Range versus Rate in IEEE 802.11g Wireless Local Area Networks

by

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Abstract

To determine the effectiveness of a family of modulation and coding options for wireless local area network (WLAN) applications, it is useful to understand how data throughput and distance are traded. In this paper, a mathematical model is presented that allows for a rational comparison of IEEE 802.11g proposals. In this study the legacy CCK systems are compared to the PBCC, CCK/OFDM and 11a/OFDM. The comparison demonstrates that while PBCC and 11a/OFDM follow similar rate versus range curves, the additional overhead required for 802.11b backwards compatibility of the CCK/OFDM has a severe rate versus range penalty .

1. Introduction

This paper is organized in two parts. In the first part, the background information required compute the range and throughput of a WLAN system is described. In the following section, a comparison of various alternatives considered by the Task Group G is presented.

The analysis shows the superiority of the PBCC based systems over the CCK/OFDM ones. For the highest mandatory rate, PBCC-22 achieves a throughput of 12.8 Mbps at a range that is 95% of the CCK-11 system while the CCK/OFDM-24 achieves 13.0 Mbps at a range that is 76% in AWGN. In terms of area, these factors are 90% and 58% coverage, respectively. With 100 ns of multipath, the range numbers become 92% and 74%. It is interesting to note that 11a/OFDM, which does not suffer from the large overhead required to be backwards compatible with the 11b preamble, has the same ranges as CCK/OFDM but much higher throughput. For 11a/OFDM-24, the throughput is 18.5 Mbps. The curves for PBCC and 11a/OFDM, shown in Figure 4, demonstrate that for ranges up to 60% of the CCK-11 range, the two schemes are very competitive, while the CCK/OFDM system significantly lags both solutions in all cases.

2. Background Development

The calculation of user data rate or throughput versus distance involves several components that include:

- Calculation of symbol signal-to-noise ratio (Es/No) required for maximal operational packet-error-rate (PER)
- Translation of waveform signal power to symbol energy
- Determine receiver noise floor power spectral density (No) and receiver sensitivity
- Formulate propagation loss model that relates receiver signal power to distance
- Determine the maximum throughput of the system including effects of preambles and acknowledgments
- Determine effects of multipath distortion on receiver performance

2.1 Symbol SNR and PER

In bandpass digital transmission, a basic concept is the discrete time, 2-dimensional *symbol*. In WLAN applications for example, *phase shift keying* (PSK) and *quadrature amplitude modulation* (QAM) symbols are transmitted by the sender to convey the intended message. At the receiver, a detection process is used to process the corrupted symbol to determine the message that was transmitted. The corruption of the symbol can include both noise and signal distortion. The noise in the receiver is typically a function of how well the receiver radio can amplify the very small receive signal to bring it to a level that is required by the detection process. The bulk of the noise is modeled as additive white Gaussian noise since the source of the noise is wide band (relative to the signal). The dominant form of signal distortion is can be attributed to *multipath distortion* which arises from multiple refections of the signal during propagation.

The symbol *signal-to-noise ratio* (SNR) relates the average symbol signal power Es to the variance of the symbol noise No (*i.e.*, the noise in 2 dimensions). For a PSK signal, the symbol energy is constant, $E_s = A^2$, where A is the radius of the circle. For QAM, the symbol energy is generally not constant; the average symbol energy $E_s = A^2$for 4-QAM (which is the same as QPSK) and $E_s = 5A^2$ for 16-QAM. In *Figure 1* , an 8-PSK symbol with Es/No = 10 dB is shown.

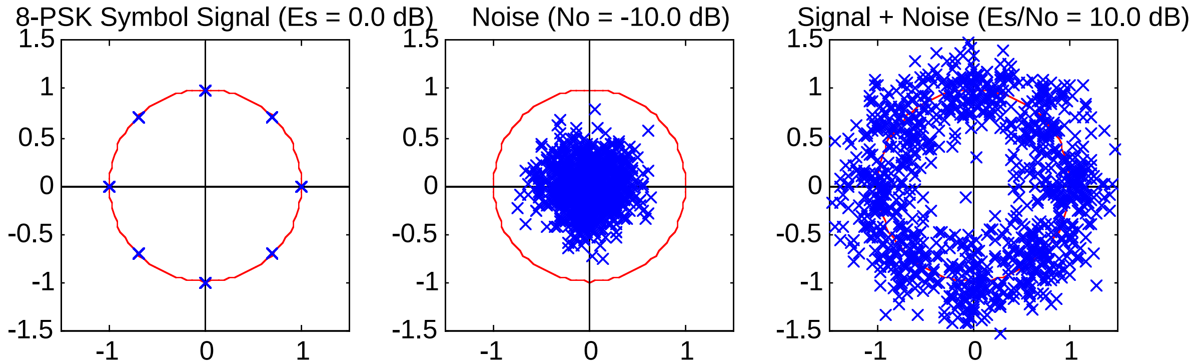

Figure 1 Signal Plus Noise in 8-PSK

The effect of the Es/No value on system performance is reflected in the *packet error rate* (PER) of the detector. In the IEEE 802.11 working groups, a threshold PER of 10^{-2} (one packet error in 100 packet transmissions) is considered the maximum acceptable value. Notice that due to the incorporation of a reliable error detection code within the body of the packet, it can be assumed that an error corrupted packet will be detected and rejected (and typically retransmitted). When the PER rises above the threshold, the system typically backs down to a more reliable, albeit slower transmission mode. The PER is also a function of packet length, for small BER (*bit error rate*) the PER is approximately N*BER where N is the length of the packet in bits. Thus, for a packet with 1000 bytes of data and a PER less than 10^{-2} requires a BER of less than 1.25 x 10^{-6}.

The detector performance is affected by the choice of transmission signal constellation set and the form of *forward error control* (FEC) designed into the transmission system as well as the detection algorithm used at the receiver. In Table 3, the value of Es/No required to achieve a PER of 10^{-2} in *additive white Gaussian noise* (AWGN) is given. For example, the table shows that the CCK-11 system requires at least 7.8 dB of Es/No for an acceptable PER while the PBCC-11 system requires 4.3 dB of SNR. This 3.5 dB improvement in SNR is a direct consequence of the 64 state *binary convolutional code* (BCC) [2] specified in the IEEE 802.11b standard for PBCC transmission [1]. Notice that the OFDM-12 systems, which incorporate a similar 64 state code, has the same coding gain advantage over CCK-11. All of these systems use a QPSK signal set and transmit at a rate of 1 bit-per-symbol due to the presence of a rate 1/2 FEC encoder.

The higher rate systems incorporate various signal sets and FEC codes. Consider the systems that transmit 2 bits-per-symbol. As a reference, uncoded QPSK requires a threshold Es/No of 13.5 dB. The PBCC-22 system combines 8-PSK modulation with a 256 state BCC with a 2/3 code rate. The threshold for PBCC-22 is 8.5 dB, an improvement of 5 dB over uncoded QPSK; this 5 dB improvement is known as the *coding gain*. The OFDM-24 systems use 16-QAM symbols with the same 64 state BCC as OFDM-12; the threshold Es/No is 10.0 dB, a 3.5 dB coding gain over uncoded QPSK.

2.2 Signal Power to Symbol Energy, Receiver Noise and Sensitivity

The signal and noise energy collected at the radio and baseband processor is a function of several factors. With the proper design of transmit signal and receiver structures, incorporating such concepts as "matched filtering", the symbol signal-to-noise ratio will satisfy the equation

$$E_s / N_o = \frac{P_R T_s}{N_o}$$

where P_R is the receive signal waveform power, T_s is the symbol period and N_o is the noise floor power spectral level.

Intuitively, the symbol energy is derived from the product of signal power (energy per second) and a symbol period (seconds). Notice that such factors as "excess bandwidth", which are important in system design, do not play a role in the equation that matched signal power to symbol energy.

The noise level N_o of the receiver is difficult to estimate analytically since many factors are needed. Such factors include the "noise figure" of the receiver amplifiers and other physical quantities. The fact that the noise floor level (*i.e.*, the power spectral density height) and the symbol noise variance (*i.e.,* the 2 dimensional noise variance) are the same is the fact that white noise has the interesting property that the amount of noise is "the same in all directions". If white noise with a power spectral density level of N_o is past through a filter with impulse response h(t) or transfer function H(f), then the output power is equal to $N_o \|h\|^2$ where

$$\|h\|^2 = \int_{-\infty}^{\infty} |h(t)|^2 dt = \int_{-\infty}^{\infty} |H(f)|^2 df$$

independent of the shape of h(t) or H(f). (In fact, one could use this as a definition of "white" noise.) Rather than attempt to find an absolute value for the noise floor and the range, we prefer a relative analysis.

In our analysis, we take CCK-11 as the base system that is used to set a "stake in the ground" from which other systems are compared. We define a new* quantity E_o that will account for factors such as symbol rate and power overhead. The CCK-11 system has a

**In [7], this same term was labeled P_s, however, it is less confusing here to relate this quantity to energy rather than power, thus the change in terminology here.

symbol period T_s = 91 (nsec) (*i.e.,* the *symbol frequency* is 11 MHz). When the various systems are compared in terms of range, the ratio of the symbol period to the period of CCK must be considered; for CCK-11, we take $E_o = E_s$ or $E_o/E_s = 1$ (= 0 dB). For PBCC-22, which uses the same symbol rate, $E_o/E_s = 1$ (= 0 dB) also. However other PBCC modes, such as PBCC-33 , use a faster symbol rate of 16.5 MHz, T_s = 61 (nsec), to increase the data rate. In these modes the bandwidth is preserved by decreasing the excess bandwidth to about 20% from the ~80% of typical CCK-11 and PBCC-11 systems. In this case, the non-trivial ratio of symbol periods makes $E_o/E_s = 3/2$ (= 1.76 dB).

In the case of OFDM systems the equivalent symbol period is based on a 12 MHz, T_s = 83 (nsec) period. This accounts for a factor of 12/11 (= .38 dB) in the calculation of E_o. The reasoning for the 12 MHz value can be seen in many ways. For example, the OFDM systems use 48 tones to convey data. Each of the tones is allocated an equal fraction of the transmit power (ideally each tone would receive 1/48 th of the power, in fact each tone gets 1/52 of the power, more on this later) and uses a long symbol period. The symbol period for each tone is 4 usec. This period is obtained via a 64 point FFT that is cyclically extended by 25% (16 terms) to 80 points and clocked using a 20 MHz clock, resulting in a 250 kHz symbol frequency. The 12 MHz follows from the fact that 48 independent tones generating 250k symbols per second will generate 12M symbols per second in total.

There is another factor that must be considered in the calculation of E_o for OFDM systems. This factor is the OFDM *signal power overhead* that results from 2 sources. The first source is the fact that 52 equal power tones are transmitted, but 4 of the tones are used for modem tracking functions and do not carry user information; this results in a factor of 52/48 (= .348 dB). The other source is a consequence of the cyclic extension technique for mitigating the effects of multipath to minimize the occurrence of *inter-symbol interference* (ISI). The transmitted tones are orthogonal (the "O" in OFDM) over the 64 points (not the 80) or 3.2 usec (not the full symbol period of 4 usec). The receiver uses this subinterval of 3.2 usec in the detection process and thus sacrifices 5/4 (= .969 dB) of the received signal power.

Thus, for OFDM systems, the calculation of $E_o/E_s = 65/44$ (= 1.695 dB); this includes both the symbol rate difference and the signal power overhead.

2.3 Propagation Loss

The signal power observed at the input to the receiver radio is a function of several factors including transmit signal power, antenna gain and propagation loss from the channel. A common model for propagation loss as a function of distance d takes the form

$$L(d) = c \cdot d^{\nu}$$

where the exponent ν is the critical parameter of the loss model. In free space, with a spherical radiation of transmit power, the exponent ν = 2 since the area of the surface of a sphere grows with the square of the radius. In less ideal situations, such as in a building with walls and such, a larger value for the exponent ν would be observed. In the IEEE 802.15 committee, a model for propagation loss in Bluetooth systems assume a free space model up to 8 meters and a ν = 3.3 exponent for larger distances

$$L(d)=\begin{cases}\left(\frac{4d_1\pi}{\lambda}\right)^2\left(\frac{d}{d_1}\right)^2, & d\le 8=d_1,\\ \left(\frac{4d_1\pi}{\lambda}\right)^2\left(\frac{d}{d_1}\right)^\nu, & d\ge 8=d_1,\end{cases}$$

where the wavelength at 2.4 GHz is λ = .1224 meters. Note that the loss function is a continuous in the distance parameter d [6] .

In this paper, the 802.15 model at large distance is assumed, *i.e.*, ν = 3.3. To normalize relative to CCK-11, the waveform signal to noise ratio

$$P_w / N_o = \frac{c_o}{d^{3.3}}$$

where the constant

$$c_o = \frac{d_o^{3.3}\left(E_s / N_o\right)}{T_s}$$

is determined by setting d_o = 100, E_s/N_o is equal to the SNR for CCK-11 that has a PER of 10^{-2} (*i.e.*, 7.8 dB) and T_s = 91 nsec.

Note that choosing d_o = 100 forces the range of CCK-11 to be the normalized range of 100. This can be used to estimate the range of other systems once the absolute range of CCK-11 is known. For example, if a realized system has a CCK-11 range of 40 meters, then the absolute range for other systems, such as PBCC-11 can be estimated. In this case, Table 3 indicates a normalized range of 128 (*i.e.*, 28% more); this translates into an absolute range of 51.2 meters. Similarly, a PBCC-22 system will reach 38 meters, an X/OFDM-12 system will have a range of 45.2 meters and X/OFDM-24 will have 30.4 meters reach.

2.4 Rate and Throughput

It is well known that in packet systems such as IEEE 802.3 and 802.11 , the user data rate is smaller than the maximum instantaneous data rate of the transmission system. In the IEEE 802.11 *media access control* (MAC) protocol, a successful data packet transmission is followed by an acknowledgment packet. This overhead is in addition to the other factors such as guard intervals (so called SIFS and DIFS) and packet preambles and postambles. For reasons of clarity, it is assumed that the acknowledge packets are fixed length at all rates according to Table 1.

Mod	Preamble	Postamble	DIF	ACK*	Total
	usec	usec	usec	usec	usec
CCK & PBCC	96	0	50	116	262
CCK/OFDM	108	6	50	116	280
11a/OFDM	20	0	34	40	94

* ACK: Preamble, Data, SIFS

Table 1 Packet Overhead

The throughput of a system is a function of the transmission system, instantaneous rate and packet length. In this paper, packets are assumed to be long, 1000 bytes in length; this is an optimistic assumption. In addition, this analysis does not account for other forms of MAC overhead such a the MAC header, data error detection and security such as required for WEP.

In Table 3, the throughput for the various choices are listed. As an example calculation, consider the transmission of 1000 bytes (8000 bits) of data using CCK-11 or PBCC-11. The total transmission time will be T_{total} = 262+8000/11 = 989.27 usec yielding a throughput of R = 8000/T_{total} = 8.0867 Mbps.

3. Calculation of Rate versus Range

3.1 Rate and Range Data

The signal to noise ratio calculation can be summarized by the equations that relate transmit power to receive power

$$P_R = \frac{P_T}{L(d)}$$

and symbol energy to receive power

$$\frac{E_s}{N_o} = \frac{P_w \delta_P T_s \delta_T}{N_o} = \frac{P_s \delta_P \delta_T}{N_o}$$

where δ_P reflects the power overhead and δ_T accounts for symbol clock change relative to the reference (in this paper, 11 MHz for CCK-11). For the various systems, Table 2 gives the power factors which are the basis of the equation

$$E_s = E_o \delta_P \delta_T,\ E_o = P_R T_s.$$

	Mod	Rates	δP	δT
1	CCK	all	1 (0 dB)	1 (0 dB)
2	PBCC	{5.5,11,22}	1 (0 dB)	1 (0 dB)
3	PBCC	{8.25,16.5,33,49.5,66}	1 (0 dB)	22/33 (-1.76 dB)
4	OFDM	all	48/65 (-1.32 dB)	11/12 (-.38 dB)

Table 2 Eo to Es Translation

The power overhead $\delta_P \le 1$, always bounded by 1, has the effect of reducing the symbol energy available for detection from the power received by the radio. The symbol clock parameter, δ_T is the ratio of the symbol periods (or symbol frequencies) relative to the base, in this case 11 MHz (*i.e.*, the symbol rate of CCK-11). In this paper, $\delta_T \le 1$ since the symbol rates considered are 11 MHz, 12 MHz and 16.5 MHz. In Figure 2, selected Es/No curves are displayed. These curves show that with this notion of SNR, the PBCC-11 and OFDM-12 systems follow the same curve and have a significant coding gain, about 3.5 dB at a PER of 1e-2, when compared to CCK-11. Similarly, the PBCC-22 and PBCC-33 curves are identical on this graph, requiring a fraction of a dB of additional

SNR when compared to CCK-11. When one accounts for power overhead and clocking rate differences, one obtains the graph shown in Figure 3. On this scale, PBCC-33 moves 1.76 dB to the right due to the higher symbol clock frequency, OFDM-12 and OFDM-24 move 1.70 dB to the right due to the power overhead and clock difference.

The rate and range data for all modes considered in this paper is presented in Table 3 for AWGN. In Table 4, data for channels with 100 nsec multiptah distortion, generated via the IEEE 802.11 multipath model [5], is presented. This data is displayed in Figure 4 and Figure 5. In Figure 6, the throughput versus area coverage is shown.

These graphs show the superiority of the PBCC based systems over the CCK/OFDM ones. For the highest mandatory rate, PBCC-22 achieves a throughput of 12.8 Mbps at a range that is 95% of the CCK-11 system while the CCK/OFDM-24 achieves 13.0 Mbps at a range that is 76% in AWGN. In terms of area, these factors are 90% and 58% coverage, respectively. With 100 ns of multipath, the range numbers become 92% and 74%. It is interesting to note that 11a/OFDM, which does not suffer from the large overhead required to be backwards compatible with the 11b preamble, has the same ranges as CCK/OFDM but much higher throughput. For 11a/OFDM-24, the throughput is 18.5 Mbps. The curves for PBCC and 11a/OFDM, shown in Figure 4, demonstrate that for ranges up to 60% of the CCK-11 range, the two schemes are very competitive, while the CCK/OFDM system significantly lags both solutions in all cases.

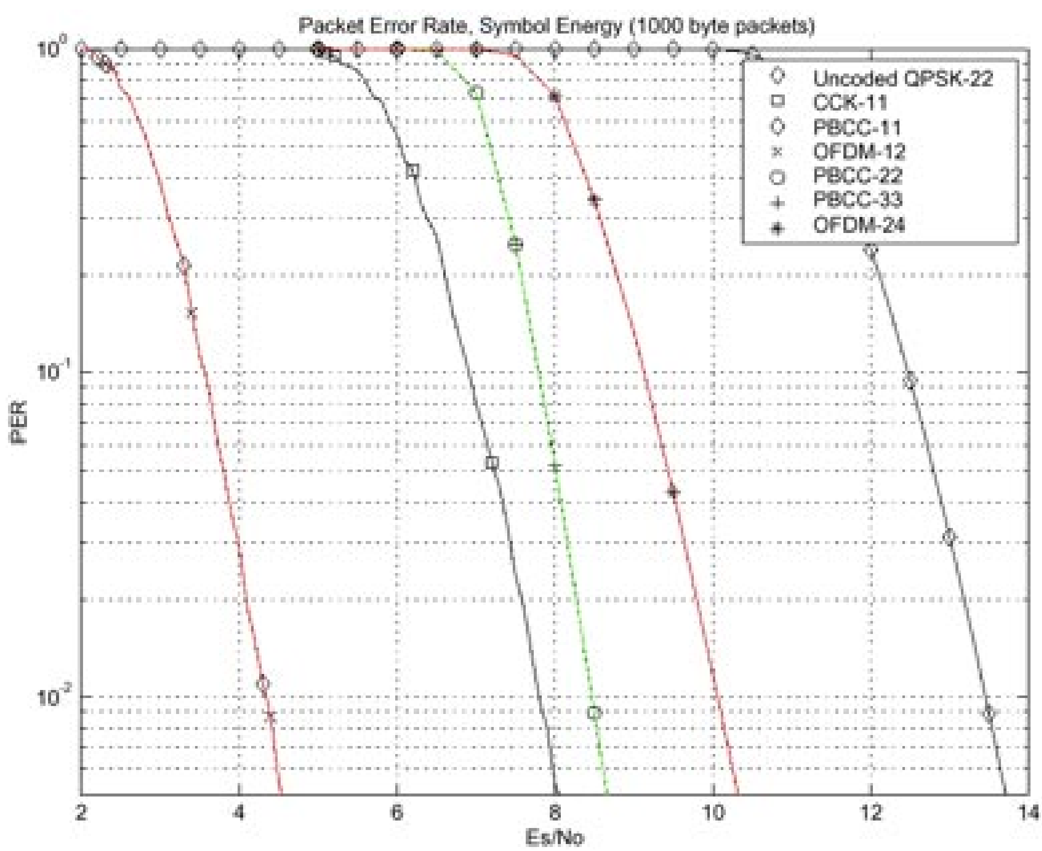

Figure 2 Selected PER versus Es/No Curves

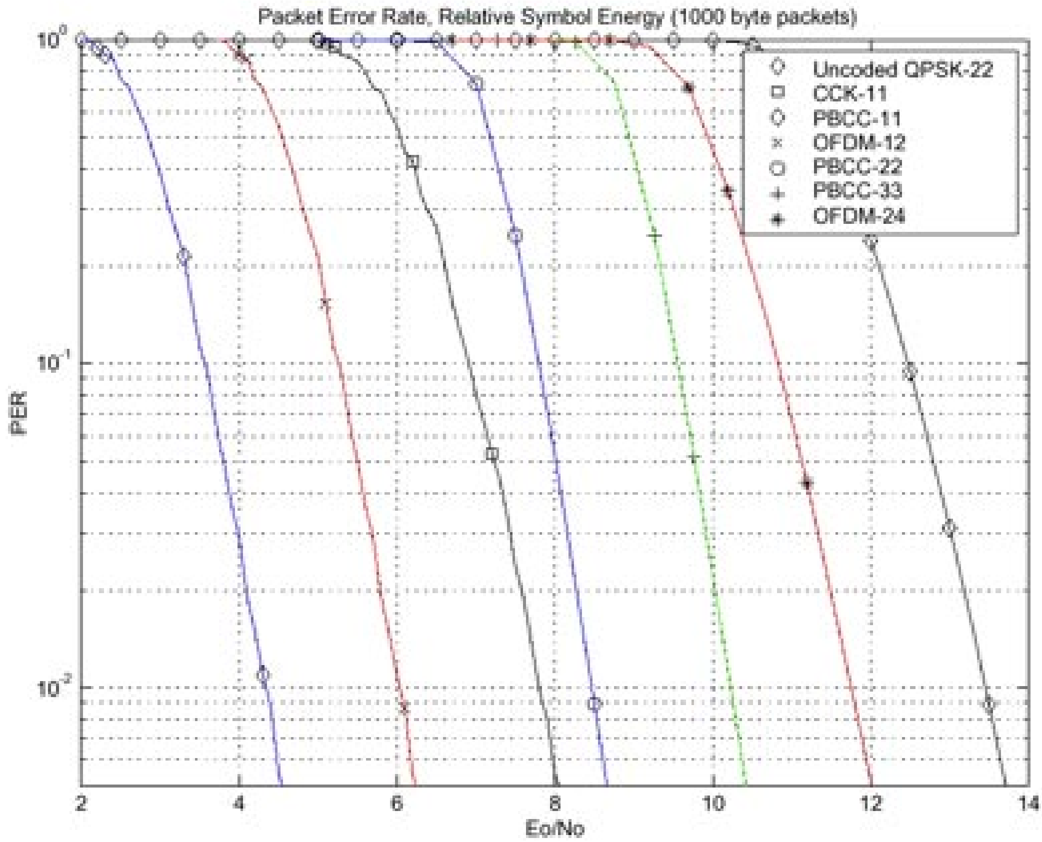

Figure 3 Selected PER versus Eo/No Curves

Item	Mod	Max Rate Mbps	Max Throughput* Mbps	Es/No (PER:10e-2) dB	Eo/No (PER: 10e-2) dB	Eo/Es dB	Range (ν = 3.3)
1	CCK-5.5	5.50	4.7	4.8	4.8	0.0	123
2	CCK-11	11.00	8.1	7.8	7.8	0.0	100**
3	Uncoded QPSK	22.00	12.8	13.5	13.5	0.0	67
4	PBCC-5.5	5.50	4.7	1.3	1.3	0.0	157
5	PBCC-8.25	8.25	6.3	1.3	3.1	1.8	142
6	PBCC-11	11.00	8.1	4.3	4.3	0.0	128
7	PBCC-16.5	16.50	10.7	4.3	6.1	1.8	113
8	PBCC-22	22.00	12.8	8.5	8.5	0.0	95
9	PBCC-33	33.00	15.9	8.4	10.2	1.8	85
10	PBCC-49.5	49.50	18.9	11.4	13.2	1.8	69
11	PBCC-66	66.00	20.9	14.4	16.2	1.8	56
12	CCK/OFDM-6	6.00	5.0	1.2	2.9	1.7	141
13	CCK/OFDM-12	12.00	8.4	4.3	6.0	1.7	113
14	CCK/OFDM-24	24.00	13.0	10.0	11.7	1.7	76
15	CCK/OFDM-36	36.00	15.9	13.2	14.9	1.7	61
16	CCK/OFDM-48	48.00	17.9	15.5	17.2	1.7	45
17	CCK/OFDM-54	54.00	18.5	18.9	20.6	1.7	41
18	11a/OFDM-6	6.00	5.6	1.2	2.9	1.7	141
19	11a/OFDM-12	12.00	10.5	4.3	6.0	1.7	113
20	11a/OFDM-24	24.00	18.6	10.0	11.7	1.7	76
21	11a/OFDM-36	36.00	25.2	13.2	14.9	1.7	61
22	11a/OFDM-48	48.00	30.5	17.6	19.3	1.7	45
23	11a/OFDM-54	54.00	32.5	18.9	20.6	1.7	41

* 1000 Byte Packets with Preamble, 1 SIFS, 1 CCK-11 ACK with Preamble, 1 DIFS

** Reference range = 100

Table 3 Range versus Rate Data, AWGN

Item	Mod	Max Rate Mbps	Max Throughput* Mbps	Es/No (PER:10e-2) dB	Eo/No (PER: 10e-2) dB	Eo/Es dB	Range (ν = 3.3)
1	CCK-11	11.00	8.1	11.1	11.1	0.0	100**
2	PBCC-11	11.00	8.1	7.0	7.0	0.0	133
3	PBCC-22	22.00	12.8	12.3	12.3	0.0	92
4	CCK/OFDM-12	12.00	8.4	8.2	9.9	1.7	109
5	CCK/OFDM-24	24.00	13.0	13.8	15.5	1.7	74
6	11a/OFDM-12	12.00	10.5	8.2	9.9	1.7	109
7	11a/OFDM-24	24.00	18.6	13.8	15.5	1.7	74

* 1000 Byte Packets with Preamble, 1 SIFS, 1 CCK-11 ACK with Preamble, 1 DIFS

** Reference range = 100

Table 4 Range versus Rate Data, AWGN plus Multipath Distortion (100 ns)

Range verus Rate in IEEE 802.11g Wireless Local Area Networks

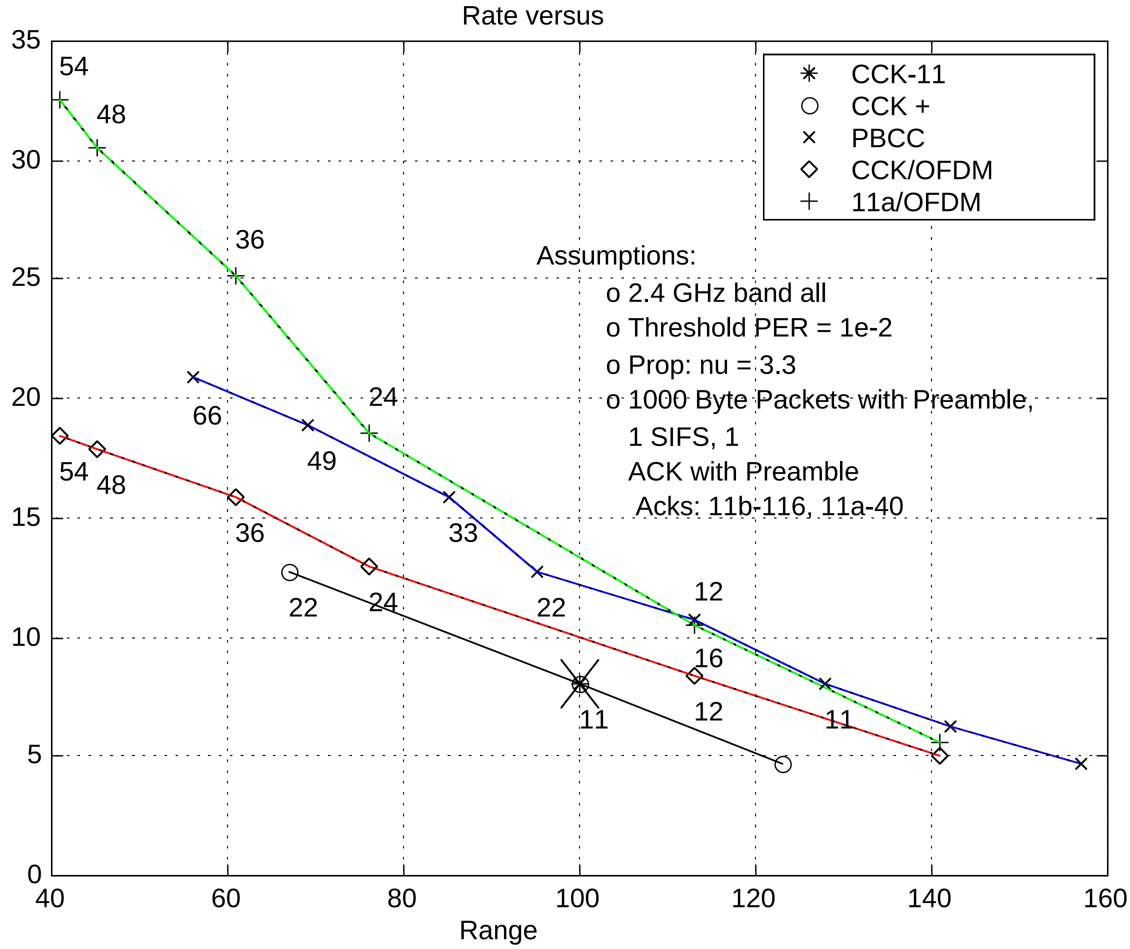

Figure 4 Rate versus Range, AWGN

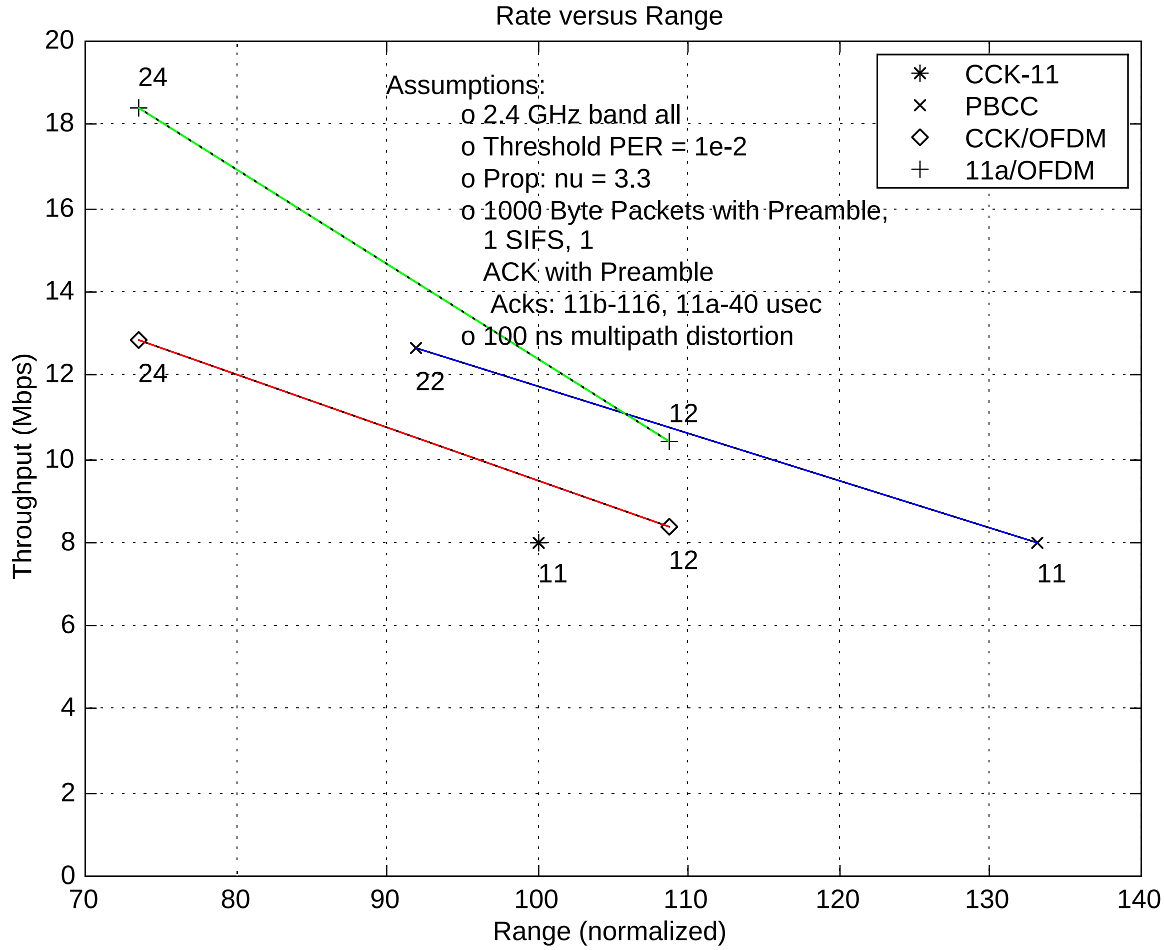

Figure 5 Rate versus Range, AWGN + Multipath Distortion

Range verus Rate in IEEE 802.11g Wireless Local Area Networks

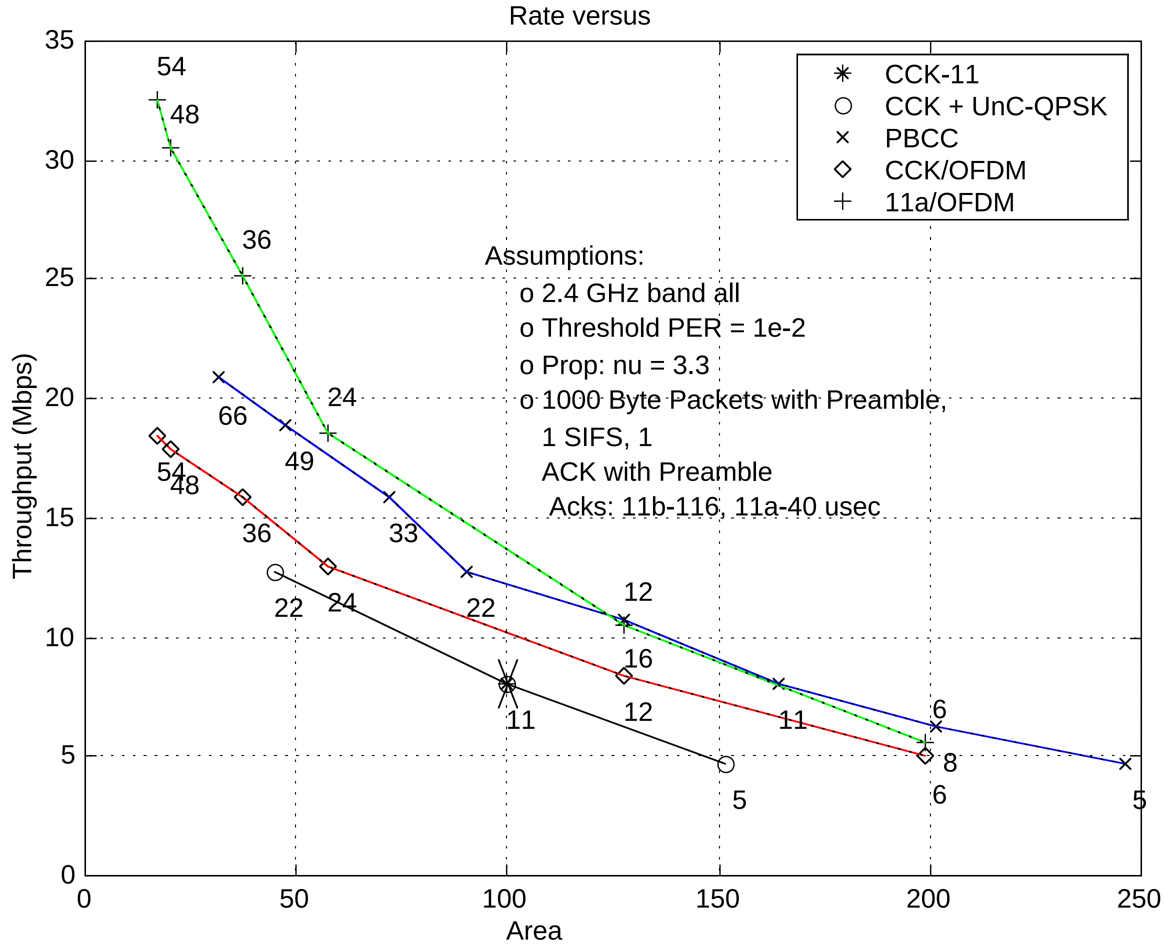

Figure 6 Rate versus Area, AWGN

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References

[1] ISO/IEC 8802-11, IEEE Std 802.11 ANSI, *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*, Reference number ISO/IEC 8802-11, IEEE Std 802.11.

[2] Stephen B. Wicker, *Error Control Systems for Digital Communications and Storage*, Prentice Hall,Englewood Cliffs, NJ, 1995.

[3] PBCC paper.

[4] CCK/OFDM paper.

[5] MP model paper.

[6] Loss model paper, IEEE 802.15/138r0, 1999.

[7] Comparison paper, IEEE 802.11/01064, Jan 2001.