Performance Comparison Analysis between IEEE 802.11a/b/g/n Standards

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ABSTRACT
Now days, in practical application scenario, with increasing demand of wireless LANs, higher data rates are required. Wireless Local Area Network (WLAN) is based on IEEE 802.11 standard and is also popular by the name as Wireless Fidelity (Wi-Fi). The task groups within the 802.11 working group introduced few extensions to the original specifications. The well known extensions of 802.11 specifications are 802.11b, 802.11a, 802.11g and 802.11n. This paper provides the major differences between various IEEE 802.11 standards, their operation, interoperability and deployment constraints. In this paper, performances of IEEE 802.11a/b/g/n standards are explained.

Keywords
IEEE 802.11a, IEEE 802.11b, IEEE 802.11g, IEEE 802.11n, CCK, DSSS, OFDM, MIMO and MATLAB.

1. INTRODUCTION
The IEEE standard [1] defines data rate of 1 Mbps to 2 Mbps for three different physical layers that is direct sequence spread spectrum (DSSS), frequency hopping spread spectrum (FHSS) and infrared (IR) techniques. From these three physical layers, the DSSS is one of the most widely used technique to provide higher data rates. For multicarrier transmission, the IEEE 802.11a [2] defines an Orthogonal Frequency Division Multiplexing (OFDM) technique to provide data rates from 6Mbps to 54 Mbps at 5 GHz band. IEEE 802.11a standard enhance the data rates from 11Mbps to 54Mbps at 5GHz band but it cannot support interoperability with older IEEE 802.11 and IEEE 802.11b devices. To provide interoperability with IEEE 802.11 and IEEE 802.11b, the characteristics of both (IEEE 802.11a and IEEE 802.11b) are combines by the IEEE 802.11g standard [3] to upgrade data rates of up to 54 Mbps at 2.4 GHz.

The IEEE 802.11 Working Group realized that the initial standard that was passed in 1997 would not be sufficient to attract implementers. Therefore, the working group established various task groups with the responsibilities to develop different extensions to the 802.11 standard. IEEE 802.11 standard has ability to sense the bit error rate (BER) of its link and implemented modulation to data rate and exchange to FEC which is used to set the BER as low error rate for data applications [4].

To upgrade the data rate of wireless connections for several applications, the IEEE 802.11 based wireless local area network (WLAN) have been widely utilized in present wireless networks. Hence, to provide data rates of up to 11Mbps at 2.4GHz band, the IEEE defines the IEEE 802.11b standard. The advanced IEEE 802.11a [5] and IEEE 802.11g [6] standards are utilized by employing the most recent modulation techniques.The IEEE 802.11n channel models are designed for indoor wireless local area networks for bandwidths of up to 100 MHz, at frequencies of 2 and 5 GHz.

Table 1: wireless LAN products on the market [7]

Product	Spectrum	Maximum physical rate	T_x	Compatible with	Major Disadvantages	Major Advantages
802.11 a	5.0 GHz	54 Mbps	OFDM	None	Smallest range of all 802.11 standard	High bit rate in less-Crowded spectrum
802.11 b	2.4 GHz	11 Mbps	DSSS	802.11	Bit rate too low for many emerging applications	Widel deploy-ed, higher range
802.11 g	2.4 GHz	54 Mbps	OFDM	802.11/ 802.11b	Limited number of collo-cated WLANs	High bit rate in 2.4 GHz spectrum
802.11 n	5 or 2.4 GHz	600 Mbps	OFDM/ MIMO	802.11a/ b/g	Difficult to Impl-ement	High-est bit rate

This paper provides a detailed description of the IEEE 802.11a/b/g/n standards and discusses their performances by comparing it to the previous IEEE 802.11 standards by using MATLAB.

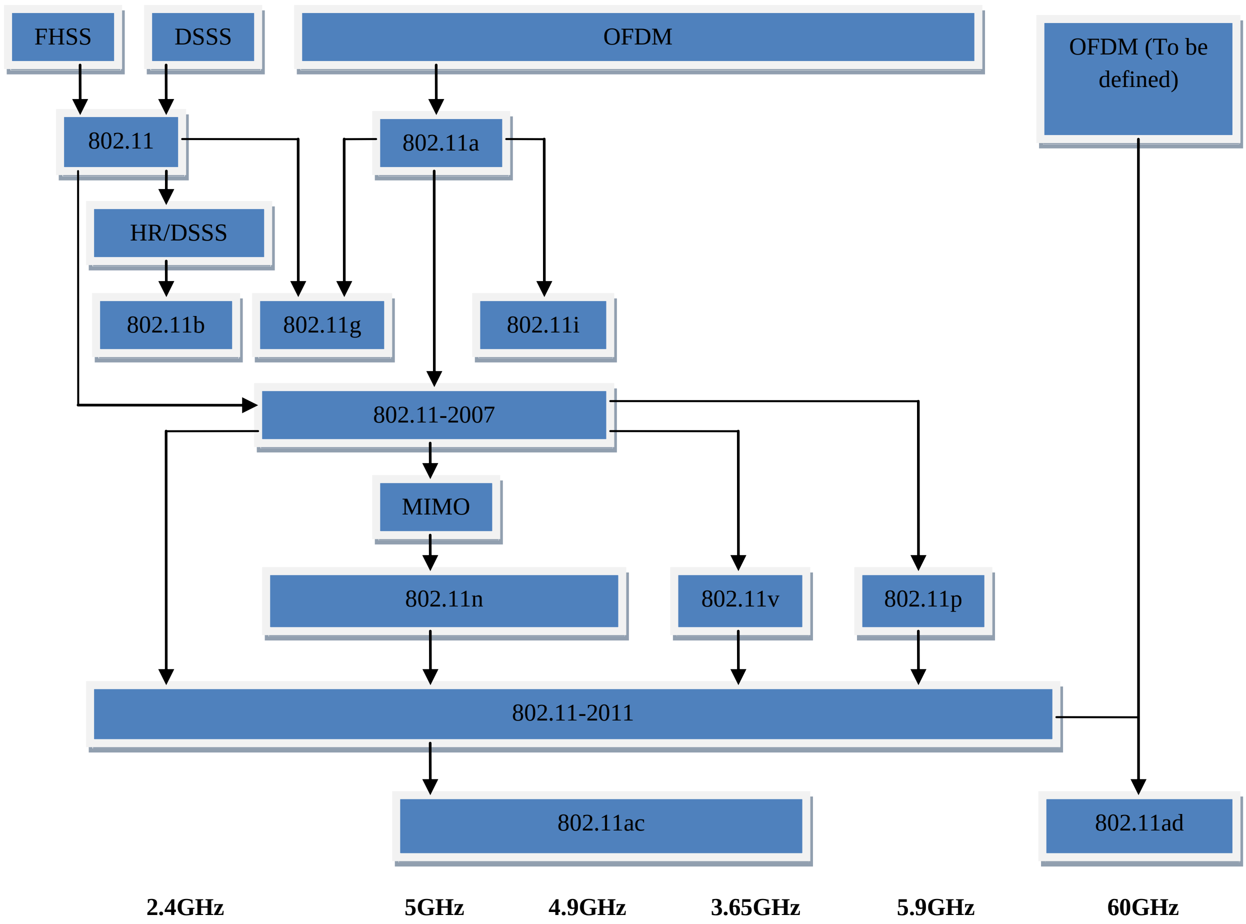

Figure 1: The 802.11 PHY Layer Amendments and Their Dependencies

2. PHY RELATED AMENDMENTS

Even though not interoperable, the DSSS and FHSS PHY initially appeared to have same possibilities in the market. Alike the FHSS PHY had a duplicate in the Home RF group that proposed at integrated data and voice services. This needed plain 802.11 with FHSS for transmission of data, accomplished with a protocol for voice that was very similar to the Digital Enhanced Cordless Telecommunications standard. Neither 802.11 nor Home RF saw FHSS extensions, despite ideas for a second generation Home RF occurred that directed at 10 Mbps. In contradict, the high data-rate scheme 802.11b was originated in December 1997 and sustained the data rates of the DSSS PHY to 11 Mbps. This induced 802.11b to eventually override FHSS, containing Home RF, in the market. Figure 1 specifies a sketch of the 802.11 PHY amendments and their dependencies [8].

2.1 IEEE 802.11a

The first extension scheme, IEEE 802.11a was introduced in September 1997. It included an OFDM (Orthogonal Frequency Division Multiplexing) PHY that supports speeds up to 54 Mbps. Communication with plain 802.11 devices is impossible, as 802.11a conducted in the 5 GHz band . This deficiency of interoperability forced to the formation of 802.11g, which carried the advantages of OFDM to the 2.4 GHz band.

Table 2 shows the physical layer parameters of the IEEE 802.11a.

Table 2: The IEEE 802.11a Physical Layer Parameters

Data Rate (Mb/s)	Modul-ation	Coding rate (R)	Coding Bits Per Subcarrier (N_{BPSC})	Coded Bits per OFDM symbol (N_{CBPS})	Data Bits Per OFDM Symbol (N_{DBPS})
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24	16-QAM	1/2	4	192	96
36	16-QAM	3/4	4	192	144
48	64-QAM	2/3	6	288	192
54	64-QAM	3/4	6	288	216

2.2 IEEE 802.11b

IEEE 802.11b standard expands the original IEEE 802.11 with Direct Sequence Spread Spectrum (DSSS) to operate up to 11 Mbps data rate in the 2.4-GHz unlicensed spectrum using complementary code keying (CCK) modulation technique. On up to three non- overlapping channels, the four data rates of 1, 2, 5.5, and 11 Mbps are specified and the lowest two rates are also permitted on up to 13 overlapping channels. The main drawback of the IEEE 802.11b standard is frequency band become common and interference from the other networking technology such as cordless phone, Bluetooth and so on.

The IEEE 802.11b is employed in a point-to multipoint configuration, wherein an access point communicates through an omnidirectional antenna with mobile clients located within range of the access point and within direct line-of-sight. Typical range depends on the output power, audio frequency environment, and sensitivity of the receiver.

2.3 IEEE 802.11g

IEEE 802.11 introduced the 802.11g [9] standard in late 2001. IEEE 802.11g extends the physical layer of IEEE 802.11 wireless local area networks with data rates up to 54Mbps using the same frequency band as IEEE 802.11b. This extension provides backwards compatibility with the IEEE 802.11b extension and the two are commonly used together when deploying IEEE 802.11 wireless networks. Although IEEE 802.11g is backwards compatible with the previously approved IEEE 802.11b extension, it may minimize the overall throughput of the network to deploy combined IEEE 802.11b/g networks. This is due to the legacy overhead of the backwards compatibility for the IEEE 802.11b.

The different IEEE 802.11g Physical layers parameters [10] are shown in table 3.

Table 3: The Different IEEE 802.11g Physical Layers Parameters

Physical Layer	Supported Rates (Mbps)	PLCP preamble + header delay		PLCP preamble + header length	
		Long	Short	Long	Short
ERP-DSSS (essential)	1, 2, 5.5, 11	192 µs	96 µs	192 bits	120 bits
ERP-OFDM (essential)	6, 9, 12, 18, 24, 36, 48, 54	20 µs		40 bits	
ERP-PBCC (arbitrary)	1, 2, 5.5, 11, 22, 33	192 µs	96 µs	192 bits	120 bits
DSSS-OFDM (arbitrary)	6, 9, 12, 18, 24, 36, 48, 54	192 µs	96 µs	192 bits	120 bits

The first two layers are necessary from the above four physical layers; each IEEE 802.11g device must provide them. The last two physical layers are arbitrary. For the distinctive physical layers of the IEEE 802.11 g specifications column 2 of table 4.3 outline the supported data rates.

2.4 IEEE 802.11n

The Fifth Amendment is the IEEE 802.11n for the IEEE 802.11 standard. This amendment provides, among various other things, the ability to use wider channels, delayed acknowledgements and frame aggregation. The physical layer of IEEE 802.11n operates in three modes:

- **Non-HT (Legacy) Mode** is used for compatibility with legacy products which do not support the new MAC layer format. The AP operates in the old IEEE 802.11a/b/g format, thus all new features are disabled. This mode can only use 20MHz channel-width.
- **HT Mixed Mode** is a mode for mixing legacy IEEE 802.11a/b/g with the new upgraded modes of IEEE 802.11n. This mode allows stations which only support legacy communication to communicate with the AP but opens up the enhanced modes to stations able to communicate over the new IEEE 802.11n frame format, in addition to also having support for older devices not capable of the upgraded operating modes.
- **High Throughput (Greenfield) Mode** is used with APs that want to transmit exclusively over the new IEEE 802.11n MAC layer frame format. This format is known as Greenfield and provides all the new features of IEEE 802.11n. Stations which only communicate with IEEE 802.11a/b/g cannot support the AP in this mode.

3. Extended Modulation Techniques

Shortly after the original IEEE 802.11 standard was published, the IEEE 802 Executive Committee approved two extensions to the original IEEE 802.11 standard. These were named IEEE 802.11a and IEEE 802.11b and provided methods and mechanisms to achieve higher physical data rates in the wireless medium.

3.1 IEEE 802.11a - OFDM in the 5GHz

A method of encoding digital data on multiple carrier frequencies is known as orthogonal frequency-division multiplexing (OFDM). IEEE 802.11a was the first approved extension to the IEEE 802.11 standard. The main feature of OFDM modulation in IEEE 802.11 standard is to provide modes with different code rates and modulation schemes due to good performance on highly dispersive channels which are selected through link adaptation [11]. This extension adopts the OFDM scheme to the physical layer, which provides rates up to 54Mbps operating in the Unlicensed National Information Infrastructure 5.0 GHz frequency band.

The OFDM modulation scheme in IEEE 802.11a is based on the principle of sub-carriers which are orthogonal to a base sub-carrier. Each subcarrier is modulated from a high-speed binary signal divided into several lower speed signals, in association with one of the channels in the same band. The U-NII 5GHz frequency band is in some countries custom to local laws and organizations, which may specify the allowed transmission power and some channels, may be expelled.

Table 4 shows the bit error rate for different modulation techniques are shown in table-3. The bit error rate versus Eb/N0 comparison between different modulation techniques using Rayleigh channel for 802.11a extension are shown in figure 2.

Table 4: IEEE 802.11a BER rate for different modulation using Rayleigh channel

E_b/N_o (dB)	Rayleigh Theory	BPSK	QPSK	MSK
0	0.1464	0.1445	0.0788	0.0788
1	0.1267	0.1275	0.0561	0.0562
2	0.1085	0.1088	0.0374	0.0374
3	0.0919	0.0913	0.0229	0.0227
4	0.0771	0.0768	0.0127	0.0124
5	0.0642	0.0642	0.0060	0.0059
6	0.0530	0.0524	0.0024	0.0023
7	0.0435	0.0437	0.0008	0.0008
8	0.0355	0.0356	0.0002	0.0002
9	0.0288	0.0292	0.0000	0.0000
9.5	0.0233	0.0232	0.0000	0.0000

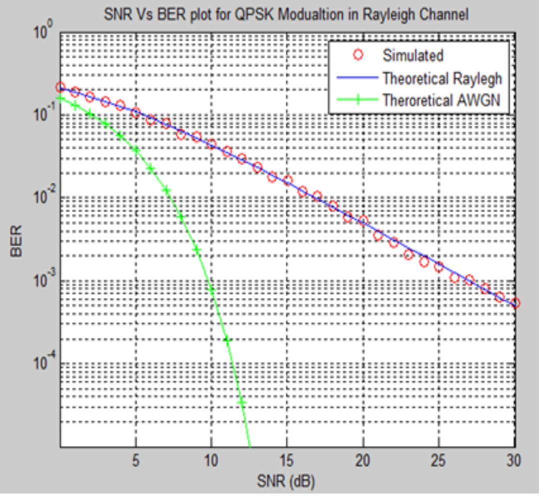

Figure 2: BER Curves for QPSK in AWGN & Rayleigh Channel

3.2 802.11b - High Rate DSSS in 2.4GHz

The physical layer extension is commonly referred to as the High Rate Direct Sequence Spread Spectrum (HR/DSSS) and it upgrades the IEEE 802.11 legacy data rates of 1Mbps and 2Mbps with data rates of 5.5Mbps and 11Mbps. This is made possible by the extension defining two new Physical Layer Convergence Protocol (PLCP) preambles; namely short and long preamble. The long preamble employs the same PLCP preamble and header as the legacy IEEE 802.11 DSSS Physical Layer (PHY). It operates in the 1Mbps and 2 Mbps data rates and provides backwards compatibility with IEEE 802.11 wireless networks.

DSSS modulation technique used in the 2.4GHz frequency band and is the primary technique used in IEEE 802.11b. Due to its redundancy in the carrying signal, the DSSS modulation technique is somewhat tolerant to noise and even if the signal is distorted during transfer, the original sequence can still be extracted from the transmission.

Table 5 shows the IEEE 802.11b BER and using AWGN channel BER rate on different data rates for 802.11b is shown in figure 3.

Table 5: BER for IEEE 802.11b

E_b/N_o	BER (11Mbps)	BER (10Mbps)	BER (5.5Mbps)	BER (2 Mbps)
-14	.3312	.4868	.4705	.3913
-11	.2222	.4722	.4380	.3074
-8	.1022	.4480	.3814	.1980
-5	.0168	.3930	.2711	.0974
-2	.0009	.2946	.1142	.0300

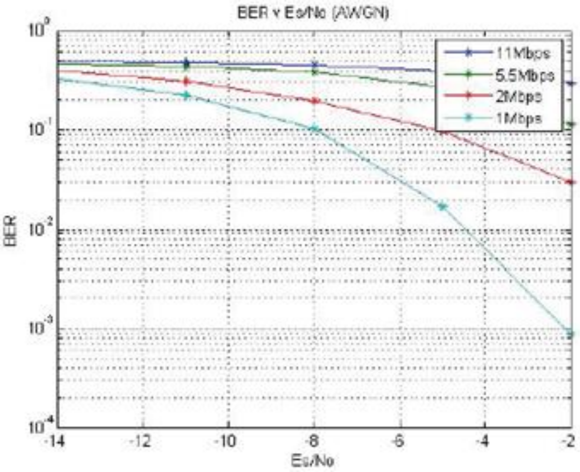

Figure 3: BER Rate on Different Data Rates for 802.11b using AWGN Channel

3.3 802.11g - Higher Rate Extensions in the 2.4GHz

IEEE 802.11g extends the physical layer of IEEE 802.11 wireless local area networks with data rates up to 54Mbps using the same frequency band as IEEE 802.11b. This extension provides backwards compatibility with the IEEE 802.11b extension and the two are commonly used together when deploying IEEE 802.11 wireless networks. Although IEEE 802.11g is backwards compatible with the previously approved IEEE 802.11b extension, it may minimize the overall throughput of the network to deploy combined IEEE 802.11b/g networks. This is due to the legacy overhead of the backwards compatibility for the IEEE 802.11b.

The physical modulation scheme used in IEEE 802.11g networks is the same OFDM scheme as used in IEEE 802.11a. Data rates supported in IEEE 802.11g are 6, 9, 12, 18, 24, 36, 48 and 54Mbps. The IEEE 802.11g standard falls back to CCK (used in 802.11b) for the 5.5 and 11Mbps data rates, and DBPSK/DQPSK+DSSS as used in the legacy IEEE 802.11 standard for 1 and 2Mbps data rates.

Table 6 and 7 shows IEEE 802.11a/b/g parameters and their explanations.

Table 6: IEEE 802.11b/g/a Parameters

Parameter	802.11a	802.11b	802.11g
T_{slot}	9µs	20 µs	9µs / 20 µs
T	1µs	1µs	1µs
T_p	16µs	144µs	16µs / 144µs
CW_{min}	15	31	31 / 15
T_{PHY}	4µs	48µs	4µs /48 µs
T_{SYM}	4µs	N/A	N/A, 4µs
T_{DIFS}	34µs	50µs	50µs / 34µs
T_{SIFS}	16µs	10µs	16µs

Table 7: Explanation of IEEE 802.11g Parameters

Parameter	Explanation
T_{slot}	Slot time in µs
T	Transmission time in µs
T_p	Transmission time of the physical preamble in µs
CW_{min}	Minimum backoff window size
T_{DIFS}	DIFS time in µs
T_{SIFS}	SIFS time in µs

3.3.1 IEEE 802.11g Performance and Capacity

The 802.11g standard supports an alternative called CTS/RTS (Clear-To-Send/ Request-To-Send) to Self, which maintains greater throughput when in mixed-cell mode due to Hidden Node Problem. As wavelength is inversely proportional to range and a signal transmitted in a lower frequency band will carry further than a signal travel in a higher frequency spectrum. Further, longer waveform tends to propagate better through solid mediums (like trees, walls glass, etc.) which will transmitted in lower in the frequency spectrum and 802.11g operates in the same 2.4 GHz portion of the radio frequency spectrum just as 802.11b does. According to rule of thumb, as the data rate increases, the range will decrease. To support data rates of 11, 5.5, 2 and 1 Mbps each, the IEEE 802.11b uses DSSS with correspondingly longer ranges as the data rates decrease and on the other side IEEE 802.11g uses OFDM to support 54, 48,36,24,18,12,9 and 6 Mbps each [12]. The combination of backward compatibility and higher performance of 802.11g is similar in idea to the wildly successful 100-Mbps Fast Ethernet standard from the wired LAN world [13].

According to the researchers statistics in the means of data transmission, DSSS is not that much efficient than OFDM because it support lower data rate than OFDM-based data rates. When comparison performance between both the latest technologies another factor which is to be considered is transmit power and receive sensitivity, because selection of transmission type of either DSSS or OFDM has an effect on the max power the transmitter can use as well as the capability of the receiver especially at higher data rate. EVM (Error Vector Magnitude) is a phenomenon when the higher power coming from the radio’s transmitter tends to desensitize which results counterintuitive effects. The comparison between simulated and theoretical BER for 802.11g is shown in figure 4.

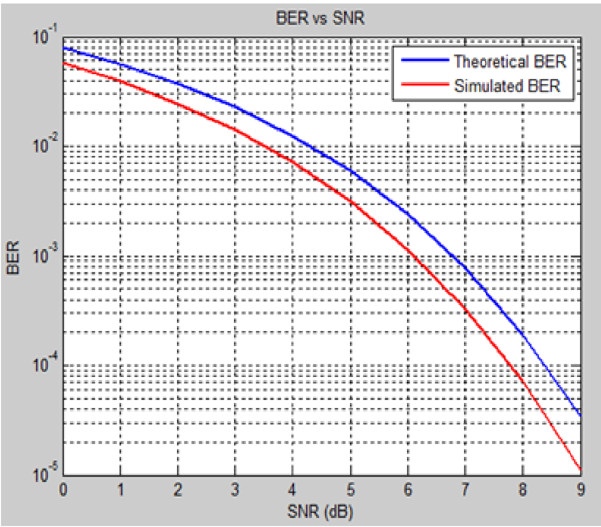

Figure 4: BER Rate for IEEE 802.11g

3.4 IEEE 802.11n -Higher Throughput using MIMO

MIMO exploits the use of multiple signals transmitted into the wireless medium and multiple signals received from the wireless medium to improve wireless performance [14]. MIMO can provide many advantages, all derived from the ability to process spatially different signals simultaneously. Two important advantages are antenna diversity and spatial multiplexing. MIMO technology offers the ability to coherently resolve information from multiple signal paths using spatially separated receive antennas using multiple antennas.

Multipath signals are the arriving reflected signals at the receiver some time after the actual or line of sight (LOS) signal has been received. Basically, multipath is recognized as interference degrading a receiver's ability to recover the intelligent messages. MIMO enables the opportunity to spatially resolve multipath signals. Thus its providing diversity gain that assign to a receiver's ability to recover the intelligent messages. Fig.5 to Fig.10 shows power spectral density curve and fading envelops for different pair of antennas for IEEE 802.11n and Fig.11 shows improved bit error rate by using mimo system in IEEE 802.11n.

Table 8: IEEE 802.11n OFDM Parameter Compared to IEEE 802.11a/g

Standards	802.11a/g	802.11n	
		Mandatory	Optional
Maximum transmission rate (Mbps)	54	130	600
Bandwidth (MHz)	20	20	40
FFT size	64	64	128
Number of subcarrier (data + pilot)	52 (48+4)	56 (52+4)	114 (108+6)
Multi-antenna scheme	signal antenna	2T x MIMO	3,4 T_X MIMO T_X Beam Forming STBC
Channel coding	Convolutional code (1/2, 2/3, 3/4)	Convolutional code (1/2,2/3,3/4, 5/6)	LDPC (1/2, 2/3,3/4,5/6)
Modulation	BPSK, QPSK, 16-QAM, 64-QAM		
Spatial stream	1	1 ~ 2	1 ~ 4
Guard interval(ns)	800	800	400
Subcarrier interval	312.5 KHz	312.5 KHz	312.5 KHz
FFT period	3.2 µs	3.2 µs	3.2 µs
Symbol period	4 µs	4 µs	4 µs

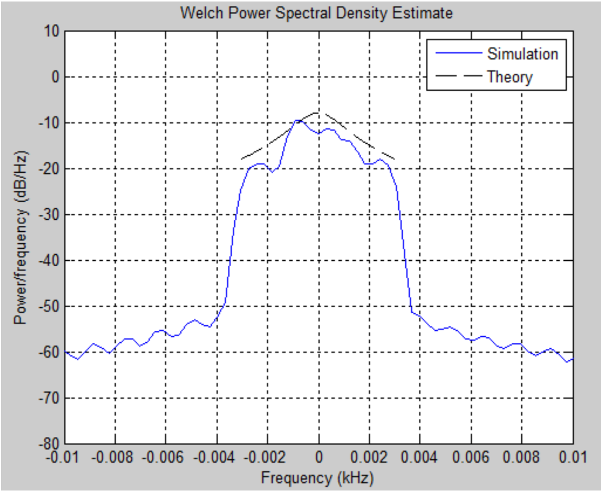

Figure 5: Welch Power Spectral Density Estimate for Antenna 1 in IEEE 802.11n

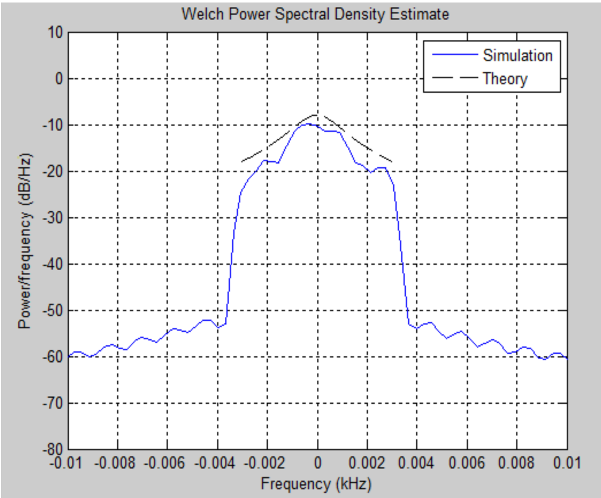

Figure 6: Welch Power Spectral Density Estimate for Antenna 2 in IEEE 802.11n

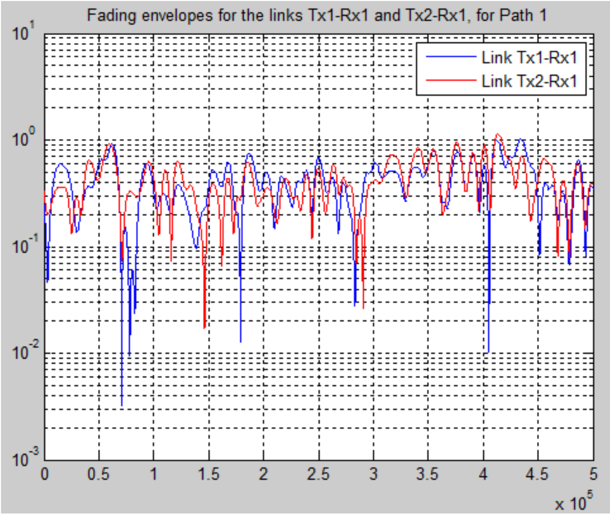

Figure 7: Fading Envelopes for Tx1-Rx1 and Tx2-Rx1 for IEEE 802.11n

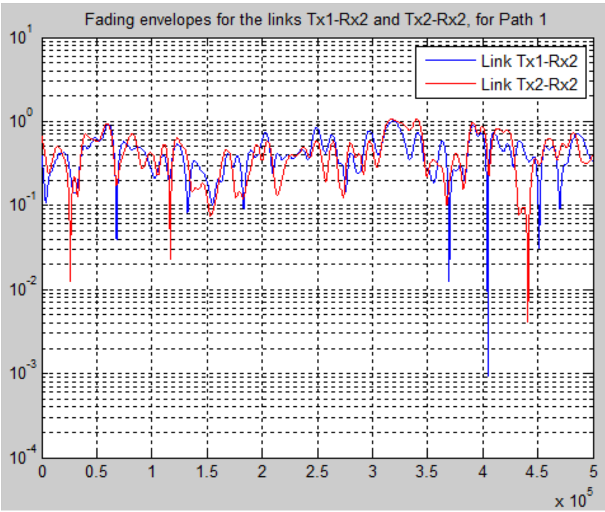

Figure 8: Fading Envelopes for Tx1-Rx2 and Tx2-Rx2 for IEEE 802.11n

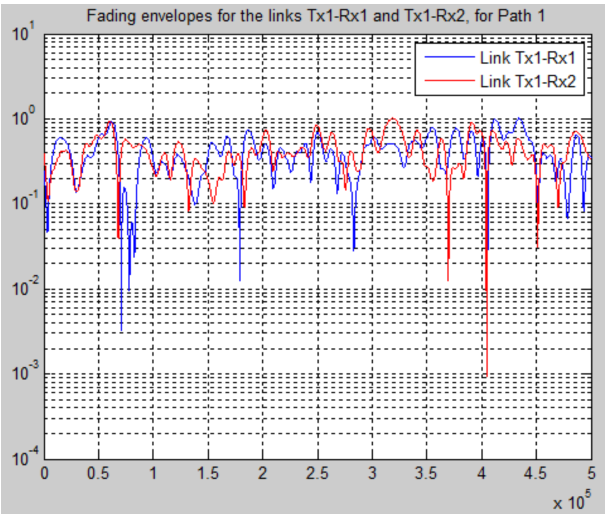

Figure 9: Fading Envelopes for Tx1-Rx1 and Tx1-Rx2 for IEEE 802.11n

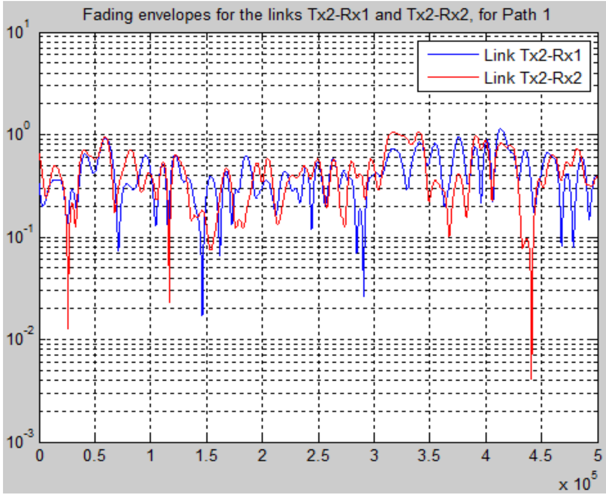

Figure 10: Fading Envelopes for Tx2-Rx1 and Tx2-Rx2 for IEEE 802.11n

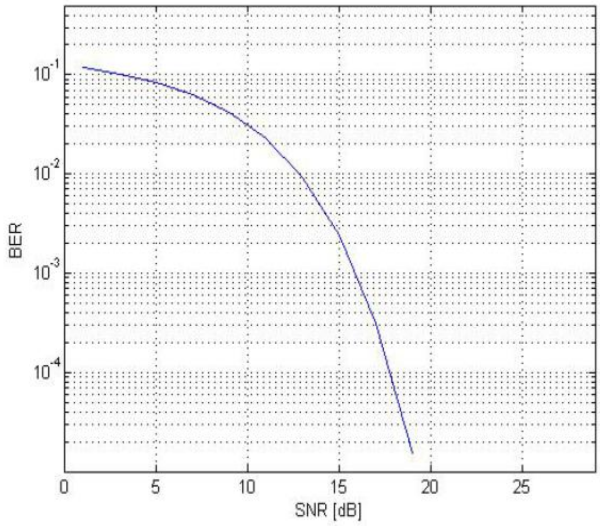

Figure 11: BER for IEEE 802.11n

4. CONCLUSION

The different extensions of IEEE 802.11 (802.11a, 802.11b, 802.11g and 802.11n) are analyzed in this paper. The performance results are compared on the basis of their range, data rates, modulation techniques used and operating frequency band. Different channel implementations are used for the simulations. For the simulation a simple AWGN channel model is used, following by simulations with multipath Rayleigh fading together with AWGN model. The BER performance for all IEEE 802.11 extensions which are a true performance estimate of digital modulation schemes degrades for every modulation scheme on decrease in Eb/No (bit energy to noise power spectral density ratio) and can be seen clearly from the "waterfall" curves. The BER curves for the various Modulation formats were plotted and a comparison of the simulated BER curves and the theoretical BER curves were made. The Welch power spectral density for simulated and theoretical result has been calculated for 802.11n and compared which shows both are nearly fit to each other and also fading envelopes for different transmitter and receiver links is calculated.

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