IEEE P802.11
Wireless LANs

Modulation and Coding in

Wireless Local Area Networks

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Abstract

This report documents the results of a preliminary study on the application of various modulation and forward error control (FEC) techniques for application to wireless local area networks (WLAN) applications. The report considers the existing quadrature phase shift keying (QPSK) -- Barker code based system. The notion of bandwidth and signal to noise ratios Es/No and Eb/No are reviewed. It is shown that the existing system obtains all of the processing from a loss in rate (a simple trade of energy for rate) which has no coding gain.

Two proposed systems, one based on offset pulse position modulation (OPPM) and the other based on M-ary Orthogonal Keying (MOK) (a short block code known as a Hadamard code) are considered. It is shown that both systems exhibit a modest coding gain. However, it is argued that they pale in comparison to other modern FEC systems.

1. Existing Barker System

1.1 Bandwidth, Symbol Rate and Information Rate

The information rate of a coded modulation signal is the product of two factors:

$$R_{\text{information}} = R_{\text{symbol}} * R_{\text{modulation}}$$

The first term is the symbol rate, $R_{\text{symbol}} = 1/T_{\text{symbol}}$, which varies inversely to the symbol period T_{symbol}. The symbol rate is measured in symbols per second (IEEE 802.11(ds) uses a symbol rate of 11 Msps). The bandwidth

$$B = (1 + a) * R_{\text{symbol}}$$

is proportional to the symbol rate. The excess bandwidth parameter $a > 0$ is related to the bandwidth efficiency of the modulated transmitted waveform. In the existing IEEE 802.11(ds) system, the excess bandwidth is almost 200% since an 11MHz symbol rate occupies a >30 MHz bandwidth.

One method of improving the information rate of the system is to decrease the excess bandwidth parameter. With the existing QPSK modulation, the a parameter can be improved with pulse shaping. However, the economics of the existing transmitter power amplifier designs requires operation with significant non-linear (saturation) operation. This precludes the use of meaningful pulse shaping.

An alternative approach is to use a constant phase modulation (CPM) such as minimum shift keying (MSK). This approach may improve the information rate though the increase of the symbol rate. However, (1) the practical benefit should be demonstrated and (2) such an approach would not be backward compatible with the existing IEEE 802.11(ds) standard.

This report is mainly concerned with improvements in the information rate though the second term:

$$R_{\text{modulation}}$$

the modulation rate (measured in bits per symbol). The study described assumes the use of QPSK modulation, however, the suggested improvements could also be achieved with other forms of modulation including MSK.

1.2 QPSK, BPSK and the Barker Sequence

In existing 802.11 (DS) wireless local area networks (LAN) systems, quadrature phase shift keying (QPSK) modulation is combined with an *n = 11* Barker code. As a basic form of modulation, the bit error rate (BER) of the system, as a function of the signal to noise ratio (SNR) E_s / N_o is presented in Figure 4. In this case, the SNR is a measure of the received signal power over the power of the noise in the bandwidth of the signal. It is assumed that the noise is white in this bandwidth (the noise power spectral density (PSD) is flat across the band). The noise is also assumed to be Gaussian (Normal) in distribution.

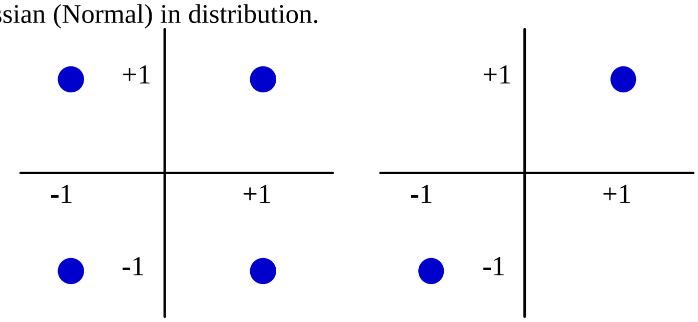

Figure 1: QPSK and BPSK Signal Set

Figure 4 shows how a reduction of data rate can improve the BER as a function of the channel SNR: E_s / N_o. For example, BPSK, which operates at a normalized data rate of 1 bit per symbol, has a $10\log_{10}(2) = 3.01..$ dB improvement over QPSK, which operates at a rate of 2 bits per symbol. Also shown on this graph is the BER performance of an *n=11* Barker encoded data with QPSK modulation. In this system, the data rate is 2/11 bits per symbol and the improvement is $10\log_{10}(11) = 10.41..$ dB over QPSK or $10\log_{10}(11/2) = 7.41..$ dB over BPSK. It should be clear from this picture that a trade between rate and SNR can be directly obtained. However, Shannon, in 1948 [1], argued that through the use of FEC techniques, one could do better than to simply trade rate for SNR.

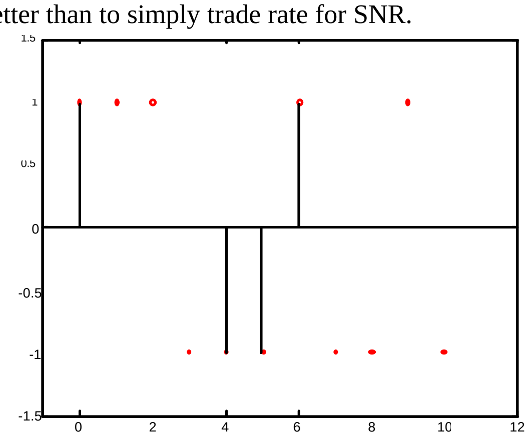

Figure 2: n = 11 Barker code

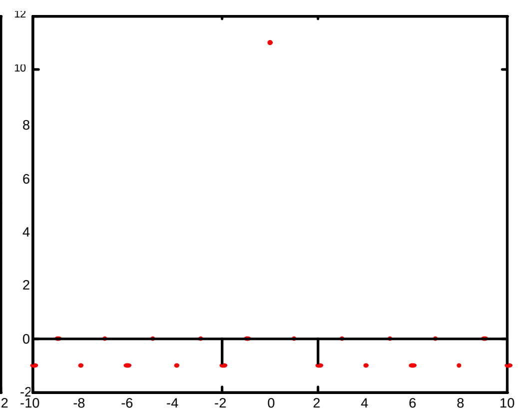

Figure 3: n = 11 Barker auto-correlation

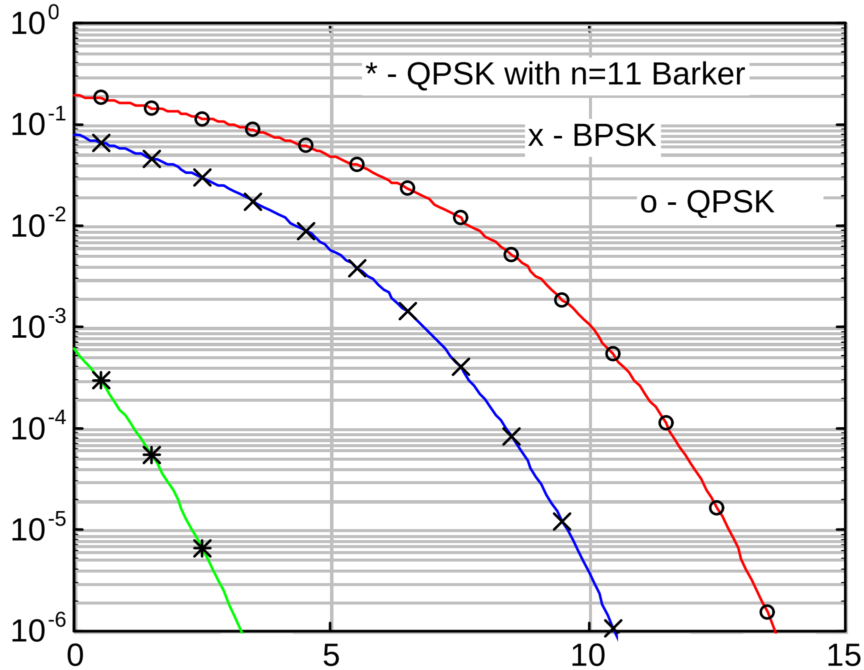

Figure 4: BPSK, QPSK and Barker QPSK with Es/No

In order to correctly attribute the gain of an FEC system, one most account for the gain due to a change of data rate correctly. In systems that operate at a low rate (in terms of bit per symbol), the accepted measure is to define another SNR: E_b / N_o where the energy per bit $E_b = E_s / R$, where R is the normalized rate. The utility of this definition is apparent from Figure 5. In this graph, the three base systems are shown to have virtually identical performance. Thus, on the E_b / N_o, a simple trade-off of rate for energy is cancelled. In fact, a “coding gain” is achieved only when an improvement is obtained on this scale. Thus the total gain, in dB, will be the sum of the energy for rate gain plus the coding gain.

Comment:1 - Uncoded QPSK requires an Es/No of 12.7 dB to achieve 10-5 bit error rate (BER) and 9.7 dB on an Eb/No scale. Uncoded BPSK requires 9.7 dB to achieve 10-5 BER on both Es/No and Eb/No scales. The 11-bit Barker DSS system requires Es/No of 2.4dB to achieve 10-5 BER. The decoding complexity is: 10 adds per bit and 1 (binary) comparision. A data rate of 2Mbps requires a symbol (chip) rate of 11 MHz.

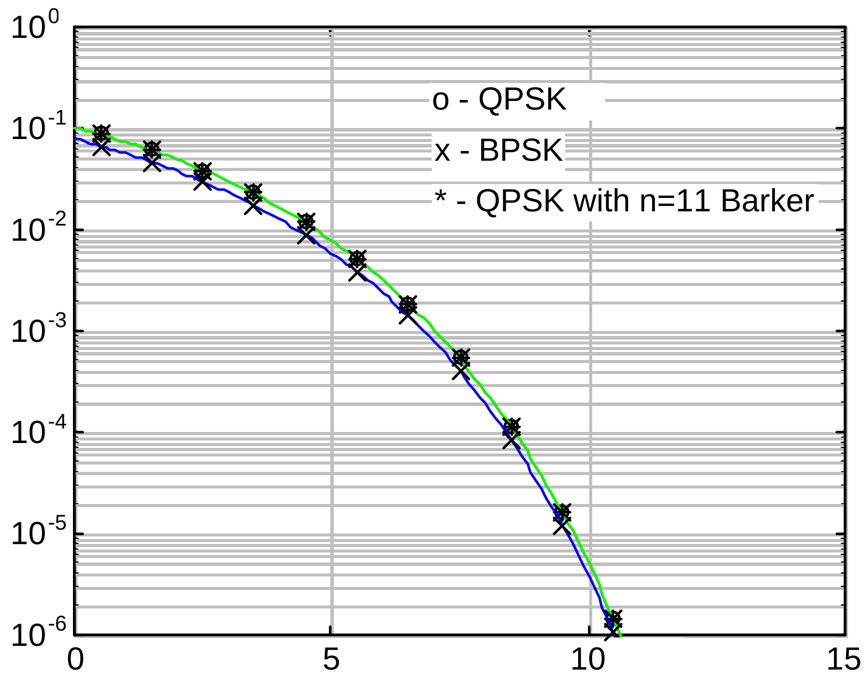

Figure 5: BPSK, QPSK and Barker QPSK with Eb/No

2. Overlapped Pulse Position Modulation

One proposal for an advanced wireless LAN solution has been proposed by Israel Bar-David and Rajeev Krishnamoorthy of Lucent Technologies [2]. In this system, the data rate is improved, relative to the Barker code system, by increasing the size of the signal set with an overlapped pulse position modulation (OPPM) approach. In this scheme, the position of the barker code is used to convey information (the PPM). The system is overlapped since the transmission of the Barker code occurs at the same rate (once every 11 symbols). The overlapped signals are added together; thus what once was a binary signal on each carrier becomes a five level signal (in non-overlapped symbols, the original points, say {+1,-1} appear, in overlapped positions all sums, {+2,0,-2} can appear).

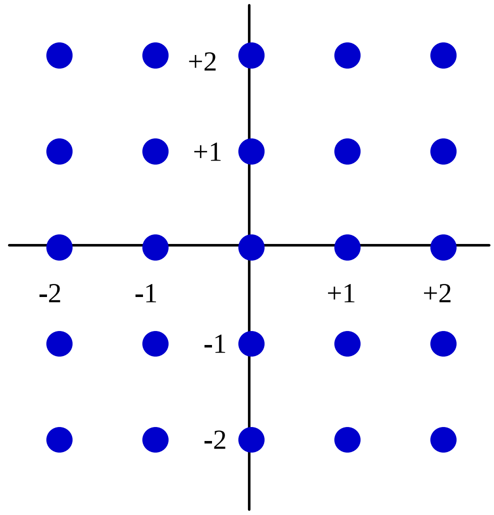

Figure 6: OPPM Signal Set

In OPPM, memory is introduced in the encoding. To build an optimal detector for this scheme requires a method, such as the Viterbi algorithm [3], to decode (this is the same algorithm that is useful for decoding binary convolutional and trellis codes). The results of a Viterbi based simulation is presented in Figures 7 and 8. The trellis involved 16 states 16 branches leaving each state (256 branches in total). The proposed system has a variety of rates, the one simulated was the highest rate solution. In this scheme, a sign bit plus 3 shift bits are used to modulated each carrier, thus the rate of the system is 2*4/11 = .73 bits per symbol. This is a 4 times improvement in data rate as compared to the original 1 bit per Barker code system. The simulation results show a small coding gain of 2.2dB. Combined with the energy gain of 4.4dB for the rate loss, the net gain is 6.6dB.

This system appears to have problems in wireless LAN applications, the reasons are several fold. The two most important concerns involve complexity of the decoder and complexity of the modulation. The complexity of the system translates into only a modest coding gain. While the simulation approach was somewhat direct, I believe simplifications of the detector will not significantly reduce the computational load without degrading performance. The decoder would be very complex and the gains would be very modest. Secondly, the introduction of a 5 level transmission signal set to obtain a net rate of less than 1 bit per symbol seems unwise. Such a signaling scheme would require an unduly complex modem function. In particular, the transmitting function would require a very linear amplifier to support the multiple signal levels. In addition, the receiver would require a linear analog frontend as well as possibly an adaptive equalizer with larger dynamic range that might be a significant cost.

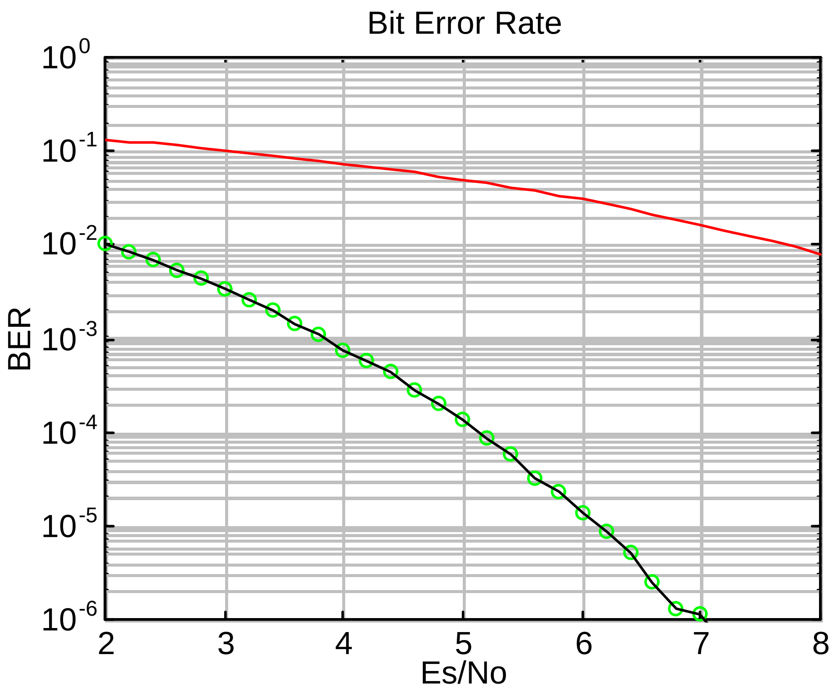

Figure 7: OPPM, n = 11 Barker + 8 positions with Es/No

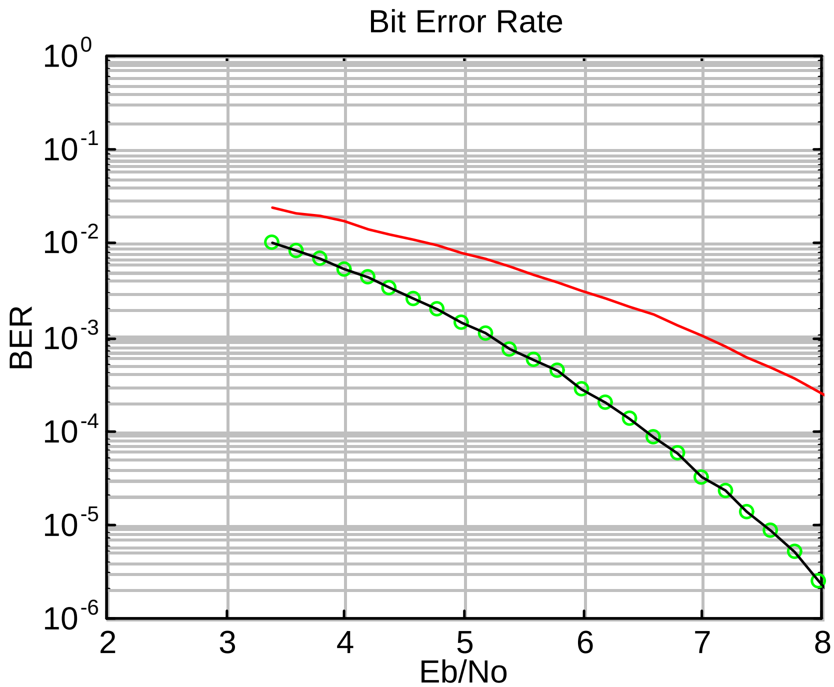

Figure 8: OPPM, n = 11 Barker + 8 positions with Eb/No

Comment: 2 - Consider a Soft-decision decoding of a OPPM with 11bit Barker and pulse shift of 0-7 symbols and Viterbi decoding (256 state). The rate of this code is 8/11 = .727 bits per symbol. This code shows a coding gain (Eb/No scale) of 2.2dB (= 9.7-7.5 dB) for a net gain of 4.4+2.2 = 6.6dB on an Es/No scale. The complexity of the decoder is very high. The data rate would be 8 Mbps (@11MHz symbol rate).

3. M-ary Orthogonal Keying

A second proposal has been promoted by the Harris corp. [4]. The scheme that they suggest is called M-ary Orthogonal Keying (MOK) (strictly speaking, it should be called M-ary Bi-Orthogonal Keying since the signal set consists of a set of orthogonal signals plus the negatives of each signal). However, in the case when the block length of the code $n = 8$ and the number of information bits $k = 4$, the MOK modulation, which is based on Hadamard matrices ([5], page 44), is a code that is equivalent to an *(n = 8, k = 4) Extended Hamming code* (EHC) (one of the first error correcting code (ECC) [1]). This code has a generator matrix:

G =	1	0	0	0	1	1	1	0
	0	1	0	0	1	1	0	1
	0	0	1	0	1	0	1	1
	0	0	0	1	0	1	1	1

With modulation, the transmitted codewords are described by the matrix:

X =	1	1	1	1	1	1	1	1
	-1	1	1	1	-1	-1	-1	1
	1	-1	1	1	-1	-1	1	-1
	-1	-1	1	1	1	1	-1	-1
	1	1	-1	1	-1	1	-1	-1
	-1	1	-1	1	1	-1	1	-1
	1	-1	-1	1	1	-1	-1	1
	-1	-1	-1	1	-1	1	1	1
	1	1	1	-1	1	-1	-1	-1
	-1	1	1	-1	-1	1	1	-1
	1	-1	1	-1	-1	1	-1	1
	-1	-1	1	-1	1	-1	1	1
	1	1	-1	-1	-1	-1	1	1
	-1	1	-1	-1	1	1	-1	1
	1	-1	-1	-1	1	1	1	-1
	-1	-1	-1	-1	-1	-1	-1	-1

which is a *(n = 8, M = 16 = 2^4, d = 4)* Hadamard code [5, page 49]. Each pair of rows of this matrix is either orthogonal or the negative of each other.

A simulation of this system, displayed in Figures 9 and 10, reveals a modest coding gain of 2.3dB. Since the system operates at a rate of 1 bit per symbol, the net gain is 5.3dB. The complexity of this code is small. The number of additions per data bit is 14 (there are 7 additions to correlate with a given row and you need to correlate with the first 8 rows, thus there are 56 adds per codeword processed); the number of (binary) compares per data bit is 3.75 (a 16 way comparison requires 15 binary compares). The data rate would be 11Mbps (@11MHz symbol rate).

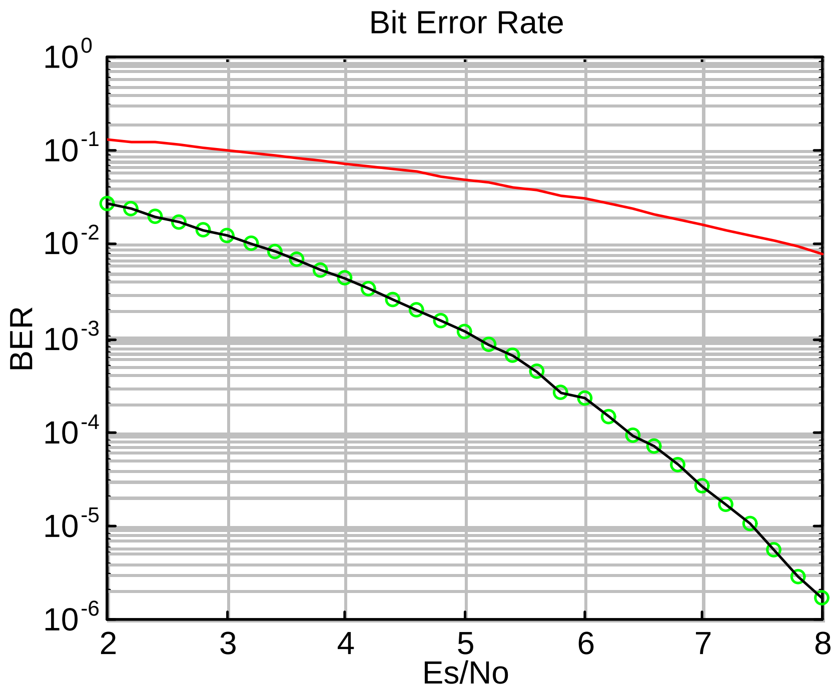

Figure 9: (n=8, k=4) MOK with Es/No

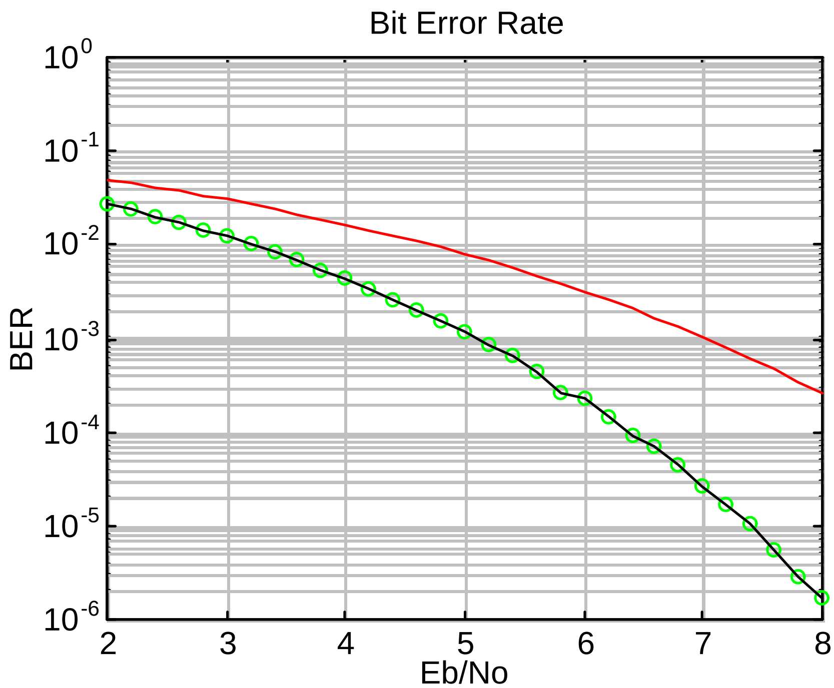

Figure 10: (n=8, k=4) MOK with Eb/No

Comment: 3 - Consider a soft-decision decoding of a (n=8, k=4) Extended Hamming Code (n=8 MOK). This code shows a coding gain (Eb/No scale) of 2.3dB (= 9.7-7.4 dB) for a net gain of 3.0+2.3 = 5.3dB. Decoding complexity: 14 adds, 3.75 compares per data bit. The data rate would be 11Mbps (@11MHz symbol rate).

4. Conclusions

This report considers several choices for improving the performance of wireless LAN systems. The results are summarized in the following table:

Code	R	(@11MHz)	C.G.	N.G.	Adds	Cmps
11 Barker	2/11	2Mbps	0dB	10.4dB	10	1
OPPM	8/11	8Mbps	2.2dB	6.6dB	HIGH	HIGH
(8,16,4) MOK	1	11Mbps	2.3dB	5.3dB	14	3.75
(16,32,8) MOK	5/8	6.9Mbps	~5.0dB	~10.1dB	48	6.2

The table shows the RATE: code rate (R) in bits per symbol, the bit rate with an 11MHz symbol rate, the NOISE MARGIN: the coding gain (C.G.), the net gain (N.G.) and the COMPLEXITY: adds per bit, compares per bit. The standard Barker system is the first row of the table. The Lucent OPPM scheme is the second line. The complexity is not computed, but is excessive. This scheme also requires linear transmitters and receivers and possibly an extensive adaptive equalizer. The Harris MOK scheme, $n = 8$ is the third line (and extension to $n = 16$ is the fourth).

When one compares the type of coding used in many modern digital communications systems, such as: Telephone line modems (e.g., v.34, x2, 56k), Digital TV and cable modems (e.g., J.83/IEEE 802.14/MCNS), Satellite TV distribution (e.g., DSS, primestar), cellular and PCS phones (e.g., IS-95, CDMA-PCS, GSM), the feeling is the proposed coding schemes for high performance WLAN's are unassuming.

5. References

[1] C. E. Shannon, “A mathematical theory of communication,” *Bell System Technical Journal*, vol. 27, pp. 379--423, 623--656, Oct. 1948.

[2] Israel Bar-David and Rajeev Krishnamoorthy, “Barker Code Position Modulation for High-Rate Communications in ISM Bands,” *Bell Labs Technical Journal*, vol. 1, no. 2, pp. 21-40, Autumn 1996.

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[5] F. J. MacWilliams and N. J. A. Sloane, *The Theory of Error-Correcting Codes*, Amsterdam: North-Holland, 1977.

[6] Stephen B. Wicker, *Error Control Systems for Digital Communications and Storage*, Englewood Cliffs, NJ 07632, Prentice Hall, 1995.