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IEEE Standard for Low-Rate Wireless Networks

IEEE Computer Society

Developed by the
LAN/MAN Standards Committee

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IEEE Std 802.15.4™-2020
(Revision of IEEE Std 802.15.4-2015)

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IEEE Standard for Low-Rate Wireless Networks

Developed by the

LAN/MAN Standards Committee
of the
IEEE Computer Society

Approved on 6 May 2020

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

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Many individuals have participated in the IEEE P802.15 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 three 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 revisions. Many of these members also worked on amendments.

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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 P802.15 Working Group participated in the development of the second revision, IEEE Std 802.15.4-2011:

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*

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

Emad Afifi
Gahng-Seop Ahn
Roberto Aiello
Arthur Astrin
Taehan 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
Kuor-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 Gottlib
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

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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

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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
Chandrashekhar 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 Gottlib
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

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Introduction

This introduction is not part of IEEE Std 802.15.4-2020, IEEE Standard for Low-Rate Wireless Networks.

This is the fourth revision of IEEE Std 802.15.4. From the beginning, the goal of the IEEE P802.15 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 beacon-enabled personal area networks (PANs)

— 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 Project Authorization Request (PAR) for IEEE Std 802.15.4-2015 was first proposed in July 2013 and was approved in October 2013 by IEEE's New Standards Committee (NesCom). After three working group ballots and two IEEE SA Committee ballots, the final standard was approved in December 2015, just over two years from start to finish.

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The current revision of the standard was revised 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.

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IEEE Standard for Low-Rate Wireless Networks

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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 ~~various license-free bands~~ 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 ~~one~~ of the alternate PHYs provide ~~provides~~ precision ranging capability that is accurate to one meter. Multiple PHYs are defined to support a variety of frequency bands.

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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.[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]

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).[3]

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

[1]ANSI publications are available from the American National Standards Institute (http://www.ansi.org/)

[2]CFR publications are available from the U.S. Government Printing Office (http://www.gpo.gov/).

[3]FIPS publications are available from the National Technical Information Service (NTIS) (http://www.ntis.org/).

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

[6]IETF RFCs are available from the Internet Engineering Task Force (http://www.ietf.org/).

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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.[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 ~~(frequency may either increase or decrease)~~.

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 ~~a set of~~ devices in the group.

[7] *IEEE Standards Dictionary Online* ~~subscription~~ 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. ~~http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.~~

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

key: Privileged information that is ~~may be~~ 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 ~~secret~~ key that is shared between precisely two devices.

mobile device: A device whose location in the network can ~~may~~ change ~~during use~~.

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 ~~data~~: 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.

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.

~~**symmetric key:** A secret key that is shared between two or more parties that may be used for encryption/decryption or integrity protection/integrity verification, depending on its intended use.~~

~~**timeslot:** A defined period of time during which a frame and an acknowledgment may be exchanged between devices.~~

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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
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 modulationStandard for Low-Rate Wireless Networks
BPSK	binary phase-shift keying
BSN	beacon sequence number
CAP	contention access period

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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 identifier
CMB	China medical band
CP	cyclic prefix
CoU	chirp on ultra-wide band
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

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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
DSME	deterministic and synchronous multi-channel extension
DSN	data sequence number
DSSS	direct sequence spread spectrum
EBSN	enhanced beacon sequence number
ED	energy detection (also in 6.2.8, extended duration)
EIRP	effective isotropic radiated power
Enh-Ack	enhanced acknowledgment
ESDU	encapsulated service data unit
EUI-64	64-bit extended unique identifier
EVM	error-vector magnitude
~~FCC~~	~~Federal Communications Commission~~
FCS	frame check sequence
FEC	forward error correction
FFD	full-function device

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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
HRP	high rate pulse repetition frequency
ID	identifier
IDFT	inverse discrete Fourier transform
IE	information element
IFS	interframe space or spacing
Imm-Ack	immediate acknowledgment
IPI	idle power indicator
ISR	interference-to-signal ratio
I-RIT	implicit receiver initiated transmission
LBT	listen before talk

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LCP	linear combination of pulses
LE	low energy
LECIM	low-energy, critical infrastructure monitoring
LEIP	location enhancing information postamble
LFSR	linear feedback shift register
LIFS	long interframe spacing
LMR	land mobile radio
LRP	low rate pulse repetition frequency
LQI	link quality indication
LR-WPAN	low-rate wireless personal area network
LSB	least significant bit
LTF	long training field
MAC	medium access control
MBAN	medical body area network
MCPS	MAC common part sublayer
MCPS-SAP	MAC common part sublayer service access point
MCS	modulation and coding scheme
MD	multi-superframe duration
MDSSS	multiplexed direct sequence spread spectrum
MFR	MAC footer

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MHR	MAC header
MIC	message integrity code
MLME	MAC sublayer management entity
MLME-SAP	MAC sublayer management entity service access point
MPM	multi-PHY management
MSB	most significant bit
MSK	minimum shift keying
MPDU	MAC protocol data unit
~~MPSK~~	~~m-ary phase shift keying~~
MSDU	MAC service data unit
NRNSC	nonrecursive and nonsystematic code
OFDM	orthogonal frequency division multiplexing
OOK	on-off keying
O-QPSK	offset quadrature phase-shift keying
OUI	organizationally unique identifier
OVSF	orthogonal ~~orthongonal~~ variable spreading factor
PAN	personal area network
~~PC~~	~~personal computer~~
PCA	priority channel access
~~PD~~	~~physical layer data~~

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PD-SAP	physical layer data service access point
PER	packet error rate
P-FSK	position-based frequency shift keying
PHR	PHY header
PHY	physical layer
PIB	personal area network information base
PICS	protocol implementation conformance statement
PLME	physical layer management entity
PLME-SAP	physical layer management entity service access point
PN	pseudo-random noise
PPDU	PHY protocol data unit
PPM	pulse position modulation
PRBS	pseudo-random binary sequence
PRF	pulse repetition frequency
PSD	power spectral density
PSDU	PHY service data unit
~~PSSS~~	~~parallel sequence spread spectrum~~
QAM	quadrature ~~quardrature~~ amplitude modulation
QPSK	quadrature phase-shift keying
RCC	rail communications and control

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RCCN	rail communications and control network
RCPI	received channel power indicator
RDEV	ranging-capable device
RF	radio frequency
RFD	reduced-function device
RFD-RX	reduced function device—receive only
RFD-TX	reduced function device—transmit only
RFID	radio frequency identification
RFRAME	ranging frame
RIT	receiver initiated transmission
~~RIV~~	~~remainder initialization value~~
RMARKER	ranging marker
RSC	recursive and systematic ~~systematice~~ code
RS-GFSK	rate switch Gaussian frequency shift keying
RSNI	received signal noise indicator
RSSI	receive signal strength indicator
RX	receive or receiver
SAB	slot allocation bitmap
SD	superframe duration
SF	spreading factor

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SFD	start-of-frame delimiter
SHR	synchronization header
SIFS	short interframe spacing
SiPC	single parity check
SNR	signal-to-noise ratio
SPC	super PAN coordinator
SRM	spectrum resource measurement
STF	short training field
SUN	smart utility network
TASK	ternary amplitude shift keying
TBPC	turbo product code
TID	transaction identifier
TMCTP	TVWS multichannel cluster tree PAN
TPC	transmission power control ~~turbo product code~~
TRLE	time-slot relaying based link extension
TSCH	timeslotted channel hopping
TVWS	television white space
TX	transmit or transmitter
UWB	ultra-wide band
WPAN	wireless personal area network

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4. Format conventions

4.1 General

Throughout this standard, unless otherwise stated, data structures exposed in interfaces are represented using the conventions and formats defined in this clause.

NOTE—It is important to note that interfaces are depicted in this standard as bit serial by convention but can ~~may~~ be implemented in other forms, e.g., 4- or 8-bit parallel.[8]

Within the PHY, data structures are passed to the reference modulator input in bit-serial convention. PHY specific coding may change the bit-order and encode multiple information bits into symbols. Hence the over-the-air interface may express the data structure content in a manner different than the conventions defined here.

After all applicable expansion, the size of a MAC frame shall be less than the maximum PHY service data unit (PSDU) size supported by the PHY in use.

4.2 Fields

The general format of a data structure is shown in Figure 4-1. Each field is represented by a column in the figure giving the size of the field and the name and/or type of the datum encoded in the field. The convention of a data structure is recursive in that a field may contain a data structure which is in turn composed of fields.

Octets: 2	Bits: 0–5	6–7	…
Field Name/Type (Number datum)	Field Name/Type (Bit string datum)	Field Name/Type (Bit string datum)	…

Figure 4-1—General data structure format

[8]Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

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