Eldad Perahia
Robert Stacey

Next Generation Wireless LANs

802.11n and 802.11ac

SECOND EDITION

CAMBRIDGE

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Intel Corporation

ROBERT STACEY
Apple Inc.

CAMBRIDGE
UNIVERSITY PRESS

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University Printing House, Cambridge CB2 8BS, United Kingdom

Published in the United States of America by Cambridge University Press, New York

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781107016767

First published 2008
Reprinted with corrections 2010

Second edition 2013
Reprinted 2013

Printed by CPI Group (UK) Ltd, Croydon CR0 4YY

A catalog record for this publication is available from the British Library

Library of Congress Cataloging-in-Publication Data
Perahia, Eldad, 1967 – author.
Next generation wireless LANs : 802.11n, 802.11ac, and Wi-Fi direct / Eldad Perahia, Intel Corporation, Robert Stacey, Apple Inc. – Second edition.
pages cm
ISBN 978-1-107-01676-7 (hardback)
1. Wireless LANs. I. Stacey, Robert, 1967 – author. II. Title.
TK5105.78.P47 2013
621.39′8–dc23

2012033809

ISBN 978-1-107-01676-7 Hardback

To my wife Sarah and our son Nathan

— Eldad Perahia

To my wife Celia and son Zachary

— Robert Stacey

Next Generation Wireless LANs

If you've been searching for a way to get up to speed on IEEE 802.11n and 802.11ac WLAN standards without having to wade through the entire 802.11 specification, then look no further.

This comprehensive overview describes the underlying principles, implementation details, and key enhancing features of 802.11n and 802.11ac. For many of these features, the authors outline the motivation and history behind their adoption into the standard. A detailed discussion of the key throughput, robustness, and reliability enhancing features (such as MIMO, multi-user MIMO, 40\80\160 MHz channels, transmit beamforming, and packet aggregation) is given, in addition to clear summaries of the issues surrounding legacy interoperability and coexistence.

Now updated and significantly revised, this 2nd edition contains new material on 802.11ac throughout, including revised chapters on MAC and interoperability, as well as new chapters on 802.11ac PHY, and multi-user MIMO, making it an ideal reference for designers of WLAN equipment, network managers, and researchers in the field of wireless communication.

Eldad Perahia is a Principal Engineer in the Standards and Technology Group at Intel Corporation. He is Chair of the IEEE 802.11 Very High Throughput in 60 GHz Task Group (TGad), the IEEE 802.11 Very High Throughput in <6 GHz Task Group (TGac) Coexistence Ad Hoc Co-Chair, the IEEE 802.11 liaison from the IEEE 802.19 Wireless Coexistence Working Group, and the former Chair of the IEEE 802.11 Very High Throughout Study Group. He was awarded his Ph.D. in Electrical Engineering from the University of California, Los Angeles and holds 21 patents in various areas of wireless communications.

Robert Stacey is a Wireless Systems Architect at Apple, Inc. He is the IEEE 802.11 Very High Throughput in <6 GHz Task Group (TGac) Technical Editor and MU-MIMO Ad Hoc Co-Chair. He was a member of the IEEE 802.11 High Throughput Task Group (TGn) and a key contributor to the various proposals, culminating in the final joint proposal submission that became the basis for the 802.11n draft standard. He holds numerous patents in the field of wireless communications.

"The authors are renowned experts in the field. The book is a must read for engineers seeking knowledge of recent advances in WLAN technologies."

Dr Osama Aboul-Magd; IEEE 802.11ac Task Group Chair.

"First edition of the book "Next Generation Wireless LANs" by Eldad and Robert is excellent and very popular. The second edition adds newly developed IEEE 802.11ac standard with the same excellence in addressing technical features and easy to read writing style."

Vinko Erceg, Broadcom Corporation

"The 802.11 standard has been evolving for over 20 years and now contains nearly 3000 pages of information. The authors have had direct involvement in writing many of those pages. This book represents a significant accomplishment in conveying and explaining the engineering behind the features for two of the most important radio options provided by the standard. Radio engineers approaching the standard for the first time as well as those already engaged in product development will find this text remarkably rewarding."

Bruce Kraemer, Marvell Semiconductor and Chair, IEEE 802.11 Working Group

This endorsement solely represents the views of the person who is endorsing this book and does not necessarily represent a position of either the company, the IEEE or the IEEE Standards Association.

Foreword

The first version of the 802.11 standard was ratified in 1997 after seven long years of development. However, initial adoption of this new technology was slow, partly because of the low penetration of devices that needed the "freedom of wireless."

The real opportunity for 802.11 came with the increased popularity of laptop computers just a few years later. This popularity brought a rapidly growing user base wanting network connectivity not only while connected to an Ethernet cable at home or at work, but also in between: in hotels, airports, conference centers, restaurants, parks, etc. 802.11 provided a cheap and easy way to make laptop mobility a reality for anyone who wanted it.

However, technology by itself is rarely sufficient, particularly in the networking space, where interoperability of devices from multiple vendors is almost always the key to market success. Having been formed as WECA in 1999, the Wi-Fi Alliance was ready to provide certification of multi-vendor interoperability.

With the right technology from the IEEE 802.11 Working Group, certified interoperability from the Wi-Fi Alliance, and a real market need based on a growing installed base of laptops, the conditions were ripe for the Wi-Fi market to take off, and indeed it did. By 2007 virtually every new laptop contains Wi-Fi as standard equipment. More importantly, and unlike some other "successful" wireless technologies, many of these devices are used regularly. With this wide use came a growing understanding of the power of cheap, easy-to-deploy, and easy-to-manage interoperable Wi-Fi networks.

The natural next step was for people to ask, "What else can we use Wi-Fi for?" The answer is increasingly becoming "everything, everywhere!" Not just laptops, but now almost anything mobile and even many fixed devices contain Wi-Fi, and they are used in a phenomenal range of applications, including data, voice, games, music, video, location, public safety, vehicular, etc. In 2007, more than 300 million Wi-Fi devices were shipped. By 2012, some analysts are forecasting that more than one billion Wi-Fi devices will be shipped every year.

The 2.4 GHz 802.11b 11 Mb/s DSSS/CCK PHY and the basic 802.11 contention-based MAC provided the basis for a great industry. However, the rapid growth of the Wi-Fi market challenged the capabilities of the technology. It was not long before better security (802.11i certified by the Wi-Fi Alliance as WPA/WPA2TM) and better Quality of Service (802.11e certified by the Wi-Fi Alliance as WMMTM and WMM Power Save) were defined, certified, and deployed.

It was also not long before higher data rates were demanded for greater data density and to support the many new and exciting devices and applications. 802.11a, providing

54 Mbps based on OFDM in the 5 GHz band, failed to garner significant support because two radios were required to maintain backward compatibility with 2.4 GHz 802.11b devices; the cost of two radios was often too high. The real success story was 802.11g, which provided 54 Mbps based on OFDM in the 2.4 GHz band in a way that was backward-compatible with 802.11b.

The success of 802.11g drove the use of Wi-Fi to new heights and expanded the demands on the technology yet again; everyone wanted more. Fortunately, the technology continued to develop and in 2002 the IEEE 802.11 Working Group started defining the next generation of PHY and MAC features as part of 802.11n. 802.11n will define mechanisms to provide users some combination of greater throughput, longer range and increased reliability, using mandatory and optional features in the PHY (including MIMO technology and 40 MHz channels) and the MAC (including more efficient data aggregation and acknowledgements).

Interestingly, 802.11n operates in both the 2.4 GHz and 5 GHz bands. It is expected that 5 GHz operation will be more popular than when 802.11a was introduced, because 2.4 GHz is now more congested, the number of available channels in the 5 GHz band has been expanded with the introduction of DFS and TPC technology, there is more need for high throughput 40 MHz channels, and the cost of dual-band radios has decreased.

The 802.11n standard is not yet complete, and is unlikely to be ratified by the IEEE until at least mid 2009. Until August 2006, the Wi-Fi Alliance had a policy to not certify 802.11n products until the standard was ratified. However, some vendors decided the market could not wait for ratification of the 802.11n standard and started releasing pre-standard products. These products were often not interoperable at the expected performance levels because they were not based on a common interpretation of the draft 802.11n specification. The problem for the Wi-Fi Alliance was that these products were adversely affecting the reputation of Wi-Fi. The Wi-Fi Alliance decided the only way forward was to certify the basic features of 802.11n from a pre-standard draft. Such a decision is not without precedent. In 2003, certification of WPA started before the 802.11i standard was ratified and in 2004 certification of WMM started before 802.11e was ratified. The Wi-Fi Alliance commenced certification of 802.11n draft 2.0 on 26 June 2007.

The decision has turned out to be the right one for the industry and for users. The Wi-Fi CERTIFIED 802.11n draft 2.0 programme has been remarkably successful, with more than 150 products certified in less than five months. This represents a significantly higher number of certified products than for the 802.11g programme during a similar period after launch. The Wi-Fi Alliance's certification program has helped ensure interoperability for the many products that will be released before the ratification of the 802.11n standard. This is particularly important given that the likely ratification date of the 802.11n standard has been extended by more than a year since the decision to start a certification program was announced by the Wi-Fi Alliance. The next challenge for the Wi-Fi Alliance is to ensure a backward-compatible transition path from the 802.11n draft 2.0 as certified by the Wi-Fi Alliance to the final ratified standard.

Standards are never the most accessible of documents. The 802.11 standard is particularly difficult to understand because it has been amended so many times by different groups and editors over a long period. A draft amendment to the standard, such as

802.11n D2.0, is even harder to interpret because many clauses are still being refined and the refinement process often has technical and political aspects that are only visible to those participating full time in the IEEE 802.11 Working Group.

Books like this one are invaluable because they provide the details and the background that allow readers to answer the questions, "What is likely to be in the final standard and how does it work?" Eldad and Robert should be congratulated on taking up the challenge.

Dr. Andrew Myles
Chairman of the BoD
Wi-Fi Alliance
6 December 2007

Preface to the first edition

Having worked on the development of the 802.11n standard for some time, we presented a full day tutorial on the 802.11n physical layer (PHY) and medium access control (MAC) layer at the IEEE Globecom conference held in San Francisco in December 2006. Our objective was to provide a high level overview of the draft standard since, at the time, there was very little information on the details of the 802.11n standard available to those not intimately involved in its development. After the tutorial, we were approached by Phil Meyler of Cambridge University Press and asked to consider expanding the tutorial into a book.

Writing a book describing the standard was an intriguing prospect. We felt that a book would provide more opportunity to present the technical details in the standard than was possible with the tutorial. It would fill the gap we saw in the market for a detailed description of what is destined to be one of the most widely implemented wireless technologies. While the standard itself conveys details on what is needed for interoperability, it lacks the background on why particular options should be implemented, where particular aspects came from, the constraints under which they were designed, or the benefit they provide. All this we hoped to capture in the book. The benefits various features provide, particularly in the physical layer, are quantified by simulation results. We wanted to provide enough information to enable the reader to model the physical layer and benchmark their simulation against our results. Finally, with the amended standard now approaching 2500 pages, we hoped to provide an accessible window into the most important aspects, focusing on the throughput and robustness enhancements and the foundations on which these are built.

The book we came up with is divided into three parts. The first part covers the physical layer (PHY), and begins with background information on the 802.11a/g OFDM PHY on which the 802.11n PHY is based and interoperates, and proceeds with an overview of spatial multiplexing, the key throughput enhancing technology in 802.11n. This is followed by details on exactly how high throughput is achieved in 802.11n using spatial multiplexing and wider, 40 MHz channels. This in turn is followed by details on robustness enhancing features such as receive diversity, spatial expansion, space-time block codes, and low density parity check codes.

The second part covers the medium access control (MAC) layer. This part provides background on the original 802.11 MAC as well as the 802.11e quality of service (QoS) enhancements. It gives an overview of why changes were needed in the MAC to achieve higher throughput, followed by details on each of the new features introduced. Given the large installed base of 802.11 devices, coexistence and interoperability are considered crucial to the smooth adoption of the standard. To this end, the book provides a detailed discussion on features supporting coexistence and interoperability.

In the third part we provide details on two of the more advanced aspects of the standard, transmit beamforming and link adaptation. These topics are covered in a section of their own, covering both the PHY and the MAC.

Writing this book would not have been possible without help from our friends and colleagues. We would like to thank Thomas (Tom) Kenney and Brian Hart for reviewing the PHY portion of the book and Tom Kenney and Michelle Gong for reviewing the MAC portion of the book. They provided insightful comments, suggestions, and corrections that significantly improved the quality of the book.

One of the goals of this book is to provide the reader with a quantitative feel of the benefit of the PHY features in the 802.11n standard. This would have been impossible without the extensive simulation support provided to us by Tom Kenney. He developed an 802.11n PHY simulation platform that includes most of the 802.11n PHY features and is also capable of modeling legacy 802.11a/g. The simulation includes all the 802.11n channel models. Furthermore, Tom modeled receiver functionality such as synchronization, channel estimation, and phase tracking. The simulation also included impairments such as power amplifier non-linearity and phase noise to provide a more realistic measure of performance.

The simulation supports both 20 MHz and 40 MHz channel widths. With the 40 MHz simulation capability, Tom generated the results given in Figure 5.8 in Section 5.1.5 modeling MCS 32 and Figure 5.9 in Section 5.1.7 which illustrates the range and throughput improvement of 40 MHz modes. With the MIMO/SDM capability of the simulation in both AWGN channel and 802.11n channel models, Tom produced the results for Figures 5.12–5.15 in Section 5.3. By designing the simulation with the flexibility to set the transmitter and receiver to different modes, he also produced the results given in Figure 5.18 in Section 5.4 modeling the behavior of a legacy 802.11a/g device receiving a GF transmission. Tom also incorporated short guard interval into the simulation with which the results for sensitivity to time synchronization error in Figures 5.20–5.22 in Section 5.5 were generated.

Tom designed the simulation with the ability to select an arbitrary number of transmitter and receiver antennas independent from the number of spatial streams. Using this capability he produced the results for receive diversity gain in Figures 6.2–6.4 in Section 6.1 and spatial expansion performance in Figures 6.5 and 6.6 in Section 6.2. Tom also incorporated space-time block coding and low density parity check coding into the simulation and generated the results given in Figures 6.8, 6.9, 6.14, 6.15, and 6.16 in Section 6.3 and Figure 6.24 in Section 6.4.

To accurately model the performance of a transmit beamforming system, it is important to include aspects like measurement of the channel state information, beamforming weight computation, and link adaptation. Tom incorporated all of these functions into the simulation to generate the waterfall curves in Figures 13.11–13.16 and the throughput curves in Figures 13.17 and 13.18 in Section 13.8.

We sincerely hope our book provides you with insight and a deeper understanding of the 802.11n standard and the technology upon which it is built.

Preface to the second edition

While 802.11n was a revolutionary enhancement over 802.11a/g, and necessitated an entire book for proper presentation of the new technology, 802.11ac is more of an evolutionary improvement over 802.11n by providing wider bandwidth channels and multi-user MIMO. As such we felt that the treatment of new 802.11ac features could be addressed by a few extra chapters in an update of our original 802.11n book, now an 802.11n/ac book.

The new single user Very High Throughput physical layer packet structure is described in a new Chapter 7, including a description of 80 MHz and 160 MHz waveforms. The new downlink multi-user MIMO mechanism in 802.11ac is presented in a new Chapter 14. Enhancements to channel access for 802.11ac have been added to Chapter 11. Several new basic service set and clear channel assessment rules to manage 80 MHz and 160 MHz operation and coexistence are described in Chapter 11. Modifications to 802.11n channel model Doppler component are given in Chapter 3 and Chapter 13. Furthermore, we discuss the simplification of single user transmit beamforming in 802.11ac in Chapter 13.

We would like to again thank our friends and colleagues for their help with preparing the new material for the second edition. In particular, Thomas Kenney reviewed the MAC, PHY, and MU-MIMO material. He also updated the 802.11n PHY simulation platform to 802.11ac and provided all the 802.11ac PHY simulation results illustrated in Figures 7.9, 7.10, 7.20, and 7.21. Sameer Vermani reviewed the MU-MIMO chapter and graciously provided the MU-MIMO simulation results in Figure 14.2. We are also thankful to Simone Merlin who reviewed the MAC and MU-MIMO chapters.

Abbreviations

μs	microseconds
2G	second generation (cellular)
3G	third generation (cellular)
AC	access category
ACK	acknowledgement
ADC	analog-to-digital converter
ADDBA	add block acknowledgement
ADDTS	add traffic stream
AGC	automatic gain control
AID	association identifier
AIFS	arbitration inter-frame space
A-MPDU	aggregate MAC protocol data unit
A-MSDU	aggregate MAC service data unit
AoA	angle of arrival
AoD	angle of departure
AP	access point
APSD	automatic power save delivery
A-PSDU	aggregate PHY service data unit
AS	angular spectrum
ASEL	antenna selection
AWGN	additive white Gaussian noise
BA	block acknowledgement
BAR	block acknowledgement request
BCC	binary convolution code
BF	beamforming
BICM	bit interleaved coded modulation
bps	bits-per-second
BPSCS	coded bits per single carrier for each spatial stream
BPSK	binary phase shift keying
BSS	basic service set
BSSID	BSS identifier
BW	bandwidth
CBPS	coded bits per symbol

CBPSS	coded bits per spatial stream
CBW	channel bandwidth
CCA	clear channel assessment
CCDF	complementary cumulative distribution function
CCK	complementary code keying
CFP	contention free period
CP	contention period
CRC	cyclic redundancy code
CS	carrier sense
CSD	cyclic shift diversity
CSI	channel state information
CSMA	carrier sense multiple access
CSMA/CA	carrier sense multiple access with collision avoidance
CSMA/CD	carrier sense multiple access with collision detection
CTS	clear to send
CW	contention window
DA	destination address
DAC	digital-to-analog converter
dB	decibels
dBc	decibels relative to carrier
dBi	decibels isotropic relative to an antenna
dBm	decibel of measured power referenced to one milliwatt
DBPS	data bits per OFDM symbol
dBr	dB (relative)
DC	direct current
DCF	distributed coordination function
DELBA	delete block acknowledgement
DIFS	DCF inter-frame space
DL MU-MIMO	downlink multi-user multiple-input multiple-output
DLS	direct link session
DS	distribution system
DSL	digital subscriber line
DSSS	direct sequence spread spectrum
DTIM	delivery traffic indication message
DVD	digital versatile disc
DVR	digital video recorder
EAP	extensible authentication protocol
EDCA	enhanced distributed channel access
EIFS	extended inter-frame space
EIRP	equivalent isotropically radiated power
EOF	end of frame
ERP	enhanced rate PHY
ESS	extended service set

ETSI	European Telecommunications Standards Institute
EVM	error vector magnitude
EWC	Enhanced Wireless Consortium
FCC	Federal Communications Commission
FCS	frame check sequence
FEC	forward error correction
FFT	fast Fourier transform
FHSS	frequency hopped spread spectrum
FS	free space
FTP	file transfer protocol
GF	Greenfield
GF-HT-STF	Greenfield High Throughput Short Training field
GHz	gigahertz
GI	guard interval
GIF	graphics interchange format
GO	group owner
GPS	global positioning system
HC	hybrid coordinator
HCCA	HCF controlled channel access
HCF	hybrid coordination function
HEMM	HCCA, EDCA mixed mode
HT	high throughput
HTC	high throughput control
HT-DATA	High Throughput Data field
HT-LTF	High Throughput Long Training field
HTSG	High Throughput Study Group
HT-SIG	High Throughput Signal field
HT-STF	High Throughput Short Training field
HTTP	hypertext transfer protocol
Hz	Hertz
IBSS	independent basic service set
IC	interference cancellation
IDFT	inverse discrete Fourier transform
IEEE	Institute of Electrical and Electronic Engineers
IFFT	inverse fast Fourier transform
IFS	inter-frame space
I/O	input/output
IP	Internet Protocol
IPv6	Internet Protocol version 6
IR	infrared
ISI	inter-symbol interference
ISM	industrial, scientific, and medical
JPEG	Joint Photographic Experts Group

kHz	kilohertz
km/h	kilometers per hour
LAN	local area networking
LDPC	low density parity check
LLC	logical link control
L-LTF	Non-HT (Legacy) Long Training field
LNA	low noise amplifier
LOS	line-of-sight
LSB	least significant bit
L-SIG	Non-HT (Legacy) Signal field
L-STF	Non-HT (Legacy) Short Training field
LTF	Long Training field
m	meters
MAC	medium access control
MAI	MRQ or ASEL indication
MAN	metropolitan area networking
Mbps	megabit per second
MCS	modulation and coding scheme
MF	mixed format
MFB	MCS feedback
MFSI	MCS feedback sequence indication
MHz	megahertz
MIB	management information base
MIMO	multiple-input multiple-output
ML	maximum likelihood
MMPDU MAC	management protocol data unit
MMSE	minimum mean-square-error
MPDU	MAC protocol data unit
MPEG	Moving Picture Experts Group
MRC	maximal-ratio combining
MRQ	MCS request
Msample/s	mega-samples per second
MSB	most significant bit
MSDU	MAC service data unit
MSE	mean-square-error
MSFI	MCS feedback sequence identifier
MSI	MCS request sequence identifier
MU	multi-user
MU-MIMO	multi-user multiple-input multiple-output
NAV	network allocation vector
NDP	null data packet
NF	noise figure
NLOS	non-line-of-sight