Class C. All LoRaWAN devices have to implement Class A functions, whereas Class B and Class C are extensions to the specification of Class A.

Class A devices support bidirectional communication between a device and a gateway and allow download traffic right after an upload slot. Uplink transmission from the end device to the network server can be sent at any time (randomly), that is, ALOHA channel access. The end device then opens two receive windows at

[10] LoRaWAN and LoRa Alliance are registered trademarks of Semtech Corporation.

specified times after an uplink transmission. If the server does not respond in either of these receive windows, the next opportunity will be after the next uplink transmission from the device. The server can respond either in the first receive window or in the second receive window but should not use both windows.

Class B devices extend Class A by adding scheduled receive windows for downlink traffic from the server. Using time-synchronized beacons transmitted by the gateway, the devices periodically open receive windows. As a result, Class B schedules separate upload windows.

Class C devices extend Class A by keeping the receive windows open unless they are transmitting. This allows for low-latency communication but is many times more energy consuming than Class A devices, thereby trading in battery lifetime for lower downlink communication latency.

4.6 Sigfox

Guo, et al. [B24] overviews Sigfox, which is a proprietary LPWAN technology for long range IoT applications. It is based on a very low-rate binary phase-shift keying modulation (BPSK) for the uplink and Gaussian frequency shift keying (GFSK) for the downlink. The bandwidth of the uplink channel is region dependent, for example 600 Hz in the United States and 100 Hz in Europe. The downlink channel is 1.5 kHz. The very low signal bandwidth—accompanied by a very low payload bit-rate—enables long-range communication. The communication range is comparable to IEEE Std 802.15.4w and LoRa. The Sigfox network is typically in star topology. The payload per uplink transmission is fixed to 12 bytes.

The frequency band allocation for Sigfox is region dependent, for example, 915 MHz in the United States, 868 MHz in Europe, and 920 MHz in Japan. Similar to the other LPWAN systems, the maximum transmission power is also region dependent and follows the same restrictions. Europe also requires 1% uplink duty cycle and 10% downlink duty cycle. Consequently, Sigfox is mainly focused on the uplink traffic. A base station may cover thousands of transmitter nodes. However, it also has to follow the 10% duty cycle restriction in Europe. Hence, it can receive thousands of uplink messages per hour, but it can only transmit a few downlink messages. Generally, all base stations are controlled by Sigfox. Japan requires 10% duty cycle for active radio equipment in the 920 MHz band and this rule applies to Sigfox as well.

Sigfox uses a pure random-access scheme. The transmission is unsynchronized between the base station and the device. To guarantee a high reliability, the device emits a message on a random frequency and then sends two replicas on different frequencies and time, which is called “time and frequency diversity,” to ensure the message will be correctly received by at least one of the base stations in range.

4.7 ETSI TS 103 357

This subclause overviews sub-1 GHz frequency band technologies described in the ETSI Technical Specification TS 103 357 [B8], which defines the radio interface for three different Low Throughput Networks (LTN): clause 5 defines the “Lfour family,” clause 6 the “Telegram splitting ultra narrow band (TS-UNB) family,” and clause 7 the “Dynamic Downlink Ultra Narrow Band (DD-UNB) family.” These three radio interfaces are three different systems that address different LPWAN scenarios and are summarized in 4.7.1 to 4.7.3.

4.7.1 Lfour family

The Lfour family only offers uplink communication and no downlink is defined. The uplink uses chirp modulated BPSK or BPSK and the occupied bandwidth ranges between 50 kHz and 160 kHz. The maximum coupling loss (MCL), that is the maximum attenuation between transmitter and receiver, is between 150 dB and 155 dB. The reception network consists of base stations in a star or extended star topology. Lfour may use auxiliary time synchronization methods like the Global Positioning System (GPS) for reduced base station complexity.

The forward error correction employs a rate 1/4 low density parity check (LDPC) code, which is identical to the IEEE 802.15.4w LDPC code. Additionally, packets may be transmitted multiple times with the possibility to coherently add the multiple transmissions in the receiver.

4.7.2 Telegram splitting ultra narrow band (TS-UNB) family

The TS-UNB family offers bidirectional and unidirectional communication. The modulation uses minimum shift keying (MSK) with a symbol rate of 2.3 kS/s. For improved robustness, TS-UNB uses frequency hopping, resulting in a typical effective bandwidth of 100 kHz (standard mode) or 725 kHz (wide mode). The MCL is between 153 dB and 164 dB on the uplink and 161 dB on the downlink. TS-UNB supports a star or extended star network topology.

The forward error correction is similar to the encoding of IEEE Std 802.15.4w. It uses a rate 1/3 convolutional code and spreads the encoded data on several radio bursts, which are then transmitted on different frequencies. This offers the benefit that the data of multiple radio bursts may be lost without significantly degrading the decoding performance.

4.7.3 Dynamic Downlink Ultra Narrow Band (DD-UNB) family

The DD-UNB family only supports bidirectional communication, that is all endpoints have to support bidirectional communication. The modulation uses binary FSK with a symbol rate of 500 S/s with a Bose–Chaudhuri–Hocquenghem (BCH) forward error correction. Frequency hopping is used to improve the robustness. The specification does not define the MCL, but according to the data rate it will be in the order of 150 dB. The DD-UNB family supports a star or extended star topology. Furthermore, orphan endpoints can be connected using a relay link through another endpoint to improve coverage.

4.8 Summary

A summary of IEEE Std 802.11ah, IEEE Std 802.15.4g, IEEE Std 802.15.4w, LoRa, and Sigfox is presented in Table 2.

Table 2—Sub-1 GHz frequency band technology feature summary

Technology	PHY modulation	Channel width	PHY data rate	Typical TX range	Max TX power (ERP)	Channel access
IEEE Std 802.11ah	OFDM	1/2/4/8/16 MHz	150 kb/s–346 Mb/s	1 km	1000 mW	CSMA/TDMA
IEEE Std 802.15.4g	SUN-FSK/SUN-OFDM/SUN-O-QPSK	200/400/600/800/1200 kHz	6.25 kb/s–2.4 Mb/s	1 km	1000 mW	CSMA/TDMA/ALOHA
IEEE Std 802.15.4w	GMSK	2.3–19 kHz	600 b/s–9 kb/s	15 km	1000 mW	ALOHA/TDMA
LoRa	CSS/FSK	125/250/500 kHz	300 b/s–5.5 kb/s	15 km	1000 mW	ALOHA/TDMA
Sigfox	BPSK/QFSK	0.1/0.6/1.5 kHz	100 b/s–600 b/s	15 km	1000 mW	ALOHA

5. Use cases of the sub-1 GHz frequency band systems

5.1 Introduction

Sub-1 GHz frequency band technologies are commonly used for IoT applications such as smart utility, smart city, field monitoring, and building automation. However, based on characteristics of each technology, the expected use cases vary. As can be seen in the use cases described in the following subclauses, there is considerable overlap in use cases and thus likely need for these different systems to coexist.

For IEEE Std 802.15.4w, LoRa, and Sigfox systems, the main use cases are focused on monitoring applications. Hence, highly asymmetrical traffic can be expected with typical focus on the uplink.

5.2 IEEE Std 802.11ah use cases

IEEE 802.11ah devices are not yet widely deployed. However, the Wi-Fi Alliance® [11] has marketed this technology as Wi-Fi HaLow to promote its product development and application. As a result, Japan recently formed the 802.11ah Promotion Council (AHPC) to promote deployment of IEEE Std 802.11ah technology. AHPC proposed use case scenarios for IEEE Std 802.11ah are given in Inoue, et al. [B26] and use case scenarios proposed by the IEEE 802.11 Working Group are given in Halasz [B25] and Shetty and Karandikar [B41]. Identified use cases include the following:

- Smart home/building: home/building automation, smart appliance, home security network, content synchronization between home server and vehicles, health, wearable
- Smart power: smart grid, smart meter, smart lighting, power management for office
- Backhaul: bridging and mesh backhaul, wireless sensor network backbone in process automation, backup network for cellular drone, hot spot
- Monitoring: efficient field work and inspection at factory, remote monitoring of wildlife to prevent damage of agricultural crops, detecting deterioration of infrastructure by wireless vibration sensors
- Smart city: surveillance camera system using edge computing, advanced water pipe management, push notification customer support, advanced management in public transportation, intelligent transportation system (ITS)
- Industry: industrial process sensor, industrial automation

Some of the use cases are for outdoor, for example, smart grid, ITS, and agriculture. Some of the use cases are for indoor, for example, home/building automation.

Some of the use cases incur low network traffic, for example, smart meter and health care. Some of the use cases require high throughput to support video transmission, for example, agricultural monitoring and video surveillance.

Some of the use cases require thousands of devices, for example, smart meter. Some of the use cases require less devices, for example, home automation.

[11] WiFi Alliance is a registered trademark of Wi-Fi Alliance Corporation.

5.3 IEEE Std 802.15.4g use cases

IEEE Std 802.15.4g was originally designed for smart metering applications. The Wi-SUN Alliance™ [12] has developed specifications built on the standard. Millions of Wi-SUN and IEEE 802.15.4g devices have been deployed. In Japan, with more than 20 million smart meters already deployed by Tokyo Electric Power Company, more than 65 million smart meters are scheduled for deployment by 2023. Most utilities have chosen wireless mesh using IEEE 802.15.4 FSK at 920–928 MHz for advanced metering infrastructure (AMI) connection, and smart meter to home energy management system controller connection uses IEEE 802.15.4 FSK at 920–928 MHz. The following use case scenarios for IEEE Std 802.15.4g are provided in Beecher [B4]:

- Smart utility: AMI, peak load management, distribution automation, electric vehicle charging stations, gas and water metering, leak detection
- Smart city: street lighting, smart parking, traffic and transport systems, environmental sensing, infrastructure management
- Smart home: smart thermostats, air conditioning, heating, energy usage displays, health, well-being applications
- Machine to machine: agriculture, structural health monitoring (e.g., bridges and buildings), monitoring, asset management
- Industrial plant monitoring

5.4 LoRa use cases

Typical use cases for LoRa can be divided into the following two categories:

- Smart city: smart lighting, air quality and pollution monitoring, smart parking and vehicle management, facilities and infrastructure management, fire detection and management, and waste management
- Industrial: radiation and leak detection, smart sensor technology, item location and tracking, shipping and transportation

5.5 Sigfox use cases

Use scenarios for Sigfox include the following:

- Supply chain and logistics, retail
- Smart cities: smart lighting and public transportation, utilities and energy, smart buildings and security
- Monitoring: agriculture and environment, home and lifestyle, service and vehicle monitoring, road and structure sensors
- Industry: manufacturing

5.6 IEEE Std 802.15.4w use cases

IEEE Std 802.15.4w can be applied to all use cases for LoRa and Sigfox.

[12] Wi-SUN Alliance is a trademark of Wi-SUN Alliance, Inc.

6. Sub-1 GHz frequency band spectrum allocation

6.1 Introduction

The spectrum allocation is constrained, especially in the sub-1 GHz frequency band, where spectrum allocation varies from country to country. The constrained spectrum allocation in some regions indicates that coexistence mechanisms are needed. The following subclauses overview the spectrum allocation in the United States, Japan, and Europe.

6.2 United States

Sub-1 GHz frequency band spectrum allocation in the United States is specified by the Federal Communications Commission (FCC) [B9] and summarized in Rolfe [B40].

There are many frequency bands below 1 GHz in which radio frequency devices may operate as defined in the Code of Federal Regulations, Title 47, Part 15 [B9] though at extremely low power levels. General rules given in §15.209 prescribe very low power levels of 200 μV/m (equivalent to less than –49 dBm). Higher power levels are allowed for specific bands. For the purpose of these standards, the 902 MHz to 928 MHz band is the only band that will support both IEEE 802.11 and IEEE 802.15.4 operations. Operation of communication systems in the 902–928 MHz band is addressed in §15.247 and §15.249.

The band used by systems covered in this recommended practice is 902 MHz to 928 MHz, using the provisions of §15.247. Channel plans for this band are provided in both IEEE Std 802.11 and IEEE Std 802.15.4. Operation under this part requires either frequency hopping or a digital modulation.

Operation of IEEE Std 802.15.4 SUN FSK is considered as a frequency hopping system to comply with this part. The requirements include a minimum channel spacing of 25 kHz and maximum allowed 20 dB bandwidth of the hopping channel of 500 kHz. The SUN FSK PHY includes modes to meet these requirements with channel spacing of 200 kHz and 400 kHz defined for the band. Per channel duty cycle is limited: for 200 kHz channel spacing, the average time of occupancy on any frequency shall not be greater than 0.4 seconds within a 20 second period; for the 400 kHz channel spacing, the average time of occupancy on any frequency shall not be greater than 0.4 seconds within a 10 second period. Hopping systems have to use a pseudo-random sequence and the systems are designed so that all channels in a sequence are used equally on average over time. Not all available channels have to be included in a sequence, thus skipping over channels is allowed. The regulations prohibit coordination of transmitter sequences for the express purpose of avoiding simultaneous occupancy of a channel, that is, coordination to achieve maximum band occupancy by a single system is not allowed.

Maximum transmit power (peak conducted output power) is 1 W for systems employing at least 50 hopping channels. The channel plans for 200 kHz and 400 kHz channel spacing use 129 and 64 channels, respectively.

Systems using IEEE Std 802.11ah are considered as digital modulation systems under this regulation. To be classified as using digital modulation techniques, the minimum 6 dB bandwidth shall be at least 500 kHz. The OFDM signal used by IEEE Std 802.11ah is considered a digital modulation, and uses a minimum channel spacing of 1 MHz. Digital modulation systems are not required to employ frequency diversity, although use of hybrid systems that use both digital modulation and hopping are allowed.

For systems using digital modulation, the maximum peak conducted output power is 1 W. In addition, the power spectral density conducted from the intentional radiator to the antenna shall not be greater than 8 dBm in any 3 kHz band during any time interval of continuous transmission.

Operation under §15.249 allows any modulation technique but is limited to fixed, point-to-point operation. Field strength of the fundamental signal has to be no greater than 50 mV/m (measured at 3 meters). This is equivalent to a transmit power of +18.75 dBm. This does not fit the majority of use cases for either IEEE Std 802.11 or IEEE Std 802.15.4. For these reasons most of the applications expected to apply this standard will be operated under the provisions of §15.247.

6.3 Japan

Sub-1 GHz frequency band spectrum allocation in Japan is summarized in Nagai, et al. [B33]. There are currently three standards in the 920 MHz band for IoT devices based on radio type and transmission power: ARIB STD-T106 [B1], ARIB STD-T107 [B2], and ARIB STD-T108 [B3]. These standards regulate the spectrum for different use cases.

ARIB STD-T106 [B1] titled “920MHz-Band RFID Equipment for Premises Radio Station and Land Mobile Radio Station” specifies the regulation for radio frequency identification (RFID) equipment that uses the frequency range between 916.7 MHz and 920.9 MHz. The interrogators typically transmit powers of 1 W and more in order to supply the passive transponders using the radiated electromagnetic field.

ARIB STD-T107 [B2] titled “920MHz-Band RFID Equipment for Specified Low Power Radio Station” specifies the regulation for RFID equipment that uses the frequency range between 916.7 MHz and 923.5 MHz to identify passive transponders. However, in contrast to the previous standard, this standard only specifies medium to low output powers.

ARIB STD-T108 [B3] titled “920MHz-Band Telemeter, Telecontrol and Data Transmission Radio Equipment” specifies two systems; these are land mobile stations and specified low-power radio stations.

Land mobile stations use the frequency range between 920.5 MHz and 923.5 MHz, and a maximum transmit power of 250 mW. A radio channel shall consist of up to five consecutive unit radio channels. The channels are defined by their center frequencies located from 920.6 MHz to 923.4 MHz in steps of 200 kHz. It is prohibited to simultaneously use the radio channels with priority for passive RFID (located from 920.6 MHz to 922.2 MHz) and the radio channels whose center frequencies are located above 922.4 MHz.

Specified low-power radio stations use the frequency range between 915.9 MHz and 929.7 MHz with a maximum transmit power of 20 mW. Furthermore, the maximum transmit power is 1 mW for the channels with center frequencies from 916.0 MHz to 916.8 MHz and from 928.15 MHz to 929.65 MHz. A radio channel shall consist of up to five consecutive unit channels. The channels are defined by their center frequencies located from 916.0 MHz to 916.8 MHz and from 920.6 MHz to 928.0 MHz in steps of 200 kHz. The channels with the center frequencies from 928.15 MHz to 929.65 MHz are defined in steps of 100 kHz. It is prohibited to simultaneously use the radio channels with priority for passive RFID (located from 920.6 MHz to 922.2 MHz) and the radio channels whose center frequencies are located above 922.4 MHz.

In addition, ARIB STD-T108 [B3] also defines operational rules for the coexistence with other systems by two different types of carrier sense (CS) times: short CS stations using a carrier sense time of 128 μs and long CS stations using carrier sense times of at least 5 ms. Short CS stations are efficient, to have low power consumption with batteries, by means of short data communication with long duration. Total transmission time per arbitrary one hour per short CS station may be 720 seconds or less while the sum of transmission time per arbitrary one hour per radio channel shall be 360 seconds or less. IEEE Std 802.15.4g operates as a short CS station.

Figure 1 shows a summary of channel plans for 920 MHz band radio equipment according to ARIB STD-T106, ARIB STD-T107, and ARIB STD-T108.

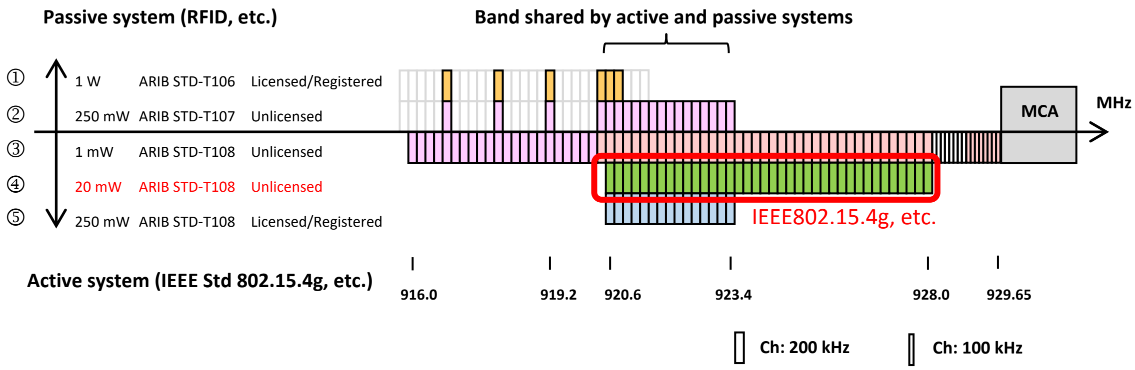

Figure 1—920 MHz band channel plan in Japan

6.4 Europe

Sub-1 GHz frequency band spectrum allocation in Europe is specified in Annex B and Annex C of ETSI EN 300 220-2 [B7] and is summarized in Robert [B37]. Table 3 lists the most relevant operational bands according to Annex B that are EU wide harmonized. Operational bands that are listed in Annex C are not EU wide harmonized and define additional frequencies between 870 MHz and 920 MHz. Additional spectrum allocations, for example for IEEE Std 802.11ah, are already defined in CEPT ERC Recommendation 70-03 [B5], and will be included in the upcoming version of ETSI EN 300 220-2 [B7]. Many EU states have already adopted the use of IEEE Std 802.11ah in the frequency range 863–868 MHz. The frequency regulation defines a bandwidth between 600 kHz and 1 MHz, a maximum transmit power of 25 mW, and a duty cycle of 2.8% for end devices and 10% for AP.

Table 3—EU wide harmonized sub-1 GHz spectrum allocation according to ETSI EN 300 220-2

Name: Frequency range	Max. TX power (ERP)	Max. bandwidth	Usage restriction
D: 169.4000 MHz to 169.4875 MHz	500 mW	50 kHz	≤1% duty cycle, ≤10% duty cycle for metering devices
H: 433.050 MHz to 434.790 MHz	10 mW	Whole band	≤10% duty cycle
J: 433.050 MHz to 434.790 MHz	10 mW	25 kHz	
K: 863 MHz to 865 MHz	25 mW	Whole band	<0.1% duty cycle or polite spectrum access
L: 865 MHz to 868 MHz	25 mW	Whole band	<1% duty cycle or polite spectrum access
M: 868.000 MHz to 868.600 MHz	25 mW	Whole band	<1% duty cycle or polite spectrum access
N: 868.700 MHz to 869.200 MHz	25 mW	Whole band	<0.1% duty cycle or polite spectrum access
O: 869.400 MHz to 869.650 MHz	500 mW	Whole band	<10% duty cycle or polite spectrum access
P: 869.700 MHz to 870.000 MHz	5 mW	Whole band	
Q: 869.700 MHz to 870.000 MHz	25 mW	Whole band	<1% duty cycle or polite spectrum access

The latest version of ETSI EN 300 220-2 allows the use of polite spectrum access instead of a classical duty cycle. The definition of polite spectrum access is given in the latest revision of ETSI EN 300 220-1 [B6]. It is a precise definition of clear channel assessment (CCA) and timing parameters, for example, a maximum transmit duration of 1 second for a single transmission. The maximum duty cycle is given by 2.7% per 200 kHz portion of spectrum usage. The duty cycle can be significantly increased if a narrow-band system uses frequency hopping. A system with a bandwidth of less than 200 kHz hopping in the 600 kHz wide band M could, therefore, reach a duty cycle of 8.1%. This means a significant extension compared to the classical 1% duty cycle.

Table 4—Applicability of different systems on EU wide operational bands

Operational band[13]	IEEE Std 802.11ah	IEEE Std 802.15.4g	IEEE Std 802.15.4w	LoRa	Sigfox
D					
H					
J					
K					
L					
M					
N					
O				Preferred Downlink	Preferred Downlink
P					
Q					

Table 4 shows the theoretical applicability of the different EU wide harmonized bands for the different systems, where the color green indicates that the band can be used, the color yellow indicates that the band can be used but with potential issues, and the color red means that the band cannot be used.

Caused by its high bandwidth IEEE Std 802.11ah is restricted to the frequencies currently assigned to operational bands K and L only. Furthermore, the high bandwidth of LoRa signals does not allow its use on bands D and J.

Potential issues with operational bands K and L: The frequencies assigned to operational bands K and L are also used by UHF RFID systems. UHF RFID readers transmit almost continuous narrow-band signals with transmit powers of more than 1 W ERP. In areas with many UHF RFID readers (e.g., airports, industrial plants) this may result in significant levels of narrow-band interference.

Potential issues with operational band O: The so-called high power band O allows a transmit power of up to 500 mW ERP in the 868 MHz band with a duty cycle of up to 10%. Consequently, the band is used as the downlink frequency for typical LoRa or Sigfox networks. This band is utilized also by other long-range system. Consequently, it is highly crowded and significant levels of interference can be expected.

7. Coexistence mechanisms and issues of the sub-1 GHz frequency band systems

7.1 Introduction

Coexistence between different transmitters and systems can be addressed by various means. Generally, coexistence can be divided into active and passive coexistence mechanisms. Using an active coexistence mechanism, a transmitter tries to reduce its impact on others. A typical example is the use of carrier sense

[13] For IEEE Std 802.11ah, suitable spectrum is not yet allocated in the current version of ETSI EN 300 220-2, but the bands K and L are the frequencies assigned in the CEPT document. The corresponding frequency bands are already assigned in many EU countries (e.g., Germany).

multiple access with collision avoidance (CSMA/CA). In contrast, a passive coexistence mechanism tries to reduce the impact of other systems on the desired signal. A typical example here is the use of FEC in addition to frequency hopping.

IEEE Std 802.11ah, IEEE Std 802.15.4g, and IEEE Std 802.15.4w provide active coexistence mechanisms, as they all offer CSMA/CA in combination with other sophisticated schemes. The details will be explained in the following subclauses. In contrast, systems like LoRa and Sigfox do not address active coexistence. Furthermore, practically all systems provide passive coexistence mechanisms.

Coexistence mechanisms, noise and interference measurement, coexistence performance, and coexistence issues are described in this clause.

7.2 IEEE Std 802.11ah coexistence mechanisms

Guo, et al. [B23] and Guo, et al. [B24] summarize the coexistence mechanisms of IEEE Std 802.11ah. From the coexistence perspective, IEEE Std 802.11ah specifically addresses the coexistence with other non-IEEE 802.11 systems, including IEEE 802.15.4 systems.

A S1G station (STA) uses energy detection (ED) based CCA with a threshold of –75 dBm per MHz to improve coexistence with other S1G systems. If a S1G STA detects energy above that threshold on its channel, then the following mechanisms might be used to mitigate interference:

- Change of operating channel
- Sectorized beamforming
- Change the schedule of RAW(s), TWT SP(s), or SST operating channels
- Defer transmission for a particular interval

However, the features such as sectorization, beamforming, RAW, TWT, and SST are optional in IEEE Std 802.11ah. For better coexistence, it is recommended that these features should be implemented.

7.3 IEEE Std 802.15.4g coexistence mechanisms

Guo, et al. [B23] summarizes the coexistence mechanisms of IEEE Std 802.15.4g, which provides a method to facilitate inter-PHY coexistence, that is among devices that use different IEEE Std 802.15.4g PHYs.

In order to mitigate interference among devices that use different IEEE Std 802.15.4g PHYs, a multi-PHY management (MPM) scheme is specified. For this purpose, the MPM scheme facilitates interoperability and negotiation among potential coordinators with different PHYs by permitting a potential coordinator to detect an operating network during its discovery phase using the common signaling mode (CSM) appropriate to the band being used. The CSM mechanism can be used in conjunction with the CCA mechanism to provide coexistence control. The CSM is a common PHY mode that uses the filtered 2FSK modulation with the 200 kHz channel and the 50 kb/s data rate. An IEEE 802.15.4g device acting as a coordinator and with a duty cycle greater than 1% should support CSM.

In a beacon-enabled network, an existing coordinator transmits an enhanced beacon (EB) at a fixed interval by using CSM. Any intending coordinator first scans for an EB until the expiration of the enhanced beacon interval or until an EB is detected, whichever occurs first. If an intending coordinator detects an EB, it shall either occupy another channel, achieve synchronization with the existing network, or stop communication.

In a non-beacon-enabled network, an existing coordinator should transmit an EB periodically using the CSM. Any intending coordinator first scans for an EB until the expiration of the enhanced beacon interval for a non-beacon-enabled network or until an EB is detected, whichever occurs first.

IEEE Std 802.15.4g does not specifically address the coexistence with non-IEEE 802.15.4g systems. However, based on CCA mode, the IEEE Std 802.15.4g coexistence approach can be different.

For CSMA/CA channel access, IEEE Std 802.15.4g allows the following CCA modes:

— ED
— CS and ED
— CS
— ALOHA

ALOHA mode would typically be used in low duty cycle applications.

If the ED mechanism is used in CSMA/CA channel access, the ED based coexistence is implicitly performed. In this case, CCA returns busy channel status if the detected energy is above the specified ED threshold. However, if the ED mechanism is not used, the passive coexistence mechanisms should be specified, for example channel switching and backoff parameter configuration.

7.4 IEEE Std 802.15.4w coexistence mechanisms

Robert [B37] presents the active and passive coexistence methods of IEEE Std 802.15.4w. The following text gives a brief summary of this document.

IEEE Std 802.15.4w has been designed for long-range applications in license-exempt frequency bands with low transmit powers of, for example, 10 mW. Accordingly, IEEE Std 802.15.4w has to offer modes with reception levels of –140 dBm and less to achieve this long-range communication. Dissimilar systems are hence not able to reliably detect an ongoing IEEE 802.15.4w transmission if it is received at such low levels. Consequently, effective passive coexistence mechanisms are necessary for reliable communications operating at these reception levels. For this purpose, IEEE Std 802.15.4w introduces the so-called split mode. The data of one frame is jointly FEC encoded and then split into at least 12 radio bursts. These bursts are then transmitted on different channels at different times. Some of the radio bursts may be lost due to collisions with other signals. However, the FEC is designed to recover the lost frames. In case of the 1/3 convolutional code one frame is split into 18 radio bursts, where only six error-free bursts are required at the receiver to restore the complete frame. Hence, reliable long-range communication can be achieved even in highly occupied license-exempt frequency bands. An additional aspect is the very low bit-rate, resulting in a very low signal bandwidth. Consequently, only very small fractions of the energy of an interferer are able to pass the filters in the IEEE 802.15.4w receiver, resulting in an overall low resulting interference level. This is comparable to the impact of ultra-wide band communication on classical communication systems.

Finally, IEEE Std 802.15.4w also supports active coexistence. It can use CCA mechanisms for coexistence, which means it does not transmit radio-bursts on occupied channels.

7.5 LoRa coexistence mechanisms

Guo, et al. [B24] summarizes the coexistence mechanisms of LoRa. LoRa and LoRaWAN typically do not assume any active coexistence mechanisms. They simply transmit without prior CCA mechanisms. This is especially critical as LoRa uses high bandwidth frequency chirps as Figure 2 illustrates. The high bandwidth chirps (e.g., 500 kHz) of LoRa signals can impair a few bits at regular intervals in the victim receiver. If the FEC in the victim receiver is not prepared for this type of interference, the performance can be highly affected.

Technically, the chirp modulation of LoRa is comparable to a spreading modulation. Consequently, LoRa offers passive coexistence according to the employed spreading factor. However, the overall capacity of a LoRa network cell is highly limited: only one transmitter can transmit on a channel with a given spreading factor at one point of time. Network cell radii of 10 km or more with packet transmission lasting seconds (e.g., for spreading factor SF = 12) highly limit the overall network capacity.

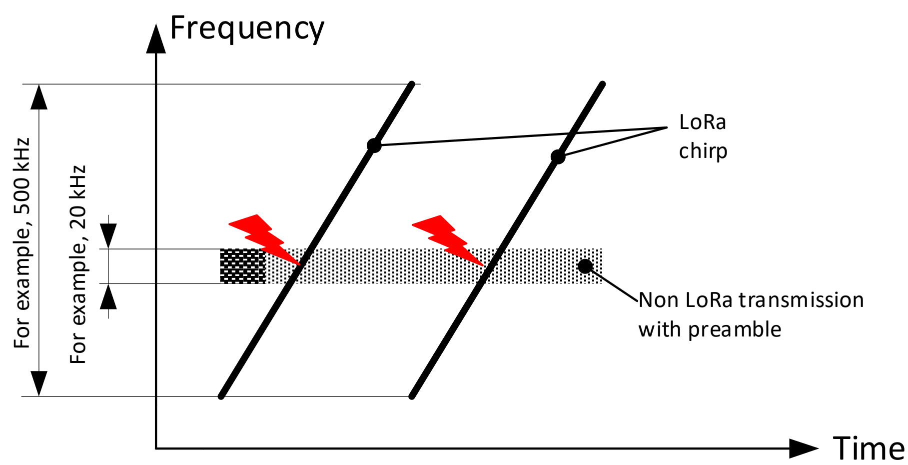

Figure 2—LoRa interference on other systems

7.6 Sigfox coexistence mechanisms

Guo, et al. [B24] summarizes the coexistence mechanisms of Sigfox, which does not use any active coexistence mechanisms. It simply follows the classical ALOHA channel access and does not use any CCA mechanisms. Therefore, it can easily interfere with other sub-1 GHz frequency systems. However, at least in the case of OFDM (e.g., IEEE Std 802.11ah, IEEE Std 802.15.4g) and frequency hopping systems (e.g., IEEE Std 802.15.4g, IEEE Std 802.15.4w) the narrow bandwidth of the signal will limit the impact of the Sigfox signal.

As the typical uplink transmission lasts for 2 seconds (Europe), the probability of collisions with other systems is very high. Consequently, the message is transmitted three times on different channels with slightly different encoding to improve the passive coexistence.

7.7 Noise and interference measurement in sub-1 GHz bands

7.7.1 Introduction

In the sub-1 GHz frequency bands, besides the IEEE 802.11 system and IEEE 802.15.4 system, there are also other radio systems such as RFID transmitting radio signals that can interfere with IEEE 802.11 systems and IEEE 802.15.4 systems. Significant levels of interference from mobile network stations have been observed. Large amounts of LoRa signals are present, especially in residential areas. Sigfox signals are not often present, but they last for seconds. In addition, some machinery can also emit powerful radio noise, which can also have severe impact on IEEE 802.11 systems and IEEE 802.15.4 systems.

To demonstrate radio noise and interfering signals to IEEE Std 802.11ah and IEEE Std 802.15.4g in the sub-1 GHz bands in a real environment, extensive measurements have been conducted at different places in Japan and Europe.

While other regions and environments will, of course, present different specific noise and interference specifics, the results of these specific studies illustrate the wide variety of systems using the sub-1 GHz unlicensed bands. Other regions are expected to experience similar diversity of uses. Many of the interference sources noted in the observations will likely be present in many other regions.

7.7.2 920 MHz band measurements in Japan

To investigate sub-1 GHz band radio noise and interfering signals in Japan, extensive measurements over the 920 MHz band have been conducted by Advanced Telecommunications Research Institute International using a real-time spectrum analyzer. The spectrum utilization was measured at several places including railway stations, university campuses, a large exhibition center, a football stadium and building. Yano, et al. [B43] presents measurement results of radio noise and interference. These measurement results raise the following concerns:

— Several types of machinery emit radio noise that may radiate sufficient energy to impact wireless communication systems:
  1) Figure 3 shows the measured noise at a railway station. Some trains continuously emit radio noise at multiple frequencies over the 920 MHz band. The level of the radio noise is stronger when the doors of the train are opened than when the doors are closed. At several open spaces, multiple unknown signals are measured over the 916 MHz to 920 MHz band. Some signals have a bandwidth of 1 MHz and non-negligible signal power.
  2) The measurement in a football stadium with a game playing shows that loudspeakers and wireless power transfer systems can be sources of high-level radio noise.
— Signals from RFID systems are found at multiple frequencies over the 920 MHz band.
— If there are many cellular users at a place, cellular signals can cause non-negligible interference due to their out-band emission.
— Several wireless communication systems including IEEE Std 802.11ah, the IEEE Std 802.15.4 family, and some original communication systems will share the 920 MHz band. They have different transmission patterns such as spectrum shape and duty cycle as shown in Figure 4, which was measured at a large exhibition center during the R&D exhibition of wireless communication technologies.

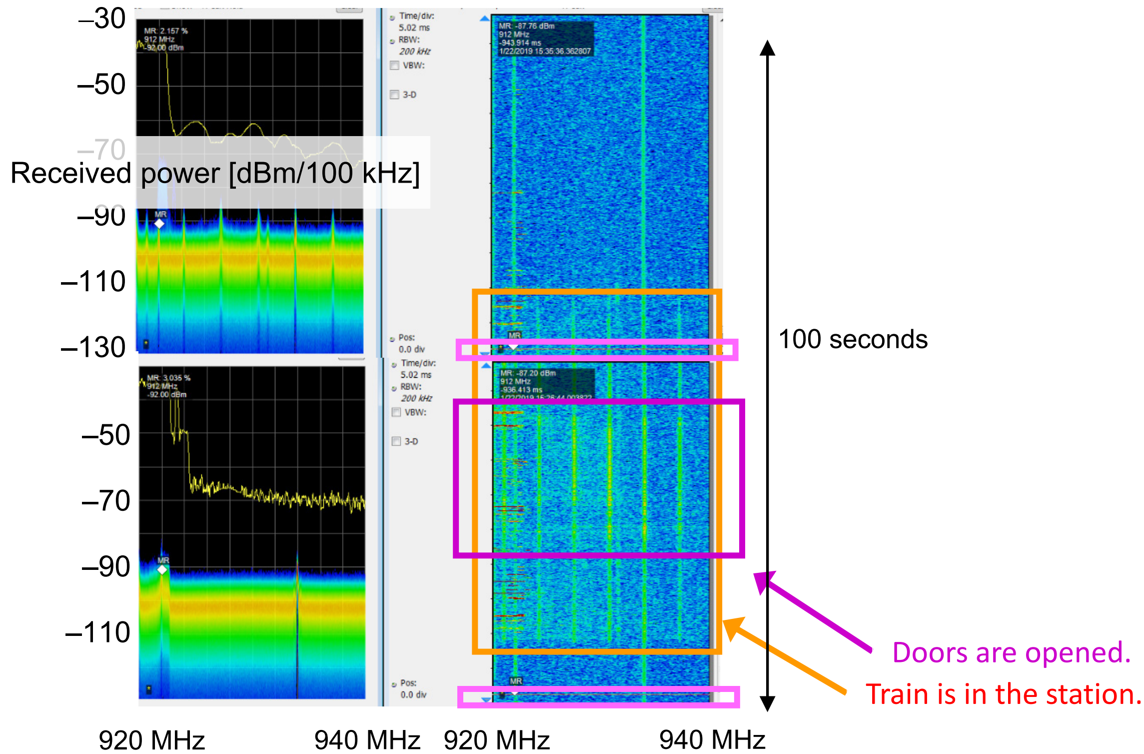

Figure 3—Spectrum utilization over 920 MHz band measured at a railway station

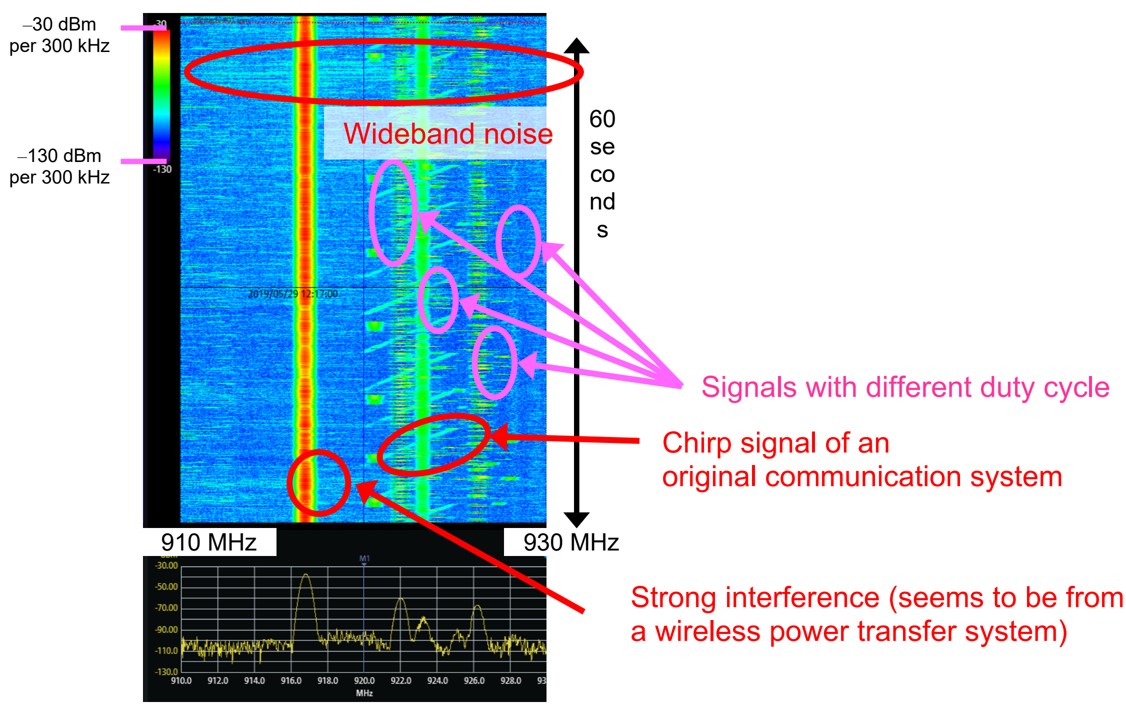

Figure 4—Spectrum utilization over 920 MHz band measured at exhibition center

These types of noise and interference can have severe impact on the performance of IEEE Std 802.11ah and IEEE Std 802.15.4g.

7.7.3 868 MHz band measurement in Europe

Robert [B36] and Guo, et al. [B24] present 868 MHz band measurement results in Europe. The University Erlangen-Nuremberg operates several LPWAN base-stations in Bavaria. These base-stations use a front-end that enables the reception of the complete short range devices (SRD) band ranging from 863 MHz to 870 MHz. Figure 5 shows the setup of the receive chain.

The stations use omni-directional antennas that are mounted on the rooftop of tall buildings. For improved robustness against signals from mobile networks, the base stations are equipped with cavity filters that suppress the frequency bands used by mobile networks to avoid non-linear effects in the following amplifier. This amplifier is used to reduce the noise figure of the following software defined radio (SDR) receiver that digitizes the complete 7 MHz wide frequency range from 863 MHz to 870 MHz using a sampling rate of 10 MHz.

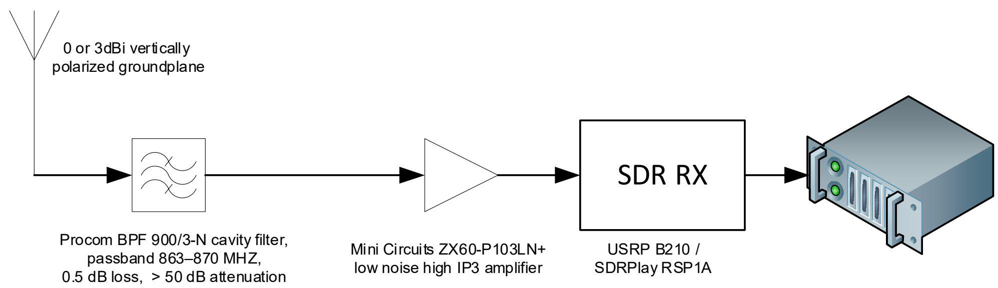

Figure 5—General Setup of Receive Part of LPWAN Base Station

Figure 6 shows the measured frequency spectrum using the base station at the Nuremberg trade-fair center. The omni-directional antenna is located on top of the tallest building (coordinates 49.416637N, 11.112435E) at a height of approximately 30 m above ground. The spectrum plot has a resolution bandwidth of approximate 8 kHz in addition to a Blackman window. The different operational bands ranging from K to P/Q are indicated. The narrow band between N and O is not assigned to SRD applications. The surrounding area consists of residential as well as industrial areas. The measurements are just examples, but they show the typical use of the SRD frequency bands. The length is limited to 300 ms due to the high sampling rate that cannot be streamed via the open Internet.

The frequency bands K and L are the frequency bands assigned to IEEE Std 802.11ah in Europe. Figure 6 shows many almost constant carriers over the complete measurement time. These carriers originate from UHF RFID. The maximum transmit power for RFID is 2 W (ERP). In contrast, the maximum transmit power of IEEE Std 802.11ah is limited to 25 mW (ERP). Hence, even distant RFID readers can lead to significant interference levels in bands K and L, if outdoor antennas are used.

The frequency band O is the frequency band typically used for downlink signals in LPWAN. It allows a maximum transmit power of 500 mW (ERP) and a duty cycle of 10%. Hence, Sigfox and many LoRa networks use this frequency band. However, as is clearly visible in Figure 6, the band is very narrow and shows a high channel load. As systems like LoRa and Sigfox will typically not use CCA, a high collision probability can be expected.

The typical frequency bands for most SRD applications based on IEEE Std 802.15.4 are the bands M and N. These frequency bands seem almost unused in Figure 6.

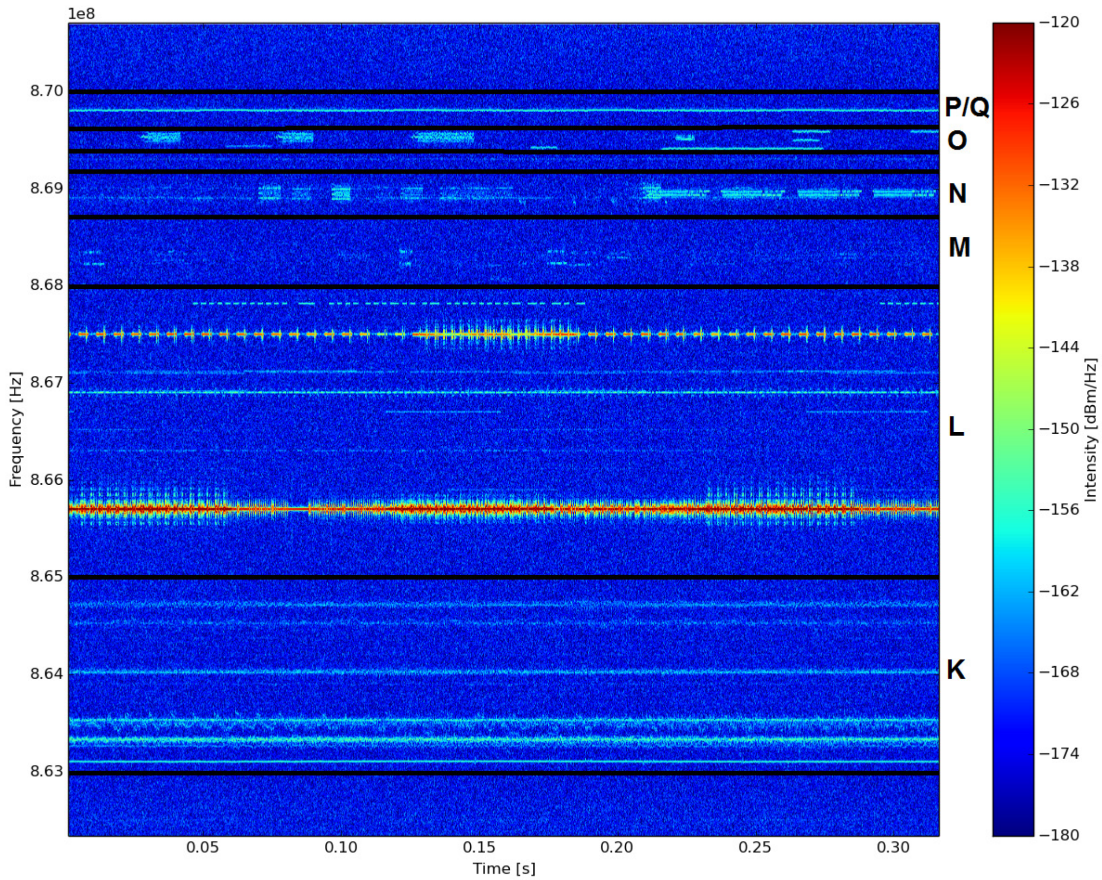

Figure 6—Measured SRD band from 863–870 MHz

Figure 7 shows a detailed view of the lower half of band M (868–868.25 MHz), again measured at the Nuremberg trade-fair center, but a few minutes after the measurements shown in Figure 6. Due to the lower sampling rate, the system was able to capture a continuous stream, from which a 10 second measurement duration is shown. Band M is typically used as the uplink for LPWAN systems, as it offers a duty cycle of 1% if CSMA/CA based on listen before talk is not used (e.g., LoRa, Sigfox).

Figure 7 shows that the band is used by a variety of systems, most of them with very short transmit times of a few milliseconds and a bandwidth of up to 100 kHz, mainly located in the upper part. Furthermore, LPWAN systems are also present. The arrows mark a single Sigfox packet, which consists of three narrow-band transmissions, each lasting 2 seconds. In addition, multiple LoRa packets are present, some of them marked by arrows. Most likely the LoRa packets use the spreading factor SF = 7, leading to relatively short transmit bursts.

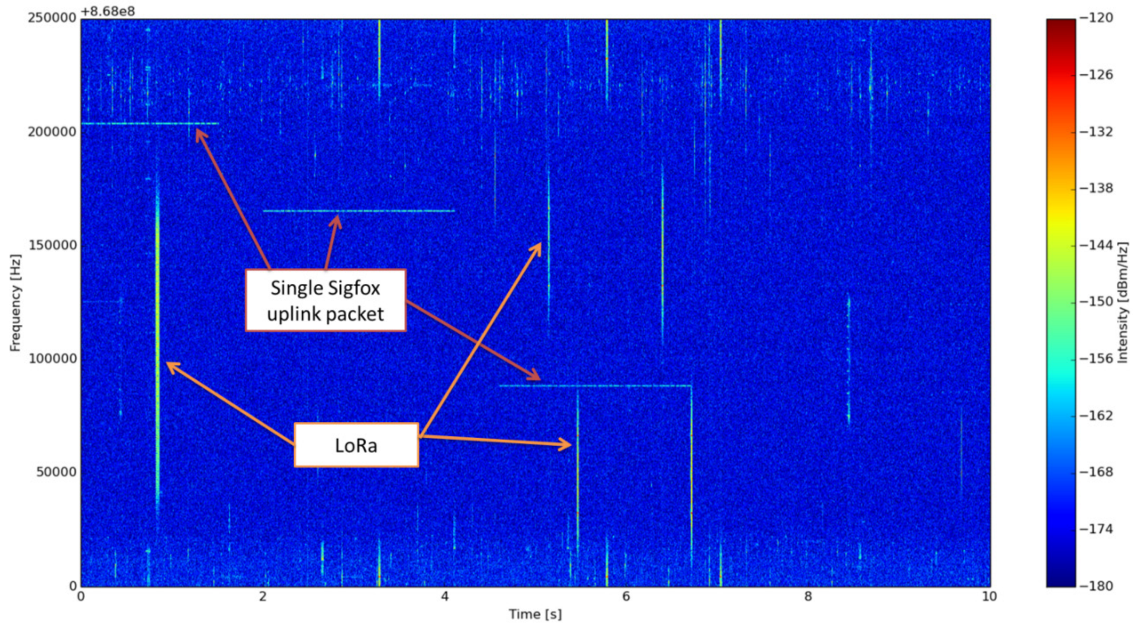

Figure 7—Measurement of band from 868–868.25 MHz at Nuremberg trade-fair center

Figure 8 shows the same frequency band measured in the Nuremberg city center (coordinates 49.452814N, 11.094451E). The omni-directional antenna was located on top of the highest building of the Nuremberg University of Applied Sciences. The distance to the station at the trade-fair center is approximately 5 km. The spectrum is also used by LoRa uplink signals. Furthermore, Figure 8 also shows a high number of short channel accesses, which are caused by the European LPWAN standard according to ETSI TS 103 357 TS-UNB. Generally, the traffic on this band is expected to grow significantly, as many new LPWAN are currently installed.

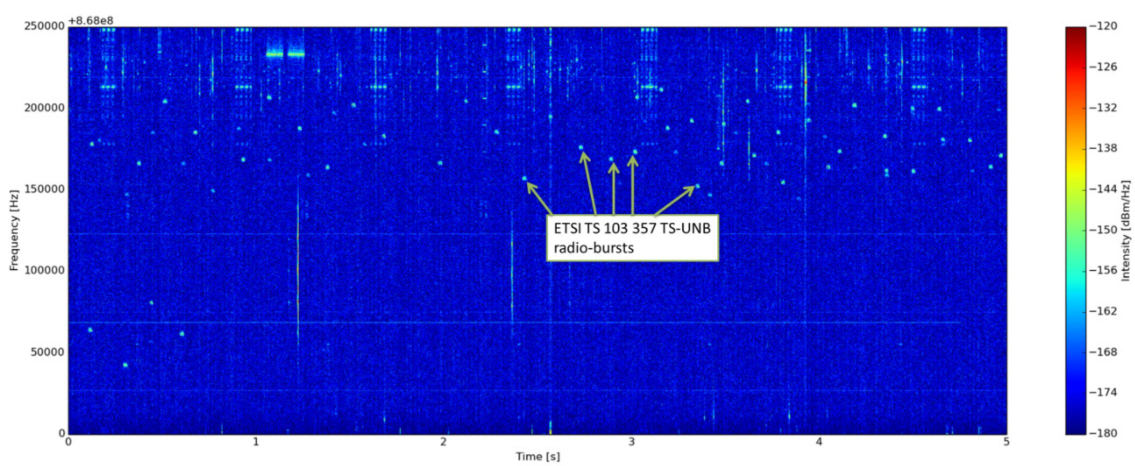

Figure 8—Measurement of band from 868–868.25 MHz at Nuremberg city center

In summary, all frequency bands are highly used. Especially IEEE Std 802.11ah will have to coexist with RFID strong narrow-band RFID signals. The high-power band O is highly occupied by the downlink of different LPWAN systems. Finally, the frequency bands M and N are also highly occupied by systems with typical short transmit bursts and LPWAN systems.

7.8 Coexistence performance of IEEE Std 802.11ah and IEEE Std 802.15.4g

Extensive simulations on IEEE Std 802.11ah and IEEE Std 802.15.4g coexistence have been conducted. The coexistence performance results have been presented in Guo, et al. [B11], Guo, et al. [B18], Guo, et al. [B19], Guo, et al. [B19], Guo, et al. [B11], Guo, et al. [B12], and Nagai, et al. [B34]. The simulation parameters are set based on [B32]. The PHY data rate for IEEE Std 802.11ah is 300 kb/s and the PHY data rate for IEEE Std 802.15.4g is 100 kb/s. In the simulation the network traffic scenarios, where further coexistence enhancement is needed, are simulated. For the networks with 50 nodes and 100 nodes, two offered network load scenarios are simulated, these are 20 kb/s and 40 kb/s. The offered network load is uniformly distributed among network nodes. For an IEEE 802.11ah node, the duty cycle is 0.13% and 0.26%. For an IEEE 802.15.4g node, the duty cycle is 0.4% and 0.8%. These duty cycles are lower than the constraint specified by any regulation. Using these scenarios, interesting findings have been discovered.

7.8.1 Data packet delivery rate

Guo, et al. [B11] presents data packet delivery rate of an IEEE 802.11ah network and an IEEE 802.15.4g network for a set of simulations, in which data packet delivery rate is measured as the ratio of the number of packets successfully delivered to the total number of packets transmitted. In the simulations, the network size for both the IEEE 802.11ah network and the IEEE 802.15.4g network is either 50 nodes or 100 nodes and the offered network load for the IEEE 802.11ah network and the IEEE 802.15.4g network is 20 kb/s or 40 kb/s.

Data packet delivery rate results reveal the following observations:

a) For all scenarios, the IEEE 802.11ah network delivers near 100% of the data packets, which indicates that network traffic and network size have less impact on IEEE 802.11ah packet delivery rate.

b) IEEE 802.11ah network traffic has impact on IEEE 802.15.4g packet delivery rate. IEEE 802.15.4g network packet delivery rate decreases as IEEE 802.11ah network traffic increases.

c) IEEE 802.15.4g network traffic has more effect on its data packet delivery rate. IEEE 802.15.4g network packet delivery rate decreases significantly as its network traffic doubles.

d) The network size has little effect on IEEE 802.15.4g network packet delivery rate.

7.8.2 Data packet latency

Guo, et al. [B11] also presents the corresponding data packet latency of an IEEE 802.11ah network and an IEEE 802.15.4g network, in which data packet latency is measured as the time difference from the time a packet transmission process starts to the time the packet receipt is successfully confirmed. In other words, the data packet latency is given by: Backoff time + Data TX time + ACK waiting time + ACK RX time.

Data packet latency results reveal the following observations:

a) For all scenarios, the IEEE 802.15.4g network achieves similar packet latency, which indicates that the IEEE 802.15.4g data packet is either delivered with the bounded delay or dropped and therefore, network traffic and network size have little impact on IEEE 802.15.4g packet latency.

b) IEEE 802.11ah network traffic has impact on its packet latency. IEEE 802.11ah data packet latency increases as its network traffic increases.

c) IEEE 802.15.4g network traffic has more impact on IEEE 802.11ah data packet latency. Doubling the IEEE 802.15.4g network traffic has a greater impact on IEEE 802.11ah packet latency than doubling the IEEE 802.11ah network traffic.

d) Network size has a major influence on IEEE 802.11ah packet latency. IEEE 802.11ah packet latency increases significantly as the number of nodes doubles, which indicates that an IEEE 802.11ah packet can be infinitely delayed.

7.8.3 IEEE Std 802.11ah and IEEE Std 802.15.4g coexistence issues to be addressed

The observations in 7.8.1 and 7.8.2 show that an IEEE 802.11ah network and an IEEE 802.15.4g network interfere with each other. Based on these findings, the coexistence technologies for IEEE Std 802.11ah and IEEE Std 802.15.4g need to:

a) Maintain IEEE 802.15.4g data packet delivery rate

b) Bound IEEE 802.11ah data packet latency

7.9 Coexistence performance of IEEE Std 802.11ah and IEEE Std 802.15.4w

IEEE Std 802.15.4w is designed for long range (~15 km) transmission with very low transmission power by using very low payload bitrate (~1 kb/s), which results in a high probability of collision with interferers. In addition, the focus of IEEE Std 802.15.4w is almost completely on uplink traffic.

Due to its very low reception levels (e.g., –140 dBm), other systems such as IEEE Std 802.11ah (–75 dBm ED threshold) may not be able to detect the IEEE 802.15.4w transmission. Listen before talk (CSMA) will not work well due to a hidden node problem.

Results of coexistence simulations of IEEE Std 802.15.4w and IEEE Std 802.11ah are provided in Robert [B36], in which all 20 simulations assume a distance of 10 m between the signal transmitter and the victim receiver. The distance between the victim receiver and the interfering transmitter varies. The results shown are the worst-case results without CCA or any interference cancellation techniques. Even coexistence simulations show no significant interference between IEEE Std 802.11ah and IEEE Std 802.15.4w, the interference occurs when the interfering transmitter is close to the victim receiver. For example, for an IEEE 802.11ah victim with MCS3 code, the frame error ratio (FER) is close to 100% when an IEEE 802.15.4w interfering transmitter is within 5 m of the victim IEEE 802.11ah receiver. Also, for an IEEE 802.15.4w victim with 19 kS/s symbol rate, the FER is close to 100% when an IEEE 802.11ah interfering transmitter is within 1 m of the victim IEEE 802.15.4w receiver. Furthermore, the simulation was performed with three nodes only, that is, one signal transmitter, one victim receiver, and one interferer. As the number of nodes increases, IEEE Std 802.15.4w expects to suffer strong interference from other systems including IEEE 802.11ah systems due to their system design.

7.10 Cause of coexistence issue between IEEE Std 802.11ah and IEEE Std 802.15.4g

Factors that can impact the coexistence performance of IEEE Std 802.11ah and IEEE Std 802.15.4g are summarized in Guo, et al. [B11]. The functional differences between IEEE Std 802.11ah and IEEE Std 802.15.4g result in the coexistence behavior of IEEE 802.11ah networks and IEEE 802.15.4g networks. The following are key CSMA/CA factors:

a) ED threshold

IEEE Std 802.11ah defines the following ED thresholds: –75 dBm for primary 1 MHz channel; –72 dBm for primary 2 MHz channel and secondary 2 MHz channel; –69 dBm for secondary 4 MHz channel; and –66 dBm for secondary 8 MHz channel.

The IEEE 802.15.4g ED threshold depends on the PHY. The ED threshold range is as follows: [–100 dBm, –78 dBm] for the OFDM PHY; [–100 dBm, –80 dBm] for the O-QPSK PHY; [–100 dBm, –78 dBm] for the FSK PHY with FEC; and [–94 dBm, –72 dBm] for the FSK PHY without FEC.

It can be seen that the IEEE 802.15.4g ED threshold is lower than the IEEE 802.11ah ED threshold.

b) CSMA/CA

IEEE 802.11ah CSMA/CA and IEEE 802.15.4g CSMA/CA are much different.

1) IEEE 802.11ah CSMA/CA allows immediate channel access. IEEE 802.15.4g CSMA/CA, however, requires backoff no matter how long channel has been idle.
2) IEEE 802.11ah backoff parameters are much smaller than IEEE 802.15.4g backoff parameters, which results in IEEE 802.11ah backoff being much faster than IEEE 802.15.4g backoff.
3) IEEE 802.11ah backoff has to perform CCA in each backoff time slot. However, IEEE 802.15.4g backoff performs CCA after the backoff procedure completes.
4) IEEE Std 802.11ah requires backoff suspension, that is, the IEEE 802.11ah device has to suspend the backoff procedure if the channel is detected to be busy and can decrease the backoff counter only if the channel is idle. On the other hand, IEEE Std 802.15.4g has no backoff suspension.

c) Channel width

IEEE 802.11ah channel width is in the unit of MHz, that is, 1 MHz/2 MHz/4 MHz/ 8 MHz/16 MHz. However, IEEE 802.15.4g channel width is in the unit of kHz, that is, 200 kHz/400 kHz/600 kHz/800 kHz/1200 kHz.

d) Data rate

IEEE Std 802.11ah defines PHY data rate from 150 kb/s to 78 Mb/s for one spatial stream and 346 Mb/s for four spatial streams. On the other hand, original IEEE Std 802.15.4g specifies PHY data rate from 6.25 kb/s to 800 kb/s. IEEE Std 802.15.4x, an amendment to IEEE Std 802.15.4g, extends the PHY data rate to 2.4 Mb/s.

e) IEEE 802.11ah BDT

Use of the bidirectional TXOP (BDT) allows IEEE 802.11ah devices to exchange a sequence of uplink and downlink PPDUs separated by SIFS. This operation combines both uplink and downlink channel access into a continuous frame exchange sequence between a pair of IEEE 802.11ah devices. One stated objective of this operation is to minimize the number of contention-based channel accesses.

In summary, the following factors are in favor of IEEE Std 802.11ah:

— Higher ED threshold allows IEEE Std 802.11ah more transmission opportunity and causes more collisions to IEEE 802.15.4g packets. More specifically, readable IEEE 802.15.4g packets with receiving energy level in the range [IEEE 802.15.4g receiver sensitivity, IEEE 802.11ah ED threshold] are ignored by the IEEE 802.11ah ED based CCA mechanism, which may result in collision with IEEE 802.15.4g packets.
— Immediate channel access allows IEEE Std 802.11ah more transmission opportunity.
— Smaller backoff parameters allow IEEE Std 802.11ah more transmission opportunity and causes more interference to the IEEE 802.15.4g transmission process.

— The wider IEEE 802.11ah channels indicates that an IEEE 802.11ah network can simultaneously interfere with multiple IEEE 802.15.4g networks.

— Higher PHY data rate enables IEEE Std 802.11ah higher throughput, that is it delivers more data.

— Bidirectional TXOP provides IEEE Std 802.11ah with more transmission opportunity.

The following factors are not in favor of IEEE Std 802.11ah:

— IEEE 802.11ah backoff has to perform CCA in each backoff time slot. The backoff procedure can proceed only if the channel is detected to be idle. On the other hand, the IEEE 802.15.4g backoff procedure is not interrupted.

— IEEE 802.11ah backoff suspension can cause a long backoff time, which increases the transmission opportunity for IEEE Std 802.15.4g. An IEEE 802.11ah packet can be infinitely delayed and non-suspension IEEE 802.15.4g backoff allows bounded delay for IEEE 802.15.4g packets, which can allow IEEE 802.15.4g devices to increase the channel access opportunity. When IEEE 802.11ah devices are on backoff suspension, IEEE 802.15.4g devices may get the chance to transmit early.

— The lower PHY data rate of IEEE Std 802.15.4g indicates that an IEEE 802.15.4g packet transmission can take more time than an IEEE 802.11ah packet does and therefore, can cause more latency for IEEE 802.11ah packet transmission.

7.11 IEEE Std 802.11ah and IEEE Std 802.15.4g coexistence performance improvement

Subclause 7.8 shows that even with a duty cycle of less than 1% and network size smaller than 100 nodes, the coexistence methods defined in IEEE Std 802.11ah and IEEE Std 802.15.4g do not work well in some scenarios. Therefore, additional coexistence mechanisms are needed to achieve better performance.

It is obvious that the coexistence performance of IEEE Std 802.11ah and IEEE Std 802.15.4g can be improved. For example, if either network performs a channel switching operation so that the two networks operate on non-overlapping frequency bands. As a result, there is no more interference.

Lin, et al. [B31] and Guo, et al. [B20] present the α-Fairness based ED-CCA and Q-Learning based backoff for IEEE Std 802.11ah to improve coexistence performance with IEEE Std 802.15.4g. The α-Fairness based ED-CCA method is proposed for IEEE Std 802.11ah to mitigate its interference on IEEE 802.15.4g packet transmission caused by its higher ED threshold. The Q-Learning based backoff is introduced to reduce the interference to the IEEE 802.15.4g packet transmission process caused by the faster backoff of IEEE Std 802.11ah. Simulation results show that both methods can improve coexistence performance.

Guo and Orlik [B10] and Guo, et al. [B22] describe a prediction-based self-transmission control method for IEEE Std 802.11ah to ease its interference impact on IEEE Std 802.15.4g. This method is an enhancement to the transmission time delay defined in IEEE Std 802.11ah. Simulation results demonstrate that this method can also improve coexistence performance of IEEE Std 802.11ah and IEEE Std 802.15.4g.

Guo, et al. [B17] introduces a hybrid CSMA/CA method for IEEE Std 802.15.4g to achieve better coexistence with IEEE Std 802.11ah. This method operates in two modes. When IEEE 802.11ah interference is not severe, hybrid CSMA/CA operates in mode-1. In this mode, the standard IEEE 802.15.4g CSMA/CA mechanism is applied. When IEEE 802.11ah interference is severe, hybrid CSMA/CA operates in mode-2. In this mode, the enhanced CSMA/CA mechanism is applied, which provides an IEEE 802.15.4g device the capability to access the channel without random backoff. Simulation results show that this method can improve coexistence performance of both IEEE Std 802.11ah and IEEE Std 802.15.4g.

Guo, et al. [B18] shows that the selection of different network profiles can also improve the coexistence performance. These profiles include frame size, network size, and backoff parameters.

8. IEEE Std 802.11ah and IEEE Std 802.15.4g coexistence model

8.1 Introduction

For both IEEE Std 802.11ah and IEEE Std 802.15.4g, there are different coexistence methods available. These coexistence methods have different features.

In terms of the scope of coexistence operation, some coexistence methods, for example channel switching, perform coexistence operations on entire network and some coexistence methods, for example frame resize, perform coexistence operations by a group of devices or on an individual device.

In terms of coexistence coordination, some coexistence methods, for example, deferring transmission time, can be performed in a fully distributed way and some coexistence methods, for example, IEEE 802.11ah RAW and IEEE 802.15.4g frequency hopping, need network level coordination. Some coexistence methods, for example hybrid coordination-based coexistence, may even need inter-network level coordination.

Based on the features of different coexistence methods, different coexistence models can be configured as shown in Guo, et al. [B14].

8.2 Coexistence operation

A summary of the coexistence operations that can be applied for IEEE 802.11ah networks and IEEE 802.15.4g networks is provided in Guo, et al. [B15] and Guo, et al. [B16]. This recommended practice classifies coexistence operations into four categories as described in 8.2.1 to 8.2.4.

8.2.1 Centralized coexistence

Assume a coordinator such as a hybrid device can communicate with both an IEEE 802.11ah network and an IEEE 802.15.4g network. This coordinator collects information from both networks, analyzes the information, and makes optimal coexistence decisions. The coordinator then instructs the networks to take coexistence actions including channel switching, beamforming, RAW scheduling, superframe structuring, deferring transmission, etc.

The coordinator can command a network, a group of devices, or a single device to perform coexistence operations. In this case, devices in the network do not make coexistence decisions. All network devices perform coexistence operations as instructed by the coordinator.

8.2.2 Cooperated (or collaborated) coexistence

Assume a coordinator can communicate with both an IEEE 802.11ah network and an IEEE 802.15.4g network. This coordinator collects information from both networks and relays information between networks so that the IEEE 802.11ah network is aware of the IEEE 802.15.4g network and the IEEE 802.15.4g network is aware of the IEEE 802.11ah network. Based on information received from the coordinator, each network makes coexistence decisions spontaneously without instruction from the coordinator. More specifically, networks perform cooperated (or collaborated) coexistence operations according to the following procedures:

— One network informs the other network, via the coordinator, about coexistence operations performed.
— The other network then makes decisions based on the information received from the coordinator. For example, the IEEE 802.11ah network switches its channel to a different frequency band that no longer overlaps with IEEE 802.15.4g channel. In this case, the IEEE 802.15.4g network may not need to take further coexistence action.

The coexistence operations that can be performed in a cooperated fashion include channel switching, IEEE 802.11ah RAW scheduling, IEEE 802.15.4g superframe structuring, etc.

8.2.3 Distributed network level coexistence

A network is aware of external interference but does not know the source of the interference. In this case, network level coexistence operation can be independently performed by a network, that is, all devices in a network perform the same coexistence operation. The coexistence operations that can be performed by IEEE 802.11ah networks include channel switching, RAW scheduling, beamforming, etc. The coexistence operations that can be performed by IEEE 802.15.4g networks include channel switching, superframe structuring, frequency hopping, etc.

8.2.4 Distributed device level coexistence

The coexistence operation is independently performed by a device.

An IEEE 802.11ah device can perform coexistence operations including transmission deferring, α-Fairness based ED-CCA, Q-Learning based backoff, etc. An IEEE 802.15.4g device can perform coexistence operations including hybrid CSMA/CA, packet size change, etc.

8.3 Coexistence model

Guo, et al. [B19] defines the coexistence model for IEEE Std 802.11ah and IEEE Std 802.15.4g. This recommended practice classifies coexistence models based on the following two criteria:

— Network coordination
— Scope of coexistence operation

8.3.1 Coexistence model based on network coordination

Coordinated coexistence requires coordination among networks, that is, the coexisting networks work collaboratively to mitigate interference. On the other hand, distributed coexistence does not need any coordination among the networks, that is, each network or device performs coexistence operations independently. Figure 9 shows a coexistence model based on network coordination.

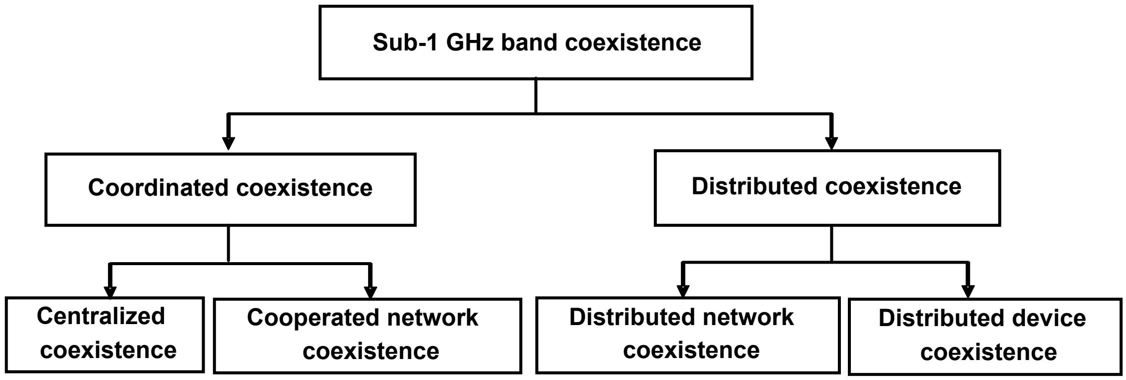

Figure 9—Coexistence model based on network coordination

8.3.2 Coexistence model based on scope of coexistence operation

Coexistence can be performed at network level or device level. Network level coexistence requires all devices in a network to perform the same coexistence operation, for example channel switching. Device level coexistence does not need all devices in a network to perform the same coexistence operation. Coexistence operations are performed by a group of devices or a single device, for example deferring transmission. Figure 10 shows a coexistence architecture based on level of operation.

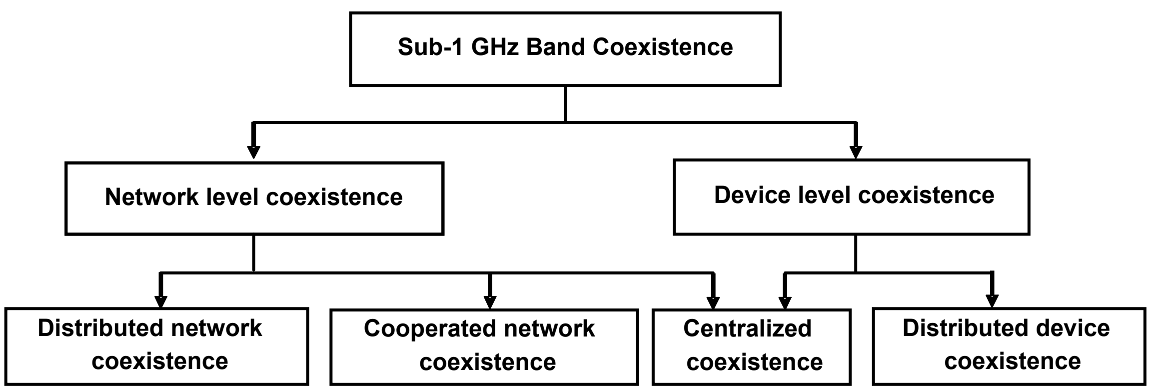

Figure 10—Coexistence model based on scope of coexistence operation

9. IEEE Std 802.11ah and IEEE Std 802.15.4g coexistence methods and recommendations

9.1 Introduction

Guo, et al. [B24] and Kitazawa [B30] provide approaches for IEEE Std 802.11ah and IEEE Std 802.15.4g coexistence. There are multiple coexistence methods available for IEEE Std 802.11ah and IEEE Std

802.15.4g. Some of the methods need cooperation between the IEEE 802.11ah network and the IEEE 802.15.4g network and some of the methods do not need network cooperation. Based on how the coexistence operation is performed, the coexistence methods can be categorized into coordinated coexistence and distributed coexistence. Both coexistence method categories have advantages and disadvantages.

Coordinated coexistence has the following advantages:

— More information sources, for example, operation channel, network load, and data pattern
— Information accuracy, for example, the number of devices and locations of devices
— Globalized optimization

Coordinated coexistence has the following disadvantages:

— Coordinator availability
— Communication overhead caused by information acquisition
— Scalability issue
— High cost due to the extra device and energy consumption on information acquisition
— Implementation complexity

Distributed coexistence has the following advantages:

— Easy to implement
— Low communication overhead
— Flexibility
— Low cost

Distributed coexistence has the following disadvantages:

— Lack of information
— Local decision

In general, coordinated coexistence should provide better performance.

Furthermore, in each category, some of methods are suitable for a network and some of methods fit a group of devices or an individual device in a network.

9.2 Coordinated coexistence methods and recommendations

9.2.1 Introduction

Coordinated coexistence assumes availability of a device such as a gateway or a hybrid device that can communicate with both the IEEE 802.11ah network and the IEEE 802.15.4g network and therefore, can coordinate the coexistence. Coordinated coexistence can be considered as a generalization of the IEEE

802.15.4g CSM mechanism. Instead of listening for an enhanced beacon, IEEE 802.11ah AP, or IEEE 802.15.4g PANC, listen for information from the coordinator to acquire information about the existence of other networks.

The following are potential information exchanges between an IEEE 802.11ah AP/IEEE 802.15.4g PANC and the coexistence coordinator:

— The IEEE 802.11ah AP and IEEE 802.15.4g PANC should report their operating channel information to the coordinator after formation of the network, and report updated channel information after channel switching.
— The IEEE 802.11ah AP and IEEE 802.15.4g PANC may report their traffic information to the coordinator, and report the latest traffic information if traffic information changes.
— The IEEE 802.11ah AP and IEEE 802.15.4g PANC may report their network information such as the number of devices, device density, and device location to the coordinator.
— The coordinator may evaluate channels (or frequency bands) based on collected information and send information to the IEEE 802.11ah APs and IEEE 802.15.4g PANCs.

The coordinated coexistence methods can be further categorized into:

— Centralized coexistence, where a powerful coordinator is available
— Cooperated/collaborated coexistence, where a limited function coordinator is available

IEEE Std 802.15.4s-2018 provides enhancements to provide spectrum resource measurement and management for IEEE 802.15.4 PHY and MAC layers. It is recommended that implementations of IEEE Std 802.15.4 use these features to support coordinated coexistence.

9.2.2 Centralized coexistence methods

9.2.2.1 Introduction

A powerful coordinator can completely manage the coexistence between networks, in which the coordinator collects information from the networks, analyzes information, and makes decisions on coexistence control. Once a coexistence decision is made, the coordinator sends the coexistence command to a network/a group of devices/a single device. The network/device performs the coexistence operation commanded by the coordinator. The following are typical centralized coexistence operations:

— Channel switching
— IEEE 802.11ah RAW scheduling
— IEEE 802.15.4g superframe structuring
— IEEE 802.11ah beamforming
— Transmission power setting

9.2.2.2 Centralized channel switching

Channel switching is an operation in which an entire network changes operation channel. It can be considered as a special case of channel hopping. Channel switching is easy to implement.

Channel switching is a favored coexistence operation to be performed, especially for centralized coexistence, where the coordinator can determine operation channels for the IEEE 802.11ah network and the IEEE 802.15.4g network to achieve the best possible performance. For example, the coordinator may assign a channel for the IEEE 802.11ah network and another channel for IEEE 802.15.4g network such that these two channels do not overlap each other, as long as such channels are available. Another advantage of centralized channel switching is that the coordinator can make sure that two networks do not randomly switch to channels that share frequency band.

Channel switching is an ideal coexistence mechanism. However, due to spectrum allocation constraints in the sub-1 GHz band, a free channel is not always available to switch to. In that case, the IEEE 802.11ah network and the IEEE 802.15.4g network are forced to share the spectrum, which is real coexistence.

9.2.2.3 Centralized IEEE 802.11ah RAW and IEEE 802.15.4g superframe construction

To achieve better coexistence performance, IEEE 802.11ah RAW should be applied together with the superframe structuring of the beacon-enabled IEEE 802.15.4g network. With the decision made by the powerful coordinator, this approach should provide good coexistence performance.

Figure 11 shows an example of centralized IEEE 802.11ah RAW-based IEEE 802.15.4g superframe construction, in which the coordinator commands the IEEE 802.11ah AP to allocate three RAWs, one for IEEE 802.15.4g beacon transmission, one for the IEEE 802.15.4g CFP period, and one for the IEEE 802.11ah CFP period. It can be seen that the RAW allocated to IEEE Std 802.11ah coincides with the IEEE 802.15.4g inactive period, where the IEEE 802.11ah beacon can also be transmitted.

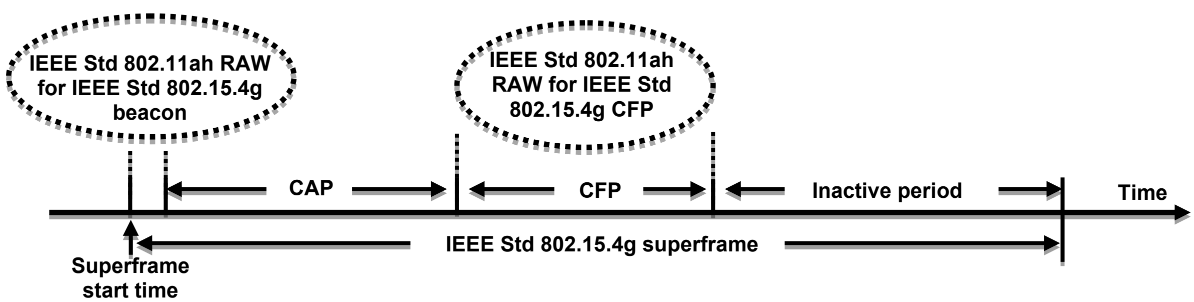

Figure 11—RAW-based superframe construction

It can be observed that this coordinated RAW aims to protect higher priority data transmitted in the CFP from interference.

This method is suitable for the beacon-enabled IEEE 802.15.4g network and the load information of both the IEEE 802.11ah network and the IEEE 802.15.4g network is available to the coordinator.

However, for the non-beacon-enabled IEEE 802.15.4g network, this coordinated RAW may not provide much benefit.

9.2.2.4 Centralized IEEE 802.11ah beamforming

With the help of a powerful coordinator, IEEE 802.11ah beamforming can also be an effective coexistence method, especially when the locations of both IEEE 802.11ah stations and IEEE 802.15.4g devices are available to the coordinator. Here, the coordinator may instruct IEEE 802.11ah stations to form their beams away from the IEEE 802.15.4g network, especially when the geometrical areas of the IEEE 802.11ah network and the IEEE 802.15.4g network are partially overlapped.

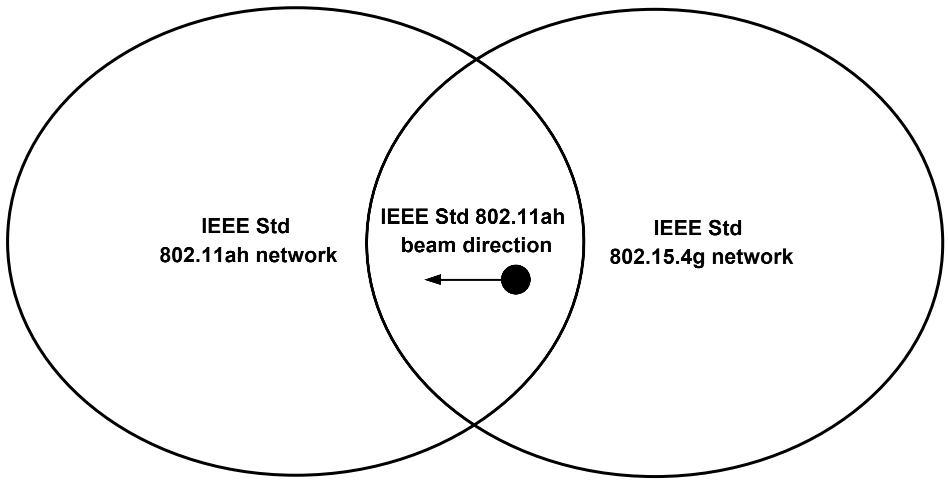

Figure 12—Coordinated beamforming

Figure 12 shows an example of IEEE 802.11ah beamforming, in which the coordinator directs a portion of the IEEE 802.11ah STAs to point their beams away from the IEEE 802.15.4g network.

The advantage of this method is that it can be applied to an IEEE 802.11ah network to coexist with both beacon-enabled and non-beacon-enabled IEEE 802.15.4g networks. The disadvantage of this method is that it requires the locations of network devices.

9.2.2.5 Centralized transmission power setting

Even though the maximum transmission power is regulated by the authority, it is possible for devices to dynamically adjust their transmission power without violating the regulations or communication protocols. Increasing transmission power may reduce the relay overhead and decreasing transmission power may achieve multi-geometrical channel access.

Adjusting transmission power may be a feasible coexistence method for centralized coexistence control with certain data patterns and/or geometric device placement, in which the centralized coordinator can manage devices to make TDMA-based transmission as defined in IEEE Std 802.15.4.

However, this approach may not work well for CSMA-based transmission.

9.2.3 Cooperated/collaborated coexistence methods

9.2.3.1 Introduction

In this case, the coordinator has limited capability and therefore, the coordinator is not able to manage coexistence between networks. It only relays information between networks. Instead, the IEEE 802.11ah AP and IEEE 802.15.4g PANC collect information from their network and exchange information via the coordinator. Based on information collected and exchanged, the IEEE 802.11ah AP/IEEE 802.15.4g PANC makes decisions on whether a coexistence action is needed. If yes, it requires its devices to perform a coexistence operation. After completion of the operation, the IEEE 802.11ah AP/IEEE 802.15.4g PANC sends information to the IEEE 802.15.4g/IEEE 802.11ah network via the coordinator.

The IEEE 802.11ah AP and IEEE 802.15.4g PANC may collect the following information from devices:

- ED ratio, that is the number of EDs above the ED threshold from unreadable transmissions divided by total number of EDs above the ED threshold in a time period
- Packet delivery ratio
- Packet latency

An IEEE 802.11ah STA or an IEEE 802.15.4g device may also spontaneously report their observations to their AP or PANC.

The cooperated/collaborated coexistence operations include the following:

- Channel switching
- IEEE 802.11ah RAW
- IEEE 802.15.4g superframe construction
- IEEE 802.11ah beamforming
- Transmission power setting
- α-Fairness based ED-CCA
- Q-Learning based CSMA/CA

9.2.3.2 Cooperated channel switching

Channel switching is still a favored coexistence operation to be performed. With the help of the coordinator, the IEEE 802.11ah network can obtain certain information about the IEEE 802.15.4g network. Similarly, the IEEE 802.15.4g network can get some information about the IEEE 802.11ah network. Therefore, the IEEE 802.11ah AP or IEEE 802.15.4g PANC can still select a channel with a lower probability of the interference. It is also possible for the IEEE 802.11ah AP or IEEE 802.15.4g PANC to select a channel that does not share frequencies with other networks.

However, in this case, it is also possible to select a channel that provides worse performance. For example, if both the IEEE 802.11ah AP and IEEE 802.15.4g PANC detect a less congested channel at the same time and then switch their networks to that channel.

9.2.3.3 Cooperated RAW

Like the case of the centralized RAW, the IEEE 802.11ah RAW should be applied together with the superframe structuring of the beacon-enabled IEEE 802.15.4g network.

In this case, the IEEE 802.11ah network may inform the IEEE 802.15.4g network via the coordinator about its RAW scheduling. Accordingly, the IEEE 802.15.4g network may plan its superframe based on the IEEE 802.11ah RAW allocation. On the other hand, the IEEE 802.15.4g network may inform the IEEE 802.11ah network via the coordinator about its superframe structure. Accordingly, the IEEE 802.11ah network may allocate its RAW based on the IEEE 802.15.4g superframe structure.

However, it is possible that the two networks make changes at the same time, which can result in worse performance.

This method is suitable when the IEEE 802.15.4g network is beacon enabled and the load information of both the IEEE 802.11ah network and IEEE 802.15.4g network have certain patterns.

9.2.3.4 Cooperated IEEE 802.11ah beamforming

With the help of the coordinator, IEEE 802.11ah beamforming is still a possible coexistence method, especially when the locations of both the IEEE 802.11ah AP and the IEEE 802.15.4g nodes are available to the IEEE 802.11ah nodes. This means that the IEEE 802.11ah nodes can form their beams away from the IEEE 802.15.4g network, especially when the IEEE 802.11ah AP and IEEE 802.15.4g PANC are not located near to each other.

9.2.3.5 Cooperated transmission power setting

Without centralized scheduling, it is difficult to realize TDMA-based transmission between two networks. Therefore, transmission power adjustment may not provide the expected coexistence result.

9.2.4 Recommendations for centralized and cooperated/collaborated coexistence

Subclauses 9.2.2 and 9.2.3 present multiple centralized and cooperated/collaborated coexistence methods. Table 5 shows the recommendations for centralized and cooperated/collaborated coexistence methods.

Table 5—Recommendations for centralized and cooperated coexistence methods

Method	Recommendation	Reference
Centralized channel switching	When the coordinator can find a channel with less interference.	9.2.2.2
Centralized IEEE 802.11ah RAW and IEEE 802.15.4g superframe construction	When the coordinator coordinates the coexistence of an IEEE 802.11ah network and a beacon-enabled IEEE 802.15.4g network.	9.2.2.3
Centralized IEEE 802.11ah beamforming	When the coordinator has information about geometric placement of IEEE 802.11ah devices and IEEE 802.15.4g devices.	9.2.2.4
Centralized transmission power setting	When the coordinator coordinates coexistence of an IEEE 802.11ah network and an IEEE 802.15.4g network with certain data patterns and/or geometric device placement.	9.2.2.5
Cooperated channel switching	When a channel with less interference is available.	9.2.3.2
Cooperated RAW	With a beacon-enabled IEEE 802.15.4g network when load information of both the IEEE 802.11ah network and the IEEE 802.15.4g network is available.	9.2.3.3
Cooperated IEEE 802.11ah beamforming	When the relative position of nodes is known or predictable and not aligned closely in space.	9.2.3.4
Cooperated transmission power setting	When received signal condition information is available per link, link adaptation capability is available in devices, and link information can be shared between transmitter and receiver.	9.2.3.5
α-Fairness based ED-CCA	When an IEEE 802.11ah device is aware of coexistence of IEEE 802.15.4g devices and the coordinator can provide necessary performance metrics such as data packet delivery rate.	9.3.7
Q-Learning based CSMA/CA	When an IEEE 802.11ah device is aware of coexistence of IEEE 802.15.4g devices and the coordinator can provide information to configure the Q-Learning rewards.	9.3.8

9.3 Distributed coexistence methods and recommendations

9.3.1 Introduction

A coordinator can effectively manage the coexistence of an IEEE 802.11ah network and an IEEE 802.15.4g network. However, the availability of a coordinator is uncertain. Therefore, the IEEE 802.11ah network and the IEEE 802.15.4g network need to have the capability to perform distributed coexistence without the assistance of a coordinator.

Even though this clause assumes that no network coordinator is available, the coexistence methods may perform better with the help of a network coordinator.

Without a coordinator, it is difficult for an IEEE 802.11ah network/IEEE 802.15.4g network to be aware of the existence of an IEEE 802.15.4g network/IEEE 802.11ah network. However, using the ED mechanism, an IEEE 802.11ah STA/IEEE 802.15.4g station/node can detect if a non-IEEE 802.11ah/non-IEEE 802.15.4g system exists. If ED is not used by the IEEE 802.15.4g network, another method can be used for this purpose, for example, the ratio of the channel occupancy time by the IEEE 802.15.4g network to the total channel busy time.

Distributed coexistence can be divided into the following:

a) Network level operation
    1) Channel switching
    2) ED threshold setting
    3) Transmission power setting
    4) Backoff parameter setting
    5) Frequency hopping
b) Device level operation
    1) Beamforming
    2) Transmission time delay
    3) α-Fairness based ED-CCA
    4) Q-Learning based CSMA/CA
    5) Prediction-based transmission delay
    6) Frame size setting

9.3.2 Distributed channel switching

Without a coordinator, channel switching becomes a random operation. In other words, switching the channel may provide better performance and it may also provide worse performance. Therefore, channel switching may not be a feasible solution in this case.

9.3.3 Distributed ED threshold setting

Dynamic ED threshold configuration by an IEEE 802.11ah device may improve coexistence performance of an IEEE 802.15.4g network. For example, lowering the IEEE 802.11ah ED threshold allows IEEE

802.11ah devices to detect more IEEE 802.15.4g transmissions. However, changing the ED threshold violates the standard. Therefore, ED threshold adjustment is not a favored operation.

9.3.4 Distributed transmission power setting

Without a coordinator, transmission power adjustment also becomes a random operation. Therefore, it is not a favored operation.

9.3.5 Distributed beamforming

Without a coordinator, IEEE 802.11ah beamforming becomes a random operation. Therefore, it is not a favored operation.

9.3.6 Distributed transmission time delay

Transmission time delay is one of the mechanisms recommended by IEEE Std 802.11ah to improve coexistence performance with other S1G systems. IEEE Std 802.15.4g also supports a backoff mechanism. Therefore, when an IEEE 802.11ah device/IEEE 802.15.4g device is aware of coexistence with IEEE 802.15.4g devices/IEEE 802.11ah devices (e.g., via a coordinator), the device should use ED based CCA for channel assessment. If the detected energy level is above the specified threshold on its channel, the transmission time delay should be used to mitigate interference. The delay duration is implementation dependent.

9.3.7 α–Fairness based ED-CCA

The α-Fairness is a technique used in various network resource sharing schemes. The α-Fairness based ED-CCA is a device level coexistence method developed for IEEE Std 802.11ah in Liu, et al. [B31] and presented in Guo, et al. [B20]. It is proposed to mitigate the IEEE 802.11ah interference impact on IEEE Std 802.15.4g caused due to the higher ED threshold of IEEE Std 802.11ah as illustrated in Figure 13.

The issue is that if the energy level of the IEEE 802.15.4g transmission detected by IEEE Std 802.11ah falls in [IEEE 802.15.4g receiver sensitivity, IEEE 802.11ah ED threshold], the transmission is readable by IEEE Std 802.15.4g. However, IEEE Std 802.11ah ignores the transmission. In this case, IEEE 802.11ah ED-CCA has two options to report channel status: idle or busy. From the IEEE Std 802.15.4g perspective, IEEE Std 802.11ah should report a busy channel if the energy source is IEEE Std 802.15.4g and reports idle channel otherwise. The challenge is that IEEE Std 802.11ah may not be able to identify the source of the energy, which could be an IEEE 802.15.4g device, far away IEEE 802.11ah device, or other device such as a LoRa device or a Sigfox device. Using α-Fairness based ED-CCA, if the detected energy level is within [IEEE 802.15.4g receiver sensitivity, IEEE 802.11ah ED threshold], IEEE 802.11ah ED-CCA reports the channel status based on a probability generated by the α-Fairness technique.

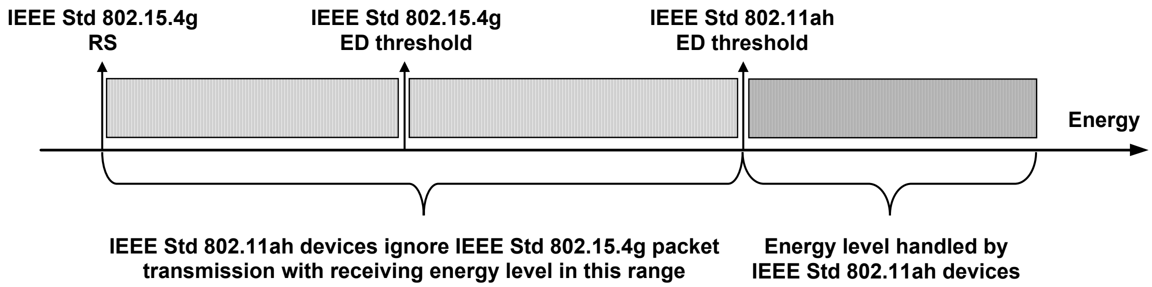

Figure 13—Interference caused by the higher ED threshold of IEEE Std 802.11ah

Define a generalized α-Fairness objective function as shown in Equation (1).

$$\mathrm{U}(P_i, P_b) = \frac{1}{1-\alpha}\left[P_i^{1-\alpha} \frac{{M_h}^{1-\alpha}}{{M_h}^{1-\alpha} + {M_g}^{1-\alpha}} + P_b^{1-\alpha} \frac{{M_g}^{1-\alpha}}{{M_h}^{1-\alpha} + {M_g}^{1-\alpha}} \right] \tag{1}$$

where

$\alpha > 0, \alpha \neq 1$	is the fairness parameter to favor IEEE Std 802.11ah or IEEE Std 802.15.4g
$P_i \geq 0$	is the probability that IEEE 802.11ah ED-CCA reports idle channel
$P_b \geq 0$	is the probability that IEEE 802.11ah ED-CCA reports busy channel
$M_h \geq 0$	is the locally observed performance metric of the IEEE 802.11ah network
$M_g \geq 0$	is the locally observed performance metric of the IEEE 802.15.4g network

The network performance metric can be packet transmission rate, packet delivery rate, etc. The α-Fairness wireless medium sharing between an IEEE 802.11ah network and an IEEE 802.15.4g network corresponding to the maximization of the objective function $U(P_i, P_b)$ subject to the condition $P_i + P_b = 1$. According to optimization theory, this optimization problem has a unique solution given by Equation (2) and Equation (3).

$$P_i^0 = \frac{1}{1 + \left(\frac{M_h}{M_g}\right)^{\frac{\alpha-1}{\alpha}}} \tag{2}$$

$$P_b^0 = \frac{1}{1 + \left(\frac{M_h}{M_g}\right)^{\frac{1-\alpha}{\alpha}}} \tag{3}$$

It can be seen that if $\alpha > 1$, more medium access opportunity is given to the network with the smaller performance metric and if $\alpha < 1$, more medium access opportunity is given to the network with the greater performance metric.

This method can be applied to a network with any number of nodes. It can improve the reliability of the IEEE 802.15.4g network. This method is suitable for the case where the IEEE 802.11ah network load is higher so that it consumes more channel resource. However, it requires modification of the IEEE 802.11ah CCA procedure and may degrade performance of the IEEE 802.11ah network if its offered load is very high. Furthermore, this method requires a metric from both networks. Even if an IEEE 802.11ah device can estimate IEEE Std 802.15.4g metrics such as channel occupancy time and ED ratio, these metrics do not directly reflect IEEE 802.15.4g network performance. For example, an IEEE 802.15.4g network may have longer channel occupancy time, but it may still have lower packet delivery rate. Therefore, selection of an appropriate performance metric is important.

When an IEEE 802.11ah device is aware of coexistence with IEEE 802.15.4g devices (e.g., via a coordinator) and detects energy between the IEEE 802.15.4g receiver sensitivity and the IEEE 802.11ah ED threshold, the device should apply the α-Fairness ED-CCA to further assess channel status.

9.3.8 Q-Learning based CSMA/CA

Q-Learning based CSMA/CA is a device level coexistence method developed for IEEE Std 802.11ah in Liu, et al. [B31] and presented in Guo, et al. [B20]. It is proposed to mitigate IEEE 802.11ah interference impact on the IEEE 802.15.4g transmission process caused by the faster CSMA/CA of IEEE Std 802.11ah. For example, this can happen during the IEEE 802.15.4g device RX2TX turn around period or the IEEE 802.15.4g ACK waiting period, which are long enough for IEEE 802.11ah device to complete the backoff procedure and start packet transmission.

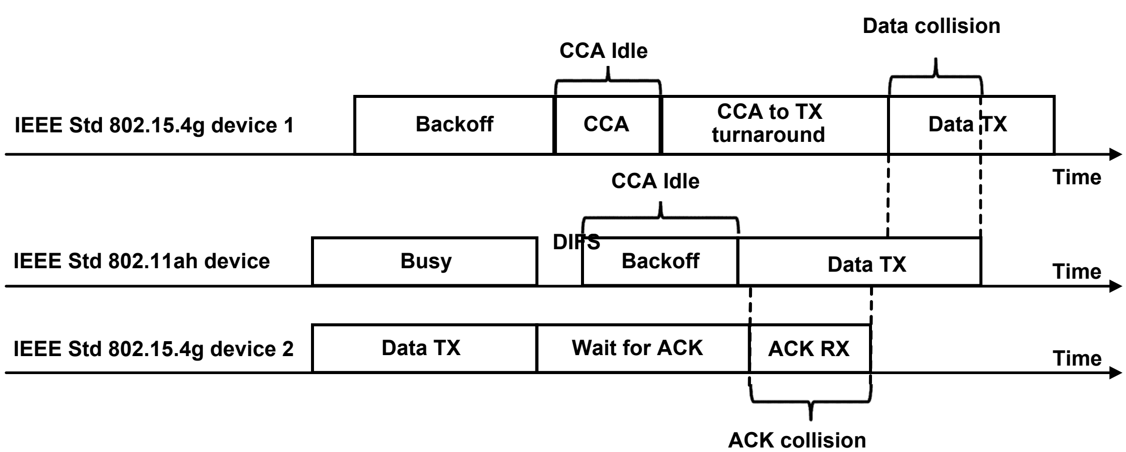

Figure 14—Interference caused by faster CSMA/CA of IEEE Std 802.11ah

As shown in Figure 14, during these time periods, the channel is idle but an IEEE 802.15.4g transmission process is taking place. Therefore, when the backoff counter (BC) reaches zero and IEEE 802.11ah ED-CCA reports idle channel, IEEE Std 802.11ah should decide whether to transmit or not. The challenge is that IEEE Std 802.11ah does not know if an IEEE 802.15.4g transmission process is in progress or not. Using Q-Learning based CSMA/CA, if BC > 0 or ED-CCA reports busy channel, the backoff process continues as specified by IEEE Std 802.11ah. If BC = 0 and ED-CCA reports idle channel, IEEE 802.11ah device applies Q-Learning to make the decision to transmit or defer some time.

Q-Learning is formulated as shown in Equation (4) and Equation (5).

$$Q_{t+1}(s,a) = (1-\tau_t)Q_t(s,a) + \tau_t(R_t(s,a) + \gamma V_t(s',b)) \tag{4}$$

$$V_t(s',b) = \max_{b \in B(s')} Q_t(s',b) \tag{5}$$

where

$Q_t(s, a)$	is the Q-Learning objective function
s'	is the state reached from state s by taking action a
$B(s')$	is the action set that can be taken at state s'
$0 < \tau_t < 1$	is the learning rate
$0 < \gamma < 1$	is the discount factor
$R_t(s, a)$	is the reward obtained by performing action a at state s at time t

To apply Q-Learning for wireless medium sharing, state set S is defined as $S = \{s_1, s_2\}$ = {Idle channel, Busy channel}, action set A is defined as $A = \{a_1, a_2\}$ = {Transmit, Backoff} and most importantly, the reward is defined based on α-Fairness as shown in Equation (6).

$$R_t(s,a) = \begin{cases} \dfrac{1}{\left|U^o - U_i^o\right| + 1'} & (s_1, a_1) \\ \sigma, & (s_1, a_2) \\ 0, & (s_2, a_1) \\ \dfrac{1}{\left|U^o - U_b^o\right| + 1'} & (s_2, a_2) \end{cases} \tag{6}$$

where

$U^o = U(P_i^o, P_b^o)$	is the α-Fairness objective function with optimal probability P_i^o and P_b^o
$\sigma > 0$	is a small parameter
U_i^o and U_b^o	are given by Equation (7) and Equation (8), respectively

$$U_i^{\ o} = \frac{\left(P_i^o\right)^{1-\alpha}}{1-\alpha}\left[\frac{M_h^{\ 1-\alpha}}{M_h^{\ 1-\alpha} + M_g^{\ 1-\alpha}}\right] \tag{7}$$

$$U_b^{\ o} = \frac{\left(P_b^o\right)^{1-\alpha}}{1-\alpha}\left[\frac{M_g^{\ 1-\alpha}}{M_h^{\ 1-\alpha} + M_g^{\ 1-\alpha}}\right] \tag{8}$$

The rational of the Q-Learning reward assignment is as follows:

a) If the channel is idle, the IEEE 802.11ah device is encouraged to transmit a packet. Therefore, positive reward is assigned to the $\{s_1, a_1\}$ pair.

b) If the channel is idle, backoff is a generous action to take. Thus, a very small reward σ is assigned to the $\{s_1, a_2\}$ pair.

c) It definitely causes interference to transmit a packet when the channel is already busy. As a result, zero reward is assigned to the $\{s_2, a_1\}$ pair to punish this behavior.

d) If the channel is busy, backoff is the right action to take. Hence, positive reward is assigned to $\{s_2, a_2\}$ pair to encourage IEEE 802.11ah device to perform backoff.

If $P_i^o > P_b^o$, the channel is more likely idle. $P_i^o > P_b^o$ also indicates that the $\{s_1, a_1\}$ pair has a greater reward. Therefore, Q-Learning tends to choose the action a_1 for the IEEE 802.11ah device. On the other hand, if $P_i^o < P_b^o$, the channel is more likely busy. $P_i^o < P_b^o$ also implies that the $\{s_2, a_2\}$ pair has a greater reward. Thus, Q-Learning tends to choose the action a_2 for the IEEE 802.11ah device. If $P_i^o = P_b^o$, Q-Learning tends to select action a_1 or action a_2 with equal probability. Notice that $\alpha > 1$, $P_i^o > P_b^o$ indicates $M_h < M_g$. Therefore, it is reasonable for the IEEE 802.11ah device to transmit more packets. Similarly, $P_i^o < P_b^o$ indicates $M_h > M_g$. As a result, it is appropriate for the IEEE 802.11ah device to do more backoff.

When an IEEE 802.11ah device is aware of coexistence with IEEE 802.15.4g devices (e.g., via a coordinator) and its backoff counter reaches zero with idle channel status, the device should apply Q-Learning based ED-CCA to make next step decision.

This method can be applied to a network with any number of nodes. It is also suitable for the case where the IEEE 802.11ah network load is higher so that it consumes more channel resource. This method can improve the performance of an IEEE 802.15.4g network. However, it requires modification of the IEEE 802.11ah backoff procedure and may degrade performance of the IEEE 802.11ah network if its offered load is very high. In addition, the definition of the reward function is the key for this method and it requires information from the IEEE 802.15.4g network. Even if an IEEE 802.11ah station can estimate IEEE Std 802.15.4g metrics such as channel occupancy time and ED ratio, these metrics do not directly reflect IEEE 802.15.4g network performance, which may be obtained from a coordinator.

Since the α-Fairness based ED-CCA and the Q-Learning based CSMA/CA aim to address different coexistence issues, an IEEE 802.11ah device can apply both methods simultaneously. In fact, applying both methods provides better performance than each individual method.

9.3.9 Prediction-based transmission time delay

Prediction-based transmission delay is a device level coexistence method proposed for IEEE Std 802.11ah to avoid interfering with upcoming IEEE 802.15.4g transmission in Guo and Orlik [B10] and presented in Guo, et al. [B22]. It is a generalized version of IEEE 802.11ah transmission time delay, where if an IEEE 802.11ah STA detects energy on its channel with level above the IEEE 802.11ah ED threshold, the STA will delay its transmission for some time. Using prediction transmission time delay, an IEEE 802.11ah STA applies a prediction algorithm to predict future IEEE 802.15.4g transmission and configures a suspension interval around predicted transmission time and suspends its transmission in the suspension interval. Figure 15 shows the concept of this approach.

In this approach, each IEEE 802.11ah STA needs to determine all IEEE 802.15.4g transmission times. It records all detected transmission times and then deletes the times corresponding to successful IEEE 802.11ah transmission and collided IEEE 802.11ah transmission. An IEEE 802.11ah STA can determine successful IEEE 802.11ah transmissions. Other transmissions are considered as the potential IEEE 802.15.4g transmissions, which include collided IEEE 802.11ah transmissions and IEEE 802.15.4g transmissions. To estimate if a potential IEEE 802.15.4g transmission can be considered as an IEEE 802.15.4g transmission, the IEEE 802.11ah STA computes the IEEE 802.11ah collision probability P_c by using the number of transmission attempts and the number of ACKs received. A potential IEEE 802.15.4g transmission is considered as a collided IEEE 802.11ah transmission with the probability P_c and a potential IEEE 802.15.4g transmission is considered as an IEEE 802.15.4g transmission with the probability $1 – P_c$.

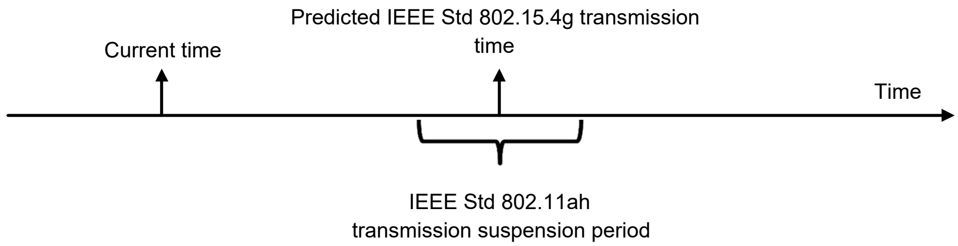

Figure 15—Prediction-based transmission time delay

Given IEEE 802.15.4g transmission time history X_1, X_2, …, X_t, the prediction algorithm predicts the next IEEE 802.15.4g transmission time X_{t+1}. There are existing time series algorithms available. Guo and Orlick [B10] applies Holt's additive trend prediction algorithm. For time series X_1, X_2, …, X_t, Holt's algorithm is formulated as Equation (9), Equation (10), and Equation (11).

$$S_t = \alpha X_t + (1-\alpha)(S_{t-1} + T_{t-1}) \tag{9}$$

$$T_t = \gamma(S_t - S_{t-1}) + (1-\gamma)T_{t-1} \tag{10}$$

$$X_t^{\wedge}(m) = S_t + mT_t \tag{11}$$

where

S_t	is the current level
T_t	represents the current slope
m	is a positive integer representing the steps ahead
$X_t^{\wedge}(m)$	is the m-step-ahead prediction
$0 < \alpha < 1$	is the level smoothing parameter
$0 < \gamma < 1$	is the slope smoothing parameter

For one step prediction, $X_t^{\wedge}(1)$ is the predicted time for next IEEE 802.15.4g transmission.

This method fits well for networks with a small number of nodes. The main advantage of this method is that it does not require any protocol change. It is a generalization of the IEEE 802.11ah transmission time delay mechanism. This method can improve IEEE 802.15.4g network performance. However, it may degrade IEEE 802.11ah network performance if its offered load is very high.

When an IEEE 802.11ah device is aware of coexistence with IEEE 802.15.4g devices (e.g., via a coordinator), it may apply prediction-based transmission time delay to improve coexistence performance.

9.3.10 Hybrid CSMA/CA

Hybrid CSMA/CA is a device level coexistence method proposed for IEEE Std 802.15.4g to achieve better coexistence with IEEE Std 802.11ah in Guo, et al. [B17].

As described in Clause 7, even though both IEEE Std 802.11ah and IEEE Std 802.15.4g use CSMA/CA for channel access, they have different functional features. Most of the features are in favor of IEEE Std 802.11ah, for example ED threshold and backoff parameters. As a result, IEEE Std 802.11ah has considerable advantage over IEEE Std 802.15.4g in channel access contention. Therefore, IEEE Std 802.11ah is much more reliable compared to IEEE Std 802.15.4g in the success of transmission. IEEE Std 802.15.4g was published four years earlier than IEEE Std 802.11ah. As a result, coexistence with other systems was not a focus for IEEE Std 802.15.4g development. Therefore, IEEE Std 802.15.4g inherited the CSMA/CA procedure in its baseline standard IEEE Std 802.15.4-2011, which works well for homogeneous IEEE 802.15.4g devices. To compete with more aggressive IEEE 802.11ah devices, IEEE 802.15.4g devices need to improve their channel access opportunity. IEEE 802.15.4g devices need to exploit the weakness of IEEE 802.11ah CSMA/CA. As described in Clause 7, IEEE 802.11ah CCA per backoff time slot and backoff suspension are two functions that are in favor of IEEE Std 802.15.4g. Therefore, IEEE 802.15.4g devices need to take these advantages to increase their channel opportunity while competing with IEEE Std 802.11ah. Hybrid CSMA/CA is a method proposed for IEEE 802.15.4g devices to improve their coexistence performance with IEEE 802.11ah devices as shown in Figure 16.

A key enhancement is that hybrid CSMA/CA allows IEEE 802.15.4g devices to perform immediate channel access when IEEE 802.11ah interference is severe. In addition, it requires only one CCA operation to increase channel access opportunity. For an IEEE 802.15.4g device performing immediate channel access, it takes random backoff if CCA returns busy channel.

It is possible that collision can occur if multiple IEEE 802.15.4g devices in a neighborhood perform immediate channel access simultaneously. Therefore, each IEEE 802.15.4g device performs immediate channel access based on an optimal probability. Assume there are N_g IEEE 802.15.4g devices in a neighborhood. It can be shown that the optimal probability is $1/N_g$. In order not to interfere with the transmission process of the immediate channel access device, the IEEE 802.15.4g neighbors that do not perform immediate channel access should increase their backoff parameters.

To perform immediate channel access, an IEEE 802.15.4g device only needs to set macMaxBE = macMinBE = 0.

The key to hybrid CSMA/CA is how to estimate IEEE 802.11ah interference severity. Several metrics can be used to perform this function.

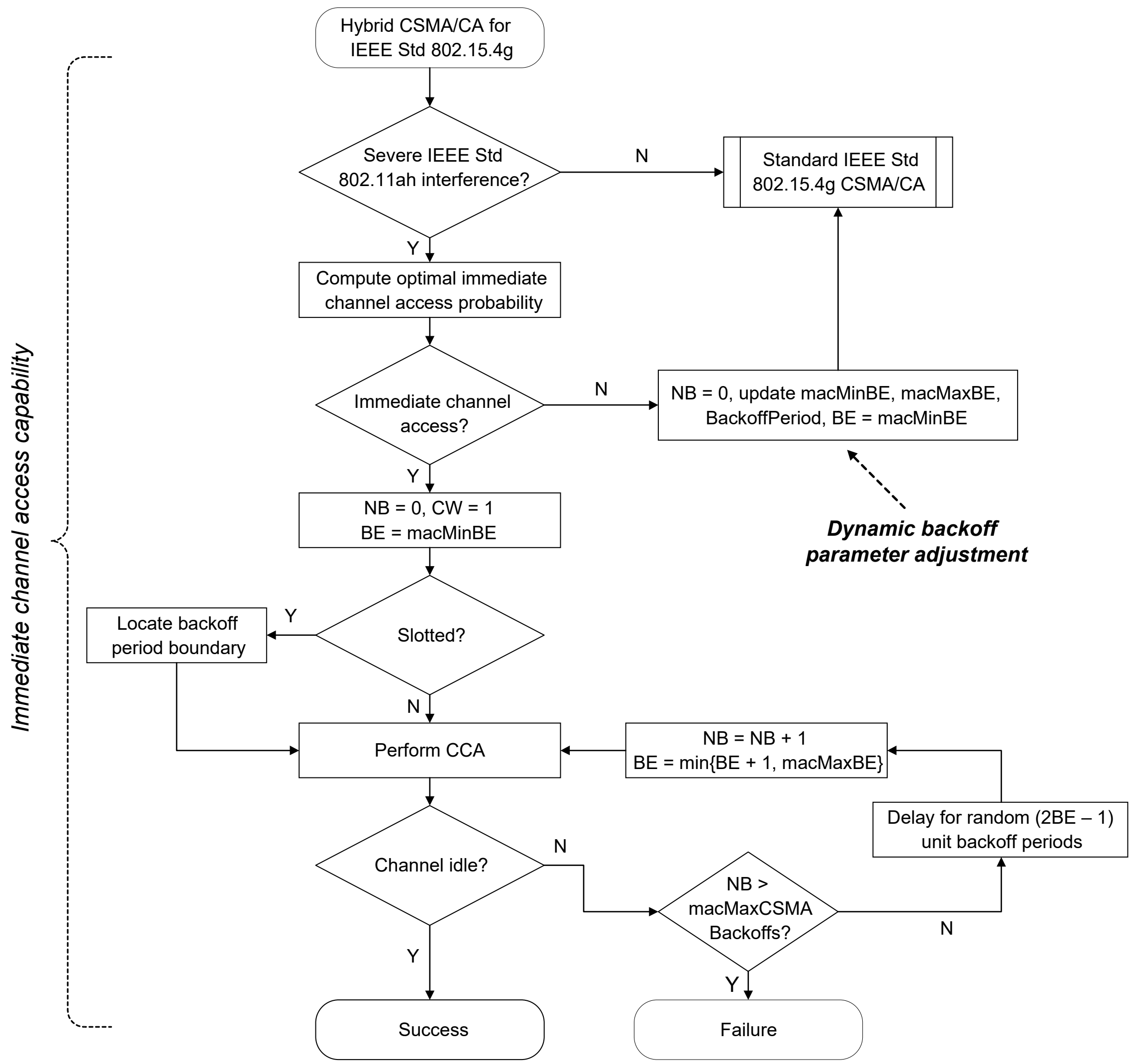

Figure 16—Hybrid CSMA/CA for IEEE Std 802.15.4g

The hybrid CSMA/CA method can be easily implemented and aims to address both IEEE Std 802.15.4g reliability and IEEE Std 802.11ah latency. It does not require any protocol change. A key advantage of this method is that it does not degrade IEEE 802.11ah network reliability while improving IEEE 802.15.4g network reliability. In some cases, it improves the performance of both the IEEE 802.11ah network and the IEEE 802.15.4g network. Therefore, it is recommended for IEEE 802.15.4g device development.

When an IEEE 802.15.4g device is aware of severe interference on its channel, it should apply the hybrid CSMA/CA method to contend for channel access. The interference severity measurement is implementation dependent.

9.3.11 Recommendations for distributed coexistence

Multiple distributed coexistence methods have been introduced. Some methods may improve coexistence performance and some methods may not be ideal candidates. Table 6 shows the recommendations for distributed coexistence methods.

Table 6—Recommendations for distributed coexistence methods

Method	Recommendation	Reference
Distributed transmission time delay	When an IEEE 802.11ah/IEEE 802.15.4g device is aware of the coexistence of IEEE 802.15.4g/IEEE 802.11ah devices.	9.3.6
α–Fairness based ED-CCA	When an IEEE 802.11ah device is aware of the coexistence of IEEE 802.15.4g devices and the detected energy level is between the IEEE 802.15.4g receiver sensitivity and the IEEE 802.11ah ED threshold.	9.3.7
Q-Learning based CSMA/CA	When an IEEE 802.11ah device is aware of the coexistence of IEEE 802.15.4g devices and its BC reaches zero with idle channel status.	9.3.8
Prediction-based transmission time delay	When an IEEE 802.11ah device is aware of the coexistence of IEEE 802.15.4g devices.	9.3.9
Hybrid CSMA/CA	When an IEEE 802.15.4g device is aware of severe interference on its channel.	9.3.10

9.4 Frequency hopping and recommendation

9.4.1 Overview

Rolfe [B39] presents frequency hopping, a coexistence method in which all devices perform channel hopping according to hopping sequences. Hopping refers to varying frequency over time. The primary goal of frequency hopping is to improve reliability by mitigating interference impact and adapting to the environment. Frequency hopping is a popular technique to improve the reliability of wireless systems in licensed exempt spectrum, especially for narrowband systems where a large number of channels can be available. Hopping is commonly used with IEEE 802.15.4 SUN FSK due to the narrow channel requirement in some regions to meet regulatory requirements, as described in Clause 6.

Rolfe [B41] provides some background on frequency hopping commonly used with the IEEE 802.15.4g FSK PHY. It shows the benefits that can be achieved with the use of channel diversity in high density environments. The primary goal of spreading transmissions across a set of channels is to enhance reliability by reducing the probability of collisions and reducing the impact of frequency selective impairments. The primary gain from channel diversity is reducing the effective duty cycle per channel and reducing aggregate occupation of a given channel. This also provides coexistence benefits for non-participating systems by reducing the effective interference footprint of the hopping systems. For the hopping system, when a dissimilar system occupies part of the band, hopping "around" can mitigate the impact of interfering systems.

The value increases with the number of available channels. The available number of channels may be limited in some regions in the sub-1 GHz bands. It depends on the probability that not all available channels are blocked all of the time, which of course increases with the number of channels. In some regions the available spectrum may not allow significant diversity and thus hopping may not improve coexistence in the presence of IEEE 802.11ah devices.

Some methods of frequency hopping can add significant latency depending on implementation choices. It may be necessary to defer a transmission opportunity until the next hop, and typically retransmissions following failed attempts should be attempted on a different channel than the initial attempt, which can add to the latency of each retransmission attempt.

Specific methods are discussed in the following subclauses. This clause deals with methods that switch among a defined channel set, termed channel hopping and also sometimes referred to as channel diversity.

9.4.2 Control methods

Some characteristics of popular hopping schemes are provided in this subclause.

Two commonly used control methods are listener directed and transmitter directed scheduling. In listener directed scheduling, each participating device determines a channel sequence and schedule it will follow for reception. This information is shared with devices that will communicate with the listener device. The sender is responsible for determining the correct channel at a given time to send to the targeted device. This is typically used for unicast exchanges. In transmitter directed scheduling, the sending device determines a schedule for transmission and makes this known to peer devices. Each device that intends to receive transmission is responsible for listening on the right channel at a given time. This is typically used for broadcast exchanges.

The time that is spent on a particular channel is termed as the dwell duration. When the dwell duration is less than the duration of a PHY protocol data unit (PPDU), this is termed as fast hopping. When the dwell duration is equal to or greater than the duration of a PPDU, this is termed as slow hopping.

IEEE Std 802.15.4w is an example of fast hopping: the PPDU is divided into multiple fragments, each sent on a different channel at a different time. In this example, forward error correction with interleaving is used so that the redundant coded information is transmitted on different channels. In this case frequency diversity is inherent in the PHY.

The application of hopping over IEEE 802.15.4 SUN FSK uses slow hopping, where one or more PPDUs are transmitted on a channel. With fixed dwell duration, the channel switch always occurs at the end of the dwell duration. If transmission cannot complete by the end of the dwell interval, the transmitter will wait for the next dwell interval. This approach provides predictable timing. Dynamic dwell duration is commonly used as well. In this approach a nominal dwell duration is known, but the time on the channel may be extended to complete a packet, packet and acknowledgment, or multiple packet exchange. Timing in this case is less predictable.

Some systems (e.g., TSCH) use a centralized or zone-wise control method, in which global synchronization is required and a global schedule is available. Once a device acquires the global time, it can join a schedule.

9.4.3 Hopping sequence selection

In effect, distributing transmission attempts dynamically over multiple channels improves the “luckiness” by reducing effective duty cycle per channel and thus collision probability. To achieve this, it is important that the method for generating sequences has a high probability that each participating device is using a unique pseudo-random channel sequence.

“Hopping” is a form of random channel access. Key to its effectiveness is a good approximation of randomness. The method used to generate sequences should produce a large number of unique sequences with a low probability that two participating devices will select the same channel for transmission at the same time. The sequence generated should provide a balanced distribution of transmission attempts across the available channels over a period of time.

Another quality of a good sequence generation scheme is that it avoids unintended synchronization. The method to generate device unique sequences should produce a large number of orthogonal sequences, that is, sequences that have few overlaps as the phase of the sequence is rotated. This property is improved by having a sequence generator that produces sequences much longer than the number of available channels.

9.4.4 Hopping sequence adaptation

Another consideration is adaptation to actual channel conditions. Many impairments in the RF environment may be frequency selective. Most schemes will thus include the ability to not use channels determined to be poor. Adaptive frequency hopping should be used when the number of available channels in the band is sufficient to allow for a large enough channel set.

Implementation of adaptive hopping should include consideration of the following:

- Evaluation of channel conditions based on repeatable metrics. Common metrics include packet failure rates.
- Dynamic evaluation is highly desirable. The environment varies over time, and a previously ‘bad’ channel may improve.
- Hysteresis to avoid too rapid abandonment of a channel. Infrequent failure is likely in an interference limited environment and/or when operating at low link margin.

9.4.5 Channel access

Access of an individual channel can use CSMA/CA, ALOHA, or hybrid techniques. Hopping lowers the effective duty cycle. With low effective duty cycle per channel, ALOHA may be most efficient.

When channel load is higher, CSMA/CA can improve performance. In some schemes, some channels may be more likely to exceed the ALOHA threshold, such as when the transmission channel is not random and/or when multiple nodes share transmission schedules for discovery, control, and management functions. Implementation of broadcast is an example of when it is necessary for multiple transmitters to use the same channel at the same time. When multiple transmitters are expected to target the same channel/time schedule with sufficient frequency to raise the effective channel loading, CSMA/CA should be used.

9.4.6 Recommendation for frequency hopping

Frequency hopping is recommended when a large number of channels are available and regulatory requirements are met.

9.5 Network offered load and duty cycle recommendation

As expected, the network load has major impact on IEEE Std 802.11ah and IEEE Std 802.15.4g coexistence performance. As the network load increases, the network performance degrades. However, in practice, the network load is determined by application, which indicates that lower layer technology is not able to adjust network load. Therefore, there is not much to be recommended for the network load.

For the radio device operating in the license-exempt bands, the duty cycle is regulated by the government. For example, in the sub-1 GHz bands, Japan requires that an active radio device cannot have a duty cycle greater than 10%. Europe even requires 1% of duty cycle for some sub-1 GHz bands. As a result, there is not much to be recommended for the duty cycle.

9.6 Network size recommendation

As illustrated in Guo, et al. [B18], network size, that is the number of devices in a network, impacts on coexistence performance of IEEE 802.11ah networks and IEEE 802.15.4g networks.

In fact, the number of devices can be adjusted during application deployment, which indicates that application developers have the opportunity to determine the network size based on cost consideration for the best performance.

In this recommended practice, an offered network load that is lower than or equal to 30 kb/s is referred to as “lower” and an offered network load that is higher than 30 kb/s is referred to as “higher”.

Recommendations:

- If the network load is lower for the IEEE 802.11ah network and the IEEE 802.15.4g network, the network size does not impact on coexistence performance very much. Therefore, the application developer should deploy as few devices as possible for cost purposes.
- If the network load for the IEEE 802.11ah network is higher and the network load for the IEEE 802.15.4g network is lower, the application developer should deploy as few as possible IEEE 802.11ah devices for cost purposes and especially for latency critical applications.
- If the network load for the IEEE 802.15.4g network is higher and the network load for IEEE 802.11ah network is lower, the application developer should deploy as many as possible IEEE 802.15.4g devices if the device is cheap, especially for reliability critical applications.

9.7 Frame size recommendation

9.7.1 Introduction

Frame size is a flexible parameter that can be configured without any restriction as long as application data is delivered to right destination with appropriate reliability and latency. However, the frame size selection should be based on the scenarios of the network load and the network size. IEEE Std 802.11ah and IEEE Std 802.15.4g coexistence performance based on frame size is presented in Guo, et al. [B18].

In this recommended practice, a network size that is smaller than or equal to 80 nodes is referred to as “small” and a network size that is more than 80 nodes is referred to as “large”. Also, a frame with payload smaller than 80 bytes is referred to as “small”, a frame with payload in between 80 bytes and 120 bytes is referred to as “medium”, and a frame with payload more than 120 bytes is referred to as “large”.

9.7.2 Small network size, high IEEE 802.11ah offered load, and low IEEE 802.15.4g offered load

9.7.2.1 IEEE 802.11ah frame size impact

IEEE 802.11ah frame size has little impact on IEEE 802.15.4g packet latency. IEEE 802.11ah frame size has impact on IEEE 802.15.4g packet delivery rate. Larger and medium IEEE 802.11ah frame size result in similar IEEE 802.15.4g packet delivery rate. However, smaller IEEE 802.11ah frame size decreases IEEE 802.15.4g packet delivery rate. IEEE 802.11ah frame size also impacts on IEEE 802.11ah packet delivery rate. Smaller IEEE 802.11ah frame size results in lower IEEE 802.11ah packet delivery rate compared to larger and medium frame sizes. IEEE 802.11ah frame size has a major impact on IEEE 802.11ah packet latency. Larger frame size increases IEEE 802.11ah packet latency compared to medium frame size.

Smaller frame size significantly increases IEEE 802.11ah packet latency, with 80% of IEEE 802.11ah packets delivered with latency greater 25 seconds, which is much longer than packet latency for larger and medium frame sizes. Therefore, IEEE 802.11ah stations should send packets with medium frame size.

9.7.2.2 IEEE 802.15.4g frame size impact

IEEE 802.15.4g frame size has no impact on IEEE 802.11ah packet delivery rate and has little impact on IEEE 802.15.4g packet latency. However, IEEE 802.15.4g frame size has impact on IEEE 802.15.4g packet delivery rate and IEEE 802.11ah packet latency. Smaller frame size decreases IEEE 802.15.4g packet delivery rate compared to medium frame size. Larger frame size slightly improves IEEE 802.15.4g packet delivery rate compared to medium frame size. In other words, IEEE 802.15.4g packet delivery rate is proportional to IEEE 802.15.4g frame size. IEEE 802.15.4g packet size has impact on IEEE 802.11ah packet latency. IEEE 802.11ah packet latency decreases slightly for smaller IEEE 802.15.4g frame size and increases moderately for larger IEEE 802.15.4g frame size. In other words, IEEE 802.11ah packet latency is also proportional to IEEE 802.15.4g frame size. Therefore, IEEE 802.15.4g nodes should send packets with larger packet size.

9.7.3 Small network size, low IEEE 802.11ah offered load, and high IEEE 802.15.4g offered load

9.7.3.1 IEEE 802.11ah frame size impact

IEEE 802.11ah frame size has no impact on IEEE 802.11ah packet delivery rate. IEEE 802.11ah frame size has little impact on IEEE 802.15.4g packet delivery rate and IEEE 802.15.4g packet latency. However, IEEE 802.11ah frame size has a moderate impact on IEEE 802.11ah packet latency. Larger frame size slightly increases IEEE 802.11ah packet latency compared to the medium frame size. Smaller frame size has longer packet latency than both larger and medium frame sizes. Therefore, IEEE 802.11ah nodes should send packets with medium frame size.

9.7.3.2 IEEE 802.15.4g frame size impact

IEEE 802.15.4g frame size has no impact on IEEE 802.11ah packet delivery rate and has little impact on IEEE 802.15.4g packet latency. However, IEEE 802.15.4g frame size has a major impact on IEEE 802.15.4g packet delivery rate. Smaller frame size significantly decreases IEEE 802.15.4g packet delivery rate compared to medium frame size. On the other hand, larger frame size improves IEEE 802.15.4g packet delivery rate compared to medium frame size. In other words, IEEE 802.15.4g packet delivery rate is proportional to IEEE 802.15.4g frame size. IEEE 802.15.4g packet size also has a major impact on IEEE 802.11ah packet latency. Smaller IEEE 802.15.4g frame size greatly increases IEEE 802.11ah packet latency. Overall, IEEE 802.11ah packet latency increases as IEEE 802.15.4g packet size decreases. In other words, IEEE 802.11ah packet latency is inversely proportional to IEEE 802.15.4g frame size. Therefore, IEEE 802.15.4g nodes should send packets with larger packet size.

9.7.4 Large network size, high IEEE 802.11ah offered load, and low IEEE 802.15.4g offered load

9.7.4.1 IEEE 802.11ah frame size impact

IEEE 802.11ah frame size has a slight impact on IEEE 802.11ah packet delivery rate. Smaller frame size slightly decreases IEEE 802.11ah packet delivery rate. IEEE 802.11ah frame size has moderate impact on

IEEE 802.15.4g packet delivery rate. Larger IEEE 802.11ah frame size slightly increases IEEE 802.15.4g packet delivery rate compared to medium frame size. However, smaller IEEE 802.11ah frame size moderately decreases IEEE 802.15.4g packet delivery rate compared to medium frame size. IEEE 802.11ah frame size has little impact on IEEE 802.15.4g packet latency. IEEE 802.11ah frame size has a major impact on IEEE 802.11ah packet latency. Larger frame size moderately increases IEEE 802.11ah packet latency compared to medium frame size. Smaller frame size significantly increases IEEE 802.11ah packet latency, with 85% of IEEE 802.11ah packets delivered with latency greater than 50 seconds, which is much longer than packet latency for larger and medium frame sizes. Therefore, IEEE 802.11ah nodes should send packets with medium frame size.

9.7.4.2 IEEE 802.15.4g frame size impact

IEEE 802.15.4g frame size has little impact on IEEE 802.11ah packet delivery rate and IEEE 802.15.4g packet latency. However, IEEE 802.15.4g frame size has impact on IEEE 802.15.4g packet delivery rate and IEEE 802.11ah packet latency. Smaller frame size moderately decreases IEEE 802.15.4g packet delivery rate compared to medium frame size. Larger frame size slightly improves IEEE 802.15.4g packet delivery rate compared to medium frame size. In other words, IEEE 802.15.4g packet delivery rate is proportional to IEEE 802.15.4g frame size. IEEE 802.15.4g packet size has impact on IEEE 802.11ah packet latency. IEEE 802.11ah packet latency decreases slightly for smaller IEEE 802.15.4g frame size and increases moderately for larger IEEE 802.15.4g frame size. In other words, IEEE 802.11ah packet latency is also proportional to IEEE 802.15.4g frame size. Therefore, IEEE 802.15.4g nodes should send packets with larger packet size.

9.7.5 Large network size, low IEEE 802.11ah offered load, and high IEEE 802.15.4g offered load

9.7.5.1 IEEE 802.11ah frame size impact

IEEE 802.11ah frame size has little impact on IEEE 802.11ah packet delivery rate. Larger frame size slightly decreases IEEE 802.11ah packet delivery rate. IEEE 802.11ah frame size has slight impact on IEEE 802.15.4g packet delivery rate and IEEE 802.15.4g packet latency. However, IEEE 802.11ah frame size has a moderate impact on IEEE 802.11ah packet latency. Larger frame size increases IEEE 802.11ah packet latency compared to the medium frame size. Smaller frame size has longer packet latency than both larger and medium frame sizes. Therefore, IEEE 802.11ah nodes should send packets with medium frame size.

9.7.5.2 IEEE 802.15.4g frame size impact

IEEE 802.15.4g frame size has little impact on IEEE 802.11ah packet delivery rate and IEEE 802.15.4g packet latency. However, IEEE 802.15.4g frame size has a major impact on IEEE 802.15.4g packet delivery rate. Smaller frame size significantly decreases IEEE 802.15.4g packet delivery rate compared to medium frame size. On the other hand, larger frame size improves IEEE 802.15.4g packet delivery rate compared to medium frame size. In other words, IEEE 802.15.4g packet delivery rate is proportional to IEEE 802.15.4g frame size. IEEE 802.15.4g packet size also has a major impact on IEEE 802.11ah packet latency. Larger IEEE 802.15.4g frame size slightly increases IEEE 802.11ah packet latency. Smaller IEEE 802.15.4g frame size significantly increases IEEE 802.11ah packet latency. Therefore, IEEE 802.15.4g nodes should send packets with larger frame size if the IEEE 802.15.4g packet delivery rate is critical and IEEE 802.15.4g nodes should send packets with medium frame size if the IEEE 802.11ah packet latency is critical.

9.7.6 Summary of frame size recommendations

Improved coexistence can be achieved when adjusting the frame size of each system according to the network conditions. Factors that affect the selection of frame size include network size, offered load for each network, and performance priorities. The performance priorities include the packet delivery rate and packet latency requirements for each of the coexisting networks. In three of the four scenarios, an optimization for both packet delivery and latency performance can be achieved by selecting a medium packet size for the IEEE 802.11ah stations and a larger packet size for the IEEE 802.15.4g stations. In the fourth scenario, adjusting the optimal IEEE 802.15.4g packet size selection depends on the desired optimization, IEEE 802.15.4 packet delivery rate or IEEE 802.11ah latency. This is illustrated in Table 7.

Table 7—Summary of frame size recommendations

<table>
<tr><th colspan="4">Scenario</th><th rowspan="3">Performance priority</th><th colspan="2" rowspan="2">Frame size recommendation</th></tr>
<tr><th rowspan="2">Reference</th><th rowspan="2">Network size</th><th colspan="2">Offered network load</th></tr>
<tr><th>IEEE Std 802.11ah</th><th>IEEE Std 802.15.4g</th><th>IEEE Std 802.11ah</th><th>IEEE Std 802.15.4g</th></tr>
<tr><td rowspan="2">9.7.2</td><td rowspan="2">Small</td><td rowspan="2">High</td><td rowspan="2">Low</td><td>IEEE 802.15.4g packet delivery rate</td><td rowspan="2">Medium</td><td rowspan="2">Large</td></tr>
<tr><td>IEEE 802.11ah packet latency</td></tr>
<tr><td rowspan="2">9.7.3</td><td rowspan="2">Small</td><td rowspan="2">Low</td><td rowspan="2">High</td><td>IEEE 802.15.4g packet delivery rate</td><td rowspan="2">Medium</td><td rowspan="2">Large</td></tr>
<tr><td>IEEE 802.11ah packet latency</td></tr>
<tr><td rowspan="2">9.7.4</td><td rowspan="2">Large</td><td rowspan="2">High</td><td rowspan="2">Low</td><td>IEEE 802.15.4g packet delivery rate</td><td rowspan="2">Medium</td><td rowspan="2">Large</td></tr>
<tr><td>IEEE 802.11ah packet latency</td></tr>
<tr><td rowspan="2">9.7.5</td><td rowspan="2">Large</td><td rowspan="2">Low</td><td rowspan="2">High</td><td>IEEE 802.15.4g packet delivery rate</td><td rowspan="2">Medium</td><td>Large</td></tr>
<tr><td>IEEE 802.11ah packet latency</td><td>Medium</td></tr>
</table>

9.8 Backoff parameter recommendation

9.8.1 Introduction

In some cases, it may be possible to configure backoff parameters. In that case, the backoff parameters should be selected for better coexistence performance. The selection of backoff parameter depends on the scenarios of the network load and the network size. Guo, et al. [B18] presents IEEE Std 802.11ah and IEEE Std 802.15.4g coexistence performance based on backoff parameters.

In this recommended practice: IEEE 802.11ah CWmin is referred to as the “smaller IEEE 802.11ah backoff contention window” and IEEE 802.11ah CWmax is referred to as the “larger IEEE 802.11ah backoff contention window”; macMinBE = 2, macMaxBE = 4, and macMaxCSMABackoffs = 3 are referred to as the “smaller IEEE 802.15.4g backoff parameters”, macMinBE = 2, macMaxBE = 5, and macMaxCSMABackoffs = 4 are referred to as the “medium IEEE 802.15.4g backoff parameters”; and macMinBE = 2, macMaxBE = 6 and macMaxCSMABackoffs = 5 are referred to as the “larger IEEE 802.15.4g backoff parameters”.

9.8.2 Small network size, high IEEE 802.11ah offered load, and low IEEE 802.15.4g offered load

Table 8 summarizes the backoff parameter impact for the case of small network size, high IEEE 802.11ah network traffic, and low IEEE 802.15.4g network traffic.

Table 8—Backoff parameter impact for small network size, high IEEE 802.11ah network traffic, and low IEEE 802.15.4g network traffic

Parameter	Effect on IEEE Std 802.11ah		Effect on IEEE Std 802.15.4g	
	Delivery rate	Latency	Delivery rate	Latency
IEEE 802.11ah backoff contention window size	None	Moderate	Small	Small
IEEE 802.15.4g backoff parameters	None	Small	Moderate	Significant

9.8.2.1 IEEE 802.11ah backoff contention window size impact

IEEE 802.11ah contention window size has no impact on IEEE 802.11ah packet delivery rate. IEEE 802.11ah contention window size has little impact on IEEE 802.15.4g packet delivery rate and IEEE 802.15.4g packet latency. IEEE 802.11ah contention window size has moderate impact on IEEE 802.11ah packet latency. Smaller contention window moderately increases IEEE 802.11ah packet latency compared to default contention window size configuration. Larger contention window size further increases IEEE 802.11ah packet latency. Therefore, IEEE 802.11ah nodes should follow standard backoff contention window configuration.

9.8.2.2 IEEE 802.15.4g backoff parameter impact

IEEE 802.15.4g backoff parameters have no impact on IEEE 802.11ah packet delivery rate. IEEE 802.15.4g backoff parameters have impact on IEEE 802.15.4g packet delivery rate. Smaller backoff parameters decrease IEEE 802.15.4g packet delivery rate compared to medium backoff parameters. Larger backoff parameters improve IEEE 802.15.4g packet delivery rate compared to medium backoff parameters. In other words, IEEE 802.15.4g packet delivery rate is proportional to IEEE 802.15.4g backoff parameters. IEEE 802.15.4g backoff parameters have small impact on IEEE 802.11ah packet latency and IEEE 802.15.4g packet latency. Both smaller and larger backoff parameters slightly decrease IEEE 802.11ah packet latency. However, IEEE 802.15.4g packet latency is proportional to backoff parameters. Therefore, IEEE 802.15.4g nodes should send packets with larger backoff parameters if IEEE 802.15.4g packet delivery rate is critical and send packets with smaller backoff parameters if IEEE 802.15.4g packet latency is critical.

9.8.3 Small network size, low IEEE 802.11ah offered load, and high IEEE 802.15.4g offered load

Table 9 summarizes the backoff parameter impact for the case of small network size, low IEEE 802.11ah network traffic, and high IEEE 802.15.4g network traffic.

Table 9—Backoff parameter impact for small network size, low IEEE 802.11ah network traffic, and high IEEE 802.15.4g network traffic

Parameter	Effect on IEEE Std 802.11ah		Effect on IEEE Std 802.15.4g	
	Delivery rate	Latency	Delivery rate	Latency
IEEE 802.11ah backoff contention window size	None	Moderate	Small	None
IEEE 802.15.4g backoff parameters	None	Small	Moderate	Significant

9.8.3.1 IEEE 802.11ah backoff contention window size impact

IEEE 802.11ah contention window size has no impact on IEEE 802.11ah packet delivery rate and IEEE 802.15.4g packet latency. IEEE 802.11ah contention window size has little impact on IEEE 802.15.4g packet delivery rate. However, IEEE 802.11ah contention window size has moderate impact on IEEE 802.11ah packet latency. Larger contention window size increases IEEE 802.11ah packet latency compared to the default contention window size. Smaller contention window size further increases IEEE 802.11ah packet latency. Therefore, IEEE 802.11ah nodes should follow standard backoff contention window size configuration.

9.8.3.2 IEEE 802.15.4g backoff parameter impact

IEEE 802.15.4g backoff parameters have no impact on IEEE 802.11ah packet delivery rate. IEEE 802.15.4g backoff parameters have impact on IEEE 802.15.4g packet delivery rate. Smaller backoff parameters decrease IEEE 802.15.4g packet delivery rate compared to medium backoff parameters. Larger backoff parameters improve IEEE 802.15.4g packet delivery rate compared to medium backoff parameters. In other words, IEEE 802.15.4g packet delivery rate is proportional to IEEE 802.15.4g backoff parameters. IEEE 802.15.4g backoff parameters have small impact on IEEE 802.11ah packet latency and IEEE 802.15.4g packet latency. Smaller backoff parameters slightly increase IEEE 802.11ah packet latency. Larger backoff parameters decrease IEEE 802.11ah packet latency. In other words, IEEE 802.11ah packet latency is inversely proportional to IEEE 802.15.4g backoff parameters. However, IEEE 802.15.4g packet latency is proportional to backoff parameters, that is, smaller backoff parameters decrease IEEE 802.15.4g packet latency and larger backoff parameters increase IEEE 802.15.4g packet latency. Therefore, IEEE 802.15.4g nodes should send packets with larger backoff parameters if IEEE 802.15.4g packet delivery rate is critical and send packets with smaller backoff parameters if IEEE 802.15.4g packet latency is critical.

9.8.4 Large network size, high IEEE 802.11ah offered load, and low IEEE 802.15.4g offered load

Table 10 summarizes the backoff parameter impact for the case of large network size, high IEEE 802.11ah network traffic, and low IEEE 802.15.4g network traffic.

Table 10 —Backoff parameter impact for large network size, high IEEE 802.11ah network traffic, and low IEEE 802.15.4g network traffic

Parameter	Effect on IEEE Std 802.11ah		Effect on IEEE Std 802.15.4g	
	Delivery rate	Latency	Delivery rate	Latency
IEEE 802.11ah backoff contention window size	Small	Significant	Small	None
IEEE 802.15.4g backoff parameters	Small	Moderate	Moderate	Small

9.8.4.1 IEEE 802.11ah backoff contention window size impact

IEEE 802.11ah contention window size has no impact on IEEE 802.15.4g packet latency. IEEE 802.11ah contention window size has little impact on IEEE 802.11ah packet delivery rate and IEEE 802.15.4g packet delivery rate. However, IEEE 802.11ah contention window size has impact on IEEE 802.11ah packet latency. Smaller IEEE 802.11ah contention window size moderately decreases IEEE 802.11ah packet latency compared to default contention window size. Larger contention window size increases the packet latency of 70% of IEEE 802.11ah packets and decreases packet latency of 30% of IEEE 802.11ah packets. Therefore, IEEE 802.11ah nodes should send packets using smaller contention window size.

9.8.4.2 IEEE 802.15.4g backoff parameter impact

IEEE 802.15.4g backoff parameters have little impact on IEEE 802.11ah packet delivery rate. However, IEEE 802.15.4g backoff parameters have impact on IEEE 802.15.4g packet delivery rate, IEEE 802.11ah packet latency and IEEE 802.15.4g packet latency. Compared to medium backoff parameters, smaller backoff parameters slightly decrease IEEE 802.15.4g packet delivery rate and larger backoff parameters slightly improve IEEE 802.15.4g packet delivery rate. In other words, IEEE 802.15.4g packet delivery rate is proportional to IEEE 802.15.4g backoff parameters. IEEE 802.15.4g backoff parameters have small impact on IEEE 802.15.4g packet latency. IEEE 802.15.4g backoff parameters have moderate impact on IEEE 802.11ah packet latency. Smaller IEEE 802.15.4g backoff parameters moderately decrease IEEE 802.11ah packet latency compared to medium backoff parameters. Larger IEEE 802.15.4g backoff parameters further decrease IEEE 802.11ah packet latency. Therefore, IEEE 802.15.4g nodes should send packets with larger backoff parameters.

9.8.5 Large network size, low IEEE 802.11ah offered load, and high IEEE 802.15.4g offered load

Table 11 summarizes the backoff parameter impact for the case of large network size, low IEEE 802.11ah network traffic, and high IEEE 802.15.4g network traffic.

Table 11 —Backoff parameter impact for large network size, low IEEE 802.11ah network traffic, and high IEEE 802.15.4g network traffic

Parameter	Effect on IEEE Std 802.11ah		Effect on IEEE Std 802.15.4g	
	Delivery rate	Latency	Delivery rate	Latency
IEEE 802.11ah backoff contention window size	Small	Moderate	Small	Small
IEEE 802.15.4g backoff parameters	Small	Moderate	Moderate	Moderate

9.8.5.1 IEEE 802.11ah backoff contention window size impact

IEEE 802.11ah contention window size has little impact on IEEE 802.11ah packet delivery rate, IEEE 802.15.4g packet delivery rate, and IEEE 802.15.4g packet latency. However, IEEE 802.11ah contention window size has impact on IEEE 802.11ah packet latency. Larger contention window size increases IEEE 802.11ah packet latency compared to the default contention window size. Smaller IEEE 802.11ah contention window size decreases IEEE 802.11ah packet latency compared to the default contention window size. Therefore, IEEE 802.11ah nodes should send packets with smaller backoff contention window size.

9.8.5.2 IEEE 802.15.4g backoff parameter impact

IEEE 802.15.4g backoff parameters have little impact on IEEE 802.11ah packet delivery rate. However, IEEE 802.15.4g backoff parameters have impact on IEEE 802.15.4g packet delivery rate, IEEE 802.11ah packet latency, and IEEE 802.15.4g packet latency. Compared to medium backoff parameters, larger backoff parameters slightly increase IEEE 802.15.4g packet delivery rate compared to smaller and medium backoff parameters. IEEE 802.15.4g backoff parameters have impact on IEEE 802.15.4g packet latency. Compared to medium backoff parameters, smaller IEEE 802.15.4g backoff parameters moderately decrease IEEE 802.15.4g packet latency and larger IEEE 802.15.4g backoff parameters moderately increase IEEE 802.15.4g packet latency. IEEE 802.15.4g backoff parameters have moderate impact on IEEE 802.11ah packet latency. Compared to medium backoff parameters, smaller IEEE 802.15.4g backoff parameters moderately increase IEEE 802.11ah packet latency and larger IEEE 802.15.4g backoff parameters decrease IEEE 802.11ah packet latency. In other words, IEEE 802.11ah packet latency is inversely proportional to

IEEE 802.15.4g backoff parameters. Therefore, IEEE 802.15.4g nodes should send packets with larger backoff parameters if IEEE 802.11ah packet latency is critical and send packets with smaller backoff parameters if IEEE 802.15.4g packet latency is critical.

9.8.6 Summary of backoff parameter recommendations

Table 12 summarizes backoff parameter recommendations. Selection of the IEEE 802.11ah contention window size is dominated by the network scenario. For each scenario, all four performance priorities are optimized by selecting the contention window as shown. Selection of the IEEE 802.15.4g backoff parameter values depends on both network scenario and desired performance priority, as indicated in Table 12 with "larger" or "smaller" corresponding to the definitions in 9.8.1. Where neither is specified, the selection of either yields similar performance.

Table 12—Summary of backoff parameter recommendations

Scenario				Performance priority	Backoff parameter recommendation	
Reference	Network size	Offered network load				
		IEEE Std 802.11ah	IEEE Std 802.15.4g		IEEE 802.11ah CW	IEEE 802.15.4g backoff parameters
9.8.2	Small	High	Low	IEEE 802.15.4g packet delivery rate	Standard	Larger
				IEEE 802.11ah packet latency		—
				IEEE 802.15.4g packet latency		Smaller
				IEEE 802.11ah packet delivery rate		—
9.8.3	Small	Low	High	IEEE 802.15.4g packet delivery rate	Standard	Larger
				IEEE 802.11ah packet latency		—
				IEEE 802.15.4g packet latency		Smaller
				IEEE 802.11ah packet delivery rate		—
9.8.4	Large	High	Low	IEEE 802.15.4g packet delivery rate	Smaller	Larger
				IEEE 802.11ah packet latency		Larger
				IEEE 802.15.4g packet latency		—
				IEEE 802.11ah packet delivery rate		—
9.8.5	Large	Low	High	IEEE 802.15.4g packet delivery rate	Smaller	—
				IEEE 802.11ah packet latency		Larger
				IEEE 802.15.4g packet latency		Smaller
				IEEE 802.11ah packet delivery rate		—

9.9 PHY parameter recommendation

The IEEE 802.11ah ED threshold is at least 10 dB higher than the IEEE 802.15.4g receiver sensitivity, which causes readable IEEE 802.15.4g packet transmission to be ignored by IEEE 802.11ah channel sensing. As a result, the probability of collision between IEEE 802.11ah transmission and IEEE 802.15.4g transmission increases. Therefore, it is recommended that an IEEE 802.11ah device should adjust its ED threshold if it has detected the coexistence of IEEE 802.15.4g devices. For example, the α-Fairness based ED-CCA mechanism can be applied for this purpose.

The IEEE 802.11ah CCA time is much shorter than the IEEE 802.15.4g CCA time. Therefore, it is recommended that an IEEE 802.11ah device should increase its CCA time if it has detected the coexistence of IEEE 802.15.4g devices. The increased CCA time allows IEEE 802.11ah devices to detect more IEEE 802.15.4g packet transmissions.

9.10 Application-based recommendation

Application developers should select technology based on application requirements such as network load, distribution of network load, data packet delivery rate, data packet latency, cost, device lifetime, power source, and deployment environment. It is costly if the deployed system does not work well.

Application developers should consider the potential of coexistence with other systems already deployed or to be deployed. If coexistence is possible, coexistence factors such as interference mitigation technology availability and coexistence behavior of the technology should be considered. The devices should be deployed to positions that have better communication potential and less interference from other devices. Application developers are recommended to provide devices with the capability to detect interference sources.

Application developers should also organize data in an efficient way so that lower layer technologies have a better chance for successful transmission.

9.11 Coexistence method selection recommendation

Multiple coexistence methods may be available for each network/device. An IEEE 802.11ah network/device needs to select a coexistence method that suits the condition of the network/device well.

Figure 17 shows a flow chart of coexistence method selection for IEEE 802.11ah networks.

Similarly, there are multiple coexistence methods available for an IEEE 802.15.4g network/device. An IEEE 802.15.4g network/device also needs to select a coexistence method that fits the condition of the IEEE 802.15.4g network/device well.

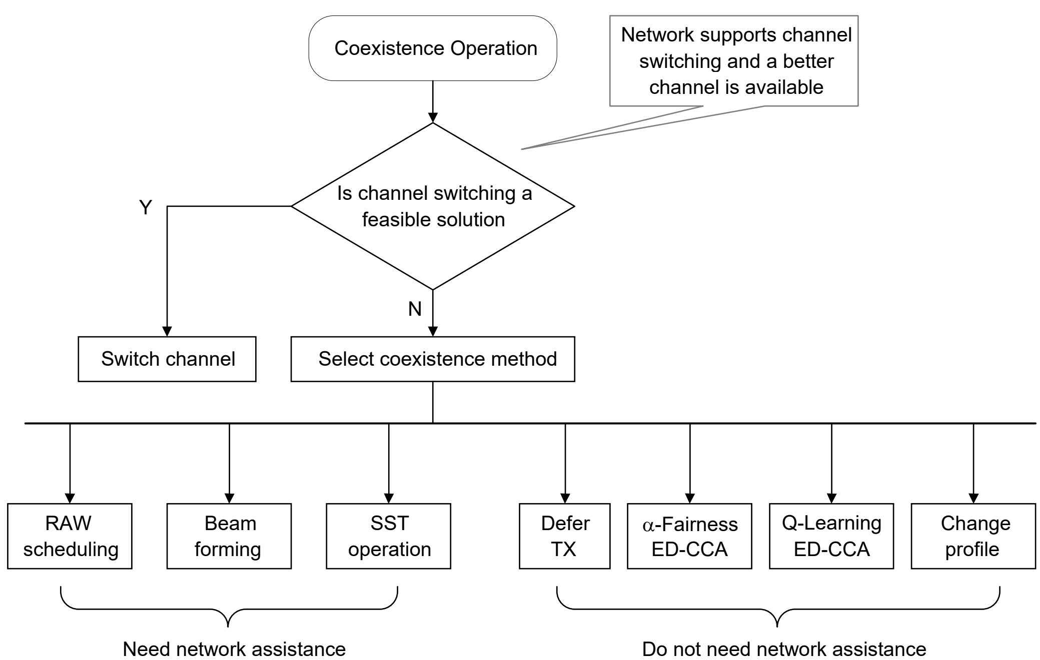

Figure 17—IEEE Std 802.11ah coexistence method selection

Figure 18 shows a flow chart of coexistence method selection for IEEE 802.15.4g networks.

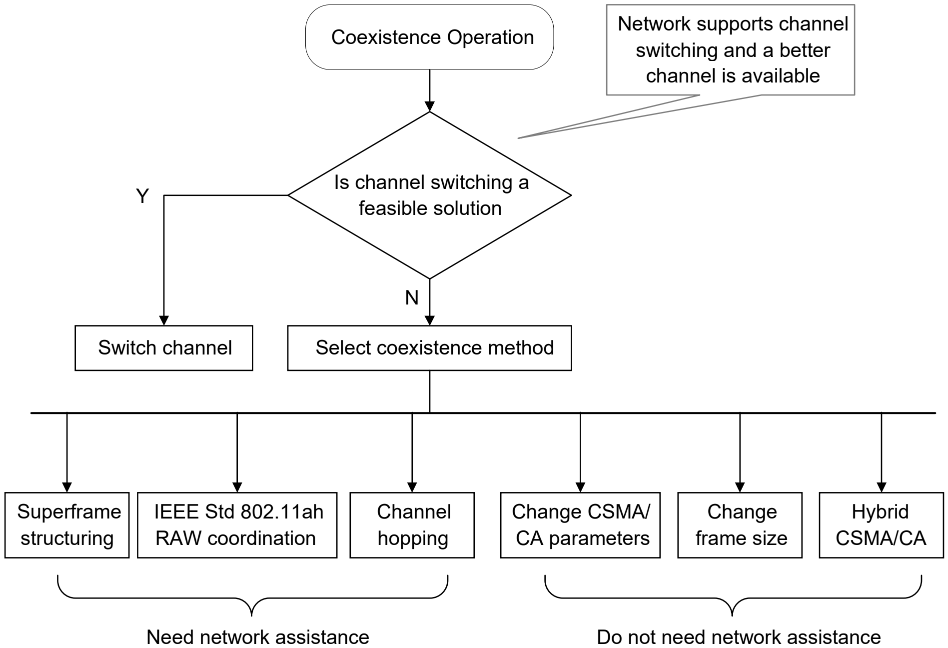

Figure 18 —IEEE Std 802.15.4g coexistence method selection

Annex A

(informative)

Coexistence fairness assessment

Applying a coexistence method is done to improve coexistence performance. In practice, network resources are constrained. In some cases, one network may need to sacrifice in order to have fair network resource sharing such as channel access.

To evaluate the fairness of the coexistence method, Nagai, et al. [B34] presents a fairness index for two coexisting networks by using a metric of normalized throughput, which is defined as the measured throughput divided by the offered load. The fairness index is defined as shown in Equation (A.1).

$$Fairness\_Index = \frac{\left(\Sigma_{i=1}^{m} x_i + \Sigma_{j=1}^{n} y_j\right)^2}{(n+m)\left(\Sigma_{i=1}^{m} x_i^2 + \Sigma_{j=1}^{n} y_j^2\right)} \tag{A.1}$$

where

m	is the number of devices in the first network
n	is the number of devices in the second network
x_i	is the normalized throughput for device i in the first network
y_j	is the normalized throughput for device j in the second network

The performance of this fairness index has been evaluated by using an IEEE 802.11ah network and an IEEE 802.15.4g network. One of the simulation scenarios presented in Guo, et al. [B20] was used to evaluate the fairness index. Using standard coexistence mechanisms defined in IEEE Std 802.11ah, the IEEE 802.11ah network achieved a 99.9% packet delivery rate and the IEEE 802.15.4g network only delivered 54% of data packets. In this case, the fairness index is 0.916. Applying α-Fairness based ED-CCA improves the IEEE 802.15.4g packet delivery rate to 68% while maintaining the IEEE 802.11ah packet delivery rate. In this case, the fairness index is 0.965. Applying Q-Learning based CSMA/CA improves the IEEE 802.15.4g packet delivery rate to 71% while maintaining the IEEE 802.11ah packet delivery rate. In this case, the fairness index is 0.972. Applying both α-Fairness based ED-CCA and Q-Learning based CSMA/CA improves the IEEE 802.15.4g packet delivery rate to 77% while degrading the IEEE 802.11ah packet delivery rate to 99.8%. In this case, the fairness index is 0.983. This indicates that a fairness index of 1.0 gives fair coexistence.

Annex B

(informative)

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