Attachment A

11 MBps Modulation Techniques

Summary

This paper addresses concepts for higher data rates than originally contemplated for the 2.4 GHz ISM band. It shows modulation options that may be used to implement proposed high speed WLANs that will provide 1 to 11 MBps rates in this band. This architecture study looks at all options that not only make sense but obey the unique rules for this band. The FCC has allocated the ISM band for unlicensed use and has set rules for operation in the band. The rules specify that spread spectrum modulations be used to prevent interference with other users. Both Direct Sequence Spread Spectrum (DSSS) and Frequency Hop (FH) modulations are allowed. There are different rules for each of these techniques and they make for different tradeoffs for each.

The main schemes that have been considered for higher rates are variations on DSSS Modulations where more complex modulations are used in place of BPSK and QPSK for the symbol modulation. The methods considered are various forms of M-Ary Orthogonal keying, PPM, and QAM. Multiple parallel channels of FDMA or CDMA carriers are also available for consideration. These can be traded off to find the one with the best combination of properties.

One way to increase the data rate is to simply make the spread rate higher; but that reduces the number of available channels in the band for separate networks. The current IEEE 802.11 Standard implementations in the 2.4 GHz band have 3 DSSS channels with 30 MHz spacing. That is considered the minimum that will allow some degree or cell planning. The techniques that are suggested here can easily be made interoperable with the existing 802.11 networks by employing a preamble and header that is identical to the lower rate modulations.

The other option for high rate modulations involve variations on FH modulation. This is the other allowed modulation in the ISM band. Its rules restrict it to a 20 dB bandwidth of 1 MHz, and this makes it hard to consider modulations that give higher data rates than 2 MBps.

Standards

The new high rate scheme should easily integrate with the IEEE 802.11 network architecture. It should supply higher rates with little or no change of occupied bandwidth. The schemes can use the 802.11 preamble and header that are already designed to support rate switching. This ability to do on the fly rate switching affords the capability to maintain links in a stressed environment and fill coverage gaps. By down shifting to lower rates, additional range and interference tolerance can be achieved.

Waveform Selection

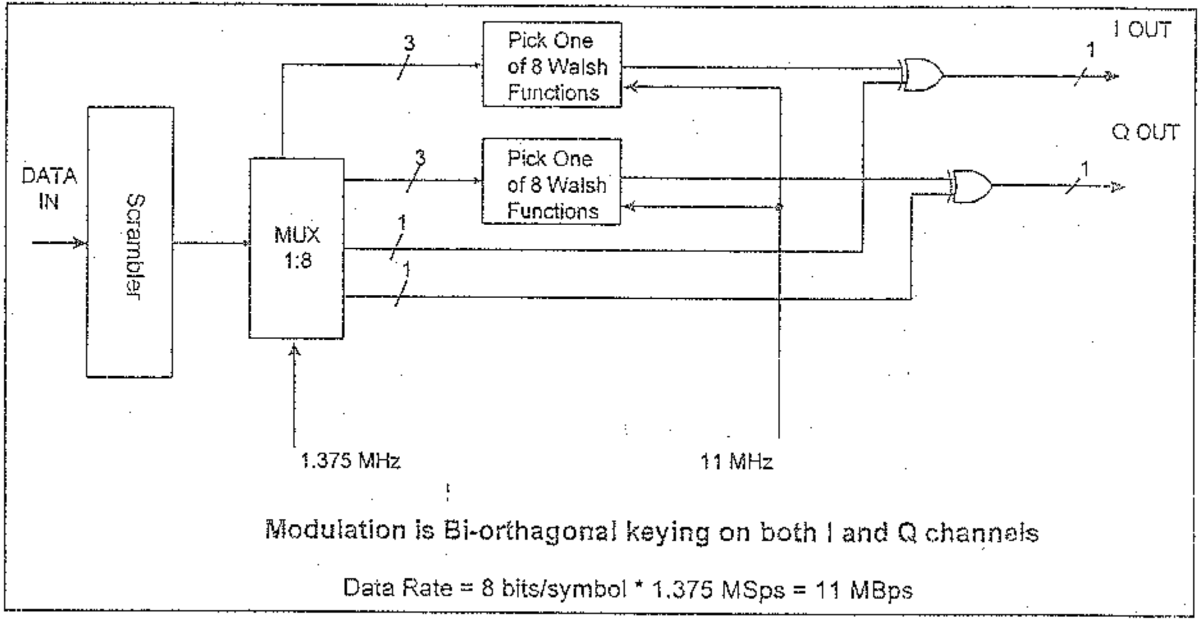
Some of the candidates like Spread Spectrum with 16 PSK can be discarded quickly on the basis of poor energy efficiency which results in a poor interference rejection capability. Others like very wideband spreading can be discarded due to the limited ISM bandwidth and the need to have at least three channels in the band to implement co-located or overlapping networks.

The high energy efficiency spread spectrum waveforms considered were: MOK, CCSK, PPM, OCDM, and OFDM. The trade criteria consist of multipath rejection, interference rejection, number of channels available, the linearity required in the PA, achievable range, and the complexity. In the table below, we included QAM for comparison. The winner in this unweighted scoring is MOK. The others do not have bad scores except for QAM, but the choice depends on how you see the importance of the various attributes.

MOK

The M-ary Orthogonal Keying (MOK) scheme is well known and has been shown to have outstanding properties. It was extensively studied in the 60's where analog implementation techniques were considered. With analog implementations, the technique didn't catch on as the complexity was too high. Now, with integrated digital implementations, we can effectively use the technique and gain the benefits of this waveform.

A variation called M-ary Bi-Orthogonal Keying (MBOK) allows one more bit per symbol essentioally free. It allows multi-channel operation in the ISM band by virtue of keeping the total spread bandwidth the same as the existing 802.11 standard. The spreading is actually more uniform than the 802.11 Barker words, but it has the same chipping rate and the same spectrum shape. The spectrum is filtered to 17 MHz at the 3 dB points and to 35 dB at beyond 22 MHz. This allows three non-interfering channels in the ISM band from 2.40 to 2.483 GHz with allowance for spectral energy reduction at the band edges. With more aggressive filtering you might squeeze 4 channels into the band.



Modulation is Bi-orthagonal keying on both I and Q channels

Data Rate = 8 bits/symbol * 1.375 MSps = 11 MBps

Figure 1 shows how the Bi-Orthogonal modulation is formed

MBOK is a power efficient modulation which means that you will get a good range for the higher data rate. It is robust in having good tolerance for interference and multipath.

Scheme	MBOK	CCSK	QAM	OCDM	OFDM
Multipath	2	5	4	1	1
Jamming	1	1	4	1	1
Spectrum	2	2	3	2	1
AM Mod	2	2	3	4	4
Range	1	2	5	2	2
Complexity	2	1	3	2	5
Total Score	10	13	22	12	14

Table 2, Trade matrix of modulation choices

The M-ary Bi-Orthogonal Keying (MBOK) scheme is well known and rated most of a chapter in Lindsey and Simons book: 'Telecommunications Systems Design', published in 1973. It should therefore have no patent issues other than specific implementation related techniques. M-ary orthogonal keying (MOK) can be shown to be a generalization of many standard waveforms such as FSK.

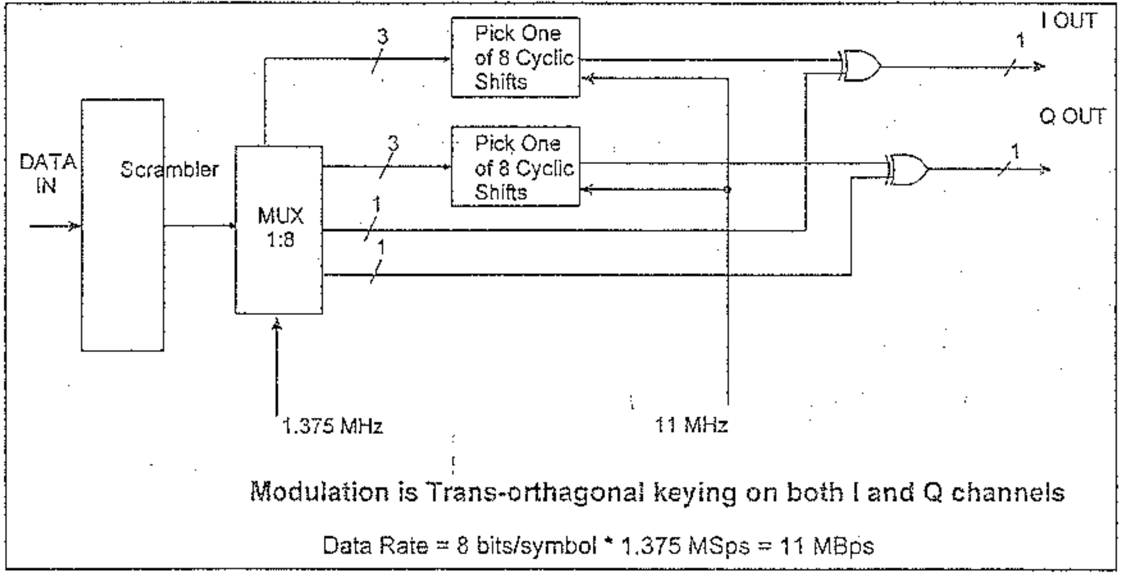
Figure 1 shows how this waveform is created. In this scheme, the spread function is picked from a set of M orthogonal vectors by the data word. Since the I and Q channels can be considered independent when coherently processed, both can be modulated this way. Bi-Orthogonal keying extends this by using both true and inverted versions of the spread function. This allows packing 8 bits into each symbol. The most well known orthogonal vector set is the Walsh function set. It is available for 8 and 16 chip vectors and has true orthogonality.

To make the modulation have the same bandwidth as the existing 802.11 DS modulation, the chipping rate is kept at 11 Mcps while the symbol rate is increased to 1.375 MSps. This makes the overall bit rate 11 Mbps. This also makes it easy to make the system interoperable with the 802.11 preamble and header. Since the spread rate remains constant, the only thing that changes when transitioning into the data from the header is the data clock rate. The figure below shows how the waveform is modulated.

MBOK modulation has been shown to have slightly better Eb/N0 performance than BPSK due to embedded coding properties. This makes the waveform the most power efficient of the candidates. This allows the modulation to tolerate more interference than other waveforms.

Since there are more bits per symbol with this modulation, it naturally requires more Es/N0 than BPSK, but the increase is minimized. The spectrum of this waveform is sinx/x, which is the same as the 802.11 waveform.

The multipath performance will depend on the Eb/N0 and phase distortion tolerance of the waveform. We have shown through simulation, that this signal will have an adequate performance in the indoor environment. It is obviously worse than the 1 Mbps case which can tolerate an SNR of 0 dB.



Modulation is Trans-orthagonal keying on both I and Q channels

Data Rate = 8 bits/symbol * 1.375 MSps = 11 MBps

Figure 2 shows how to modulate MOK with Cyclic Code Shift Keying

To use both I and Q channels independently requires that the system process the signal coherently with an absolute phase knowledge. This is not a large concern as the BPSK preamble and header can supply the necessary means to lock up a PLL in a given state. This and the parallel correlators for the demodulation moderately increase the complexity of the demodulator.

CCSK

The M-Ary Orthogonal Keying theme can be also accomplished with Cyclic Code Shift Keying (CCSK) which is a form of Pulse Position Modulation (PPM). This modulation is simpler to demodulate than MBOK since only one sequence needs to be correlated for. CCSK can be used with an 11 bit Barker sequence at 1 MSps, if desired. The modulation can be applied by time shifting the position of the correlation into one of 8 positions. The remaining 3 out of 11 positions cannot be effectively used to get more bits. This basic scheme gives 3 bits per symbol. BPSK modulating the symbol gives another bit, for a total of 4 bits per symbol. By using both I and Q channels independently, 8 bits per symbol can be achieved. This, however, would not give us the 10 MBps desired since the number of bits per symbol is not great enough. A 20% higher spread rate is needed to make the 10 MBps.

The CCSK modulation technique is not quite as efficient as MOK since the symbols are not entirely orthogonal (they are trans-orthogonal). Cyclically shifted Barker words are reasonably good, however, and achieve close to the same Eb/N0 as MOK.

The CCSK scheme is similar to the a PPM scheme except the correlation pulse is pulse position modulated rather than the whole symbol. This will result in lower AM in the transmitted waveform and therefore lower PA cost.

The main problem with any variety of PPM is the multipath susceptibility when the multipath delay spread gets to be more than a chip's length. Therefore, long (for indoors) multipath will severely degrade these methods. The CCSK scheme is quite simple to demodulate and requires very little added hardware over the basic 802.11 waveform. The modulator for the waveform is shown above.

PPM

PPM is a popular waveform and is efficient to implement. For the purposes of this discussion, we will consider the waveform to be DSSS symbols of 11 chip Barker words that are time shifted to impart up to 3 bits in the time shift. The symbols can also be BPSK or QPSK modulated to give 1 or 2 more bits per symbol. Alternatively, both I and Q channels can be PPM modulated independently with BPSK symbol modulation to make a total of 8 bits per symbol. This gives a total bit rate of 8 MBps.

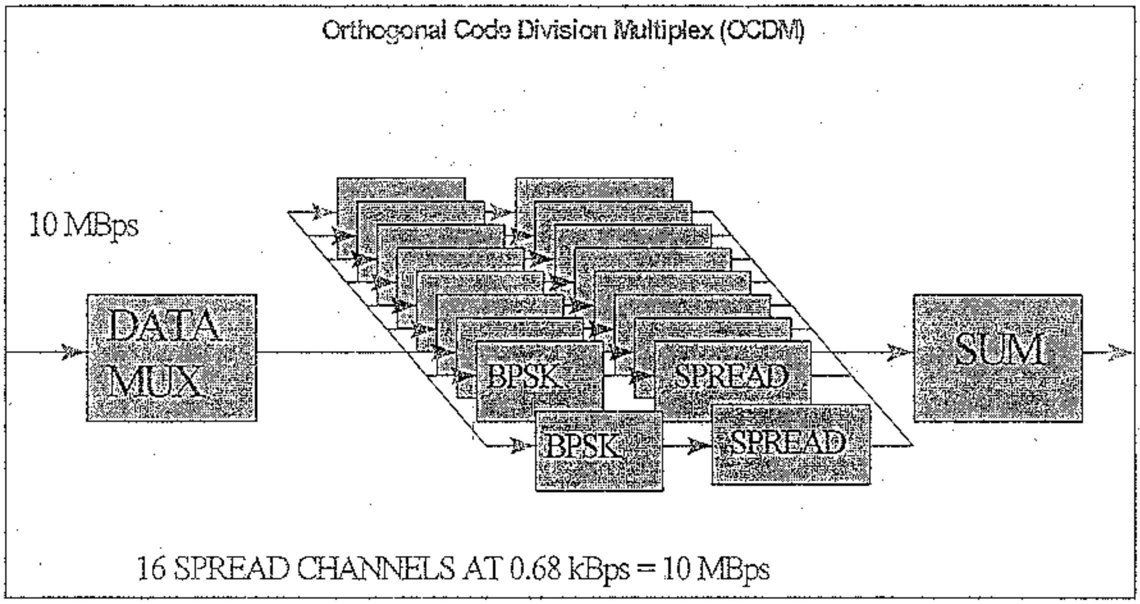


Figure 3 shows how the OCDM waveform is modulated.

One of the properties of the PPM scheme is that adjacent symbols are overlapped or have gaps between them. This makes for 6 dB of amplitude modulation and makes the transmit Power Amplifier less efficient. Lucent Technologies has recently showed a variation where the 11 chip pulses are overlapped by 3 positions to get about 20% more data rate. This exacerbates the amplitude modulation.

QAM

QAM with spreading is straightforward in concept, but suffers from low efficiency. While this modulation has its uses, it is very sensitive to multipath, since 1024 QAM requires a very clean, undistorted signal. The Eb/No performance of QAM is not as good as MOK since it has both phase and amplitude components. This sensitivity to distortion implies the use of an equalizer which is undesirable on two counts. First, it requires a training sequence which will increase the length of the preamble. Second, it will increase the cost to add the equalizer.

OCDM

The Orthogonal Code Division Multiplex (OCDM) modulation method uses multiple spread channels on the same frequency simultaneously. This method sendsmultiple streams of data on orthogonal channels. Sharp has announced that they are using OCDM for their 10 Mbps modem. They use CCSK Barker words for the 'orthogonal' PN spread channels. Basically, this technique uses multiple CDMA channels to send more data. Golden Bridge announced a technique using Walsh codes for the spreading and get better orthogonality. Basically, 16 parallel channels of 16 chip orthogonal symbols are BPSK modulated and summed in an analog sense. This provides 16 parallel channels of data at a modest symbol rate. It could be said to have a 12 dB processing gain. The OCDM scheme produces a high degree of amplitude modulation as it sums 16 independent channels. This is undesirable in that it needs a very linear PA to meet the spectral mask. It also causes more power consumption and rules out limiting in the receiver.

The OCDM technique has good Eb/N0 and a sinx/x spectrum. The processing needed to demodulate it is about the same as the MOK scheme. Figure 3 shows how the waveform is modulated.

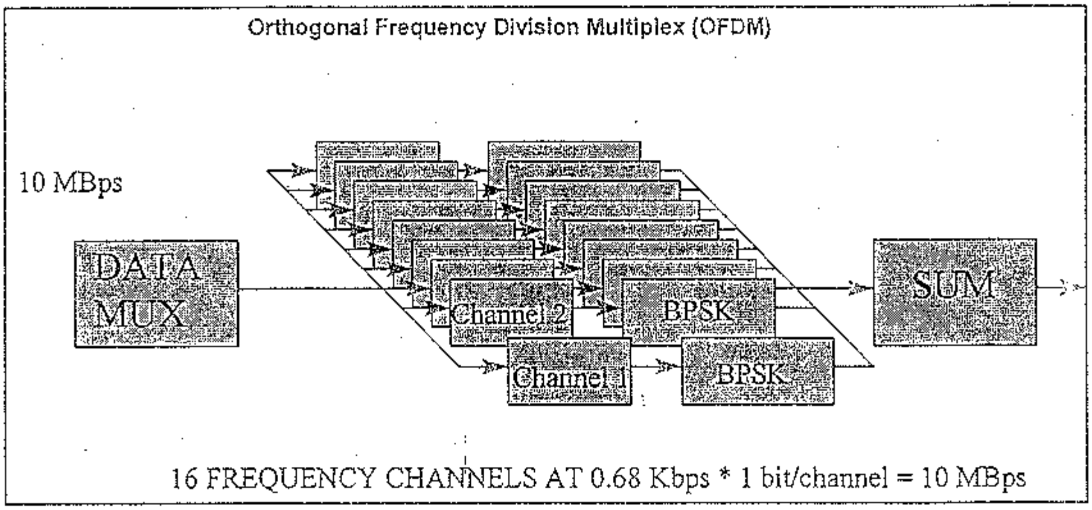


Figure 4 Orthogonal Frequency Division Modulation

OFDM

Orthogonal Frequency Division Multiplex (OFDM) has been adopted by one or more announced 10 Mbps suppliers. It takes the approach of multiple frequency channels at regular spacing with each one modulated by PSK. MIL-STD 188C has used this technique for decades in wireline and radio modems. It is commonly radiated over Single Sideband Radios since it is very tolerant of spectral notches due to multipath fading. Some form of Diversity is necessary to make it work in this environment since a narrowband fade can remove one or more of the carriers. By spreading symbol energy over multiple frequencies, a robust link can be made. This modulation makes best use of the spectrum with the channel filled edge to edge somewhat uniformly. This makes for the least interference to other users with the most noise like spectrum.

The long symbols of OFDM are said to make it more multipath resistant.

The summing of 16 independent carriers can produce large amplitude modulation which makes the transmitter difficult. It also rules out limiting in the receiver.

The processing of OFDM is traditionally done with FFTs and inverse FFTs. These are generally more complex and power hungry than the simple correlation techniques used for the other waveforms. Each of the BPSK or QPSK modulated carriers can employ differential coding to make the baseband processing somewhat simpler.

A recommendation: MBOK

The above trade study has shown that MBOK is a good candidate for the high rate modulation. Here we further examine the performance that might be achieved with this modulation.

PHY Performance Analysis

The excellent range that the M-ary Bi-Orthogonal Keying modulation achieves is due to the fact that MBOK has better power efficiency than BPSK. This can be understood by considering the waveform to have coding properties. The code vectors are selected to have maximum distance. In BPSK, each bit is detected independently. In MOK, a code vector is detected out of an orthogonal set.

The recommended waveform also allows options for lower rates which are more robust, giving fall back rates for stressed links. Harris has run simulations on the two basic types of modulation proposed for the dual rate hardware. These simulations show that the Binary MBOK modulation can achieve 150' range reliably. The simulations show that the high rates are more susceptible to multipath than the lower rates as would be expected from the higher required Eb/N0. There also is the cross rail interference that must be contended with. This is where the multipath interference comes in 90 degrees twisted from the desired carrier. In this case, the information that was on the I channel interferes with the Q channel. If the I and Q channels are not protected by a different cover sequence, there will be significant interference. This performance leads to a recommendation that antenna diversity be used.

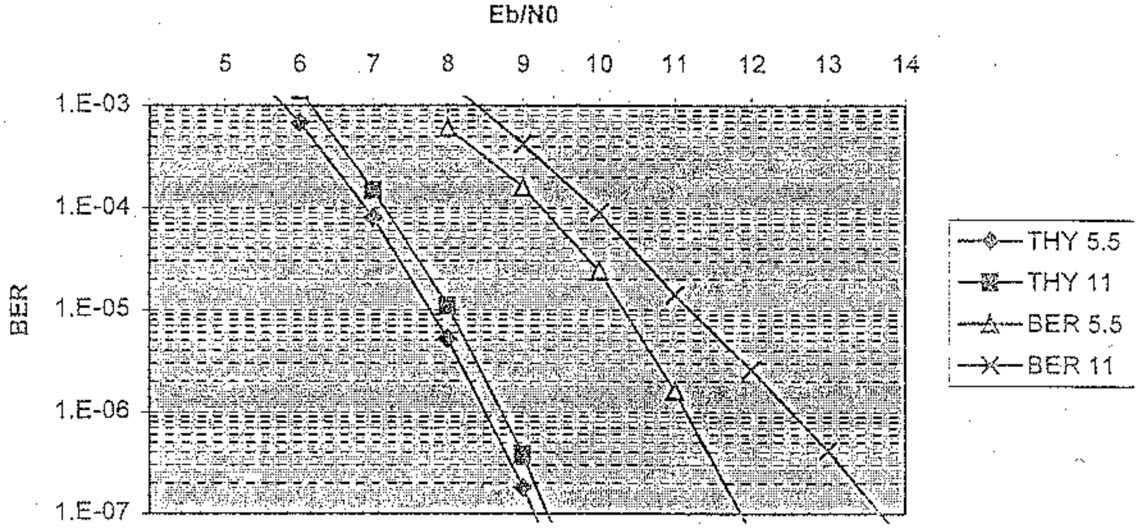


Figure 5, Bit error rates for the new modulations.

The Eb/N0 performance of the MBOK scheme is better than BPSK of the same rate. This performance is due the embedded coding properties of the MOK modulation. The modulation basically ties several bits together so that the receiver is forced to make a symbol decision. If a symbol is in error then all of the bits in that symbol are suspect, but not all will be in error. Thus, the symbol error rate and the bit error rates are similar, but not identical. While the SNR required to make the symbol decision correctly is higher than required to make one bit decision, it is not as high as would be required to make all of the bit decisions separately. Thus, some coding gain is evident in the basic spreading waveform.

Figure 5 shows the simulations of the Es/N0 performance of Binary MBOK and Quadrature MBOK. The theoretical curves agree with data published in several texts[1].

The Es/N0 performance of the waveform can be calculated by adding 10 log(bits per symbol) or 6 dB to the basic 5.5 MBps biphase waveform to account for the 4 bits per symbol. For the 11 MBps case, add 3 dB more when using both I and Q channels which share the carrier power (10 log(8) = 9 dB). This gives a required Es/N0 of 13.6 dB for the 5.5 MBps case and 16.8 dB for the 11 MBps case. This Es/N0 is calculated in the symbol rate bandwidth, so when the spread rate bandwidth is considered, the SNR (in this bandwidth) is 9 dB lower or (13.6 - 9) = 4.6 dB for the 5.5 MBps case and 7.8 dB for the 11 MBps case. The operating Eb/N0 of the 1 MBps 802.11 waveform using the PRISM chip set has been measured at 13 dB. This differs from the ideal performance due to two factors. First, there is a 6 fold error extension due to differential decoding and descrambling and second, there are implementation losses. With 10.4 dB processing gain due to spreading, the operating SNR in the spread bandwidth is 2.6 dB. With QPSK, this is increased by 3 dB to 5.6 dB since the I and Q

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[1] Lindsey and Simon, "Telecommunication Systems Engineering", Prentis Hall, Publisher

channels split the carrier power. One factor that has not been accounted for in the theoretical analysis for the MBOK waveforms is the descrambling effect on the 5.5 MBps and 11 MBps links. No factor was included above for that effect. Thus, the net Eb/N0 is slightly worse for these, but owing to the grouping into symbols, the effect is not great.

One way to analyze the effective processing gain of the spreading of a DSSS waveform is to consider the bandwidth ratios between the spread and unspread (correlated) waveforms. In the IEEE 802.11 BPSK (1 MBps) case, the spread rate is 11 MCps and the symbol rate is 1 MSps. Thus, the IF signal can be passed through a 22 MHz filter and then despread and filtered again in a 2 MHz filter. This is an 11 to one ratio and discards 91 % of the jamming energy. In the 11 MBps case, the chip rate is the same but the symbol rate is 1.375 MSps. This only gives an 8 to 1 or 9 dB ratio for the bandwidth reduction. Clearly some more processing gain is needed to make the processing gain requirement. This comes from the inherent processing gain of the waveform. Above, we showed where the MBOK waveform performs up to 1.6 dB better than BPSK.

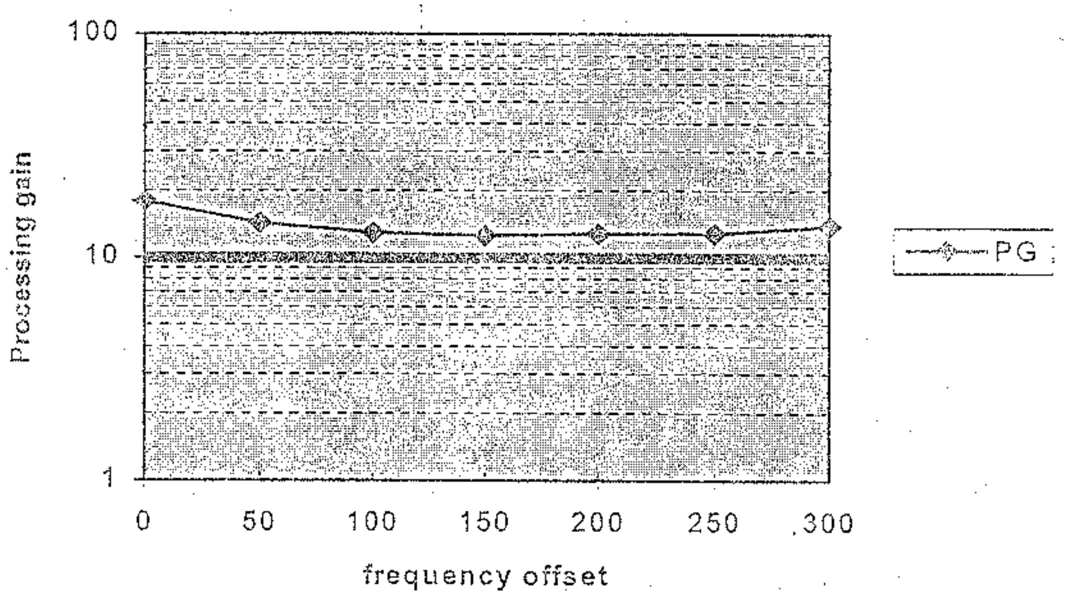

Figure 6, CW jamming data

Figure 6 shows data taken running the CW jamming test run to verify the FCC mandated processing gain.. The data was taken with the whole radio RF to Rf using the packet error rate test mode to predict the jamming margin. We only ran positive frequencies, since the results are symmetrical.

Thus, using the FCC formula:

$PG = SNRo + Mj + Loss$

where PG is the processing gain

Mj is the jamming margin

Loss is estimated to be 2 dB

and SNRo is the theoretical Es/N0 for the waveform.

We get:

$PG = 13.6 - 1.5 + 2 = 14.1$ dB for 5.5 MBps

$PG = 16.8 - 6.0 + 2 = 12.8$ dB for 11 MBps

Thus, our data shows a 2.8 dB PG margin over the FCC requirements for the 11 MBps case and 4.1 dB PG margin for the 5.5 MBps case.

Range

Simulations using a Raleigh fading path model were used to predict the packet error rates at various ranges due to multipath and attenuation.

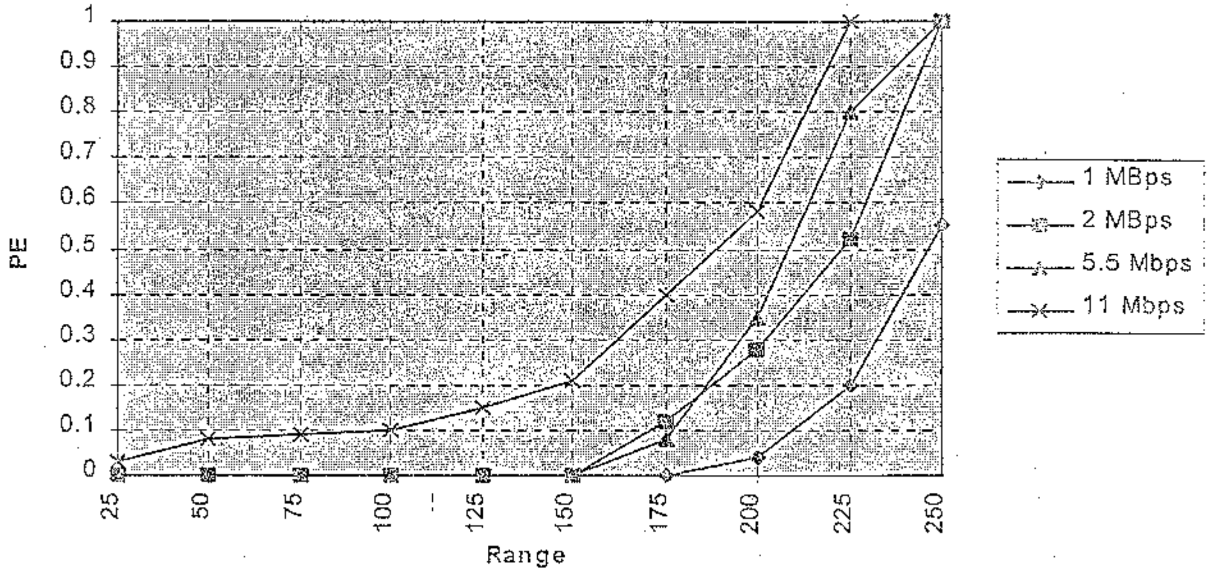

Figure 7, Link range with multipath and no antenna diversity or coding

The simulations show that the probability of a missed packet is strongly influenced by multipath as the required Es/N0 becomes higher. This is intuitively correct as the ratio of the multipath to the signal must improve if the Es/N0 needs to better. This result shown in figures 7 and 8 shows a need to implement antenna diversity to achieve good performance.

A 15 % PER will reduce the network throughput by at least 30% due to the need to retransmit packets. When antenna diversity is taken into account, the PER values can be squared

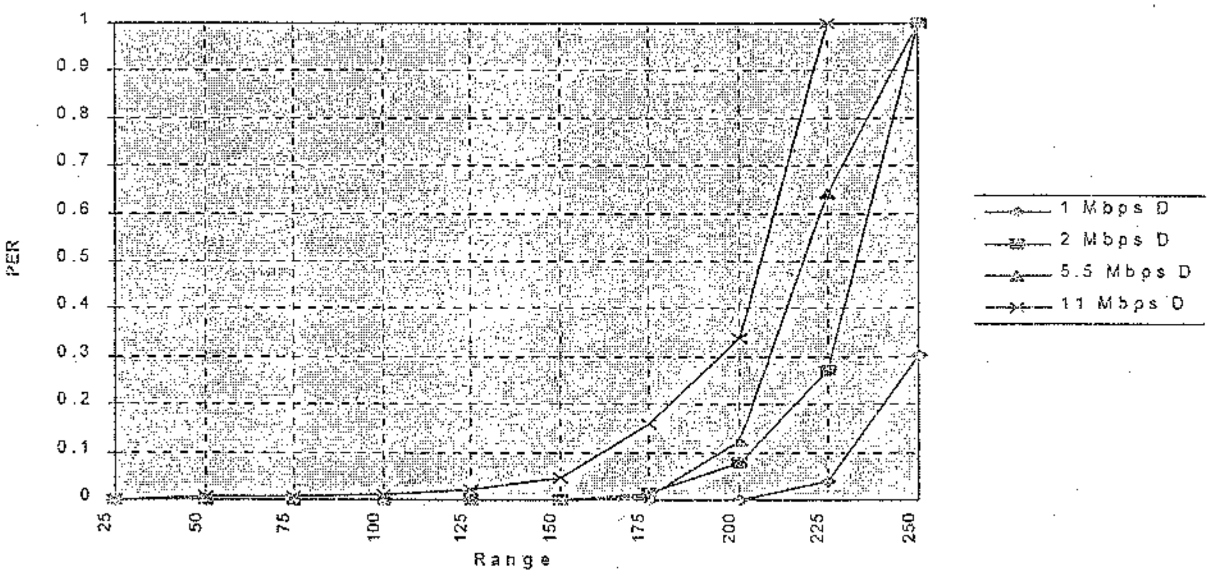

Figure 8, Link range with multipath and antenna diversity assuming optimum diversity. The performance of the 5.5 MBps case is substantially better as illustrated by figure 7. This curve was taken with +20 dBm TX power, so it is slightly better than the table values above.

The essential message of this data is that stressed links can be substantially improved by lowering the raw data rate which can be readily accomplished with the suggested architecture. The other message is that antenna diversity will greatly improve the 11 MBps throughput when multipath is an issue.

Data Throughput

The raw data rate only indicates the best rate that the physical layer can support in a continuous mode. The achieved data rate in a network will depend on many factors such as protocol overhead and packet overhead. If an interoperable design is chosen for the IEEE 802.11 network, the packet will be burdened by a preamble sized for 1 MBps operation. This will be an overkill for the high rates and will lower the effective rate as shown in figure 9. Short packets are effected more by the fixed length preamble. This analysis assumes that the 802.11 preamble of 192 us is used for all packets. The two curves show the cases of full protocol with data, and ACK versus the best performance without the ACK.

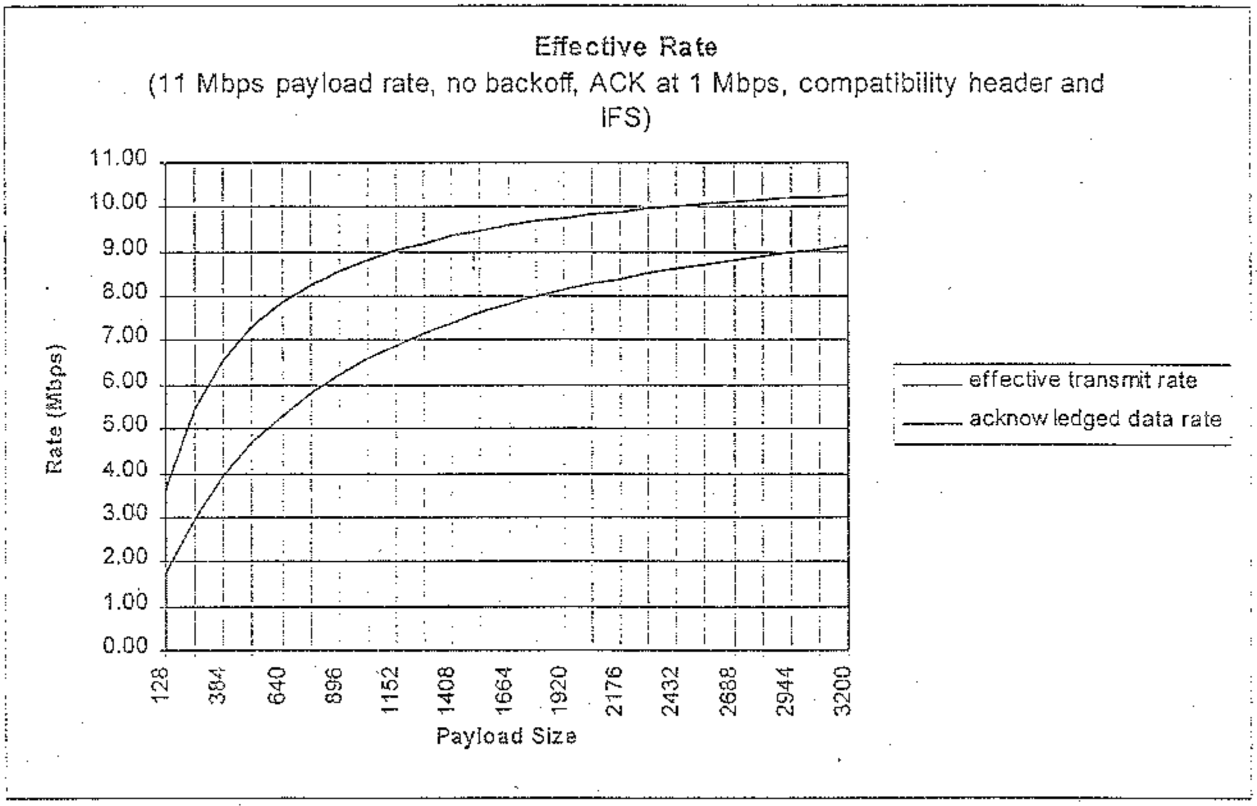

Figure 9, Packet overhead effects.