



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

STANDARDS

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

Developed by the

LAN/MAN Standards Committee
of the
IEEE Computer Society

Approved 25 March 2021

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®

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2021 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 26 April 2021. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

PDF: ISBN 978-1-5044-7487-0 STD24652
Print: ISBN 978-1-5044-7488-7 STDPD24652

IEEE prohibits discrimination, harassment, and bullying.

For more information, visit <https://www.ieee.org/about/corporate/governance/p9-26.html>.

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE Standards documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page (<https://standards.ieee.org/ipr/disclaimers.html>), appear in all standards and may be found under the heading “Important Notices and Disclaimers Concerning IEEE Standards Documents.”

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE SA) Standards Board. IEEE develops its standards through an accredited consensus development process, which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE Standards are documents developed by volunteers with scientific, academic, and industry-based expertise in technical working groups. Volunteers are not necessarily members of IEEE or IEEE SA, and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE does not warrant or represent the accuracy or completeness of the material contained in its standards, and expressly disclaims all warranties (express, implied and statutory) not included in this or any other document relating to the standard, including, but not limited to, the warranties of: merchantability; fitness for a particular purpose; non-infringement; and quality, accuracy, effectiveness, currency, or completeness of material. In addition, IEEE disclaims any and all conditions relating to results and workmanlike effort. In addition, IEEE does not warrant or represent that the use of the material contained in its standards is free from patent infringement. IEEE Standards documents are supplied “AS IS” and “WITH ALL FAULTS.”

Use of an IEEE standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity, nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: THE NEED TO PROCURE SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE UPON ANY STANDARD, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Translations

The IEEE consensus development process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English version published by IEEE is the approved IEEE standard.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE SA Standards Board Operations Manual shall not be considered or inferred to be the official position of IEEE or any of its committees and shall not be considered to be, nor be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that the presenter's views should be considered the personal views of that individual rather than the formal position of IEEE, IEEE SA, the Standards Committee, or the Working Group.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE or IEEE SA. However, **IEEE does not provide interpretations, consulting information, or advice pertaining to IEEE Standards documents.**

Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its Societies and Standards Coordinating Committees are not able to provide an instant response to comments, or questions except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in evaluating comments or in revisions to an IEEE standard is welcome to join the relevant IEEE working group. You can indicate interest in a working group using the Interests tab in the Manage Profile & Interests area of the [IEEE SA myProject system](#). An IEEE Account is needed to access the application.

Comments on standards should be submitted using the [Contact Us](#) form.

Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not constitute compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Data privacy

Users of IEEE Standards documents should evaluate the standards for considerations of data privacy and data ownership in the context of assessing and using the standards in compliance with applicable laws and regulations.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under US and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, IEEE does not waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate licensing fees, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400; <https://www.copyright.com/>. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every 10 years. When a document is more than 10 years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit [IEEE Xplore](#) or [contact IEEE](#). For more information about the IEEE SA or IEEE's standards development process, visit the IEEE SA Website.

Errata

Errata, if any, for all IEEE standards can be accessed on the [IEEE SA Website](#). Search for standard number and year of approval to access the web page of the published standard. Errata links are located under the Additional Resources Details section. Errata are also available in [IEEE Xplore](#). Users are encouraged to periodically check for errata.

Patents

IEEE Standards are developed in compliance with the [IEEE SA Patent Policy](#).

IMPORTANT NOTICE

IEEE Standards do not guarantee or ensure safety, security, health, or environmental protection, or ensure against interference with or from other devices or networks. IEEE Standards development activities consider research and information presented to the standards development group in developing any safety recommendations. Other information about safety practices, changes in technology or technology implementation, or impact by peripheral systems also may be pertinent to safety considerations during implementation of the standard. Implementers and users of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations.

Participants

At the time this IEEE recommended practice was completed, the IEEE 802.19 Working Group had the following membership:

Stephen Shellhammer, *IEEE 802.19 Working Group Chair*
Tuncer Baykas, *IEEE 802.19 Working Group Vice-Chair*

Benjamin A. Rolfe, *Task Group 3 Chair*
Shoichi Kitazawa, *Task Group 3 Vice-Chair*
Jianlin Guo, *Task Group 3 Technical Editor*
Harry Bims, *Task Group 3 Secretary*

Osama Aboulmagd
Eugene Baik
David Barras
William Carney
Luc Darmon
Subir Das
Rolf de Vegt
Anthony Fagan
Sho Furuichi
James Gilb
Tim Godfrey
Timothy Harrington
Chris Hartman
Robert Heile
Jay Holcomb
Sung Hyun Hwang

Yasuhiko Inoue
Vincent Knowles Jones IV
Paul Kettle
James Lansford
Jae Seung Lee
Apurva Mody
Yuichi Morioka
Yukimasa Nagai
Alireza Nejatian
Jaroslaw Niewczas
Paul Nikolich
Yujin Noh
Philip Orlik
Stephen [kiwin] Palm
James Petranovich
Demir Rakanovic

Joerg Robert
Jon Walter Rosdahl
Kazuyuki Sakoda
Ioannis Sarris
Naotaka Sato
Peter Sauer
Dorothy Stanley
Takenori Sumi
Chen Sun
Mineo Takai
Prabodh Varshney
Billy Verso
Leif Wilhelmsson
Hassan Yaghoobi
Kazuto Yano
Chunhui Zhu

The following members of the individual Standards Association balloting group voted on this recommended practice. Balloters may have voted for approval, disapproval, or abstention.

Robert Aiello
Song-Haur An
Amelia Andersdotter
Abdoulaye Berthe
Harry Bims
William Byrd
Paul Cardinal
Juan Carreon
Pin Chang
Charles Cook
Todor Cooklev
Hendricus De Ruijter
Liu Fangfang
Avraham Freedman
David Goodall
Jianlin Guo
Marco Hernandez
Werner Hoelzl
Klaus Hueske
Tetsushi Ikegami
Yasuhiko Inoue

Pranav Jha
Volker Jungnickel
Piotr Karocki
Stuart Kerry
Yongbum Kim
Shoichi Kitazawa
Pi-Cheng Law
Rick Murphy
Yukimasa Nagai
Nabil Nasser
Philip Orlik
Satoshi Oyama
Bansi Patel
Arumugam Paventhan
Clinton Powell
Venkatesha Prasad
R. K. Rannow
Lakshman Raut
Maximilian Riegel
Robert Robinson
Benjamin A. Rolfe

Ruben E. Salazar Cardozo
Stephan Sand
Naotaka Sato
Stephen Shellhammer
Ian Sherlock
Dorothy Stanley
Walter Struppler
Don Sturek
Mark Sturza
Takenori Sumi
Mark-Rene Uchida
Dmitri Varsanofiev
Prabodh Varshney
John Vergis
Billy Verso
Xiaohui Wang
Lisa Ward
Scott Willy
Kazuto Yano
Yu Yuan
Oren Yuen

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

Gary Hoffman, *Chair*
Jon Walter Rosdahl, *Vice Chair*
John D. Kulick, *Past Chair*
Konstantinos Karachalios, *Secretary*

Edward A. Addy
Doug Edwards
Ramy Ahmed Fathy
J. Travis Griffith
Joseph L. Koepfinger*
Thomas Koshy
David J. Law

Howard Li
Daozhuang Lin
Kevin Lu
Daleep C. Mohla
Chenhui Niu
Damir Novosel
Annette Reilly
Dorothy Stanley

Mehmet Ulema
Lei Wang
F. Keith Waters
Karl Weber
Sha Wei
Howard Wolfman
Daidi Zhong

*Member Emeritus

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

1. Overview	13
1.1 Scope	13
1.2 Word usage	13
2. Normative references	14
3. Definitions, acronyms, and abbreviations	14
3.1 Definitions	14
3.2 Acronyms and abbreviations	15
4. Overview of the sub-1 GHz frequency band systems	17
4.1 Introduction	17
4.2 IEEE Std 802.11ah	17
4.3 IEEE Std 802.15.4g	18
4.4 IEEE Std 802.15.4w	20
4.5 LoRa	21
4.6 Sigfox	22
4.7 ETSI TS 103 357	22
4.7.1 Lfour family	22
4.7.2 Telegram splitting ultra narrow band (TS-UNB) family	23
4.7.3 Dynamic Downlink Ultra Narrow Band (DD-UNB) family	23
4.8 Summary	23
5. Use cases of the sub-1 GHz frequency band systems	24
5.1 Introduction	24
5.2 IEEE Std 802.11ah use cases	24
5.3 IEEE Std 802.15.4g use cases	25
5.4 LoRa use cases	25
5.5 Sigfox use cases	25
5.6 IEEE Std 802.15.4w use cases	25
6. Sub-1 GHz frequency band spectrum allocation	26
6.1 Introduction	26
6.2 United States	26
6.3 Japan	27
6.4 Europe	28
7. Coexistence mechanisms and issues of the sub-1 GHz frequency band systems	29
7.1 Introduction	29
7.2 IEEE Std 802.11ah coexistence mechanisms	30
7.3 IEEE Std 802.15.4g coexistence mechanisms	30
7.4 IEEE Std 802.15.4w coexistence mechanisms	31
7.5 LoRa coexistence mechanisms	31
7.6 Sigfox coexistence mechanisms	32
7.7 Noise and interference measurement in sub-1 GHz bands	32
7.7.1 Introduction	32
7.7.2 920 MHz band measurements in Japan	33
7.7.3 868 MHz band measurement in Europe	35
7.8 Coexistence performance of IEEE Std 802.11ah and IEEE Std 802.15.4g	38
7.8.1 Data packet delivery rate	38
7.8.2 Data packet latency	38

7.8.3 IEEE Std 802.11ah and IEEE Std 802.15.4g coexistence issues to be addressed.....	39
7.9 Coexistence performance of IEEE Std 802.11ah and IEEE Std 802.15.4w	39
7.10 Cause of coexistence issue between IEEE Std 802.11ah and IEEE Std 802.15.4g	39
7.11 IEEE Std 802.11ah and IEEE Std 802.15.4g coexistence performance improvement	41
8. IEEE Std 802.11ah and IEEE Std 802.15.4g coexistence model	42
8.1 Introduction	42
8.2 Coexistence operation.....	42
8.2.1 Centralized coexistence.....	42
8.2.2 Cooperated (or collaborated) coexistence	42
8.2.3 Distributed network level coexistence	43
8.2.4 Distributed device level coexistence	43
8.3 Coexistence model.....	43
8.3.1 Coexistence model based on network coordination.....	43
8.3.2 Coexistence model based on scope of coexistence operation	44
9. IEEE Std 802.11ah and IEEE Std 802.15.4g coexistence methods and recommendations.....	44
9.1 Introduction	44
9.2 Coordinated coexistence methods and recommendations.....	45
9.2.1 Introduction.....	45
9.2.2 Centralized coexistence methods	46
9.2.3 Cooperated/collaborated coexistence methods	48
9.2.4 Recommendations for centralized and cooperated/collaborated coexistence	50
9.3 Distributed coexistence methods and recommendations	51
9.3.1 Introduction.....	51
9.3.2 Distributed channel switching.....	51
9.3.3 Distributed ED threshold setting.....	51
9.3.4 Distributed transmission power setting.....	52
9.3.5 Distributed beamforming	52
9.3.6 Distributed transmission time delay.....	52
9.3.7 α -Fairness based ED-CCA	52
9.3.8 Q-Learning based CSMA/CA	54
9.3.9 Prediction-based transmission time delay	56
9.3.10 Hybrid CSMA/CA	57
9.3.11 Recommendations for distributed coexistence.....	60
9.4 Frequency hopping and recommendation	60
9.4.1 Overview.....	60
9.4.2 Control methods.....	61
9.4.3 Hopping sequence selection.....	61
9.4.4 Hopping sequence adaptation	62
9.4.5 Channel access	62
9.4.6 Recommendation for frequency hopping.....	62
9.5 Network offered load and duty cycle recommendation	62
9.6 Network size recommendation	63
9.7 Frame size recommendation	63
9.7.1 Introduction.....	63
9.7.2 Small network size, high IEEE 802.11ah offered load, and low IEEE 802.15.4g offered load .	63
9.7.3 Small network size, low IEEE 802.11ah offered load, and high IEEE 802.15.4g offered load .	64
9.7.4 Large network size, high IEEE 802.11ah offered load, and low IEEE 802.15.4g offered load .	64
9.7.5 Large network size, low IEEE 802.11ah offered load, and high IEEE 802.15.4g offered load .	65
9.7.6 Summary of frame size recommendations	66
9.8 Backoff parameter recommendation.....	66
9.8.1 Introduction.....	66
9.8.2 Small network size, high IEEE 802.11ah offered load, and low IEEE 802.15.4g offered load .	66
9.8.3 Small network size, low IEEE 802.11ah offered load, and high IEEE 802.15.4g offered load .	67
9.8.4 Large network size, high IEEE 802.11ah offered load, and low IEEE 802.15.4g offered load .	68

9.8.5 Large network size, low IEEE 802.11ah offered load, and high IEEE 802.15.4g offered load .	69
9.8.6 Summary of backoff parameter recommendations	70
9.9 PHY parameter recommendation.....	71
9.10 Application-based recommendation	72
9.11 Coexistence method selection recommendation	72
Annex A (informative) Coexistence fairness assessment.....	74
Annex B (informative) Bibliography.....	75

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*).

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/>).

⁴ The IEEE standards or products referred to in Clause 2 are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

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 LoRa⁶ and Sigfox⁷ 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 HaLow⁸, 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-SUN⁹) 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 802.15.4eTM [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 device 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