WiFi PHY standards review – from early 802.11 to ‘ac’ and ‘ad’

M. Rahaim and T.D.C. Little
Department of Electrical and Computer Engineering
Boston University, Boston, MA 02215
{mrahaim, tdcl}@bu.edu

MCL Technical Report No. 04-29-2014

Abstract

The emergence of wireless communication devices and wireless applications over the past two decades has created a growing need for high speed wireless access in the home and workplace. The IEEE 802.11 standards series, or WiFi, has developed various standards to adapt to the increasing requirements of the wireless data link. The IEEE 802.11 protocol suite has been widely adopted across the world and continues to grow as the de facto standard set for indoor wireless local area networks. In this report, we provide a short description of the early standards and review the state of the art protocols defined in 802.11ac and 802.11ad.

Keywords – Wireless Communications, Wireless Local Area Network (WLAN), WiFi, Orthogonal Frequency Division Multiplexing (OFDM), IEEE Standards.

Not Published.

1. Introduction

The IEE 802.11 protocol suite defines a set of standards for medium access control (MAC) and physical layer (PHY) specifications in wireless local area networks (WLANs). The protocols are specified for various Industrial, Scientificm and Medical (ISM) bands around 2.4GHz, 5GHz, and 60GHz. The IEEE standards association considers “standards” to be the protocols denoted by 802.11 followed by the publication year, such as IEEE 802.11-1999; however the “amendments” are created by task groups and released as revisions to the standard. The IEEE 802.11-2007 standard consolidates amendments 802.11a, 802.11b, 802.11d, 802.11e, 802.11g, 802.11h, 802.11i, and 802.11j and additional amendments were again consolidated in standard release IEEE 802.11-2012. While various amendments incorporate extensions or corrections to the standard, amendments 802.11a, 802.11b, 802.11g, 802.11n, 802.11ac, and 802.11ad are the base amendments to the PHY layer modulation and coding schemes. In the following, details are provided for the widely adopted earlier protocols as well as the newly released 802.11ac and 802.11ad protocols that offer potential data rates in the Gigabit per second range. This document focuses primarily on the various physical layer modulation and coding schemes (MCS) and leaves the review of MAC specifications for future work.

2. Early Protocols

The initial version of the IEEE 802.11 standard was released in 1997 with specified data rates of either 1 or 2 Mbps and operation solely in the 2.4GHz band. This “legacy mode” protocol is commonly referred to as 802.11-1997 or 802.11-1999; however this version of the protocol is seldom found in commercial products. This version of the standard implements either frequency hopping spread spectrum (FHSS) or direct sequence spread spectrum (DSSS) for interference mitigation. The FHSS specification implements Gaussian Frequency Shift Keying (GFSK) with either 2 or 4 frequencies (i.e., symbols) corresponding to 1 or 2 bits per symbol, respectively. DSSS uses either Binary Phase Shift Keying (BPSK) with 1 bit per symbol or Quadrature Phase Shift Keying (QPSK) with 2 bits per symbol. Another difference is that while FHSS hops through all of the available channels, DSSS is limited to a 22MHz range – allowing for selection of a range that has minimal interference. The spread spectrum techniques each observe 11Mchip/s and implement an 11 chip code; therefore the BPSK and QPSK symbols provide 1 and 2 Mbps throughput, respectively.

$$Throughput = \frac{Chip\ Rate}{Chips\ per\ Sym} \cdot Bits\ per\ Sym$$

The release of the 802.11a and 802.11b amendments in September 2009 allowed the standard to reach potential data rates on the order of 10’s of Mbps. Although both standards were released around the same time frame, the 802.11b standard was more common for a few years because the equipment required by the 802.11a standard was more complex (i.e., OFDM modulation, 5GHz operation) and didn’t begin appearing in commercial products until 2001. The release of 802.11g incorporated OFDM modulation in the 2.4GHz range and provided backwards compatibility with 802.11b devices, leading to many commercial products that incorporated mixed 802.11a/g for operation in either the 2.4 or 5GHz ranges while still allowing for connectivity to available 802.11b devices. As throughput requirements began to reach the potential data rate limits of 802.11a/g devices, 802.11n was developed in order to maintain operation in the 2.4 and 5GHz bands with higher throughput through use of increased per-user spectrum allocation, increased modulation orders, and channel parallelization through multiple input-multiple output (MIMO). The PHY specifications for each of these amendments are described below.

2.1 802.11a – Released September 1999

The IEEE 802.11a amendment was the first 802.11 specification to utilize the 5GHz band and OFDM. With the growing use of the 2.4GHz ISM band for various devices (WLAN and otherwise), many countries opened the 5GHz band from 5.725GHz to 5.875GHz (150MHz total bandwidth). Each channel has 20MHz of bandwidth, B, and utilizes an OFDM frame with an 800ns guard interval ($T_{GI} = 800\text{ns}$). Active carriers implement BPSK, QPSK, Quadrature Amplitude Modulation with order 16 (16-QAM) or Quadrature Amplitude Modulation with order 64 (64-QAM). The corresponding number of bits per symbol, N_{bps}, are 1, 2, 4, and 6, respectively. The coding rate, R, for the potential forward error correction schemes are 1/2, 2/3, or 3/4. Since the specification uses OFDM rather than single carrier modulation, multiple subcarriers provide data in each symbol. Subcarrier spacing, f_c, is defined as 312.5Khz which can be calculated assuming a 64 point FFT:

$$f_c = \frac{B}{N_{FFT}}$$

The specification considers 52 information carriers from $f_0 - 26f_c$ to $f_0 + 26f_c$ (f_0 does not carrier information, but may be a constant value to improve carrier synchronization at the transmitter and receiver) and the additional "carriers" are unused such that the signal bandwidth is 16.25MHz with a 1.875MHz guard band on each side. The number of carriers with active data, N_{AC}, is 48 (4 carriers are reserved for signal overhead). The period of the data symbol, T_{data}, and full OFDM symbol, T_{sym}, are:

$$T_{data} = \frac{1}{f_c} = 3.2\mu\text{s} \qquad\qquad T_{sym} = T_{data} + T_{GI}$$

and the PHY throughput for specific MCS is

$$Throughput = (R)(N_{bps})(N_{AC})\left(\frac{1}{T_{sym}}\right)$$

The specifications and calculated throughput for the 8 Modulation and coding schemes in 802.11a are shown in the table below. *Note: I don't believe the specification indicates MCS numbers (i.e., 0-7) for 802.11a; however I have put them in the table for conformity with other 802.11 standards.*

Table 1: Modulation and Coding Schemes for 802.11a

MCS	Mod Scheme	Coded bits per carrier	Coding Rate	FFT Size	Number of active data carriers	Subcarrier Spacing (MHz)	Data period (microsec)	Data Rates (Mbps)
0	BPSK	1	0.50	64	48	0.3125	3.20	6
1	BPSK	1	0.75	64	48	0.3125	3.20	9
2	QPSK	2	0.50	64	48	0.3125	3.20	12
3	QPSK	2	0.75	64	48	0.3125	3.20	18
4	16-QAM	4	0.50	64	48	0.3125	3.20	24
5	16-QAM	4	0.75	64	48	0.3125	3.20	36
6	64-QAM	6	0.67	64	48	0.3125	3.20	48
7	64-QAM	6	0.75	64	48	0.3125	3.20	54

2.2 802.11b – Released September 1999

The 802.11b standard is specified to operate in the 2.4GHz band with backwards compatibility for legacy 802.11-1997 standard devices. This standard continues the use of DSSS; but moves away from FHSS. The scheme has four modes of operation. The first two, Differential BPSK (DBPSK) and Differential QPSK (DQPSK), operate at 1 and 2 Mbps, respectively, and are compatible with the legacy 802.11-1997 standard. *Note: I've seen discussions of the legacy standard without mentioning differential coding, so I'm not exactly sure how compatibility works. The symbols are the same; but bit mapping is different, so I'm not sure if the Differential coding is negotiated. It seems like the legacy version should also be implementing Differential coding; but I haven't verified this.* In addition, 802.11b specifies a complementary code keying (CCK) scheme that utilizes a sequence of 8 "chips" and also transmits at 11Mchip/s. Data can be encoded with either 4 bits per chip sequence or 8 bits per chip sequence, corresponding to 5.5Mbps or 11Mbps, respectively. For the 5.5Mbps specification, each 4 bit symbol (b0, b1, b2, b3) is used to determine the complex chip sequence and the DQPSK phase rotation. First, bits b2 and b3 are used to determine which of the complex valued chip sequences below are generated:

(b2, b3)	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
00	j	1	j	-1	j	1	-1	1
01	-j	-1	-j	1	j	1	-j	1
10	-j	1	-j	-1	-j	1	j	1
11	j	-1	j	1	-j	1	j	1

In this table, j represents the value on the imaginary or quadrature axis of the complex plane. Once the complex chip sequence is determined, bits b0 and b1 are used to determine the DQPSK phase rotation that is to be applied. In the case of the 11Mbps specification, a similar process is observed however bits b2 through b7 are used to determine one of 64 possible chip sequences instead of the 4 sequences shown in the table above. The 5.5 and 11Mbps rates can also be achieved with packet binary convolution coding (PBCC) where the data bits are passed through a half rate binary convolution encoder and mapped to BPSK or QPSK symbols (without differential encoding). The full set of modulation and coding schemes are shown below. *Note: I define a "symbol" to incorporate a full chip sequence.*

Table 2: Modulation and Coding Schemes for 802.11b

MCS	Modulation Scheme	Chip Rate (MHz)	Chips per Symbol	Symbol Rate (MHz)	Bits per symbol	Code Rate	Data Rate (Mbps)
0	DBPSK, DSSS	11	11	1	1	--	1
1	DQPSK, DSSS	11	11	1	2	--	2
2	CCK, DQPSK	11	8	1.375	4	--	5.5
3	CCK, DQPSK	11	8	1.375	8	--	11
4	PBCC, BPSK	--	--	11	1	1/2	5.5
5	PBCC, QPSK	--	--	11	2	1/2	11

2.3 802.11g – Released June 2003

The success of OFDM in 802.11a motivated the standardization of a similar scheme for use in the 2.4GHz spectrum; however the objective (and much of the technical difficulty) included backwards compatibility with other 802.11 devices operating in the 2.4GHz range. Hence, the 802.11g amendment incorporates the OFDM modulation and coding schemes from 802.11a – specified for channels in the 2.4GHz band – as well as the legacy schemes from 802.11b and the IEEE 802.11-1997 standard. In addition, two optional schemes specified in the amendment modify the PBCC schemes in 802.11b to implement 8-PSK with varying clock rates and 2/3 rate binary convolution encoder in order to achieve 22 or 33Mbps throughput. There is some additional overhead in the packet headers for 802.11g to maintain compatibility; however the primary modulation and coding schemes have the theoretical rates listed in the following figure. *Note: OFDM Symbol rate is* $1/T_{sym}$.

Table 3: Modulation and Coding Schemes for 802.11g

MCS	Modulation Scheme	Chip Rate (MHz)	Chips per Symbol	Symbol Rate (MHz)	Bits per symbol	Code Rate	# of active carriers	Data Rate (Mbps)
0	DBPSK, DSSS	11	11	1	1	--	--	1
1	DQPSK, DSSS	11	11	1	2	--	--	2
2	CCK, DQPSK	11	8	1.375	4	--	--	5.5
3	CCK, DQPSK	11	8	1.375	8	--	--	11
4	PBCC, BPSK	--	--	11	1	1/2	--	5.5
5	PBCC, QPSK	--	--	11	2	1/2	--	11
6	PBCC, 8PSK	--	--	11	3	2/3	--	22
7	PBCC, 8PSK	--	--	16.5	3	2/3	--	33
8	OFDM, BPSK	--	--	0.25	1	1/2	48	6
9	OFDM, BPSK	--	--	0.25	1	3/4	48	9
10	OFDM, QPSK	--	--	0.25	2	1/2	48	12
11	OFDM, QPSK	--	--	0.25	2	3/4	48	18
12	OFDM, 16-QAM	--	--	0.25	4	1/2	48	24
13	OFDM, 16-QAM	--	--	0.25	4	3/4	48	36
14	OFDM, 64-QAM	--	--	0.25	6	2/3	48	48
15	OFDM, 64-QAM	--	--	0.25	6	3/4	48	54

2.4 802.11n – Released October 2009

With the drastic growth in wireless capacity requirements of the early to mid-2000's, the 802.11 working group began a task for higher capacity links as an evolution of the widely popular 802.11a/g devices. The 802.11n amendment utilizes strictly OFDM signaling and develops protocols that improve link rates in the 2.4 and 5GHz bands by 1-) increasing bandwidth & number of OFDM carriers, 2-) increasing the code rate, and 3-) decreasing the guard interval in order to increase the per channel capacity. In addition, 802.11n adds spatial multiplexing through MIMO and specifies **up to 4 parallel spatial streams**. In this specification, the MCS index specifies the possible encoding combinations; however the throughput is also a function of the number of active carriers (which depends on bandwidth), guard interval, and number of spatial streams, N_{SS}.

$$Throughput = (N_{SS})(R)(N_{bps})(N_{AC})\left(\frac{1}{T_{data} + T_{GI}}\right)$$

Regarding the number of active carriers, the specification allows for either **20 MHz bandwidth** (as was the case with previous specifications) or **40 MHz bandwidth**. The specification maintains a subcarrier spacing of 312.5KHz (therefore $T_{data} = 3.2\mu s$) as with the previous specifications for OFDM (64 point FFT for 20 MHz, 128 point FFT for 40 MHz); however a **20MHz signal utilizes 52 active data carriers** as opposed to 48 and a **40 MHz signal utilizes 108 active data carriers**. The guard interval can also be modified in order to increase throughput. The amendment specifies operation for the previous interval of **800ns** as well as a shorter interval of **400ns**. The table below shows the single channel variations of MCS 0-7 with all the potential combinations of bandwidth and guard intervals.

Table 4: Modulation and Coding Schemes for 802.11n

B (MHz)	FFT Size	N_{AC}	T_{GI} (µs)	T_{sym} (µs)	MCS Index	Mod Scheme	N_{bps}	R	Throughput (Mbps)
20	64	52	0.8	4	0	BPSK	1	1/2	6.5
20	64	52	0.8	4	1	QPSK	2	1/2	13
20	64	52	0.8	4	2	QPSK	2	3/4	19.5
20	64	52	0.8	4	3	16-QAM	4	1/2	26
20	64	52	0.8	4	4	16-QAM	4	3/4	39
20	64	52	0.8	4	5	64-QAM	6	2/3	52
20	64	52	0.8	4	6	64-QAM	6	3/4	58.5
20	64	52	0.8	4	7	64-QAM	6	5/6	65
20	64	52	0.4	3.6	0	BPSK	1	1/2	7.2
20	64	52	0.4	3.6	1	QPSK	2	1/2	14.4
20	64	52	0.4	3.6	2	QPSK	2	3/4	21.7
20	64	52	0.4	3.6	3	16-QAM	4	1/2	28.9
20	64	52	0.4	3.6	4	16-QAM	4	3/4	43.3
20	64	52	0.4	3.6	5	64-QAM	6	2/3	57.8
20	64	52	0.4	3.6	6	64-QAM	6	3/4	65
20	64	52	0.4	3.6	7	64-QAM	6	5/6	72.2
40	128	108	0.8	4	0	BPSK	1	1/2	13.5
40	128	108	0.8	4	1	QPSK	2	1/2	27
40	128	108	0.8	4	2	QPSK	2	3/4	40.5
40	128	108	0.8	4	3	16-QAM	4	1/2	54
40	128	108	0.8	4	4	16-QAM	4	3/4	81
40	128	108	0.8	4	5	64-QAM	6	2/3	108
40	128	108	0.8	4	6	64-QAM	6	3/4	121.5
40	128	108	0.8	4	7	64-QAM	6	5/6	135
40	128	108	0.4	3.6	0	BPSK	1	1/2	15
40	128	108	0.4	3.6	1	QPSK	2	1/2	30
40	128	108	0.4	3.6	2	QPSK	2	3/4	45
40	128	108	0.4	3.6	3	16-QAM	4	1/2	60
40	128	108	0.4	3.6	4	16-QAM	4	3/4	90
40	128	108	0.4	3.6	5	64-QAM	6	2/3	120
40	128	108	0.4	3.6	6	64-QAM	6	3/4	135
40	128	108	0.4	3.6	7	64-QAM	6	5/6	150

Note that for each setting in the graph above, throughput can be increased by 2x, 3x, or 4x if 2, 3, or 4 spatial streams are used, respectively – leading to a range of throughput values from *6.5Mbps* (MCS 0, 800ns GI, 20 MHz Bandwidth, single channel) to *600 Mbps* (MCS7, 400ns GI, 40MHz Bandwidth, 4 parallel channels. It should also be noted that most commercial products do not reach the theoretical rates described in the specification. Typically, 802.11n devices offer single channel or 2 spatial streams while some products offer up to 3. I'm not aware of any commercial 802.11n products that offer the full 4 channel 600Mbps throughput.

3. Gigabit WiFi

After the 802.11n amendment was released, the WiFi Alliance and the 802.11 working group began focusing on a targeted milestone of Gigabit per second wireless connectivity. Two paths were taken that led to the 802.11ac and 802.11ad amendments – each with potential throughput of approximately 7Gbps. The 802.11ac task group worked on a continued evolution of the 5GHz ISM band – with improved performance via similar techniques to the jump from 802.11a/g to 802.11n. On the other hand, the 802.11ad working group focused on use of the 60GHz band which provides a much wider bandwidth but has a shorter range and is high attenuated by objects in the environment.

3.1 802.11ac – Released December 2013

The 802.11ac amendment specifies all of the modulation and coding schemes from 802.11n with some additional variations to increase capacity. One major difference is that 802.11ac operates solely in the 5GHz range (as opposed to 802.11n which operates in either 2.4 or 5GHz). This is because 802.11ac offers higher bandwidth modes – including 80MHz and 160MHz in addition to the 20MHz and 40MHz options – that the 2.4GHz band can't accommodate. As with the addition of the 40MHz option in 802.11n, carrier separation remains as 312.5 KHz, therefore the FFT size doubles to 256 for the 80 MHz channel and again to 512 for a 160 MHz channel. There is also the option to use two disjoint 80 MHz channels in an 80+80 mode. In addition to the increased bandwidth, the 802.11ac amendment adds 2 new modulation and coding schemes for 256-QAM and also specifies MIMO with up to 8 spatial streams. The following table summarizes the available theoretical throughput values:

Table 5: Modulation and Coding Schemes for 802.11ac

B (MHz)	FFT Size	N_{AC}	T_{GI} (µs)	T_{sym} (µs)	MCS Index	Mod Scheme	N_{bps}	R	Throughput (Mbps)
20	64	52	0.8	4	0	BPSK	1	1/2	6.5
20	64	52	0.8	4	1	QPSK	2	1/2	13
20	64	52	0.8	4	2	QPSK	2	3/4	19.5
20	64	52	0.8	4	3	16-QAM	4	1/2	26
20	64	52	0.8	4	4	16-QAM	4	3/4	39
20	64	52	0.8	4	5	64-QAM	6	2/3	52
20	64	52	0.8	4	6	64-QAM	6	3/4	58.5
20	64	52	0.8	4	7	64-QAM	6	5/6	65
20	64	52	0.8	4	8	256-QAM	8	3/4	78
20	64	52	0.8	4	9	256-QAM	8	5/6	86.7

20	64	52	0.4	3.6	0	BPSK	1	1/2	7.2
20	64	52	0.4	3.6	1	QPSK	2	1/2	14.4
20	64	52	0.4	3.6	2	QPSK	2	3/4	21.7
20	64	52	0.4	3.6	3	16-QAM	4	1/2	28.9
20	64	52	0.4	3.6	4	16-QAM	4	3/4	43.3
20	64	52	0.4	3.6	5	64-QAM	6	2/3	57.8
20	64	52	0.4	3.6	6	64-QAM	6	3/4	65
20	64	52	0.4	3.6	7	64-QAM	6	5/6	72.2
20	64	52	0.4	3.6	8	256-QAM	8	3/4	86.7
20	64	52	0.4	3.6	9	256-QAM	8	5/6	96.3
40	128	108	0.8	4	0	BPSK	1	1/2	13.5
40	128	108	0.8	4	1	QPSK	2	1/2	27
40	128	108	0.8	4	2	QPSK	2	3/4	40.5
40	128	108	0.8	4	3	16-QAM	4	1/2	54
40	128	108	0.8	4	4	16-QAM	4	3/4	81
40	128	108	0.8	4	5	64-QAM	6	2/3	108
40	128	108	0.8	4	6	64-QAM	6	3/4	121.5
40	128	108	0.8	4	7	64-QAM	6	5/6	135
40	128	108	0.8	4	8	256-QAM	8	3/4	162
40	128	108	0.8	4	9	256-QAM	8	5/6	180
40	128	108	0.4	3.6	0	BPSK	1	1/2	15
40	128	108	0.4	3.6	1	QPSK	2	1/2	30
40	128	108	0.4	3.6	2	QPSK	2	3/4	45
40	128	108	0.4	3.6	3	16-QAM	4	1/2	60
40	128	108	0.4	3.6	4	16-QAM	4	3/4	90
40	128	108	0.4	3.6	5	64-QAM	6	2/3	120
40	128	108	0.4	3.6	6	64-QAM	6	3/4	135
40	128	108	0.4	3.6	7	64-QAM	6	5/6	150
40	128	108	0.4	3.6	8	256-QAM	8	3/4	180
40	128	108	0.4	3.6	9	256-QAM	8	5/6	200
80	256	234	0.8	4	0	BPSK	1	1/2	29.3
80	256	234	0.8	4	1	QPSK	2	1/2	58.5
80	256	234	0.8	4	2	QPSK	2	3/4	87.8
80	256	234	0.8	4	3	16-QAM	4	1/2	117
80	256	234	0.8	4	4	16-QAM	4	3/4	175.5
80	256	234	0.8	4	5	64-QAM	6	2/3	234
80	256	234	0.8	4	6	64-QAM	6	3/4	263.3
80	256	234	0.8	4	7	64-QAM	6	5/6	292.5
80	256	234	0.8	4	8	256-QAM	8	3/4	351
80	256	234	0.8	4	9	256-QAM	8	5/6	390

80	256	234	0.4	3.6	0	BPSK	1	1/2	32.5
80	256	234	0.4	3.6	1	QPSK	2	1/2	65
80	256	234	0.4	3.6	2	QPSK	2	3/4	97.5
80	256	234	0.4	3.6	3	16-QAM	4	1/2	130
80	256	234	0.4	3.6	4	16-QAM	4	3/4	195
80	256	234	0.4	3.6	5	64-QAM	6	2/3	260
80	256	234	0.4	3.6	6	64-QAM	6	3/4	292.5
80	256	234	0.4	3.6	7	64-QAM	6	5/6	325
80	256	234	0.4	3.6	8	256-QAM	8	3/4	390
80	256	234	0.4	3.6	9	256-QAM	8	5/6	433.3
160	512	468	0.8	4	0	BPSK	1	1/2	58.5
160	512	468	0.8	4	1	QPSK	2	1/2	117
160	512	468	0.8	4	2	QPSK	2	3/4	175.5
160	512	468	0.8	4	3	16-QAM	4	1/2	234
160	512	468	0.8	4	4	16-QAM	4	3/4	351
160	512	468	0.8	4	5	64-QAM	6	2/3	468
160	512	468	0.8	4	6	64-QAM	6	3/4	526.5
160	512	468	0.8	4	7	64-QAM	6	5/6	585
160	512	468	0.8	4	8	256-QAM	8	3/4	702
160	512	468	0.8	4	9	256-QAM	8	5/6	780
160	512	468	0.4	3.6	0	BPSK	1	1/2	65
160	512	468	0.4	3.6	1	QPSK	2	1/2	130
160	512	468	0.4	3.6	2	QPSK	2	3/4	195
160	512	468	0.4	3.6	3	16-QAM	4	1/2	260
160	512	468	0.4	3.6	4	16-QAM	4	3/4	390
160	512	468	0.4	3.6	5	64-QAM	6	2/3	520
160	512	468	0.4	3.6	6	64-QAM	6	3/4	585
160	512	468	0.4	3.6	7	64-QAM	6	5/6	650
160	512	468	0.4	3.6	8	256-QAM	8	3/4	780
160	512	468	0.4	3.6	9	256-QAM	8	5/6	866.7

Similar to the specifications for 802.11n, the throughput values for 802.11ac can be multiplied for each available spatial stream; however in 802.11ac there is a maximum of 8 streams compared to 4 in 802.11n. The throughputs for 802.11ac hence range from *6.5Mbps* (MCS 0, 800ns GI, 20 MHz Bandwidth, single channel) to *6933.3 Mbps* or *6.93 Gbps* (MCS9, 400ns GI, 160MHz Bandwidth, 8 parallel channels).

3.2 802.11ad – Released December 2012

The final amendment to be discussed is 802.11ad. While there are many interesting differences relating to the channel model for 60GHz transmission, the focus of this analysis will be the modulation and coding schemes specified in the amendment. The 802.11ad amendment specifies a larger set of modulation and coding schemes (32 compared to 10 for 802.11ac); however each MCS has only one mode (i.e., there aren't a range of values for bandwidth, guard interval, number of spatial streams). The

32 schemes are broken into 4 catagories: the Control PHY (CPHY), the Single Carrier PHY (SCPHY), the OFDM PHY (OFDMPHY), and the Low Power Single Carrier PHY (LPSCPHY). The OFDMPHY utilizes 2.64GHz clock rate and the others have a clock rate of 2/3 the OFDM clock (also the system clock), or 1.76MHz.

The CPHY is the default MCS that allows devices to communicate and negotiate which of the high rate links to use. Since it used primarily for control data and negotiation, the link must be very robust and hence uses differential encoding, 32x spreading, and a code rate of 1/2 (in addition to the use of BPSK modulation). The pi-2 DBPSK modulation implies that the constellation is rotated by pi/2 after each symbol and that the bit mapping is differentially encoded (i.e., depends on the previous symbol). For a BPSK modulator, the pi/2 rotation ensures that each symbol has a 90° phase shift from the previous (as opposed to either 0° or 180° with conventional BPSK or DBPSK). The spreading is done with a 32 sample Golay code and a low density parity check (LDPC) with code rate 1/2 is used to ensure operation even at very low SNR. The throughput the determined by:

$$Throughput_{CPHY} = (B)\left(N_{bps}\right)(R)\left(\frac{1}{N_{Spread}}\right) = 27.5\text{Mbps}$$

The schemes belonging to the SCPHY share similar encoding steps, but have various modulation orders and code rates (MCS 1 also uses a 2x repetition code that halves the throughput). The pi/2 rotation is used for each of the modulation schemes; however I don't believe it has an effect on the performance of QPSK or QAM. It seems to be used across the board to maintain compatibility across schemes in the modulation / demodulation stages. Each scheme in the SCPHY implements an LDPC with codeword length of 672; however the data bits carried per codeword can be either 336, 504, 420, or 546, relating to a code rate of 1/2, 3/4, 5/8, or 13/16, respectively. In addition, a block code of 512 symbols, N_{Bsyms}, is used with a 64 symbol guard interval, N_{GIsyms}. The throughput is determined by

$$Throughput_{SCPHY} = (B)\left(N_{bps}\right)(R)\left(\frac{1}{N_{Rep}}\right)\left(1 - \frac{N_{GIsyms}}{N_{Bsyms}}\right)$$

Table 6: Modulation and Coding Scheme for 802.11ad CPHY and SCPHY

	MCS Index	B (MHz)	Mod	N_{bps}	Spread / Reps	R	N_{GIsyms}	N_{Bsyms}	Throughput (Mbps)
CPHY	0	1760	Pi/2 DBPSK	1	32	1/2	--	--	27.5
SCPHY	1	1760	Pi/2 BPSK	1	2	1/2	64	512	385
	2	1760	Pi/2 BPSK	1	1	1/2	64	512	770
	3	1760	Pi/2 BPSK	1	1	5/8	64	512	962.5
	4	1760	Pi/2 BPSK	1	1	3/4	64	512	1155
	5	1760	Pi/2 BPSK	1	1	13/16	64	512	1251.25
	6	1760	Pi/2 QPSK	2	1	1/2	64	512	1540
	7	1760	Pi/2 QPSK	2	1	5/8	64	512	1925
	8	1760	Pi/2 QPSK	2	1	3/4	64	512	2310
	9	1760	Pi/2 QPSK	2	1	13/16	64	512	2502.5
	10	1760	Pi/2 16QAM	4	1	1/2	64	512	3080
	11	1760	Pi/2 16QAM	4	1	5/8	64	512	3850
	12	1760	Pi/2 16QAM	4	1	3/4	64	512	4620

Table 7: Modulation and Coding Schemes for 802.11ad OFDM PHY

	MCS Index	B (MHz)	Mod	N_{bps}	R	P_{GI}	N_{FFT}	N_{AC}	Throughput (Mbps)
OFDM PHY	13	2640	SQPSK	1	1/2	0.25	512	336	693
	14	2640	SQPSK	1	5/8	0.25	512	336	866.25
	15	2640	QPSK	2	1/2	0.25	512	336	1386
	16	2640	QPSK	2	5/8	0.25	512	336	1732.5
	17	2640	QPSK	2	3/4	0.25	512	336	2079
	18	2640	16-QAM	4	1/2	0.25	512	336	2772
	19	2640	16-QAM	4	5/8	0.25	512	336	3465
	20	2640	16-QAM	4	3/4	0.25	512	336	4158
	21	2640	16-QAM	4	13/16	0.25	512	336	4504.5
	22	2640	64-QAM	6	5/8	0.25	512	336	5197.5
	23	2640	64-QAM	6	3/4	0.25	512	336	6237
	24	2640	64-QAM	6	13/16	0.25	512	336	6756.75

Table 8: Modulation and Coding Schemes for 802.11ad LPSC PHY

	MCS Index	B (MHz)	Mod	N_{bps}	R	N_{GIsyms}	N_{Bsyms}	R_H	Throughput (Mbps)
LPSC PHY	25	1760	Pi/2 BPSK	1	13/16	64	512	8/16	626
	26	1760	Pi/2 BPSK	1	13/16	64	512	8/12	834
	27	1760	Pi/2 BPSK	1	13/16	64	512	8/9	1112
	28	1760	Pi/2 QPSK	2	13/16	64	512	8/16	1251
	29	1760	Pi/2 QPSK	2	13/16	64	512	8/12	1668
	30	1760	Pi/2 QPSK	2	13/16	64	512	8/9	2224
	31	1760	Pi/2 QPSK	2	13/16	64	512	8/8	2503

Each scheme in the OFDM PHY observes an FFT size of 512 with 336 active data carriers, a guard interval (or cyclic prefix) equal to 25% of the symbol period (P_{GI}), and a bandwidth of 2.64GHz. The modulation schemes for the OFDM PHY include Spread QPSK (SQPSK) where a single QPSK symbol is modulated onto two carriers that are maximally separated in frequency – such that an average of 1 bit per carrier is transmitted. MCS 15, 16, and 17 are considered "QPSK" modulation; however they are actually specified as dual carrier modulation (DCM) where 4 bits are mapped to 2 active carriers (i.e., the 2 carriers, each with 4 possible settings, have 16 possible pairings that map to the 16 possible combinations of the set of 4 bits). Given the OFDM equations in section 2.1, we can determine that

$$(T_{data})(B)\left(\frac{1}{N_{FFT}}\right) = 1$$

therefore, the OFDM throughput equation (also from section 2.1) can be modified and written:

$$Throughput_{OFDMPHY} = (B)(R)(N_{bps})\left(\frac{N_{AC}}{N_{FFT}}\right)\left(\frac{T_{data}}{T_{sym}}\right) = (B)(R)(N_{bps})\left(\frac{N_{AC}}{N_{FFT}}\right)\left(\frac{1}{1+P_{GI}}\right)$$

The low power single carrier schemes (MCS25-31) are similar to those of the SCPHY; however the LPDC is replaced by a combination of a Reed-Solomon code and Hamming block code. Each scheme has a code rate of 13/16 which stems from the Reed Solomon code (with rate 208/224) and additional Golay coded guard intervals spread throughout the 448 symbol block (compatible with the SCPHY). Within the 448 symbol block, there are 7 sub-groups each with 56 data symbols and an 8 symbol guard interval. Therefore, the RS code and the additional intervals imply

$$R = \left(\frac{56}{64}\right)\left(\frac{208}{224}\right) = \frac{13}{16}$$

The rate of the Hamming block code, R_H, is specified for each MCS and the throughput is calculated as

$$Throughput_{LPSCPHY} = (B)(R)(N_{bps})\left(1 - \frac{N_{Bsyms}}{N_{GIsyms}}\right)(R_H)$$

4. Conclusions

In conclusion, this document provides an overview of the various modulation and coding schemes used throughout multiple amendments to the IEEE 802.11 protocol suite and provides some high level discussion related to the motivation for each revision. Many reviews of the standards discuss some of the modulation methods without describing how the throughput is calculated; however this document aims to clarify confusion relating to the wide range of proposed throughput values for each of the amendments. The 802.11 protocol suite goes far beyond specifying modulation and coding; however the aim of this document is to review the 802.11 amendments that directly affect the physical layer and show the evolution of the standard relative to these physical layer specifications.

5. References

[1] IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE Std 802.11-2007 (Revision of IEEE Std 802.11-1999)* , vol., no., pp.1,1076, June 12 2007

[2] IEEE Standard for Information technology--Telecommunications and information exchange between systems Local and metropolitan area networks--Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Redline," *IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007) - Redline* , vol., no., pp.1,5229, March 29 2012.

[3] WiFi Alliance, www.wi-fi.org, last visited 4-28-14, 2014.

[4] Pejman Roshan, Jonathan Leary, *802.11 Wireless LAN Fundamentals;* Cisco Press, 2004.

[5] Justin Berg, *The IEEE 802.11 Standardization – Its History, Specifications, Implementations, and Future;* Technical Report GMU-TCOM-TR-8, George Mason University. http://telecom.gmu.edu/content/ieee-80211-standardization-its-history-specifications-implementations-and-future

[6] Qualcomm, *IEEE802.11ac: The Next Evolution of WiFi Standards*, Qualcomm Incorporated, 2012. http://www.qualcomm.com/media/documents/ieee80211ac-next-evolution-wi-fi

[7] Agilent Technologies, *Wireless LAN at 60GHz – IEEE 802.11ad explained*, Application Note, Agilent Technologies, Inc. 2013. http://cp.literature.agilent.com/litweb/pdf/5990-9697EN.pdf