

IEEE Standard for Low-Rate Wireless Personal Area Networks (WPANs)

IEEE Computer Society

Sponsored by the
LAN/MAN Standards Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 802.15.4™-2015
(Revision of
IEEE Std 802.15.4-2011)

IEEE Std 802.15.4™-2015

(Revision of
IEEE Std 802.15.4-2011)

IEEE Standard for Low-Rate Wireless Personal Area Networks (WPANs)

Sponsor

**LAN/MAN Standards Committee
of the
IEEE Computer Society**

Approved 5 December 2015

IEEE-SA Standards Board

Abstract: The protocol and compatible interconnection for data communication devices using low-data-rate, low-power, and low-complexity short-range radio frequency (RF) transmissions in a wireless personal area network (WPAN) are defined in this standard. A variety of physical layers (PHYs) have been defined that cover a wide variety of frequency bands.

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 personal area network, WPAN

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

Copyright © 2016 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 22 April 2016. Printed in the United States of America.

IEEE and IEEE 802 are registered trademarks in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

Print: ISBN 978-1-5044-0854-5 STD20893
PDF: ISBN 978-1-5044-0846-2 STDPD20893

IEEE prohibits discrimination, harassment and bullying.

For more information, visit <http://www.ieee.org/web/aboutus/whatis/policies/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 documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page, appear in all standards and may be found under the heading “Important Notice” or “Important Notices and Disclaimers Concerning IEEE Standards Documents.”

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

IEEE Standards documents (standards, recommended practices, and guides), both full-use and trial-use, are developed within IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (“IEEE-SA”) Standards Board. IEEE (“the Institute”) develops its standards through a consensus development process, approved by the American National Standards Institute (“ANSI”), which brings together volunteers representing varied viewpoints and interests to achieve the final product. Volunteers are not necessarily members of the Institute 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 or any of the information or the soundness of any judgments contained in its standards.

IEEE does not warrant or represent the accuracy or content 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. 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: PROCUREMENT OF 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 should be considered 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, or 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 his or her views should be considered the personal views of that individual rather than the formal position of IEEE.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE. However, IEEE does not provide 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 official 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 revisions to an IEEE standard is welcome to join the relevant IEEE working group.

Comments on standards should be submitted to the following address:

Secretary, IEEE-SA Standards Board
445 Hoes Lane
Piscataway, NJ 08854 USA

Laws and regulation

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not imply 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.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under U.S. 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 fee, 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. 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 ten years. When a document is more than ten years old and has not undergone a revision process, it is reasonable to conclude that its content, 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 the IEEE-SA Website at <http://ieeexplore.ieee.org/Xplore/home.jsp> or contact IEEE at the addresses listed previously. For more information about the IEEE SA or IEEE's standards development process, visit the IEEE-SA Website at <http://standards.ieee.org>.

Errata

Errata, if any, for all IEEE standards can be accessed on the IEEE-SA Website at the following URL: <http://standards.ieee.org/findstds/errata/index.html>. Users are encouraged to check this URL for errata periodically.

Patents

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE-SA Website at <http://standards.ieee.org/about/sasb/patcom/patents.html>. Letters of Assurance may indicate whether the submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

Participants

At the time this standard was sent to sponsor ballot, the IEEE P802.15 Working Group had the following voting members:

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*

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 | Shinsuke Hara | Robert Moskowitz |
| Keiji Akiyama | Timothy Harrington | James P. Neill |
| Arthur Astrin | James Hartman | Chin-Sean Sum |
| Philip Beecher | Marco Hernandez | Paul Nikolich |
| Frederik Beer | Ken Hiraga | John Notor |
| Chandrashekhar P. S. Bhat | Iwao Hosako | Hiroyo Ogawa |
| Kiran Bynam | Yeong Min Jang | Taejoon Park |
| Edgar Callaway | Seong-Soon Joo | Glenn Parsons |
| Chris Calvert | Akifumi Kasamatsu | Charles Perkins |
| Radhakrishna Canchi | Shuzo Kato | Albert Petrick |
| Kapseok Chang | Toyoyuki Kato | Clinton C. Powell |
| Soo-Young Chang | Jeritt Kent | Verotiana Rabarijaona |
| Clint Chaplin | Jaehwan Kim | Ivan Reede |
| Stephen Chasko | Youngsoo Kim | Richard Roberts |
| Paul Chilton | Shoichi Kitazawa | Ruben E. Salazar Cardozo |
| Sangsung Choi | Tero Kivinen | Noriyuki Sato |
| Hendricus de Ruijter | Ryuji Kohno | Norihiko Sekine |
| Guido Dolmans | Fumio Kojima | Kunal Shah |
| Igor Dotlic | Thomas Kuerner | Stephen Shellhammer |
| Stefan Drude | Byung-Jae Kwak | Shusaku Shimada |
| Dietmar Eggert | Lee Seung Lee | Gary Stuebing |
| Shahriar Emami | Myung Lee | Don Sturek |
| Andrew Estrada | Sangjae Lee | Mineo Takai |
| David Evans | Huan-Bang Li | Kou Togashi |
| George Flammer | Liang Li | Billy Verso |
| Kiyoshi Fukui | Qing Li | Gabriel Villardi |
| Matthew Gillmore | Michael Lynch | Brian Weis |
| Tim Godfrey | Itaru Maekawa | Makoto Yaita |
| Elad Gottlib | Hiroyuki Matsumura | Peter Yee |
| Jussi Haapola | Michael McLaughlin | Yu Zeng |
| Rainer Hoch | Michael McInnis | Chunhui (Allan) Zhu |
| | Kenichi Mori | |

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

| | | |
|--------------------|-----------------------|--------------------------|
| Philip Beecher | Jeritt Kent | Benjamin A. Rolfe |
| Monique Brown | Patrick W. Kinney | Ruben E. Salazar Cardozo |
| Edgar Callaway | Tero Kivinen | Cristina Seibert |
| Soo-Young Chang | Amarjeet Kumar | Kunal Shah |
| James P. K. Gilb | Michael McInnis | Shusakh Shimada |
| Tim Godfrey | Robert Moskowitz | Chin-Sean Sum |
| Jussi Haapola | Clinton C. Powell | Larry Taylor |
| Timothy Harrington | Verotiana Rabarijaona | Billy Verso |

The following members of the individual balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention.

| | | |
|----------------------|----------------------|-------------------------|
| Rick Alfvén | Noriyuki Ikeuchi | Yoshihiro Ohba |
| Nobumitsu Amachi | Akio Iso | Okundu Omeni |
| Butch Anton | Atsushi Ito | Satoshi Oyama |
| Stefan Aust | Raj Jain | Stephen Palm |
| Michael Bahr | Oyvind Janbu | Arumugam Paventhan |
| Madhusudan Banavara | Michael Johas Teener | Dalibor Pokrajac |
| Philip E. Beecher | Adri Jovin | Clinton C. Powell |
| Harry Bims | Naveen Kakani | Venkatesha Prasad |
| Gennaro Boggia | Shinkyō Kaku | Verotiana Rabarijaona |
| Riccardo Brama | Piotr Karocki | Demir Rakanovic |
| Nancy Bravin | Ruediger Kays | R. K. Rannow |
| Vern Brethour | Jeritt Kent | Maximilian Riegel |
| Monique Brown | Stuart Kerry | Robert Robinson |
| William Byrd | Yongbum Kim | Osman Sakr |
| Brent Cain | Patrick W. Kinney | Ruben E. Salazar Carazo |
| Edgar Callaway | Tero Kivinen | John Sant'off |
| Radhakrishna Canchi | Fumihide Kojima | Naotaka Sato |
| Juan Carreon | Bruce Kraemer | Bartien Sengupta |
| Suresh Channarasappa | Yasushi Kudoh | Kumar Shah |
| Keith Chow | Amarjeet Kumar | Shin-aki Shimada |
| Charles Cook | Jeremy Landt | Suresh Shrivastava |
| Steven Crowley | Hyeong Ho Lee | Daniel Smolinski |
| Sourav Dutta | James Lepp | Thomas Starai |
| Richard Edgar | Arthur H. Light | Rene Struik |
| David Evans | Vincent Lipsio | Walter Struppler |
| Liu Fangfang | William Lumpkins | Patricia Thaler |
| Michael Fischer | Elvis Maculuba | David Thompson |
| Avraham Freedman | James Marin | Ha-Nguyen Tran |
| Devon Gayle | Roger Marks | Mark-Rene Uchida |
| James P. K. Gilb | Michael McInnis | Lorenzo Vangelista |
| Gregory Gillooly | Michael McLaughlin | Dmitri Varsanofiev |
| Joel Goergen | Apurva Mody | Prabodh Varshney |
| Randall Groves | Jose Morales | Raj Vaswani |
| Chris Guy | Ronald Arias | George Vlantis |
| Rainer Hach | Jin-Ho Nair | Khurram Waheed |
| Timothy Harrington | Yoshi Nakada | Hung-Yu Wei |
| Marco Hernandez | Michael Newman | Brian Weis |
| Guido Hiertz | Chiu Ngo | Andreas Wolf |
| Werner Hoelzl | Nick S. A. Nikjoo | Oren Yuen |
| Tetsushi Ikegami | Paul Nikolich | Daidi Zhong |

When the IEEE-SA Standards Board approved this standard on 5 December 2015, it had the following membership:

John Kulick, Chair
Jon Walter Rosdahl, Vice Chair
Richard H. Hulett, Past Chair
Konstantinos Karachalios, Secretary

| | | |
|----------------------|---------------------|------------------------|
| Masayuki Ariyoshi | Joseph L. Koepfing* | Stephen J. Shellhammer |
| Ted Barse | David J. Law | Adrian P. Stephens |
| Stephen Dukes | Hung Ling | Yatin Trivedi |
| Jean-Phillippe Faure | Andrew Myles | Phillip Winston |
| J. Travis Griffith | T. W. Olsen | Don Wright |
| Gary Hoffman | Glenn Parsons | Yu Yuan |
| Michael Janezic | Ronald C. Peterson | Daidi Zhong |
| | Annette D. Reilly | |

*Member Emeritus

Historical participants

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.

The following members of the IEEE P802.15 Working Group participated in the development of the original standard, IEEE Std 802.15.4-2003:

Robert F. Heile, Chair
James D. Allen, Vice Chair
Patrick W. Kinney, Secretary
Michael D. McInnis, Assistant Secretary and Editor

Ian C. Gifford, Task Group 1 Chair
Stephen J. Shellhammer, Task Group 2 Chair
John R. Barr, Task Group 3 Chair

Patrick W. Kinney, Task Group 4 Chair
Phil Jamieson, Task Group 4 Vice Chair
José A. Gutierrez, Task Group 4 Editor-in-Chief
Marco Naeve, Task Group 4 Secretary

Monique Bourgeois, MAC Technical Editor
Said Moridi, PHY Technical Editor
Phil Jamieson, Layer Management Technical Editor
Greg Breen, Low-Band PHY Technical Editing
Ed Callaway, Networking Technical Editing
Paul Gorday, High-Band PHY Technical Editing
Marco Naeve, General Description Technical Editing
David Conkling, PICS/SDLs Technical Editing
Robert D. Moor, Coexistence Technical Editing
Farruk Dacus, Regulatory Technical Editing

Roberto Aiello
Masaaki Akahane
Richard Alfvin
Arun Arunachala
Naiel Askar
Venkat L. Balakrishnan
Daniel Bailey
Jay Bannister
James Bauer
J. Ganesh Balakrishnan
Anand Batra
Timothy Blaney
Kenneth Boehike
Stan Bottoms
Mark V. Bowles
Chuck Brabenac
Soo-Young Chang
Francois Po-Shin Chin
Aik Chindapol

Craig Conkling
Anand Dabak
Kai Dombrowski
Mary DuVal
Michael Dydyk
Jason L. Ellis
Mark W. Fidler
Jeff R. Foerster
David S. Furuno
Pierre Gandolfo
Atul Garg
James Gilb
Nada Golmie
Yasuo Harada
Allen Heberling
Barry Herold
Robert Y. Huang
Eran Iglor
Katsumi Ishii

Jeyhan Karaoguz
Masami Katagiri
Joy H. Kelly
Stuart J. Kerry
Yongsuk Kim
Young Hwan Kim
Günter Kleindl
Bruce P. Kraemer
DoHoon Kwon
Jim Lansford
David Leeper
Liang Li
Yeong-Chang Maa
Steven March
Ralph Mason
Jim Meyer
Leonard E. Miller
Akira Miura
Andreas Molisch

Antonio Mondragon
Tony Morelli
Chiu Ngo
Kei Obara
Knut Odman
John B. Pardee
Jongun Park
Dave Patton
Marcus Pendergrass
Gregg Rasor
Ivan Reede
Jim Richards
Glyn Roberts
Richard Roberts
William Roberts
Chris Rogers
Philippe Rouzet

Chandos Rypinski
John H. Santhoff
Mark Schrader
Tom Schuster
Erik Schylander
Michael Seals
Nick Shepherd
Gadi Shor
William Shvodian
Thomas Siep
Kazimierz Siwiak
Carl Stevenson
Rene Struik
Shigeru Sugaya
Kazuhisa Takamura
Katsumi Takaoka

Teik-Kheong Tan
Larry Taylor
Stephen E. Taylor
Hans vanLeeuwen
Ritesh Vishwakarma
Thierry Walrant
Jing Wang
Fijio Watanabe
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
Edul Batliwala
Pratik Bose
Boaz Carmeli
Farron Dacus
Martin Digon
Ian C. Gifford

Ed Hogervorst
Stephen Korfhage
Charles Luebke
Masahiro Maeda
Ian Marsden
Chris Marshall
Paul Marshall
Fred Martin
Ralph Mason
Rod Miller
Phil Rudland

Niel Schreiner
Nick Shepherd
Ar. Singer
Ralph D'Souza
Carl Stevenson
Mark Tilinghast
Hans Van Leeuwen
Jacco van Muiswinkel
Luis Pereira
Richard Wilson
Wim Zwart

The following members of the IEEE P802.15 Working Group participated in the development of the first revision, IEEE Std 802.15.4-2006:

Robert F. Heile, Chair
James D. Allen, Vice Chair
Patrick W. Kinney, Assistant Vice Chair
James P. K. Gilb, Editor-in-Chief
Patrick W. Kinney, Secretary
Michael D. McInnis, Assistant Secretary and Editor

John R. Barr, Task Group 3b Chair
Reed Fisher, Task Group 3c Chair
Patrick W. Kinney, Task Group 4a Chair
Myung Lee, Task Group 5 Chair

Robert D. Poor, Task Group 4b Chair
Marco Naeve, Task Group 4b Vice Chair
Monique B. Brown, Task Group 4b Editor-in-Chief
Eric T. Gnoske, Task Group 4b Secretary

Philip E. Beecher, MAC Contributing Editor
Monique B. Brown, MAC Technical Editor
Edgar H. Callaway, Jr., MAC Contributing Editor
Francois Chin, PHY Contributing Editor
Robert C. Cragie, MAC/Security Contributing Editor

Paul Gorday, *PHY Contributing Editor*
James P. K. Gilb, *Draft D3 Editor-in-Chief*
Øyvind Janbu, *MAC/PHY/Security Contributing Editor*
Marco Naeve, *General Description/PICS Editor, MAC Contributing Editor*
Clinton C. Powell, *PHY Technical Editor*
Joseph Reddy, *Security Contributing Editor*
Zachary Smith, *MAC Contributing Editor*
René Struik, *Security Contributing Editor*
Andreas C. Wolf, *PHY Contributing Editor*

Roberto Aiello
 Richard Alfvén
 Mikio Aoki
 Takashi Arita
 Larry Arnett
 Arthur Astrin
 Yasaman Bahreini
 Jay Bain
 Alan Berkema
 Bruce Bosco
 Mark Bowles
 Charles Brabenec
 David Brenner
 Vern Brethour
 Ronald Brown
 Bill Carney
 Kuor-Hsin Chang
 Jonathon Cheah
 Kwan-Wu Chin
 Sarm-Goo Cho
 Sungsoo Choi
 Yun Choi
 Chun-Ting Chou
 Manoj Choudhary
 Celestino Corral
 Joe Decuir
 Javier Del Prado Pavon
 Kai Dombrowski
 Stefan Drude
 Amal Ekbal
 Jason Ellis
 Shahriar Emami
 Paul Everest
 Mark W. Fidler
 Kris Fleming
 Amir Freund
 Camillo Gentile
 Ian Gifford
 Sung-Wook Goh
 Sorin Goldenberg
 Vivek Gupta
 Rainer Hach
 Robert Hall
 Shinsuke Hara
 Jeff Harris
 Allen Heberling
 Eric Heinze
 Barry Herold
 Keisuke Higuchi
 Jin-Meng Ho
 Patrick Houghton
 Robert Huang

Tian-Wei Huang
 Hideto Ikeda
 Tetsushi Ikegami
 Adrian Jennings
 Ho-In Jeon
 Tzyy Hong Jiang
 David Julian
 Jeyhan Karaoguz
 Michael Kelly
 Stuart Kerry
 Jae-Hyon Kim
 Jaeyoung Kim
 Jinkyong Kim
 Yongsuk Kim
 Kursat Kimyacioglu
 Matthias Kindler
 Guenter Kleindl
 Ryuji Kohno
 Mike Krell
 Yasushi Kudo
 Akiomi Kunisa
 Yuzo Kuramochi
 Jiun-You Lai
 Ismail Lakkis
 John Lampe
 Kyung Kuk Lee
 Wooyong Lee
 David Leeper
 Huan-Bang Li
 Haixiang Liang
 Ian Macnamara
 Akira Maeki
 Patricia Martigne
 Abbie Mathew
 Taisuke Matsumoto
 Gustaf Max
 Michael McLaughlin
 Charlie Mellone
 Klaus Meyer
 Samuel Mo
 Andreas Molisch
 Mark Moore
 Ken Naganuma
 Yves-Paul Nakache
 Hiroyuki Nakase
 Saishankar Nandagopalan
 Chiu Ngo
 Erwin Noble
 John O'Conor
 Knut Odman
 Hiroyo Ogawa
 Yasuyuki Okuma

Philip Orlik
 Laurent Ouvry
 John Pardee
 Nirmalendu Patra
 Dave Patton
 Xiaoming Peng
 Tony Pollock
 Vidyasagar Premkumar
 Yihong Qi
 Raad Raad
 Pekka Ranta
 Dani Raphaeli
 Gregg Rasor
 Charles Razzell
 Ivan Reede
 Yuko Rikuta
 Terry Robar
 Glyn Roberts
 Richard Roberts
 Benjamin A. Rolfe
 Philippe Rouzet
 Chandos Rypinski
 Ali Sadri
 Saeid Safavi
 Zafer Sahinoglu
 Tomoki Saito
 Syed Saleem
 Kamran Sayrafian
 Jean Schwoerer
 Erik Schylander
 Alireza Seyedi
 Sanjeev Sharma
 Siddharth Shetty
 John Shi
 Shusaku Shimada
 Yuichi Shiraki
 Gadi Shor
 William Shvodian
 Thomas Siep
 Michael Sim
 Kazimierz Siwiak
 V. Somayazulu
 Amjad Soomro
 Carl Stevenson
 Kazuaki Takahashi
 Kenichi Takizawa
 Teik-Kheong Tan
 Mike Tanahashi
 Yasushi Tanaka
 James Taylor
 Arnaud Tonnerre
 Ichihiko Toyoda

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 Alfvín, *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
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 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

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

Introduction

This introduction is not part of IEEE Std 802.15.4™-2015, IEEE Standard for Low-Rate Wireless Personal Area Networks (WPANs).

This is the third 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 time stamping 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 current 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 sponsor ballots, the final standard was approved in December 2015, just over two years from start to finish.

Contents

| | | |
|---------|---|----|
| 1. | Overview..... | 35 |
| 1.1 | Scope..... | 35 |
| 1.2 | Purpose..... | 35 |
| 2. | Normative references..... | 36 |
| 3. | Definitions, acronyms, and abbreviations..... | 37 |
| 3.1 | Definitions..... | 37 |
| 3.2 | Acronyms and abbreviations..... | 38 |
| 4. | Format conventions..... | 42 |
| 4.1 | General..... | 42 |
| 4.2 | Fields..... | 42 |
| 4.3 | Numbers..... | 43 |
| 4.4 | Strings..... | 43 |
| 4.5 | Reserved fields and values..... | 43 |
| 5. | General description..... | 44 |
| 5.1 | Introduction..... | 44 |
| 5.2 | Special application spaces..... | 44 |
| 5.2.1 | Smart utility network (SUN)..... | 44 |
| 5.2.2 | Rail communications and control (RCC)..... | 44 |
| 5.2.3 | Television white space (TVWS)..... | 45 |
| 5.2.4 | Radio frequency identification (RFID)..... | 45 |
| 5.2.5 | Low-energy, critical infrastructure monitoring (LECIM)..... | 45 |
| 5.2.6 | Medical body area network (MBAN) services..... | 45 |
| 5.3 | Components of the IEEE 802.15.4 WPAN..... | 45 |
| 5.4 | Multi-PHY management (MPM) of the SUN WPAN..... | 45 |
| 5.5 | Network topologies..... | 46 |
| 5.5.1 | Star network formation..... | 46 |
| 5.5.2 | Peer-to-peer network formation..... | 47 |
| 5.6 | Architecture..... | 48 |
| 5.6.1 | PHY..... | 49 |
| 5.6.2 | MAC sublayer..... | 49 |
| 5.7 | Functional overview..... | 50 |
| 5.7.1 | Superframe structure..... | 50 |
| 5.7.1.1 | Beacon superframe..... | 50 |
| 5.7.1.2 | DSME multi-superframe structure..... | 51 |
| 5.7.1.3 | Slotframes..... | 51 |
| 5.7.1.4 | TMCTP superframe..... | 51 |
| 5.7.2 | Data transfer model..... | 52 |
| 5.7.2.1 | Types of data transfer models..... | 52 |
| 5.7.2.2 | Data transfer to a coordinator..... | 52 |
| 5.7.2.3 | Data transfer from a coordinator..... | 52 |
| 5.7.2.4 | Peer-to-peer data transfers..... | 53 |
| 5.7.3 | Frame structure..... | 53 |
| 5.7.4 | Access methods..... | 53 |

| | | |
|---------|--|----|
| 5.7.4.1 | Frame acknowledgment | 53 |
| 5.7.4.2 | Frak | 54 |
| 5.7.4.3 | Data verification | 54 |
| 5.7.5 | Power consumption considerations | 54 |
| 5.7.5.1 | Low-energy mechanisms | 54 |
| 5.7.6 | Security | 55 |
| 5.8 | Concept of primitives..... | 56 |
| 5.9 | Deprecation of features | 56 |
| 6. | MAC functional description | 57 |
| 6.1 | Device types and conventions..... | 57 |
| 6.2 | Channel access..... | 57 |
| 6.2.1 | Superframe structure..... | 57 |
| 6.2.1.1 | Contention access period (CAP)..... | 59 |
| 6.2.1.2 | Contention-free period (CFP) | 59 |
| 6.2.1.3 | BOP..... | 59 |
| 6.2.2 | Incoming and outgoing superframe timing..... | 59 |
| 6.2.3 | Enhanced Beacon frame timing for MPM procedure | 60 |
| 6.2.4 | IFS..... | 61 |
| 6.2.5 | Random access methods | 61 |
| 6.2.5.1 | CSMA-CA algorithm..... | 61 |
| 6.2.5.2 | TSCH CCA algorithm | 64 |
| 6.2.5.3 | TSCH CSMA-CA retransmission algorithm | 64 |
| 6.2.5.4 | CSMA-CA with PCA | 66 |
| 6.2.5.5 | LECIM ALOHA PCA | 69 |
| 6.2.6 | TSCH slotframe structure | 69 |
| 6.2.6.1 | General..... | 69 |
| 6.2.6.2 | Absolute slot number (ASN) | 70 |
| 6.2.6.3 | Links | 70 |
| 6.2.6.4 | Multiple slotframes | 70 |
| 6.2.7 | LE functional description..... | 71 |
| 6.2.7.1 | LE contention access period (LE CAP)..... | 71 |
| 6.2.7.2 | LE superframe structure..... | 71 |
| 6.2.7.3 | LE-incoming and outgoing superframe timing..... | 71 |
| 6.2.7.4 | LE scan | 71 |
| 6.2.8 | Superframe use for TMCTP operation | 72 |
| 6.2.9 | Rail communications and control network (RCCN) superframe structure..... | 72 |
| 6.2.10 | Channel hopping..... | 73 |
| 6.3 | Starting and maintaining PANs | 75 |
| 6.3.1 | Scanning through channels | 75 |
| 6.3.1.1 | ED channel scan..... | 75 |
| 6.3.1.2 | Active and passive channel scan..... | 75 |
| 6.3.1.3 | Orphan channel scan | 78 |
| 6.3.1.4 | RIT passive channel scan..... | 80 |
| 6.3.2 | PAN ID conflict resolution | 81 |
| 6.3.2.1 | Detection | 81 |
| 6.3.2.2 | Resolution | 82 |
| 6.3.3 | Starting and realigning a PAN | 82 |
| 6.3.3.1 | Starting a PAN..... | 82 |
| 6.3.3.2 | Realigning a PAN..... | 82 |
| 6.3.3.3 | Realignment in a PAN | 84 |
| 6.3.3.4 | Updating superframe configuration and channel PIB attributes..... | 84 |
| 6.3.4 | Beacon generation..... | 84 |

| | | |
|----------|--|-----|
| 6.3.5 | Device discovery..... | 86 |
| 6.3.6 | TSCH PAN formation | 86 |
| 6.4 | Association and disassociation | 87 |
| 6.4.1 | Association..... | 87 |
| 6.4.2 | Disassociation | 90 |
| 6.4.3 | Fast association | 92 |
| 6.5 | Synchronization | 93 |
| 6.5.1 | General..... | 93 |
| 6.5.2 | Synchronization with beacons | 93 |
| 6.5.3 | Synchronization without beacons | 95 |
| 6.5.4 | Synchronization in TSCH PAN | 95 |
| 6.5.4.1 | Timeslot communication | 96 |
| 6.5.4.2 | Node synchronization | 97 |
| 6.5.5 | Orphaned device realignment | 98 |
| 6.6 | Transaction handling..... | 98 |
| 6.7 | Transmission, reception, and acknowledgment..... | 99 |
| 6.7.1 | Transmission..... | 99 |
| 6.7.2 | Reception and rejection | 101 |
| 6.7.3 | Extracting pending data from a coordinator | 102 |
| 6.7.4 | Use of acknowledgments and retransmissions | 104 |
| 6.7.4.1 | No acknowledgment | 104 |
| 6.7.4.2 | Acknowledgment | 105 |
| 6.7.4.3 | Retransmissions | 106 |
| 6.7.5 | Transmission timing restrictions..... | 106 |
| 6.7.6 | Guard time | 107 |
| 6.7.7 | Promiscuous mode..... | 109 |
| 6.7.8 | Transmission scenarios | 109 |
| 6.7.9 | Device announcement..... | 110 |
| 6.8 | GTS allocation and management..... | 111 |
| 6.8.1 | GTS general requirements | 111 |
| 6.8.2 | CAP maintenance | 112 |
| 6.8.3 | GTS allocation | 112 |
| 6.8.4 | GTS usage..... | 113 |
| 6.8.5 | GTS deallocation | 114 |
| 6.8.6 | GTS reallocation | 115 |
| 6.8.7 | GTS expiration..... | 117 |
| 6.9 | Ranging..... | 117 |
| 6.9.1 | Ranging requirements | 117 |
| 6.9.2 | Set-up activities before a ranging exchange | 117 |
| 6.9.3 | Finish-up activities after a ranging exchange | 117 |
| 6.9.4 | Managing DPS..... | 118 |
| 6.9.5 | The ranging exchange | 119 |
| 6.10 | PHY parameter change notification procedure..... | 120 |
| 6.10.1 | Signaling using Beacon frames..... | 120 |
| 6.10.2 | Signaling using multipurpose frames | 120 |
| 6.11 | Deterministic and synchronous multi-channel extension (DSME) | 121 |
| 6.11.1 | DSME command requirements..... | 121 |
| 6.11.2 | DSME multi-superframe structure..... | 121 |
| 6.11.3 | Channel diversity | 123 |
| 6.11.3.1 | Channel adaptation | 123 |
| 6.11.3.2 | Channel hopping..... | 124 |
| 6.11.4 | CAP reduction..... | 126 |
| 6.11.5 | DSME GTS allocation and management..... | 126 |
| 6.11.5.1 | DSME GTS allocation | 127 |

| | | |
|----------|---|-----|
| 6.11.5.2 | DSME GTS deallocation | 130 |
| 6.11.5.3 | DSME GTS expiration..... | 131 |
| 6.11.5.4 | DSME GTS retrieve..... | 131 |
| 6.11.5.5 | DSME GTS change | 132 |
| 6.11.6 | Beacon scheduling | 132 |
| 6.11.7 | Time synchronization | 133 |
| 6.11.8 | Deferred beacon..... | 134 |
| 6.11.9 | Passive channel scan..... | 134 |
| 6.12 | LE transmission, reception and acknowledgment | 134 |
| 6.12.1 | LE transmission, reception, and acknowledgment with positive handshakes | 134 |
| 6.12.2 | Coordinated sampled listening (CSL)..... | 135 |
| 6.12.2.1 | CSL idle listening | 136 |
| 6.12.2.2 | CSL transmission..... | 136 |
| 6.12.2.3 | Unicast transmission | 137 |
| 6.12.2.4 | Broadcast transmission | 137 |
| 6.12.2.5 | CSL reception | 138 |
| 6.12.2.6 | CSL over multiple channels..... | 138 |
| 6.12.2.7 | Turning off CSL mode to reduce latency | 138 |
| 6.12.3 | RIT | 138 |
| 6.12.3.1 | General..... | 138 |
| 6.12.3.2 | Periodic RIT data request transmission and reception..... | 139 |
| 6.12.3.3 | RIT transmission..... | 141 |
| 6.12.4 | Implicit RIT (I-RIT)..... | 143 |
| 6.13 | Starting and maintaining TMCTPs | 143 |
| 6.14 | MPM procedure for inter-PHY coexistence | 146 |
| 6.15 | TVWS access procedures | 149 |
| 6.16 | Channel timing management (CTM)..... | 149 |
| 7. | MAC frame formats..... | 151 |
| 7.1 | Device extended address..... | 151 |
| 7.2 | General MAC frame format..... | 151 |
| 7.2.1 | Frame Control field..... | 151 |
| 7.2.1.1 | Frame Type field..... | 152 |
| 7.2.1.2 | Security Enabled field..... | 152 |
| 7.2.1.3 | Frame Pending field..... | 152 |
| 7.2.1.4 | AR field..... | 153 |
| 7.2.1.5 | PAN ID Compression field..... | 153 |
| 7.2.1.6 | Sequence Number Suppression | 154 |
| 7.2.1.7 | IE Present field..... | 154 |
| 7.2.1.8 | Destination Addressing Mode field | 154 |
| 7.2.1.9 | Frame Version field | 154 |
| 7.2.1.10 | Source Addressing Mode field | 155 |
| 7.2.2 | Sequence Number field..... | 155 |
| 7.2.3 | Destination PAN ID field | 155 |
| 7.2.4 | Destination Address field..... | 155 |
| 7.2.5 | Source PAN ID field..... | 156 |
| 7.2.6 | Source Address field | 156 |
| 7.2.7 | Auxiliary Security Header field | 156 |
| 7.2.8 | IE field | 156 |
| 7.2.9 | Frame Payload field | 156 |
| 7.2.10 | FCS field | 156 |
| 7.3 | Format of individual frame types..... | 158 |
| 7.3.1 | Beacon frame format | 158 |

| | | |
|----------|---|-----|
| 7.3.1.1 | Beacon frame MHR field..... | 159 |
| 7.3.1.2 | IEs field..... | 160 |
| 7.3.1.3 | Superframe Specification field | 160 |
| 7.3.1.4 | GTS Info field..... | 161 |
| 7.3.1.5 | Pending Address field..... | 162 |
| 7.3.1.6 | Beacon Payload field | 162 |
| 7.3.2 | Data frame format..... | 163 |
| 7.3.2.1 | Data frame MHR field | 163 |
| 7.3.2.2 | Data Payload field..... | 163 |
| 7.3.3 | Ack frame format..... | 163 |
| 7.3.4 | MAC command frame format..... | 165 |
| 7.3.4.1 | MHR field | 165 |
| 7.3.4.2 | Command ID field | 165 |
| 7.3.4.3 | Payload field | 165 |
| 7.3.5 | Multipurpose frame format..... | 165 |
| 7.3.5.1 | Frame Type field..... | 166 |
| 7.3.5.2 | Long Frame Control field | 166 |
| 7.3.5.3 | Destination Addressing Mode field | 166 |
| 7.3.5.4 | Source Addressing Mode field | 166 |
| 7.3.5.5 | PAN ID Present field | 166 |
| 7.3.5.6 | Security Enabled field..... | 167 |
| 7.3.5.7 | Sequence Number Suppression field | 167 |
| 7.3.5.8 | Frame Pending field..... | 167 |
| 7.3.5.9 | Frame Version field | 167 |
| 7.3.5.10 | Ack Request field..... | 167 |
| 7.3.5.11 | IEs Present field..... | 167 |
| 7.3.5.12 | Sequence Number field..... | 167 |
| 7.3.5.13 | Destination PAN ID field | 167 |
| 7.3.5.14 | Destination Address field..... | 167 |
| 7.3.5.15 | Source Address field..... | 167 |
| 7.3.5.16 | Auxiliary Security Header field..... | 167 |
| 7.3.5.17 | IEs field..... | 168 |
| 7.3.5.18 | Payload field | 168 |
| 7.3.6 | Extended frame format | 168 |
| 7.4 | IEs | 168 |
| 7.4.1 | IE list termination | 168 |
| 7.4.2 | Header IEs..... | 169 |
| 7.4.2.1 | Header IE format | 169 |
| 7.4.2.2 | Vendor Specific Header IE | 171 |
| 7.4.2.3 | CSL IE | 171 |
| 7.4.2.4 | RIT IE | 171 |
| 7.4.2.5 | DSME PAN descriptor IE..... | 172 |
| 7.4.2.6 | Rendezvous Time IE..... | 174 |
| 7.4.2.7 | Time Correction IE | 174 |
| 7.4.2.8 | Extended DSME PAN descriptor IE | 175 |
| 7.4.2.9 | Fragment Sequence Context Description (FSCD) IE | 176 |
| 7.4.2.10 | Simplified Superframe Specification IE | 177 |
| 7.4.2.11 | Simplified GTS Specification IE | 178 |
| 7.4.2.12 | LECIM Capabilities IE | 178 |
| 7.4.2.13 | RCC Capabilities IE..... | 180 |
| 7.4.2.14 | RCCN Descriptor IE..... | 182 |
| 7.4.2.15 | Global Time IE | 183 |
| 7.4.2.16 | DA IE..... | 183 |
| 7.4.2.17 | Header Termination 1 IE | 184 |

| | | | |
|-------|----------|---|-----|
| | 7.4.2.18 | Header Termination 2 IE | 184 |
| 7.4.3 | | Payload IEs | 184 |
| | 7.4.3.1 | Encapsulated Service Data Unit (ESDU) IE..... | 184 |
| | 7.4.3.2 | MLME IE..... | 185 |
| | 7.4.3.3 | Payload Termination IE..... | 185 |
| 7.4.4 | | Nested IE..... | 185 |
| | 7.4.4.1 | Format of Nested IE..... | 185 |
| | 7.4.4.2 | TSCH Synchronization IE | 188 |
| | 7.4.4.3 | TSCH Slotframe and Link IE | 188 |
| | 7.4.4.4 | TSCH Timeslot IE | 190 |
| | 7.4.4.5 | Hopping timing IE | 191 |
| | 7.4.4.6 | Enhanced Beacon Filter IE | 191 |
| | 7.4.4.7 | MAC Metrics IE | 192 |
| | 7.4.4.8 | All MAC Metrics IE | 192 |
| | 7.4.4.9 | Coexistence Specification IE | 193 |
| | 7.4.4.10 | SUN Device Capabilities IE | 193 |
| | 7.4.4.11 | SUN FSK Generic PHY IE..... | 199 |
| | 7.4.4.12 | Mode Switch Parameter IE | 200 |
| | 7.4.4.13 | PHY Parameter Change IE | 200 |
| | 7.4.4.14 | O-QPSK PHY Mode IE..... | 201 |
| | 7.4.4.15 | PCA Allocation IE | 201 |
| | 7.4.4.16 | LECM DSSS Operating Mode IE | 202 |
| | 7.4.4.17 | LECM FSK Operating Mode IE..... | 204 |
| | 7.4.4.18 | TVWS PHY Operating Mode Description IE | 205 |
| | 7.4.4.19 | TVWS Device Capabilities IE..... | 208 |
| | 7.4.4.20 | TVWS Device Category IE | 213 |
| | 7.4.4.21 | TVWS Device Identification IE | 213 |
| | 7.4.4.22 | TVWS Device Location IE..... | 214 |
| | 7.4.4.23 | TVWS Channel Information Query IE..... | 215 |
| | 7.4.4.24 | TVWS Channel Information Source IE..... | 217 |
| | 7.4.4.25 | CTM IE..... | 218 |
| | 7.4.4.26 | Timestamp IE..... | 219 |
| | 7.4.4.27 | Timestamp Difference IE..... | 219 |
| | 7.4.4.28 | TMCTP Specification IE | 219 |
| | 7.4.4.29 | RCC PHY Operating Mode IE | 220 |
| | 7.4.4.30 | Vendor Specific Nested IE | 221 |
| | 7.4.4.31 | Channel hopping IE | 221 |
| 7.5 | | MAC commands | 222 |
| | 7.5.1 | Command ID field | 222 |
| | 7.5.2 | Association Request command | 223 |
| | 7.5.3 | Association Response command | 224 |
| | 7.5.4 | Disassociation Notification command | 225 |
| | 7.5.5 | Data Request command | 226 |
| | 7.5.6 | PAN ID Conflict Notification command | 227 |
| | 7.5.7 | Orphan Notification command | 227 |
| | 7.5.8 | Beacon Request command..... | 228 |
| | 7.5.9 | Enhanced Beacon Request command | 228 |
| | 7.5.10 | Coordinator realignment command | 228 |
| | 7.5.11 | GTS request command..... | 230 |
| | 7.5.12 | DSME Association Request command..... | 230 |
| | 7.5.13 | DSME Association Response command | 232 |
| | 7.5.14 | DSME GTS Request command | 233 |
| | 7.5.15 | DSME GTS Response command..... | 235 |
| | 7.5.16 | DSME GTS Notify command..... | 237 |

| | | |
|----------|--|-----|
| 7.5.17 | DSME Information Request command..... | 238 |
| 7.5.18 | DSME Information Response command | 238 |
| 7.5.19 | DSME Beacon Allocation Notification command | 239 |
| 7.5.20 | DSME Beacon Collision Notification command..... | 240 |
| 7.5.21 | DSME Link Report command | 240 |
| 7.5.22 | RIT Data Request command..... | 241 |
| 7.5.23 | DBS Request command | 242 |
| 7.5.24 | DBS Response command..... | 243 |
| 7.5.25 | RIT Data Response command | 244 |
| 7.5.26 | Vendor Specific command..... | 244 |
| 8. | MAC services | 245 |
| 8.1 | Overview..... | 245 |
| 8.2 | MAC management service..... | 245 |
| 8.2.1 | Primitives supported by the MLME-SAP interface..... | 245 |
| 8.2.2 | Common requirements for MLME primitives..... | 247 |
| 8.2.3 | Association primitives | 248 |
| 8.2.3.1 | MLME-ASSOCIATE.request..... | 248 |
| 8.2.3.2 | MLME-ASSOCIATE.indication | 249 |
| 8.2.3.3 | MLME-ASSOCIATE.response | 251 |
| 8.2.3.4 | MLME-ASSOCIATE.confirm | 252 |
| 8.2.4 | Disassociation primitives | 254 |
| 8.2.4.1 | MLME-DISASSOCIATE.request | 254 |
| 8.2.4.2 | MLME-DISASSOCIATE.indication | 256 |
| 8.2.4.3 | MLME-DISASSOCIATE.confirm | 256 |
| 8.2.5 | Communications notification primitives | 257 |
| 8.2.5.1 | MLME-BEACON-NOTIFY.indication..... | 257 |
| 8.2.5.2 | MLME-COMM-STATUS.indication | 260 |
| 8.2.5.3 | MLME-IE-NOTIFY.indication | 262 |
| 8.2.6 | Primitives for reading and writing PIB attributes | 264 |
| 8.2.6.1 | MLME-GET.request..... | 264 |
| 8.2.6.2 | MLME-GET.confirm..... | 264 |
| 8.2.6.3 | MLME-SET.request | 265 |
| 8.2.6.4 | MLME-SET.confirm | 265 |
| 8.2.7 | GTS management primitives | 266 |
| 8.2.7.1 | MLME-GTS.request | 266 |
| 8.2.7.2 | MLME-GTS.confirm | 267 |
| 8.2.7.3 | MLME-GTS.indication..... | 268 |
| 8.2.8 | Primitives for orphan notification..... | 269 |
| 8.2.8.1 | MLME-ORPHAN.indication..... | 269 |
| 8.2.8.2 | MLME-ORPHAN.response..... | 270 |
| 8.2.9 | Primitives for resetting the MAC sublayer | 271 |
| 8.2.9.1 | MLME-RESET.request | 271 |
| 8.2.9.2 | MLME-RESET.confirm | 271 |
| 8.2.10 | Primitives for specifying the receiver enable time | 272 |
| 8.2.10.1 | MLME-RX-ENABLE.request..... | 272 |
| 8.2.10.2 | MLME-RX-ENABLE.confirm..... | 273 |
| 8.2.11 | Primitives for channel scanning..... | 274 |
| 8.2.11.1 | MLME-SCAN.request..... | 274 |
| 8.2.11.2 | MLME-SCAN.confirm..... | 277 |
| 8.2.12 | Primitives for updating the superframe configuration | 279 |
| 8.2.12.1 | MLME-START.request..... | 279 |
| 8.2.12.2 | MLME-START.confirm..... | 282 |

| | | |
|----------|---|-----|
| 8.2.13 | Primitives for synchronizing with a coordinator | 283 |
| 8.2.13.1 | MLME-SYNC.request | 283 |
| 8.2.13.2 | MLME-SYNC-LOSS.indication | 284 |
| 8.2.14 | Primitives for requesting data from a coordinator | 286 |
| 8.2.14.1 | MLME-POLL.request | 286 |
| 8.2.14.2 | MLME-POLL.confirm | 287 |
| 8.2.15 | Primitives for specifying dynamic preamble | 287 |
| 8.2.15.1 | MLME-DPS.request | 288 |
| 8.2.15.2 | MLME-DPS.confirm | 288 |
| 8.2.15.3 | MLME-DPS.indication | 289 |
| 8.2.16 | Primitives for channel sounding | 289 |
| 8.2.16.1 | MLME-SOUNDING.request | 289 |
| 8.2.16.2 | MLME-SOUNDING.confirm | 289 |
| 8.2.17 | Primitives for ranging calibration | 290 |
| 8.2.17.1 | MLME-CALIBRATE.request | 291 |
| 8.2.17.2 | MLME-CALIBRATE.confirm | 291 |
| 8.2.18 | Primitives for Beacon Generation | 292 |
| 8.2.18.1 | MLME-BEACON.request | 292 |
| 8.2.18.2 | MLME-BEACON.confirm | 294 |
| 8.2.18.3 | MLME-BEACON-REQUEST.indication | 295 |
| 8.2.19 | Primitives for TSCH | 296 |
| 8.2.19.1 | MLME-SET-SLOTFRAME.request | 296 |
| 8.2.19.2 | MLME-SET-SLOTFRAME.confirm | 297 |
| 8.2.19.3 | MLME-SET-LINK.request | 297 |
| 8.2.19.4 | MLME-SET-LINK.confirm | 299 |
| 8.2.19.5 | MLME-TSCH-MODE.request | 300 |
| 8.2.19.6 | MLME-TSCH-MODE.confirm | 301 |
| 8.2.19.7 | MLME-KEEP-ALIVE.request | 301 |
| 8.2.19.8 | MLME-KEEP-ALIVE.confirm | 302 |
| 8.2.20 | Primitives for DSME GTS management | 302 |
| 8.2.20.1 | MLME-DSME-GTS.request | 302 |
| 8.2.20.2 | MLME-DSME-GTS.indication | 305 |
| 8.2.20.3 | MLME-DSME-GTS.response | 306 |
| 8.2.20.4 | MLME-DSME-GTS.confirm | 308 |
| 8.2.21 | Primitives for reporting the link status | 309 |
| 8.2.21.1 | MLME-DSME-LINK-REPORT.request | 309 |
| 8.2.21.2 | MLME-DSME-LINK-REPORT.indication | 310 |
| 8.2.21.3 | MLME-DSME-LINK-REPORT.confirm | 311 |
| 8.2.22 | Operating parameter change primitives | 311 |
| 8.2.22.1 | MLME-PHY-OP-SWITCH.request | 311 |
| 8.2.22.2 | MLME-PHY-OP-SWITCH.indication | 313 |
| 8.2.22.3 | MLME-PHY-OP-SWITCH.confirm | 315 |
| 8.2.23 | TMCTP DBS allocation primitives | 316 |
| 8.2.23.1 | MLME-DBS.request | 316 |
| 8.2.23.2 | MLME-DBS.indication | 317 |
| 8.2.23.3 | MLME-DBS.response | 318 |
| 8.2.23.4 | MLME-DBS.confirm | 319 |
| 8.2.24 | Primitives for device announcement | 320 |
| 8.2.24.1 | MLME-DA.request primitive | 320 |
| 8.2.24.2 | MLME-DA.indication primitive | 321 |
| 8.2.24.3 | MLME-DA.confirm primitive | 321 |
| 8.2.25 | RIT data commands | 322 |
| 8.2.25.1 | MLME-RIT-REQ.indication | 322 |
| 8.2.25.2 | MLME-RIT-RES.request | 324 |

| | | | |
|-----|-----------|--|-----|
| | 8.2.25.3 | MLME-RIT-RES.indication | 325 |
| | 8.2.25.4 | MLME-RIT-RES.confirm | 327 |
| 8.3 | | MAC data service | 328 |
| | 8.3.1 | MCPS-DATA.request | 328 |
| | 8.3.2 | MCPS-DATA.confirm | 332 |
| | 8.3.3 | MCPS-DATA.indication | 335 |
| | 8.3.4 | MCPS-PURGE.request | 338 |
| | 8.3.5 | MCPS-PURGE.confirm | 338 |
| 8.4 | | MAC constants and PIB attributes | 339 |
| | 8.4.1 | MAC constants | 339 |
| | 8.4.2 | MAC PIB attributes | 340 |
| | 8.4.2.1 | General MAC PIB attributes for functional organization | 345 |
| | 8.4.2.2 | TSCH-specific MAC PIB attributes | 348 |
| | 8.4.2.2.1 | TSCH MAC PIB attributes for macSlotframeTable | 348 |
| | 8.4.2.2.2 | TSCH MAC PIB attributes for macLinkTable | 349 |
| | 8.4.2.2.3 | TSCH MAC PIB attributes for macTimeslotTemplate | 350 |
| | 8.4.2.3 | MAC PIB attributes for hopping sequence | 351 |
| | 8.4.2.4 | DSME specific MAC PIB attributes | 352 |
| | 8.4.2.5 | LE specific MAC PIB attributes | 355 |
| | 8.4.2.6 | MAC performance metrics specific MAC PIB attributes | 357 |
| | 8.4.2.7 | Enhanced Beacon Request command specific MAC PIB attributes | 358 |
| | 8.4.2.8 | Enhanced Beacon frame specific MAC PIB attributes | 359 |
| 9. | | Security | 360 |
| | 9.1 | Overview | 360 |
| | 9.2 | Functional description | 360 |
| | 9.2.1 | Outgoing frame security procedure | 360 |
| | 9.2.2 | KeyDescriptor lookup procedure | 362 |
| | 9.2.3 | Incoming frame security procedure, Security Enabled field is set to one | 362 |
| | 9.2.4 | Incoming frame security procedure, Security Enabled field is set to zero | 364 |
| | 9.2.5 | DeviceDescriptor lookup procedure | 365 |
| | 9.2.6 | SecurityLevelDescriptor lookup procedure | 366 |
| | 9.2.7 | Incoming IE security level checking procedure | 366 |
| | 9.2.8 | Incoming IE key usage policy checking procedure | 367 |
| | 9.2.9 | Incoming security level checking procedure | 367 |
| | 9.2.10 | Incoming key usage policy checking procedure | 367 |
| | 9.3 | Security operations | 368 |
| | 9.3.1 | Integer and octet representation | 368 |
| | 9.3.2 | CCM* nonce | 368 |
| | 9.3.2.1 | CCM* nonce for non-TSCH mode | 368 |
| | 9.3.2.2 | CCM* nonce for TSCH mode | 368 |
| | 9.3.2.3 | CCM* nonce for Fragment frames | 369 |
| | 9.3.3 | CCM* prerequisites | 369 |
| | 9.3.4 | CCM* transformation data representation | 370 |
| | 9.3.4.1 | Key and nonce data inputs | 370 |
| | 9.3.4.2 | a data and m data | 370 |
| | 9.3.4.3 | c data output | 370 |
| | 9.3.5 | CCM* inverse transformation data representation | 371 |
| | 9.3.5.1 | Key and nonce data inputs | 371 |
| | 9.3.5.2 | c data and a data | 371 |
| | 9.3.5.3 | m data output | 372 |
| | 9.4 | Auxiliary security header | 372 |
| | 9.4.1 | Security Control field | 372 |

| | | |
|-------------|--|-----|
| 9.4.1.1 | Security Level field..... | 372 |
| 9.4.1.2 | Key Identifier Mode field | 373 |
| 9.4.1.3 | Frame Counter Suppression field | 374 |
| 9.4.1.4 | ASN in Nonce | 374 |
| 9.4.2 | Frame Counter field..... | 374 |
| 9.4.3 | Key Identifier field..... | 375 |
| 9.4.3.1 | Key Source field | 375 |
| 9.4.3.2 | Key Index field | 375 |
| 9.5 | Security-related MAC PIB attributes..... | 375 |
| 10. | General PHY requirements..... | 381 |
| 10.1 | General requirements and definitions..... | 381 |
| 10.1.1 | Operating frequency range..... | 382 |
| 10.1.2 | Channel assignments..... | 387 |
| 10.1.2.1 | Channel numbering for 780 MHz band | 387 |
| 10.1.2.2 | Channel numbering for 868 MHz, 915 MHz, and 2450 MHz bands | 387 |
| 10.1.2.3 | Channel numbering for CSS PHY | 388 |
| 10.1.2.4 | Channel numbering for HRP UWB PHY | 388 |
| 10.1.2.5 | Channel numbering for MSK PHY 433 MHz band | 389 |
| 10.1.2.6 | Channel numbering for MSK PHY 2450 MHz band | 390 |
| 10.1.2.7 | Channel numbering for LRP UWB PHY | 392 |
| 10.1.2.8 | Channel numbering for SUN and TVWS PHYs | 392 |
| 10.1.2.9 | Channel numbering for 2380 MHz band | 395 |
| 10.1.2.10 | Channel numbering for LECIM PHYs | 395 |
| 10.1.2.10.1 | Channel numbering for LECIM DSSS PHY | 396 |
| 10.1.2.10.2 | Channel numbering for LECIM FSK PHY | 396 |
| 10.1.2.11 | Channel numbering for RCC PHYs..... | 397 |
| 10.1.3 | Minimum LIFS and SIFS periods..... | 398 |
| 10.1.4 | RF power measurement | 399 |
| 10.1.5 | Transmit power | 399 |
| 10.1.6 | Out-of-band spurious emission | 399 |
| 10.1.7 | Receiver sensitivity definitions..... | 399 |
| 10.1.8 | Common signaling mode (CSM) for SUN PHY | 400 |
| 10.2 | General radio specifications..... | 400 |
| 10.2.1 | TX-to-RX turnaround time | 400 |
| 10.2.2 | RX-to-TX turnaround time | 400 |
| 10.2.3 | Error-vector magnitude (EVM) definition..... | 400 |
| 10.2.4 | Receiver maximum input level of desired signal..... | 401 |
| 10.2.5 | Receiver ED..... | 401 |
| 10.2.6 | Link quality indicator (LQI) | 402 |
| 10.2.7 | Clear channel assessment (CCA)..... | 402 |
| 11. | PHY services | 404 |
| 11.1 | Overview..... | 404 |
| 11.2 | PHY constants..... | 404 |
| 11.3 | PHY PIB attributes | 404 |
| 12. | O-QPSK PHY | 411 |
| 12.1 | PPDU format..... | 411 |
| 12.1.1 | SHR field format..... | 411 |
| 12.1.1.1 | Preamble field | 411 |

| | | |
|----------|---|-----|
| 12.1.1.2 | SFD field..... | 411 |
| 12.1.2 | PHR field format..... | 411 |
| 12.1.2.1 | Frame Length field..... | 411 |
| 12.1.2.2 | PHY Payload field..... | 411 |
| 12.2 | Modulation and spreading..... | 412 |
| 12.2.1 | Data rate..... | 412 |
| 12.2.2 | Reference modulator diagram..... | 412 |
| 12.2.3 | Bit-to-symbol mapping..... | 412 |
| 12.2.4 | Symbol-to-chip mapping..... | 412 |
| 12.2.5 | O-QPSK modulation..... | 414 |
| 12.2.6 | Pulse shape..... | 414 |
| 12.2.7 | Chip transmission order..... | 415 |
| 12.3 | O-QPSK PHY RF requirements..... | 415 |
| 12.3.1 | Operating frequency range..... | 415 |
| 12.3.2 | Transmit power spectral density (PSD) mask..... | 416 |
| 12.3.3 | Symbol rate..... | 416 |
| 12.3.4 | Receiver sensitivity..... | 416 |
| 12.3.5 | Receiver interference rejection..... | 416 |
| 12.3.6 | TX-to-RX turnaround time..... | 417 |
| 12.3.7 | RX-to-TX turnaround time..... | 417 |
| 12.3.8 | EVM..... | 417 |
| 12.3.9 | Transmit center frequency tolerance..... | 417 |
| 12.3.10 | Transmit power..... | 417 |
| 12.3.11 | Receiver maximum input level of desired signal..... | 417 |
| 12.3.12 | Receiver ED..... | 417 |
| 12.3.13 | LQI..... | 417 |
| 13. | Binary phase-shift keying (BPSK) PHY..... | 418 |
| 13.1 | PPDU format..... | 418 |
| 13.2 | Modulation and spreading..... | 418 |
| 13.2.1 | BPSK PHY data rates..... | 418 |
| 13.2.2 | Reference modulator..... | 418 |
| 13.2.3 | Differential encoding..... | 418 |
| 13.2.4 | Bit-to-chip mapping..... | 419 |
| 13.2.5 | BPSK modulation..... | 419 |
| 13.2.5.1 | Pulse shape..... | 419 |
| 13.2.5.2 | Chip transmission order..... | 419 |
| 13.3 | BPSK PHY RF requirements..... | 419 |
| 13.3.1 | Operating frequency range..... | 419 |
| 13.3.2 | 915 MHz band transmit PSD mask..... | 419 |
| 13.3.3 | Symbol rate..... | 420 |
| 13.3.4 | Receiver sensitivity..... | 420 |
| 13.3.5 | Receiver interference rejection..... | 420 |
| 13.3.6 | TX-to-RX turnaround time..... | 420 |
| 13.3.7 | RX-to-TX turnaround time..... | 420 |
| 13.3.8 | EVM..... | 421 |
| 13.3.9 | Transmit center frequency tolerance..... | 421 |
| 13.3.10 | Transmit power..... | 421 |
| 13.3.11 | Receiver maximum input level of desired signal..... | 421 |
| 13.3.12 | Receiver ED..... | 421 |
| 13.3.13 | LQI..... | 421 |
| 14. | Amplitude shift keying (ASK) PHY..... | 422 |

| | | |
|---------|---|-----|
| 14.1 | Status of ASK PHY | 422 |
| 14.2 | PPDU format..... | 422 |
| 14.2.1 | Preamble field for ASK PHY | 422 |
| 14.2.2 | SFD for ASK PHY | 422 |
| 14.3 | Modulation and spreading | 422 |
| 14.3.1 | ASK PHY data rates | 422 |
| 14.3.2 | Reference modulator..... | 423 |
| 14.3.3 | Bit-to-symbol mapping | 423 |
| 14.3.4 | Symbol-to-chip mapping | 423 |
| 14.3.5 | ASK modulation | 424 |
| 14.3.6 | Pulse shape..... | 426 |
| 14.3.7 | Chip transmission order | 426 |
| 14.4 | ASK PHY RF requirements..... | 426 |
| 14.4.1 | Operating frequency range..... | 426 |
| 14.4.2 | 915 MHz band transmit PSD mask..... | 426 |
| 14.4.3 | Symbol rate | 426 |
| 14.4.4 | Receiver sensitivity..... | 427 |
| 14.4.5 | Receiver interference rejection | 427 |
| 14.4.6 | TX-to-RX turnaround time | 427 |
| 14.4.7 | RX-to-TX turnaround time | 427 |
| 14.4.8 | EVM..... | 427 |
| 14.4.9 | Transmit center frequency tolerance..... | 427 |
| 14.4.10 | Transmit power | 427 |
| 14.4.11 | Receiver maximum input level of desired signal..... | 428 |
| 14.4.12 | Receiver ED | 428 |
| 14.4.13 | LQI..... | 428 |
| 14.4.14 | Example of PSSS encoding | 428 |
| 15. | Chirp spread spectrum (CSS) PHY | 430 |
| 15.1 | CSS PPDU format | 430 |
| 15.1.1 | Preamble field | 430 |
| 15.1.2 | SFD field..... | 430 |
| 15.1.3 | PHR field | 431 |
| 15.1.4 | PHY Payload field | 431 |
| 15.2 | Modulation and spreading | 431 |
| 15.2.1 | Data rates | 431 |
| 15.2.2 | Reference modulator..... | 431 |
| 15.2.3 | De-multiplexer (DEMUX)..... | 431 |
| 15.2.4 | Serial-to-parallel mapping | 431 |
| 15.2.5 | Data-symbol-to-bi-orthogonal-codeword mapping | 432 |
| 15.2.6 | Parallel-to-serial converter and QPSK symbol mapping..... | 436 |
| 15.2.7 | DQPSK coding | 436 |
| 15.2.8 | DQPSK-to-DQCSK modulation..... | 437 |
| 15.2.9 | CSK generator..... | 437 |
| 15.2.10 | Bit interleaver | 437 |
| 15.3 | Waveform and subchirp sequences..... | 438 |
| 15.3.1 | Graphical presentation of chirp symbols (subchirp sequences)..... | 438 |
| 15.3.2 | Active usage of time gaps | 438 |
| 15.3.3 | Mathematical representation of the continuous time CSS base-band signal | 439 |
| 15.3.4 | Raised cosine window for chirp pulse shaping..... | 441 |
| 15.3.5 | Subchirp transmission order | 441 |
| 15.3.6 | Example of CSK signal generation..... | 442 |
| 15.4 | CSS RF requirements..... | 443 |

| | | |
|----------|--|-----|
| 15.4.1 | Transmit power spectral density (PSD) mask and signal tolerance..... | 443 |
| 15.4.2 | Symbol rate..... | 444 |
| 15.4.3 | Receiver sensitivity..... | 444 |
| 15.4.4 | Receiver interference rejection..... | 444 |
| 15.4.5 | TX-to-RX turnaround time..... | 444 |
| 15.4.6 | RX-to-TX turnaround time..... | 444 |
| 15.4.7 | Transmit center frequency tolerance..... | 444 |
| 15.4.8 | Transmit power..... | 445 |
| 15.4.9 | Receiver maximum input level of desired signal..... | 445 |
| 15.4.10 | Receiver ED..... | 445 |
| 15.4.11 | LQI..... | 445 |
| 16. | HRP UWB PHY..... | 446 |
| 16.1 | General..... | 446 |
| 16.2 | HRP UWB PPDU format..... | 446 |
| 16.2.1 | PPDU encoding process..... | 447 |
| 16.2.2 | Symbol structure..... | 449 |
| 16.2.3 | PSDU timing parameters..... | 450 |
| 16.2.4 | Preamble timing parameters..... | 452 |
| 16.2.5 | SHR field..... | 454 |
| 16.2.5.1 | SYNC field..... | 454 |
| 16.2.5.2 | SFD field..... | 457 |
| 16.2.6 | PHR field..... | 457 |
| 16.2.7 | PHY Payload field..... | 458 |
| 16.3 | Modulation..... | 459 |
| 16.3.1 | Modulation mathematical framework..... | 459 |
| 16.3.2 | Spreading..... | 459 |
| 16.3.3 | FEC..... | 461 |
| 16.3.3.1 | Reed-Solomon encoding..... | 461 |
| 16.3.3.2 | Systematic convolutional encoding..... | 462 |
| 16.4 | RF requirements..... | 463 |
| 16.4.1 | Operating frequency bands..... | 463 |
| 16.4.2 | Channel assignments..... | 464 |
| 16.4.3 | Regulatory compliance..... | 464 |
| 16.4.4 | Operating temperature range..... | 464 |
| 16.4.5 | Baseband impulse response..... | 464 |
| 16.4.6 | Transmit PSD mask..... | 466 |
| 16.4.7 | Chip rate clock and chip carrier alignment..... | 467 |
| 16.4.8 | TX-to-RX turnaround time..... | 467 |
| 16.4.9 | RX-to-TX turnaround time..... | 467 |
| 16.4.10 | Transmit center frequency tolerance..... | 467 |
| 16.4.11 | Receiver maximum input level of desired signal..... | 467 |
| 16.4.12 | Receiver ED..... | 467 |
| 16.4.13 | LQI..... | 467 |
| 16.4.14 | CCA..... | 467 |
| 16.5 | HRP UWB PHY optional pulse shapes..... | 467 |
| 16.5.1 | HRP UWB PHY optional chirp on UWB (CoU) pulses..... | 468 |
| 16.5.2 | HRP UWB PHY optional continuous spectrum (CS) pulses..... | 469 |
| 16.5.3 | HRP UWB PHY linear combination of pulses (LCP)..... | 470 |
| 16.6 | Extended preamble for optional CCA mode 6..... | 471 |
| 16.7 | Ranging..... | 472 |
| 16.7.1 | Ranging counter..... | 472 |
| 16.7.2 | Crystal characterization..... | 472 |

| | | |
|----------|---|-----|
| 16.7.2.1 | Ranging tracking offset..... | 472 |
| 16.7.2.2 | Ranging tracking interval..... | 472 |
| 16.7.3 | Ranging FoM | 473 |
| 17. | GFSK PHY | 475 |
| 17.1 | PPDU formats | 475 |
| 17.2 | Modulation..... | 475 |
| 17.2.1 | GFSK PHY data rates | 475 |
| 17.2.2 | Reference modulator diagram..... | 475 |
| 17.2.3 | Data whitening | 475 |
| 17.2.4 | GFSK modulation | 476 |
| 17.3 | GFSK PHY RF requirements | 476 |
| 17.3.1 | Operating frequency range..... | 476 |
| 17.3.2 | Transmit PSD mask | 476 |
| 17.3.3 | Symbol rate | 477 |
| 17.3.4 | Receiver sensitivity..... | 477 |
| 17.3.5 | Receiver interference rejection | 477 |
| 17.3.6 | TX-to-RX turnaround time | 477 |
| 17.3.7 | RX-to-TX turnaround time | 477 |
| 17.3.8 | Transmit center frequency tolerance..... | 477 |
| 17.3.9 | Transmit power | 477 |
| 17.3.10 | Receiver maximum input level of desired signal..... | 477 |
| 17.3.11 | Receiver ED | 478 |
| 17.3.12 | LQI..... | 478 |
| 18. | MSK PHY | 479 |
| 18.1 | PPDU formats | 479 |
| 18.2 | Data rate..... | 479 |
| 18.3 | SFD for the MSK PHY | 479 |
| 18.4 | MSK modulation..... | 480 |
| 18.4.1 | Reference modulator diagram..... | 480 |
| 18.4.2 | Data whitening | 480 |
| 18.4.3 | Bit-to-symbol mapping | 480 |
| 18.4.4 | Signal modulation | 480 |
| 18.5 | MSK PHY requirements | 481 |
| 18.5.1 | Operating frequency range..... | 481 |
| 18.5.2 | Transmit PSD mask | 481 |
| 18.5.3 | Symbol rate | 481 |
| 18.5.4 | Transmit center frequency tolerance..... | 482 |
| 18.5.5 | Transmit power | 482 |
| 18.5.6 | Receiver maximum input level of desired signal..... | 482 |
| 18.5.7 | Modulation frequency deviation tolerance | 482 |
| 18.5.8 | Zero crossing tolerance | 482 |
| 19. | LRP UWB PHY specification | 483 |
| 19.1 | Overview..... | 483 |
| 19.2 | LRP UWB PHY symbol structure | 483 |
| 19.2.1 | Base mode LRP UWB PHY symbol structure | 483 |
| 19.2.1.1 | Base mode LRP UWB PHY PSDU synchronization signal | 484 |
| 19.2.2 | Extended mode LRP UWB PHY symbol structure | 484 |
| 19.2.2.1 | Extended mode LRP UWB PHY PSDU synchronization signal | 485 |

| | | |
|----------|---|-----|
| 19.2.3 | Long-range mode LRP UWB PHY symbol structure | 486 |
| 19.2.3.1 | Long-range mode LRP UWB PHY PSDU synchronization signal | 486 |
| 19.3 | LRP UWB SHR | 487 |
| 19.3.1 | LRP UWB SHR preamble | 487 |
| 19.3.1.1 | LRP UWB base mode SHR preamble | 487 |
| 19.3.1.2 | RP UWB extended mode SHR preamble | 487 |
| 19.3.1.3 | LRP UWB long-range mode SHR preamble | 487 |
| 19.3.2 | LRP UWB SHR SFD | 487 |
| 19.4 | LRP UWB PHR | 487 |
| 19.4.1 | Encoding Type field | 488 |
| 19.4.2 | Header Extension field | 488 |
| 19.4.3 | SECDED field | 489 |
| 19.4.4 | Frame Length field | 489 |
| 19.4.5 | LEIP Length field | 489 |
| 19.4.6 | LEIP Position field | 489 |
| 19.5 | LRP UWB PSDU | 490 |
| 19.6 | LRP UWB location enhancing information postamble | 490 |
| 19.7 | LRP UWB transmitter specification | 490 |
| 19.7.1 | Pulse shape | 490 |
| 19.7.2 | Pulse timing | 491 |
| 19.7.3 | Transmit PSD mask | 491 |
| 19.8 | LRP UWB receiver specification | 492 |
| 20. | SUN FSK PHY | 493 |
| 20.1 | Introduction | 493 |
| 20.2 | PPDU format for SUN FSK | 493 |
| 20.2.1 | SHR field format | 494 |
| 20.2.1.1 | Preamble field | 494 |
| 20.2.1.2 | SFD | 494 |
| 20.2.2 | PHR field format | 495 |
| 20.2.3 | Mode Switch PHR | 495 |
| 20.2.4 | PHY Payload field | 497 |
| 20.3 | Modulation and coding for SUN FSK | 497 |
| 20.3.1 | Reference modulator | 499 |
| 20.3.2 | Bit-to-symbol mapping | 500 |
| 20.3.3 | Modulation quality | 501 |
| 20.3.3.1 | Frequency deviation tolerance | 501 |
| 20.3.3.2 | Zero crossing tolerance | 502 |
| 20.3.4 | FEC | 502 |
| 20.3.5 | Code-symbol interleaving | 505 |
| 20.4 | Data whitening for SUN FSK | 506 |
| 20.5 | Mode switch mechanism for SUN FSK | 506 |
| 20.6 | SUN FSK PHY RF requirements | 509 |
| 20.6.1 | Operating frequency range | 509 |
| 20.6.2 | Regulatory compliance | 509 |
| 20.6.3 | Radio frequency tolerance | 509 |
| 20.6.4 | Channel switch time | 510 |
| 20.6.5 | Transmitter symbol rate | 510 |
| 20.6.6 | Transmit spectral mask | 510 |
| 20.6.7 | Receiver sensitivity | 510 |
| 20.6.8 | Receiver interference rejection | 511 |
| 20.6.9 | TX-to-RX turnaround time | 511 |
| 20.6.10 | RX-to-TX turnaround time | 511 |

| | | |
|----------|--|-----|
| 20.6.11 | Transmit power | 511 |
| 20.6.12 | Receiver maximum input level of desired signal | 511 |
| 20.6.13 | Receiver ED | 511 |
| 20.6.14 | LQI | 511 |
| 21. | SUN OFDM PHY | 512 |
| 21.1 | Introduction | 512 |
| 21.2 | PPDU format for SUN OFDM | 512 |
| 21.2.1 | Short Training field (STF) | 512 |
| 21.2.1.1 | Frequency domain STF | 512 |
| 21.2.1.2 | Time domain STF generation | 515 |
| 21.2.1.3 | Time domain STF repetition | 515 |
| 21.2.1.4 | STF normalization | 516 |
| 21.2.2 | Long Training field (LTF) | 516 |
| 21.2.2.1 | Frequency domain LTF | 516 |
| 21.2.2.2 | Time domain LTF generation | 519 |
| 21.2.2.3 | LTF normalization | 519 |
| 21.2.3 | PHR | 519 |
| 21.2.4 | PSDU field | 520 |
| 21.3 | Data rates for SUN OFDM | 520 |
| 21.4 | Modulation and coding for SUN OFDM | 521 |
| 21.4.1 | Reference modulator diagram | 521 |
| 21.4.2 | Bit-to-symbol mapping | 521 |
| 21.4.3 | PIB attribute values for phySymbolsPerOctet | 523 |
| 21.4.4 | FEC | 523 |
| 21.4.5 | Interleaver | 524 |
| 21.4.6 | Frequency spreading | 526 |
| 21.4.6.1 | Frequency spreading by 2x | 526 |
| 21.4.6.2 | Frequency spreading by 4x | 526 |
| 21.4.6.3 | No spreading | 527 |
| 21.4.7 | Pilot tones/null tones | 527 |
| 21.4.8 | Cyclic prefix (CP) | 530 |
| 21.4.9 | PPDU Tail field | 530 |
| 21.4.10 | Pad field | 530 |
| 21.4.11 | Scrambler and scrambler seeds | 531 |
| 21.5 | SUN OFDM PHY RF requirements | 532 |
| 21.5.1 | Operating frequency range | 532 |
| 21.5.2 | Transmit power spectral density (PSD) mask | 532 |
| 21.5.3 | Receiver sensitivity | 532 |
| 21.5.4 | Adjacent channel rejection | 532 |
| 21.5.5 | Alternate channel rejection | 533 |
| 21.5.6 | TX-to-RX turnaround time | 533 |
| 21.5.7 | RX-to-TX turnaround time | 533 |
| 21.5.8 | EVM definition | 533 |
| 21.5.9 | Transmit center frequency and symbol tolerance | 535 |
| 21.5.10 | Transmit power | 535 |
| 21.5.11 | Receiver maximum input level of desired signal | 535 |
| 21.5.12 | Receiver ED | 535 |
| 21.5.13 | LQI | 535 |
| 22. | SUN O-QPSK PHY | 536 |
| 22.1 | Introduction | 536 |

| | | |
|----------|---|-----|
| 22.2 | PPDU format for SUN O-QPSK | 536 |
| 22.2.1 | SHR field format | 536 |
| 22.2.1.1 | Preamble field format | 536 |
| 22.2.1.2 | SFD field format | 537 |
| 22.2.2 | PHR field format | 537 |
| 22.2.3 | PHY Payload field | 538 |
| 22.3 | Modulation and coding for SUN O-QPSK | 538 |
| 22.3.1 | Reference modulator | 538 |
| 22.3.2 | SHR coding and spreading | 539 |
| 22.3.3 | PHR coding and spreading | 540 |
| 22.3.4 | PSDU coding and spreading for DSSS | 540 |
| 22.3.5 | PSDU coding and spreading for MDSSS | 542 |
| 22.3.6 | FEC | 543 |
| 22.3.7 | Code-bit interleaving | 545 |
| 22.3.8 | Bit differential encoding (BDE) | 546 |
| 22.3.9 | DSSS bit-to-chip mapping | 547 |
| 22.3.10 | MDSSS bit-to-chip mapping | 551 |
| 22.3.11 | Chip whitening | 555 |
| 22.3.12 | Pilot insertion | 556 |
| 22.3.13 | Modulation parameters for O-QPSK | 557 |
| 22.4 | Support of legacy devices of the 780 MHz, 915 MHz, and 2450 MHz O-QPSK PHYs | 558 |
| 22.5 | SUN O-QPSK PHY RF requirements | 558 |
| 22.5.1 | Operating frequency range | 558 |
| 22.5.2 | Transmit power spectral density (PSD) mask | 558 |
| 22.5.3 | Receiver sensitivity | 559 |
| 22.5.4 | Adjacent channel rejection | 559 |
| 22.5.5 | TX-to-RX turnaround time | 560 |
| 22.5.6 | RX-to-TX turnaround time | 560 |
| 22.5.7 | EVM definition | 560 |
| 22.5.8 | Transmit center frequency and symbol tolerance | 560 |
| 22.5.9 | Transmit power | 561 |
| 22.5.10 | Receiver maximum input level of desired signal | 561 |
| 22.5.11 | Receiver ED | 561 |
| 22.5.12 | LQI | 561 |
| 22.5.13 | CCA | 561 |
| 23. | LECIM DSSS PHYs | 562 |
| 23.1 | PPDU format for DSSS | 562 |
| 23.2 | Modulation and spreading | 562 |
| 23.2.1 | Data rate | 562 |
| 23.2.2 | Reference modulator diagram | 563 |
| 23.2.3 | Convolutional FEC encoding | 563 |
| 23.2.4 | Interleaver | 564 |
| 23.2.4.1 | 256-bit fragment size | 564 |
| 23.2.4.2 | 384-bit fragment size | 564 |
| 23.2.4.3 | 512-bit fragment size | 565 |
| 23.2.5 | Differential encoding | 565 |
| 23.2.6 | Bit-to-symbol and symbol-to-chip encoding | 566 |
| 23.2.6.1 | Gold code generator | 566 |
| 23.2.6.2 | Orthogonal variable spreading factor (OVSF) code generator | 567 |
| 23.2.7 | BPSK/O-QPSK modulation | 570 |
| 23.2.7.1 | BPSK modulation | 570 |
| 23.2.7.2 | O-QPSK modulation | 570 |

| | | |
|----------|---|-----|
| 23.3 | PSDU fragmentation..... | 570 |
| 23.3.1 | Configuration..... | 571 |
| 23.3.2 | Fragmentation..... | 571 |
| 23.3.3 | Fragment packet..... | 572 |
| 23.3.4 | Calculating FICS field using MIC..... | 572 |
| 23.3.5 | Fragment acknowledgment and retransmission..... | 573 |
| 23.3.6 | Frak..... | 573 |
| 23.3.6.1 | Frak policy..... | 573 |
| 23.3.6.2 | Frak format..... | 574 |
| 23.3.7 | Reassembly..... | 575 |
| 23.4 | DSSS PHY RF requirements..... | 575 |
| 23.4.1 | Radio frequency tolerance..... | 575 |
| 23.4.2 | Channel switch time..... | 575 |
| 23.4.3 | Transmit spectral mask..... | 575 |
| 23.4.4 | Receiver sensitivity..... | 575 |
| 23.4.5 | Receiver interference rejection..... | 576 |
| 23.4.6 | TX-to-RX turnaround time..... | 577 |
| 23.4.7 | RX-to-TX turnaround time..... | 577 |
| 23.4.8 | Transmit power..... | 577 |
| 24. | LECIM FSK PHY specification..... | 578 |
| 24.1 | General..... | 578 |
| 24.2 | PPDU format for LECIM FSK PHY..... | 578 |
| 24.2.1 | SHR field format..... | 578 |
| 24.2.1.1 | Preamble field format..... | 578 |
| 24.2.1.2 | SFD field format..... | 578 |
| 24.2.2 | PHR field format..... | 578 |
| 24.2.3 | PHY Payload field..... | 579 |
| 24.3 | Modulation and coding for LECIM FSK PHY..... | 579 |
| 24.3.1 | Reference modulator..... | 579 |
| 24.3.2 | Bit-to-symbol mapping..... | 580 |
| 24.3.3 | Modulation quality..... | 581 |
| 24.3.3.1 | Frequency deviation tolerance..... | 581 |
| 24.3.3.2 | Zero crossing tolerance..... | 581 |
| 24.3.4 | FEC..... | 581 |
| 24.3.5 | Code-bit interleaving..... | 582 |
| 24.3.6 | Spreading..... | 583 |
| 24.4 | Data whitening for LECIM FSK PHY..... | 584 |
| 24.5 | LECIM FSK PHY RF requirements..... | 585 |
| 24.5.1 | Operating frequency range..... | 585 |
| 24.5.2 | Radio frequency tolerance..... | 585 |
| 24.5.3 | Channel switch time..... | 585 |
| 24.5.4 | Transmit spectral mask..... | 585 |
| 24.5.5 | Receiver sensitivity..... | 585 |
| 24.5.6 | TX-to-RX turnaround time..... | 586 |
| 24.5.7 | RX-to-TX turnaround time..... | 586 |
| 24.5.8 | Transmit power..... | 586 |
| 25. | TVWS-FSK PHY..... | 587 |
| 25.1 | PPDU format for TVWS-FSK..... | 587 |
| 25.1.1 | SHR field format..... | 587 |
| 25.1.1.1 | Preamble field format..... | 587 |

| | | |
|----------|--|-----|
| 25.1.1.2 | SFD field format | 587 |
| 25.1.2 | PHR field format | 587 |
| 25.1.3 | PHY Payload field | 588 |
| 25.2 | Modulation and coding for TVWS-FSK | 588 |
| 25.2.1 | Reference modulator | 589 |
| 25.2.2 | FEC and interleaving | 589 |
| 25.2.3 | Data whitening | 589 |
| 25.2.4 | Spreading | 589 |
| 25.2.5 | Bit-to-symbol mapping | 590 |
| 25.2.6 | Modulation quality | 590 |
| 25.2.7 | Values for phySymbolsPerOctet | 590 |
| 25.3 | TVWS-FSK RF requirements | 591 |
| 25.3.1 | Operating frequency range | 591 |
| 25.3.2 | Clock frequency and timing accuracy | 591 |
| 25.3.3 | Channel switch time | 591 |
| 25.3.4 | Receiver sensitivity | 591 |
| 25.3.5 | TX-to-RX turnaround time | 591 |
| 25.3.6 | RX-to-TX turnaround time | 591 |
| 25.3.7 | Receiver maximum input level of desired signal | 591 |
| 25.3.8 | Receiver ED | 591 |
| 25.3.9 | LQI | 591 |
| 26. | TVWS-OFDM PHY | 592 |
| 26.1 | General | 592 |
| 26.2 | PPDU format for TVWS-OFDM | 592 |
| 26.2.1 | STF | 592 |
| 26.2.1.1 | Frequency domain STF | 592 |
| 26.2.1.2 | Time domain STF generation | 593 |
| 26.2.1.3 | Time domain STF repetition | 594 |
| 26.2.1.4 | STF power boosting | 594 |
| 26.2.2 | LTF | 594 |
| 26.2.2.1 | Frequency domain LTF | 594 |
| 26.2.2.2 | Time domain LTF generation | 595 |
| 26.2.3 | PHR field format | 596 |
| 26.2.4 | PSDU field | 596 |
| 26.3 | System parameters for TVWS-OFDM | 597 |
| 26.4 | Modulation and coding for TVWS-OFDM | 597 |
| 26.4.1 | Reference modulator | 597 |
| 26.4.2 | Bit-to-symbol mapping | 598 |
| 26.4.3 | FEC | 599 |
| 26.4.4 | Interleaver | 599 |
| 26.4.5 | Pilot tones/null tones | 601 |
| 26.4.6 | CP | 602 |
| 26.4.7 | PPDU Tail field | 602 |
| 26.4.8 | Pad field | 602 |
| 26.4.9 | Scrambler and scrambler seeds | 602 |
| 26.5 | TVWS-OFDM RF requirements | 603 |
| 26.5.1 | Operating frequency range | 603 |
| 26.5.2 | Pulse shaping | 603 |
| 26.5.3 | Transmit power spectral density (PSD) mask | 603 |
| 26.5.4 | Receiver sensitivity | 603 |
| 26.5.5 | TX-to-RX turnaround time | 603 |
| 26.5.6 | RX-to-TX turnaround time | 603 |

| | | |
|----------|---|-----|
| 26.5.7 | EVM definition | 603 |
| 26.5.8 | Transmit center frequency and symbol tolerance | 605 |
| 27. | TVWS-NB-OFDM PHY | 606 |
| 27.1 | PPDU format for TVWS-NB-OFDM | 606 |
| 27.1.1 | Short Training field (STF) | 606 |
| 27.1.1.1 | Frequency domain STF | 606 |
| 27.1.1.2 | Time domain STF generation | 609 |
| 27.1.1.3 | Time domain STF repetition | 609 |
| 27.1.1.4 | STF normalization | 610 |
| 27.1.2 | Long training field (LTF) | 610 |
| 27.1.2.1 | Frequency domain LTF generation | 610 |
| 27.1.2.2 | Time domain LTF generation | 613 |
| 27.1.2.3 | Time domain LTF repetition | 614 |
| 27.1.2.4 | LTF normalization | 614 |
| 27.1.3 | PHR | 615 |
| 27.1.4 | PHY Payload field | 615 |
| 27.2 | System parameters for TVWS-NB-OFDM | 615 |
| 27.3 | Modulation and coding parameters for TVWS-NB-OFDM | 616 |
| 27.3.1 | Reference modulator | 616 |
| 27.3.2 | Scrambler and scrambler seed | 617 |
| 27.3.3 | Outer encoding | 617 |
| 27.3.4 | Inner encoding | 618 |
| 27.3.5 | Pad bit insertion | 620 |
| 27.3.6 | Spreader | 620 |
| 27.3.7 | Bit interleaving | 621 |
| 27.3.8 | Subcarrier mapping | 621 |
| 27.3.9 | Frequency interleaving | 623 |
| 27.3.10 | Pilot tones | 624 |
| 27.3.11 | Cyclic prefix | 624 |
| 27.3.12 | Pulse shaping | 624 |
| 27.3.13 | PIB attribute values for phySymbolsPerOctet | 625 |
| 27.4 | Channel aggregation for TVWS-NB-OFDM | 625 |
| 27.5 | TVWS-NB-OFDM RF requirements | 625 |
| 27.5.1 | Operating frequency range | 625 |
| 27.5.2 | Receiver sensitivity | 625 |
| 27.5.3 | TX-to-RX turnaround time | 626 |
| 27.5.4 | RX-to-TX turnaround time | 626 |
| 27.5.5 | EVM definition | 626 |
| 27.5.6 | Transmit center frequency and symbol tolerance | 627 |
| 28. | RCC LMR PHY | 628 |
| 28.1 | RCC PHY overview | 628 |
| 28.2 | PPDU format | 628 |
| 28.2.1 | SHR | 628 |
| 28.2.2 | PHR | 629 |
| 28.2.3 | PHY payload | 629 |
| 28.2.4 | Tail bits | 629 |
| 28.3 | FEC | 629 |
| 28.4 | Interleaver | 630 |
| 28.5 | Data whitening | 630 |
| 28.6 | Modulation | 631 |

| | | |
|-----------------------|--|-----|
| 28.6.1 | GMSK..... | 631 |
| 28.6.2 | 4-FSK..... | 631 |
| 28.6.3 | QPSK..... | 632 |
| 28.6.4 | p/4 DQPSK..... | 633 |
| 28.6.5 | DSSS DPSK..... | 633 |
| 28.7 | Reference modulator..... | 635 |
| 28.8 | LMR PHY RF requirements..... | 635 |
| 28.8.1 | Transmitter symbol rate tolerance..... | 635 |
| 28.8.2 | Channel switching time..... | 635 |
| 28.8.3 | Error vector magnitude..... | 635 |
| 28.8.4 | Receiver sensitivity..... | 635 |
| 28.8.5 | Receiver interference rejection..... | 635 |
| 28.8.6 | Receiver maximum input level of desired signal..... | 636 |
| 28.8.7 | TX-to-RX turnaround time..... | 636 |
| 28.8.8 | RX-to-TX turnaround time..... | 636 |
| 28.8.9 | Receiver ED..... | 636 |
| 28.8.10 | LQI..... | 636 |
| 29. | RCC DSSS BPSK PHY..... | 637 |
| 29.1 | Overview..... | 637 |
| 29.2 | RCC DSSS BPSK PHY specification..... | 637 |
| Annex A (informative) | Bibliography..... | 638 |
| Annex B (normative) | CCM* mode of operation..... | 640 |
| Annex C (informative) | Test vectors for cryptographic building blocks..... | 646 |
| Annex D (informative) | Protocol implementation conformance statement (PICS) proforma..... | 659 |
| Annex E (informative) | MPSK PHY..... | 678 |
| Annex F (normative) | Time-slot relaying based link extension (TRLE)..... | 683 |

IEEE Standard for Low-Rate Wireless Personal Area Networks (WPANs)

IMPORTANT NOTICE: IEEE Standards documents are not intended to ensure safety, security, health, or environmental protection, or ensure against interference with or from other devices or networks. Implementers 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.

This IEEE document is made available for use subject to important notices and legal disclaimers. These notices and disclaimers appear in all publications containing this document and may be found under the heading “Important Notice” or “Important Notices and Disclaimers Concerning IEEE Documents.” They can also be obtained on request from IEEE or viewed at <http://standards.ieee.org/IPR/disclaimers.html>.

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. In addition, one of the alternate PHYs provides precision ranging capability that is accurate to one meter. Multiple PHYs are defined to support a variety of frequency bands.