



IEEE Standard for Low-Rate Wireless Networks

IEEE Computer Society

Developed by the
LAN/MAN Standards Committee

IEEE Std 802.15.4™-2024
(Revision of IEEE Std 802.15.4-2020)



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LAN/MAN Standards Committee
of the
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Approved 26 September 2024
IEEE SA Standards Board

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Abstract: The physical layer (PHY) and medium access control (MAC) sublayer specifications for low-data-rate wireless connectivity with fixed, portable, and moving devices with no battery or very limited battery consumption requirements are defined in this standard. In addition, the standard provides modes that allow for precision ranging. PHYs are defined for devices operating in a variety of geographic regions.

Keywords: ad hoc network, IEEE 802.15.4™, low data rate, low power, LR-WPAN, mobility, PAN, personal area network, radio frequency, RF, short range, wireless, wireless network, wireless personal area network, WPAN

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

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PDF: ISBN 979-8-8557-1315-2 STD27377
Print: ISBN 979-8-8557-1316-9 STDPD27377

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Carlos Aldana
Ghiath Al-kadi
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Jean-Marie Andre
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Daisuke Anzai
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Ido Bettesh
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Kristian Granhaug
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Jianlin Guo
Ziyang Guo
Taeyoung Ha
Hiroshi Harada
James Hartman
Jerome Henry
Marco Hernandez
Chris Hett
Masayuki Hirata
Iwao Hosako

Lei Huang
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Yeong Min Jang
Jinjing Jiang
Seong-Soon Joo
Josep Miquel Jornet
Volker Jungnickel
Juha Juntunen
Aniruddh Kabbinala
Vishal Kalkundrikar
Akifumi Kasamatsu
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Stuart Kerry
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Ryuji Kohno
Alexander Krebs
vinod kristem
Wolfgang Kuechler
Thomas Kuerner
Hong Won Lee
Jaegook Lee
Mingyu Lee
Stefan Lemsitzer
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Sang-Kyu Lim
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Chenchen Liu
Yong Liu
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Apurva Mody
Robert Mueller
Carl Murray
Frederic Nabki
Yukimasa Nagai
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Dries Neirynck
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Paul Nikolich
Pooria Pakrooh
Clark Palmer
Glenn Parsons

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Tushar Patel
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Mohammad Rahmani
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Hiroki Saito
Stephan Sand
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Kamran Sayrafian
Jonathan Segev
Norihiko Sekine
Kunal P. Shah
Menashe Shahar
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Lochan Verma
Billy Verso
Matthias Wendt
Dag Wisland
Kanke Wu
Kuan Wu
Libra Xiao
Shang-Te Yang
Xun Yang
Zhenzhen Ye
Su Khiong Yong
Kangjin Yoon
Larry Zakaib
Sven Zeisberg
Qiyue Zou

Major contributions in the revision process were received from the following individuals:

Harry Bims	Tero Kivinen	Kunal P. Shah
Hendricus De Ruijter	Clint Powell	Gary Stuebing
Chris Hett	R. K. Rannow	Don Sturek
Roger Hislop	George Robert	Billy Verso
Klaus Hueske	Benjamin Rolfe	Lisa Ward
Shoichi Kitazawa	Ruben E. Salazar Cardozo	Hidetoshi Yokota

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Paul Cardinal	Tero Kivinen	Naotaka Sato
Juan Carreon	Mallory Knodel	Reinhard Schrage
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Steven Crowley	Takashi Kuramochi	Diana Shi
Hendricus De Ruijter	Hyeong Ho Lee	Dorothy Stanley
Lubna Dhirani	James Lepp	Eugene Stoudenmire
Xiandong Dong	Joseph Levy	Walter Struppler
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Many individuals have participated in the IEEE 802.15 Working Group during various stages of the standard's development. Since the initial publication, many amendments have added functionality or updated material in this standard, and now five revisions have been published. Here is a historical list of the working group participants who dedicated their valuable time, energy, and knowledge to the advancement of this standard at the time of its original publication and for its previous revisions. Many of these members also worked on amendments.

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Roberto Aiello
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Mathew Welborn
Richard Wilson
Stephen Wood
Edward G. Woodrow
Hirohisa Yamaguchi
Amos Young
Song-Lin Young
Nakache Yves-paul
Jim Zyren

Major contributions were received from the following individuals:

Tony Adamson
David Archer
David Avery
Venkat Bahl
Daniel Bailey
Edu Batliwala
Pratik Bose
Boaz Carmeli
Farron Dacus
Martin Digon
Ian C. Gifford

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Jacco van Muiswinkel
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Richard Wilson
Wim Zwart

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Jerry Upton
Bart Van Poucke
Chris Weber
Matthew Welborn
Magnus Wiklund

Gerald Wineinger
Patrick Worfolk
Tracy Wright
Hirohisa Yamaguchi
Kamya Yekeh Yazdandoost

Su-Khiong Yong
Zhan Yu
Serdar Yurdakul
Mahmoud Zadeh
Bin Zhen

Major contributions in the revision process were received from the following individuals:

Jon Adams
Helmut P. Adamski
Jonathan Avey
Jon Beniston
Bernd Grohmann
José A. Gutierrez
Jesper Holm
ZhiJian Hu
Phil A. Jamieson
Yuen-Sam Kwok

Colin Lanzl
Myung Lee
Zhongding Lei
Liang Li
Yong Liu
Frederick Martin
Frank Poegel
Matthias Scheide
D. C. Seward

Huai-Rong Shao
Mark Shea
Stephen J. Shellhammer
Mark A. Tillinghast
Johannes Van Leeuwen
Richard Wilson
Ping Xiong
Bing Xu
ChenYang Yang
Chunhui Zhu

The following members of the IEEE 802.15 Working Group participated in the development of the second revision, IEEE Std 802.15.4-2011:

Robert F. Heile, *Chair*
Rick Alfvén, *Co-Vice Chair*
Patrick W. Kinney, *Co-Vice Chair*
James P. K. Gilb, *Working Group Technical Editor*
Patrick W. Kinney, *Secretary*

James P. K. Gilb, *Task Group 4i Chair and Technical Editor*

Emad Afifi
Gahng-Seop Ahn
Roberto Aiello
Arthur Astrin
Taechan Bae
Michael Bahr
John Barr
Anuj Batra
Tuncer Baykas
Philip E. Beecher
Ashutosh Bhatia
Ghulam Bhatti
Gary Birk
Mathew Boytim
Peter David Bradley
Nancy Bravin
David Britz
Monique B. Brown
Sverre Brubk
Brian Buchanan
John Buffington
Kiran Bynam
Brent Cain
Edgar H. Callaway
Chris Calvert

Ruben E. Salazar Cardozo
Douglas Castor
Jaesang Cha
Russell Chandler
Kuo-Hsin Chang
Soo-Young Chang
Clint Chaplin
Hind Chebbo
Chang-Soon Choi
Sangsung Choi
Ciaran Connell
David Cypher
Matthew Dahl
David Davenport
Mark Dawkins
Hendricus de Ruijter
Upkar Dhaliwal
Gang Ding
Paul Dixon
Guido Dolmans
Igor Dotlic
Michael Dow
Dietmar Eggert
David Evans
Charles Farlow

John Farserotu
Jeffrey Fischbeck
Mike Fischer
George Flammer
Ryosuke Fujiwara
Noriyasu Fukatsu
Kiyoshi Fukui
John Geiger
Gregory Gillooly
Tim Godfrey
Paul Gorday
Elad Gottlieb
Robert Hall
Shinsuke Hara
Hiroshi Harada
Timothy Harrington
Rodney Hemminger
Marco Hernandez
Garth Hillman
Jin-Meng Ho
Wei Hong
Srinath Hosur
David Howard
Jung-Hwan Hwang
Taeho Hwang

Ichirou Ida
Tetsushi Ikegami
Akio Iso
Yeong Min Jang
Adrian Jennings
Wuncheol Jeong
Steven Jillings
Noh-Gyoung Kang
Tae-Gyu Kang
Shuzo Kato
Tatsuya Kato
Jeritt Kent
Prithpal Khakuria
Dae Ho Kim
Dong-Sun Kim
Dukhyun Kim
Jaehwan Kim
Jeffrey King
Ryuji Kohno
Fumihide Kojima
Bruce Kraemer
Raymond Krasinski
Masahiro Kuroda
John Lampe
Zhou Lan
Khanh Le
Cheolhyo Lee
Hyungsoo Lee
Myung Lee
Daniel Lewis
Huan-Bang Li
Liang Li
Sang-Kyu Lim
Jeremy Link
Mike Lynch
Robert Mason
Tomokuni Matsumura
Jeff McCullough
Michael McGillan
Michael D. McInnis
Michael McLaughlin
Charles Millet
Siamak Mirnezami
Rishi Mohindra
Emmanuel Monnerie
Rajendra Moorti

Robert Moskowitz
Hamilton Moy
Peter Murray
Theodore Myers
Chiu Ngo
Paul Nikolich
Hirohito Nishiyama
David Olson
Okundu Omeni
Ryoji Ono
Laurent Ouvry
James Pace
Hyung-Il Park
Jahng Park
Seung-Hoon Park
Taejoon Park
Ranjeet Patro
Al Petrick
Dalibor Pokrajac
Daniel Popa
Stephen Pope
Clinton C. Powell
Richard Powell
Chang-Woo Pyo
Mohammad Rahman
Sridhar Rajagopal
Jayaram Ramasastry
Marc Reed
Ivan Reede
Richard Roberts
Craig Rodine
June Chul Roh
Benjamin A. Rolfe
Seung-Moon Ryu
Didier Sagan
Kentaro Sakamoto
Will San Filippo
H. Sanderford
Kamran Sayrafian
Timothy Schmidl
Michael Schmidt
Jean Schwoerer
Cristina Seibert
Neal Seidl
Kunal Shah

Steve Shearer
Stephen Shellhammer
Shusaku Shimada
Chang Sub Shin
Cheol Ho Shin
Michael Sim
Jonathan Simon
Jaeseung Son
Paul Stadnik
René Struik
Chin-Sean Sum
Hui-Hsia Sung
Gu Sungi
Kenichi Takizawa
Hirokazu Tanaka
Larry Taylor
Mark Thompson
James Tomcik
Ichihiko Toyoda
David Tracey
Khanh Tran
Jerry Upton
Jana van Greunen
Hartman van Wyk
Michel Veillette
Billy Verso
Bhupender Virk
Joachim Walewski
Junyi Wang
Quan Wang
Xiang Wang
Andy Ward
Scott Weikel
Nicholas West
Mark Wilbur
Ludwig Winkel
Eun Tae Won
Alan Chi Wai Wong
Tao Xing
Wen-Bin Yang
Yang Yang
Kazuyuki Yasukawa
Kamya Yazdandoost
Kaoru Yokoo
Mu Zhao
Bin Zhen

Major contributions in the revision process were received from the following individuals:

Philip E. Beecher
Vern Brethour
Monique B. Brown
Edgar H. Callaway
Kuor-Hsin Chang

Clint Chaplin
James P. K. Gilb
Patrick W. Kinney
Michael D. McInnis

Clinton C. Powell
Benjamin A. Rolfe
Timothy Schmidl
René Struik
Billy Verso

The following members of the IEEE 802.15 Working Group participated in the development of the third revision, IEEE Std 802.15.4-2015:

Robert F. Heile, Chair
Rick Alfvin, Co-Vice Chair
Patrick W. Kinney, Co-Vice Chair
James P. K. Gilb, Working Group Technical Editor
Patrick W. Kinney, Secretary

Patrick W. Kinney, 802.15 Maintenance Committee Chair
Benjamin A. Rolfe, 802.15 Maintenance Committee Vice Chair
James P. K. Gilb, Technical Editor

Mounir Achir
Keiji Akiyama
Arthur Astrin
Philip Beecher
Frederik Beer
Chandrashekhara P. S. Bhat
Kiran Bynam
Edgar Callaway
Chris Calvert
Radhakrishna Canchi
Kapseok Chang
Soo-Young Chang
Clint Chaplin
Stephen Chasko
Paul Chilton
Sangsung Choi
Hendricus de Ruijter
Guido Dolmans
Igor Dotlic
Stefan Drude
Dietmar Eggert
Shahriar Emami
Andrew Estrada
David Evans
George Flammer
Kiyoshi Fukui
Matthew Gillmore
Tim Godfrey
Elad Gottlieb
Jussi Haapola
Rainer Hach

Shinsuke Hara
Timothy Harrington
James Hartman
Marco Hernandez
Ken Hiraga
Iwao Hosako
Yeong Min Jang
Seong-Soon Joo
Akifumi Kasamatsu
Shuzo Kato
Toyoyuki Kato
Jeritt Kent
Jaehwan Kim
Youngsoo Kim
Shoichi Kitazawa
Tero Kivinen
Ryuji Kohno
Fumihide Kojima
Thomas Kuerner
Byung-Jae Kwak
Jae Seung Lee
Myung Lee
Sangjae Lee
Huan-Bang Li
Liang Li
Qing Li
Michael Lynch
Itaru Maekawa
Hiroyuki Matsumura
Michael McLaughlin
Michael McInnis
Kenichi Mori

Robert Moskowitz
Jinesh P. Nair
Chiu Ngo
Paul Nikolich
John Notor
Hiroyo Ogawa
Taejoon Park
Glenn Parsons
Charles Perkins
Albert Petrick
Clinton C. Powell
Verotiana Rabarijaona
Ivan Reede
Richard Roberts
Ruben E. Salazar Cardozo
Noriyuki Sato
Norihiko Sekine
Kunal Shah
Stephen Shellhammer
Shusaku Shimada
Gary Stuebing
Don Sturek
Mineo Takai
Kou Togashi
Billy Verso
Gabriel Villardi
Brian Weis
Makoto Yaita
Peter Yee
Yu Zeng
Chunhui (Allan) Zhu

Major contributions in the revision process were received from the following individuals:

Philip Beecher
Monique Brown
Edgar Callaway
Soo-Young Chang
James P. K. Gilb
Tim Godfrey
Jussi Haapola
Timothy Harrington

Jeritt Kent
Patrick W. Kinney
Tero Kivinen
Amarjeet Kumar
Michael McInnis
Robert Moskowitz
Clinton C. Powell
Verotiana Rabarijaona

Benjamin A. Rolfe
Ruben E. Salazar Cardozo
Cristina Seibert
Kunal Shal
Shusakh Shimada
Chin-Sean Sum
Larry Taylor
Billy Verso

The following members of the IEEE 802.15 Working Group participated in the development of the fourth revision, IEEE Std 802.15.4-2020:

Robert F. Heile, Chair
Rick Alfvin, Co-Vice Chair
Patrick W. Kinney, Co-Vice Chair
James P. K. Gilb, Working Group Technical Editor
Patrick W. Kinney, Secretary

Gary Stuebing, 802.15.4md Task Group Chair
Don Sturek, 802.15.4md Task Group Vice Chair
Kunal P. Shah, 802.15.4md Technical Editor

Hendrik Ahlendorf
Koorosh Akhavan
Bernd Baer
David Barras
Tuncer Baykas
Philip Beecher
Friedbert Berens
Lennert Bober
Monique Brown
Chris Calvert
Radhakrishna Canchi
Jaesang Cha
Matthew Chang
Soo-Young Chang
Clint Chaplin
Sangsung Choi
Boris Danev
Luc Darmon
Hendricus De Ruijter
Brandon Dewberry
Anthony Fagan
Matthew Gillmore
Tim Godfrey
Jianlin Guo
Joachim Hammerschmidt
Shinsuke Hara
Hiroshi Harada
Timothy Harrington
Chris Hartman

Christopher Hett
Jay Holcomb
Oliver Holland
Iwao Hosako
Brima Ibrahim
Tetsushi Ikegami
Yeong Min Jang
Seongah Jeong
Seong-Soon Joo
Volker Jungnickel
Paul Kettle
Shoichi Kitazawa
Tero Kivinen
Daniel Knobloch
Ryuji Kohno
Fumihide Kojima
Ann Krieger
Thomas Kuerner
Jack Lee
Mingyu Lee
Frank Leong
Huan-Bang Li
Zheda Li
Sang-Kyu Lim
Thomas Lorbach
Masood Maqbool
Vinayagam Mariappan
Alejandro Marquez

Michael McInnis
Apurva Mody
Ayman Naguib
Jaroslaw Niewczas
Paul Nikolich
Philip Orlik
Aditya Padaki
Glenn Parsons
Charles Perkins
Albert Petrick
Joe Pollard
Clinton Powell
Demir Rakanovic
Ivan Reede
Joerg Robert
Benjamin Rolfe
Ren Sakata
Ruben E. Salazar Cardozo
Ioannis Sarris
Peter Sauer
Nikola Serafimovski
Tushar Shah
Stephen Shellhammer
Karthik Srinivasagopalan
Billy Verso
Johannes Wechsler
Brian Weis
Peter Yee
Shaun Yu

Major contributions in the revision process were received from the following individuals:

Harry Bims
Hendricus De Ruijter
Chris Hett
Roger Hislop
Klaus Hueske
Shoichi Kitazawa

Tero Kivinen
Clint Powell
R. K. Rannow
George Robert
Benjamin Rolfe
Ruben E. Salazar Cardozo

Kunal P. Shah
Gary Stuebing
Don Sturek
Billy Verso
Lisa Ward
Hidetoshi Yokota

Introduction

This introduction is not part of IEEE Std 802.15.4-2024, IEEE Standard for Low-Rate Wireless Networks.

This is the fifth revision of IEEE Std 802.15.4. From the beginning, the goal of the IEEE 802.15 Working Group was to produce a standard that enabled very low-cost, low-power communications. The initial standard, IEEE Std 802.15.4-2003, defined two optional physical layers (PHYs), operating in different frequency bands with a simple and effective medium access control (MAC).

In 2006, the standard was revised and added two more PHY options. The MAC remained backward compatible, but the revision added MAC frames with an increased version number and a variety of MAC enhancements, including the following:

- Support for a shared time base with a data timestamping mechanism
- Support for beacon scheduling
- Synchronization of broadcast messages in personal area networks (PANs) using superframe structure
- Improved MAC layer security

In 2011, the standard was revised to include the three amendments approved subsequent to the 2006 revision. This effort added four more PHY options along with the MAC capability to support ranging. Additionally, the organization of the standard was changed so that each PHY would have a separate clause, and the MAC clause was split into functional description, interface specification, and security specification.

The 2015 revision of the standard was created to roll in the amendments approved subsequent to the 2011 revision: six PHY amendments and one MAC amendment, with corrigenda and clarifications. The features added by the amendments include the following:

- Enhanced frame formats maintaining backward compatibility
- Information Elements (IEs)
- Channel agility
- Extended superframe options
- Low-energy mechanisms
- An enhanced acknowledgment frame that can carry data and can be secured
- Prioritized channel access
- A variety of new PHY modulation, coding, and band options to support a wide variety of application needs including radio frequency identification (RFID), smart utility networks (SUNs), television white space (TVWS) operation, low-energy critical infrastructure monitoring (LECIM), and rail communications and control (RCC)

Much of the corrigenda and clarifications were collected from requests from individuals after the revision in 2011. Major corrigenda items included changes to the security text to correct errors and clarify the text, removal of the encrypt only mode, addition of security policy checks for the IEs, corrections regarding personal area network identifier (PAN ID) compression behavior to eliminate ambiguous specification, and changes to the IEs subclauses to include more information necessary for users of this standard.

The 2020 revision of the standard was created to include six approved amendments subsequent to the 2015 revision. This effort added two more PHY amendments and one MAC amendment, with corrigenda and clarifications. The features added by the amendments include the following:

- A variety of new PHY modulation, coding, and band options to support a wide variety of application needs including smart utility networks (SUNs), China medical band (CMB), ternary amplitude shift keying (TASK) and rate switch Gaussian frequency shift keying (RS-GFSK)

Much of the corrigenda and clarifications were collected from requests from individuals after the revision in 2015. Major corrigenda items included changes to the transmission order of the address field.

This current revision of the standard was created to include four amendments and one corrigendum subsequent to the 2020 revision. The features added by the amendments include the following:

- Enhanced ranging
- Improved robustness in interfered channels
- Enhanced security using cryptographic algorithm agility
- Data rate extensions for the SUN FSK modulation and channel parameters.

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IEEE Standard for Low-Rate Wireless Networks

1. Overview

1.1 Scope

This standard defines the physical layer (PHY) and medium access control (MAC) sublayer specifications for low-data-rate wireless connectivity with fixed, portable, and moving devices with no battery or very limited battery consumption requirements. In addition, the standard provides modes that allow for precision ranging. PHYs are defined for devices operating in a variety of geographic regions.

1.2 Purpose

The standard provides for ultra low complexity, ultra low cost, ultra low power consumption, and low data rate wireless connectivity among inexpensive devices, especially targeting the communications requirements of what is now commonly referred to as the Internet of Things. In addition, some of the alternate PHYs provide precision ranging capability that is accurate to one meter. Multiple PHYs are defined to support a variety of frequency bands.

1.3 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*).^{6, 7}

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*).

⁶ The word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷ The word *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

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

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.

ANSI X3.66-1979, Advanced Data Communication Control Procedures. ⁸ ~~1~~

Code of Federal Regulations, Title 47: Telecommunication, Part 90—Private Land Mobile Radio Services, Subpart S—Regulations Governing Licensing and Use of Frequencies in the 806–824, 851–869, 896–901, and 935–940 MHz Bands (47 CFR, Part 90, Subpart S). ² ~~2~~

Code of Federal Regulations, Title 47: Telecommunication, Part 90—Private Land Mobile Radio Services, Subpart Y—Regulations Governing Licensing and Use of Frequencies in the 4940–4990 MHz Band (47 CFR, Part 90, Subpart Y).

FIPS Pub 197, Advanced Encryption Standard (AES). ¹⁰ ~~3~~

IEEE Std 802[®]-~~2014~~, IEEE ~~Standard~~ ~~Standards~~ for Local and Metropolitan Area Networks: Overview and Architecture. ¹¹, ¹² ~~4~~, ~~5~~

IEEE Std 802.15.9[™], IEEE Standard for Transport of Key Management Protocol (KMP) Datagrams.

⁸ ⁴ANSI publications are available from the American National Standards Institute (<https://www.ansi.org/>) (~~http://www.ansi.org/~~)

² ²CFR publications are available from the U.S. Government Publishing Office (<https://www.gpo.gov/>). (~~http://www.gpo.gov/~~)

¹⁰ ³ FIPS publications are available from the National Technical Information Service, U. S. Department of Commerce (<https://www.ntis.gov/>). (~~NTIS~~) (~~http://www.ntis.org/~~)

¹¹ ⁴ IEEE publications are available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>) (~~http://standards.ieee.org/~~)

¹² ⁵The IEEE standards or products referred to in ~~this~~ Clause ² are trademarks owned by ~~of~~ The Institute of Electrical and Electronics Engineers, Incorporated ~~Inc.~~

IETF RFC 6225, Dynamic Host Configuration Protocol Options for Coordinate-Based Location Configuration Information, 2011.¹³ ~~Internet Engineering Task Force.~~⁶

[ISO/IEC 7816-4:2013, Identification cards—Integrated circuit cards—Part 4: Organization, security and commands for interchange.](#)¹⁴

[ISO/IEC 7816-5:2004, Identification cards—Integrated circuit cards—Part 5: Registration of application providers.](#)

[JIS X 6319-4:2016, Specification of implementation for integrated circuit\(s\) cards—Part 4: High speed proximity cards.](#)¹⁵

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary* should be consulted for terms not defined in this clause.¹⁶ ~~7~~

association: The service used to establish membership for a device in a network.

authentication tag: Information that allows the verification of authenticity of a message.

channel hopping: Periodically switching the channel using a sequence known to both sending and receiving devices where the entire frame is sent on a single channel.

channel offset: A number used in the channel calculation of a slotted channel hopping system to allow for different channels to be used in the same slot.

chirp: Linear frequency sweep.

¹³ ~~6~~ IETF RFCs are available from the Internet Engineering Task Force (<https://www.ietf.org/>). ~~(<http://www.ietf.org/>).~~

¹⁴ ISO publications are available from the International Organization for Standardization (<https://www.iso.org/>) and the American National Standards Institute (<https://www.ansi.org/>).

¹⁵ JIS standards are available from The Japanese Standards Association (<https://www.jsa.or.jp/>).

¹⁶ ~~The~~ ²IEEE 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.

coordinator: Any device capable of providing coordinator functions.

dependent device: A device that operates without direct Internet access to the television white space (TVWS) database and depends on another device for channel availability information.

encryption: The transformation of a message into a new representation so that privileged information is required to recover the original representation.

fragment: An individual contiguous subset of a MAC protocol data unit.

frame: The format of aggregated bits from a medium access control sublayer entity that are transmitted together in time.

group key: A key that is known only to the devices in the group.

independent device: A device that has direct access to the television white space (TVWS) database via the Internet.

key: Privileged information that is used, for example, to protect information from disclosure to, and/or undetectable modification by, parties that do not have access to this privileged information.

keying material: The combination of a key and associated security information (e.g., a nonce value).

link key: A key that is shared between precisely two devices.

mobile device: A device whose location in the network can change.

nonce: A nonrepeating value, such as an increasing counter, a sufficiently long random string, or a timestamp.

packet: The formatted, aggregated bits that are transmitted together in time across the physical medium.

payload: The contents of a data message that is being transmitted.

radio frequency identification (RFID): The use of electromagnetic or inductive coupling in the radio frequency (RF) portion of the spectrum to communicate to or from a tag through a variety of modulation and encoding schemes to uniquely read the identity of an RF tag.

scrambled timestamp sequence (STS): A sequence of pseudo-randomized pulses generated using a deterministic random bit generator (DRBG).

slotframe: A collection of timeslots repeating in time, analogous to a superframe in that it defines periods of communication opportunities.

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

STS seed: A parameter that is part of the seed input to the STS generating DRBG and which may be privileged information or not depending on the application needs.

transaction: The exchange of related, consecutive frames between two peer ~~medium access control (MAC)~~ entities, required for a successful transmission of a MAC Command frame or Data frame.

3.2 Acronyms and abbreviations

Ack	acknowledgment
AEAD	authenticated encryption with associated data
AES	advanced encryption standard
AIFS	acknowledgment interframe spacing
ANPI	average noise power indicator
<u>AOA</u>	<u>angle of arrival</u>
AR	acknowledgment request
ASK	amplitude shift keying
ASN	absolute slot number
ATI	allowed transmission interval
BCH	Bose Chaudhuri Hocquenghem
BDE	bit differential encoding
BLE	battery life extension
BOP	beacon only period
BPM	burst position modulation ~~Standard for Low Rate Wireless Networks~~

<u>BPRF</u>	<u>base pulse repetition frequency</u>
BPSK	binary phase-shift keying
BSN	beacon sequence number
CAP	contention access period
CBC-MAC	cipher block chaining message authentication code
CCA	clear channel assessment
CCM	counter mode encryption and cipher block chaining message authentication code
CCM*	extension of counter mode encryption and cipher block chaining message authentication code
CFP	contention-free period
CID	Company <u>ID</u> identifier
CMB	China medical band
CoU	chirp on ultra wideband
CP	cyclic prefix
CRC	cyclic redundancy check
CS	continuous spectrum
CSK	chirp-shift keying
CSL	coordinated sampled listing
CSM	common signaling mode
CSMA-CA	carrier sense multiple access with collision avoidance
CSS	chirp spread spectrum
DA	device announcement
DAA	detect and avoid

DBS	dedicated beacon slot
DCS	dynamic channel selection
DEMUX	de-multiplexer
DFT	discrete Fourier transform
DPS	dynamic preamble selection
DPSK	differential phase-shift keying
DQCSK	differential quadrature chirp-shift keying
DQPSK	differential quadrature phase-shift keying
DRBG	deterministic random bit generator
DSME	deterministic and synchronous multichannel extension
DSN	data sequence number
DSSS	direct sequence spread spectrum
DS-TWR	double-sided two-way ranging
EBSN	enhanced beacon sequence number
ED	energy detection (also in 10.8.2 , 6.2.8 , extended duration)
EIRP	effective isotropic radiated power
Enh-Ack	~~enhanced~~ acknowledgment
EPC	enhanced payload capacity
ERDEV	enhanced ranging capable device
ESDU	encapsulated service data unit
EUI-64	64-bit extended unique identifier
EVM	~~error~~ -vector magnitude
FCS	frame check sequence
FEC	forward error correction

~~FFD~~ ~~full function device~~

FICS fragment integrity check sequence

FoM figure of merit

Frak fragment acknowledgment

~~FSCD~~ ~~fragment sequence context description~~

FSK frequency shift keying

GDB geolocation database

GFSK Gaussian frequency-shift keying

GMSK Gaussian-filtered minimum shift keying

GTS guaranteed timeslot

HCS header check sequence

HPRF higher pulse repetition frequency

HRP high rate pulse repetition frequency

HRP-ERDEV high rate pulse repetition frequency UWB PHY based enhanced ranging capable device

ID identifier

IDFT inverse discrete Fourier transform

IE information element

IFS interframe space or spacing

Imm-Ack immediate acknowledgment

IPI idle power indicator

I-RIT implicit receiver initiated transmission

ISR interference-to-signal ratio

LBT listen before talk