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Optimizing Spectral Efficiency with LDPC Coded MQAM for Next-Generation Communication Systems

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ABSTRACT

This paper presents a coded modulation scheme combining Multilevel Quadrature Amplitude Modulation (MQAM) with Low-Density Parity-Check (LDPC) codes for wireless communication systems, offering an efficient and pragmatic approach for bandwidth-efficient transmission. The proposed scheme utilizes a single encoder and decoder without requiring an interleaver, which simplifies the implementation compared to other coded modulation techniques such as Turbo-coded modulation. Due to the complexity of analytically evaluating LDPC-coded modulation, the system's performance is assessed through extensive computer simulations. Results show that the LDPC-coded MQAM scheme with Gray mapping achieves performance close to the Shannon limit over the Additive White Gaussian Noise (AWGN) channel, using LDPC codes with a length of 2304 bits and a maximum of 30 decoding iterations. The system also performs well in flat uncorrelated Rayleigh fading channels, and its performance can be further enhanced by increasing the number of decoding iterations and code length. The proposed scheme demonstrates a significant improvement in spectral efficiency while maintaining robustness in various channel conditions.

Keywords: Coded Modulation, MQAM, LDPC Codes, Spectral Efficiency, Wireless Communication, Gray Mapping, AWGN Channel, Rayleigh Fading Channel.

1. INTRODUCTION

In modern wireless communication systems, achieving optimal power and bandwidth efficiency is essential to support high data rates and meet the growing demand for wireless capacity. Among the various modulation schemes, Quadrature Amplitude Modulation (QAM) is widely used due to its ability to transmit multiple bits per symbol, thus improving spectral efficiency. However, as the modulation order increases (e.g., 64-QAM, 256-QAM), the system becomes more sensitive to noise and interference, necessitating robust error correction techniques to maintain reliable communication. This is where Low-Density Parity-Check (LDPC) codes, a class of powerful error-correcting codes, play a significant role in improving performance.

LDPC codes have been recognized for their ability to approach the Shannon limit, the theoretical maximum capacity of a communication channel. When combined with high-order M-ary QAM modulation, LDPC codes offer a compelling solution for coded modulation; a technique where error correction is applied in the modulation process. This approach allows for high data rates while maintaining robust error performance, even in noisy or fading channels.

In this work, we explore the synergy between LDPC codes and M-ary QAM schemes to enhance both power and bandwidth efficiency. First, we review bandwidth-efficient modulation techniques and provide an overview of several typical coded modulation systems. We then present a practical LDPC-coded modulation system designed for transmission over both Additive White Gaussian Noise (AWGN) and uncorrelated Rayleigh fading channels. These channels represent common environments in wireless communication, with AWGN modeling thermal noise and Rayleigh fading accounting for signal attenuation due to multipath propagation. Finally, we propose an adaptive coded modulation (ACM) scheme with LDPC coding, optimized for flat, slowly-varying Rayleigh fading, to further enhance system performance in real-world scenarios.

This paper aims to demonstrate how LDPC codes and M-QAM modulation can be integrated effectively to achieve high spectral efficiency while ensuring reliable transmission over challenging wireless channels.

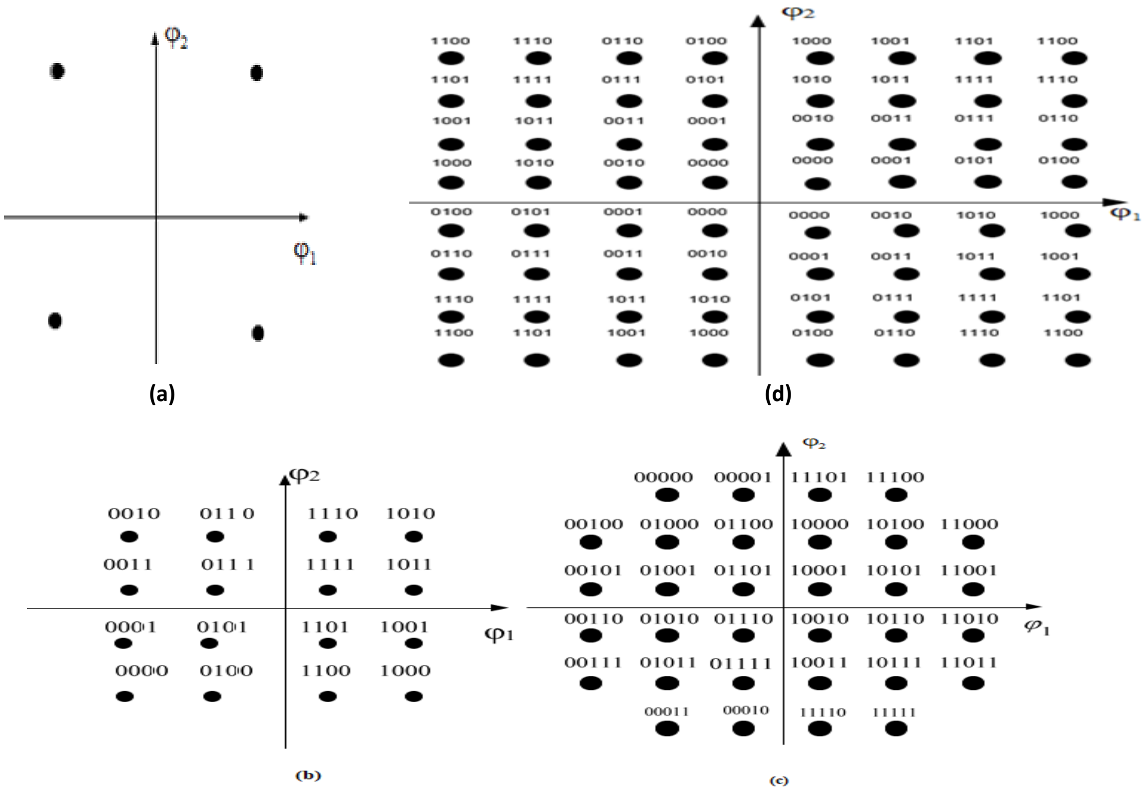

Figure 1: Signal constellations of (a) 4-QAM, (b)16-QAM, (c) 32-QAM, (d) 64-QAM

Quadrature amplitude modulation (QAM)

Among the family of bandwidth-efficient modulation schemes, PSK and QAM are often used to achieve high rate transmission. In particular, M-QAM can offer the largest spectral efficiency, since the information bits are modulated in both the amplitude and phase of the carrier wave signals. For this reason, QAM combined with Gray mapping has been widely applied over wireless links, such as in 3G and 4G mobile communication systems, broadband wireless networks and many other wireless multimedia communication systems. The simplest method of digital signaling with a QAM system is to use one-dimensional PAM independently for each signal coordinate.

Consider rectangular QAM signal constellations with $M = 2^m$, where, M is the number

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of points. They can be represented as constellations of points in the in-phase and quadrature (I/Q) plane,

$$(t) = B(t)cos2\pi f_c t + B_Q(t)sin2\pi f_c t \quad (1)$$

Where,
f_c = Carrier frequency
T = is the symbol time
B_I = The baseband signals of the in-phase
B_Q = The baseband signals of the quadrature components
B_I and B_Q can be selected over the set of

$$\{\pm r, \pm 3r, \ldots, \pm(\sqrt{M} - l)r\}$$

Where,

$$2r = r_0$$

is the minimum distance between signal points and can be computed using the following relationship.

$$r = \sqrt{\frac{3 \log2 M .Eb}{2(M-1}} \quad (2)$$

Where,
E_b =The information bit energy

2. LITERATURE REVIEW

The NB-LDPC codes, often with better error correction performance than binary LDPC codes [1], could be better adapted to high-order modulations without considering the inter-conversion between bit probability and symbol probability. These advantages of the 7-QAM constellation are verified through the calculating of PAPR, the derivation of an exact intuitive geometric infinite double series for its symbol error probability over the Additive White Gaussian Noise (AWGN) channel using the similar derivation in [32–40] and the analysis of its sensitivity to the nonlinearity of HPAs. Finally, the demodulation threshold of 7-QAM and the symbol error rate performance of the proposed coded modulation scheme are simulated.

Zhang et al. [2] proposed a CP-based UFMC system to achieve interference-free transmission and derived an analytical model with the desired signal, intersymbol interference, intercarrier interference, and noise-level. Chen et al. [3] formulated a novel adaptive filter configuration algorithm by adaptively designing the parameters of finite impulse response filters. Their adaptive filter configuration algorithm can efficiently combat different carrier-frequency offsets that are caused by the interference of multiple users.

The research work carried out by K.M.Palaniswamy[4] shows that the Adaptive modulation based MC-CDMA system or OFDMA system includes Turbo encoder in Rayleigh fading environment analyzed the BER performance for M-ary PSK, M-ary QAM for Bit Duration Bandwidth Product at 60k symbols/sec. It is found that M-ary MHPM has achieved very low BER of upto 10^{-7} due to adaptive modulation[6]. The work presented by Hala M.A Mansour[5] to analyze the performance of various concatenated coding schemes such as Serial concatenated convolutional code, Parallel concatenated convolutional code and Parallel-serial concatenated convolutional code with M-ary PSK, M-ary QAM, FSK modulation techniques through AWGN channel[10].

Hao Zhong et al[8] presents a Block LDPC codes which combines the hardware implementation of LDPC coding and decoding simultaneously and extended to partially parallel block LDPC encoder and decoders and observed that the error correcting performance was significant as compared to LDPC codes without considering the implementation constraints. Chih-Yuan Yang et al[7] studied the performance of different LDPC coded OFDM modulation schemes. Partially LDPC coded and RS-LCM code with LDPC coded modulation to achieve better performance than the BICM. Jaehong Kim[9] et al presents a class of LDPC codes suited for rate compatible puncturing over wide range for

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moderate block lengths and are linear time Encodable and simple shift register circuits suitable for incremental redundancy hybrid-automatic repeat request (ARQ) systems.

3. LDPC-CODED MODULATION SYSTEM MODEL

Assume that after encoding, the modulated M-QAM signals with Gray mapping are transmitted over both AWGN and uncorrelated Rayleigh fading channels. In this setup, the LDPC encoder and M-ary modulator are designed independently to optimize both power and bandwidth efficiency. Specifically, for the Rayleigh fading channel, we focus on the QAM schemes specified in the standard [10], including QPSK, 16-QAM, 64-QAM, and 256-QAM.

Adaptive coded modulation techniques

Adaptive coded modulation (ACM) is designed by adapting the transmit power, coding rate and modulation (size of the constellation) scheme to the corresponding channel conditions at the receiver. The basic principle of Adaptive coded modulation is that a higher data rate is transmitted during good channel conditions, while a lower data rate is transmitted during poor channel conditions.Based on these adaptive theories, [11] showed an adaptive variable-rate variable- power transmission scheme using uncoded M-QAM scheme for Rayleigh fading channels is proposed to increase spectral efficiency.

Rayleigh block-fading channel

Block-fading channels are characterized by the fact that the noise severity remains constant in blocks of some consecutive transmitted symbols but are independent from block to block. The block-fading channel can be a model for multi-carrier communication systems such as orthogonal frequency division multiplexing, frequency-hopped spread spectrum and also the slow fading channel. The term, flat means that all signal frequencies are attenuated by the same fading factor and the phase of the fading signal is uniformly distributed between 0 and 270C.
For the block-fading structure, each codeword (frame) of nsc symbols is split into several sub-blocks, and each sub-block of length nsh is affected by the same fading factor as shown in Figure 3, we define,

n_{bs}					
1	**2**	…	n_{sh}	…	n_{hc}
n_{sh} *Symbols*					
n_{sc} *symbols* $= n_{hc}$*subblocks* $=$ *one codeword*					

Figure 2: Frame structure

$n_{sc} =$ is the number of symbols per codeword
$n_{bs} =$ is the number of bits per symbol
$n_{sh} =$ is the number of symbols per sub-block
$n_{hc} =$ is the number of sub-blocks per codeword
All parameters are supposed to be an integer.

- Transmission over a slow fading channel,
  - When $n_{hc} = 1$ or $n_{hc} = n_{sc}$ such that, the entire codeword is affected by the same fading gain used for the slow-varying fading channel.
- Transmission over a fast fading channel,

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- When $n_{hc} = n_{sc}$ or $n_{sh} = 1$, each symbol is affected by an independent fading amplitude.

Figure 3 show the Bit Error Rate versus signal to Noise ratio performance of sub- blocks LDPC- MQAM modulation with ½ rate transmission over Rayleigh fading channel.

A simplified block diagram for this adaptive scheme is shown in Figure 4. At the transmitter, LDPC adaptive coded modulation provides multiple transmission modes, where each mode is specified by a modulation and a Frame error correction code pair. The transmitter selects an adaptive coded modulation mode for transmission and adapts the transmit power on a frame-by-frame basis based on the CSI feedback from the receiver.

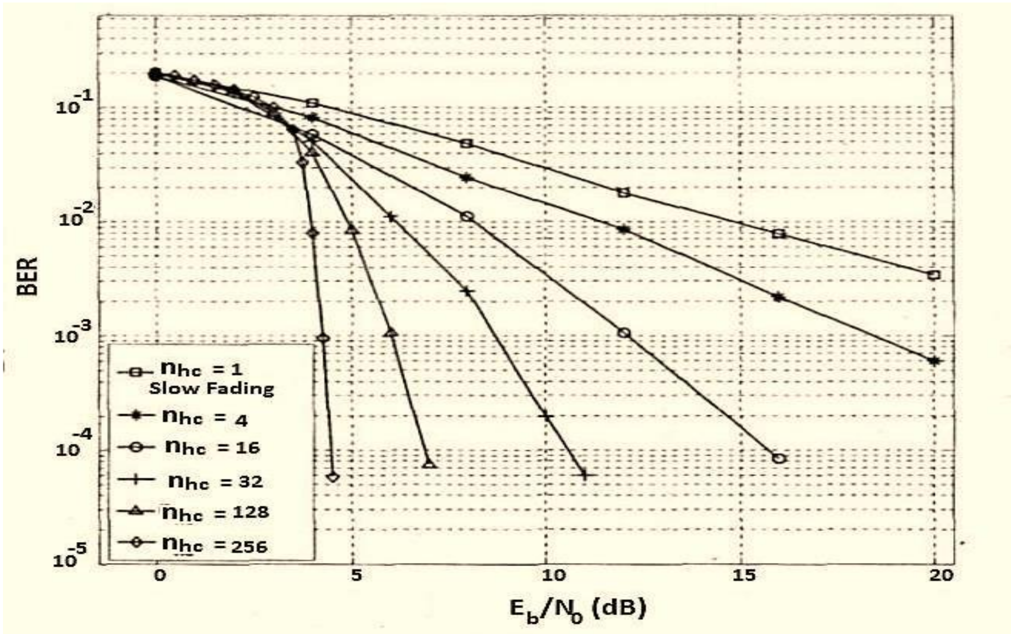

Figure 3: BER performance of MQAM- LDPC modulation over Rayleigh fading channel ½ rate transmissions

Adaptation Threshold

To select the appropriate mode for the ACM system, we need to know the SNR thresholds. We assume that L modulation and code pairs are candidates for the ACM system. The transmitter decides which pair should be used at the start of each transmission according to a given set of SNR thresholds. We adapt the method in [12] to obtain the thresholds from the BER versus SNR for each candidate of coding and modulation on AWGN channels. The threshold for a given code is then found by curve fitting on the simulated BER at a specific BERo.

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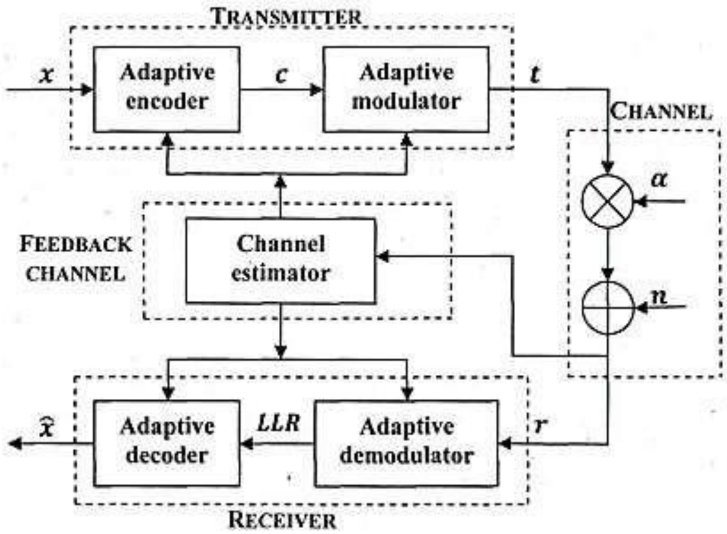

Figure 4: Adaptive LDPC coded transmission

4. PERFORMANCES OVER AN AWGN CHANNEL

We start by discussing the performance of the proposed LDPC-coded modulation scheme transmitted over an AWGN channel. Eight levels of M-QAM schemes are employed, such that QPSK (4-QAM), 8-QAM, 16-QAM, 32-QAM, 64-QAM, 128-QAM and 256-QAM which can offer uncoded spectral efficiencies from 2 to 8 bits/s/Hz.

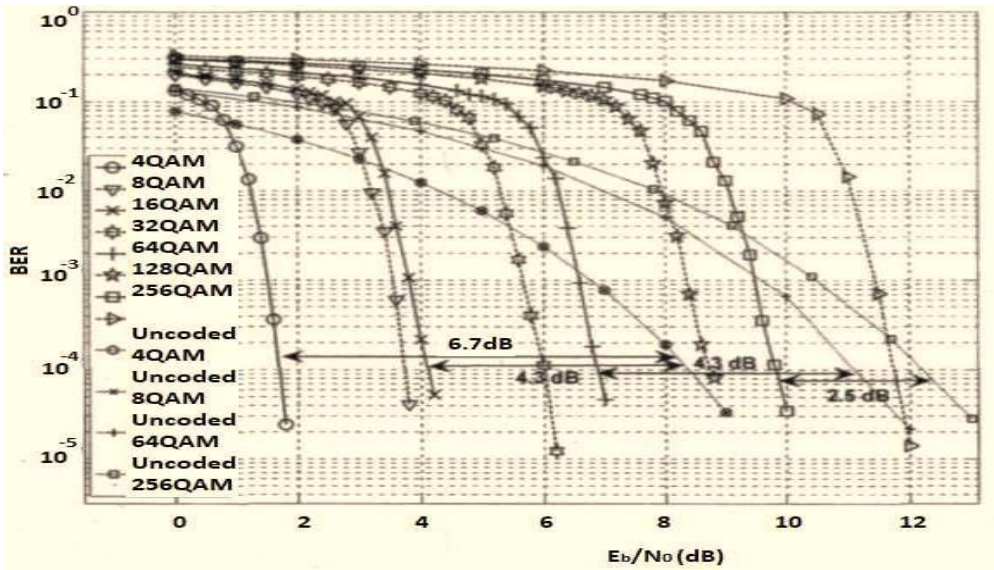

Figure 5: BER performances of LDPC-coded M-QAM with coding rate 1/2 transmitted over an AWGN channel

Table 1: Various spectral efficiencies of LDPC-coded M-QAM

Modulation scheme	Spectrum Efficiency				
	Uncoded	R(1/2)	R(2/3)	R(3/4)	R(5/6)
QPSK	2	1.1	1.3	1.6	1.8
8QAM	3	1.6	2.1	2.4	2.6

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16QAM	4	2.1	2.8	3.1	3.4
32QAM	5	2.6	3.4	4.0	4.3
64QAM	6	3.0	4.2	4.6	5.1
128QAM	7	3.6	4.8	5.4	5.9
256QAM	8	4.0	5.4	6.1	6.9

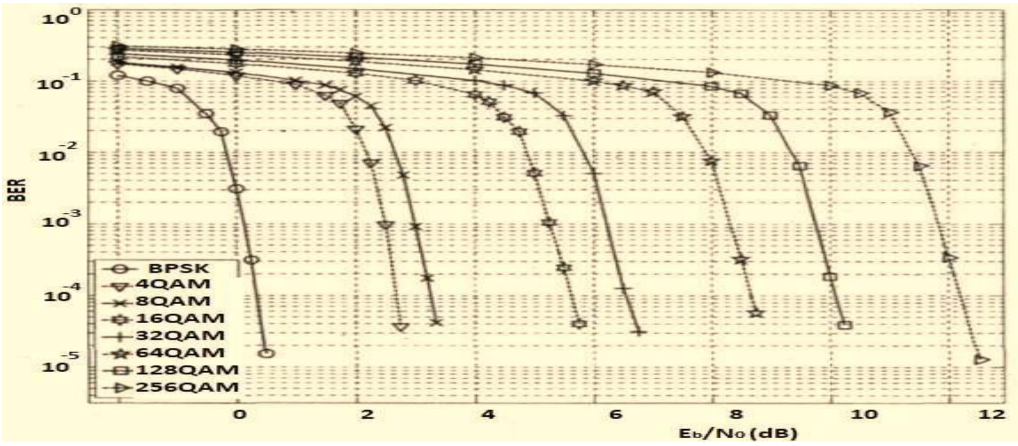

Figure 6: BER performances of LDPCTcoded M-QAM with coding rate 2/3 transmitted over an AWGN channel

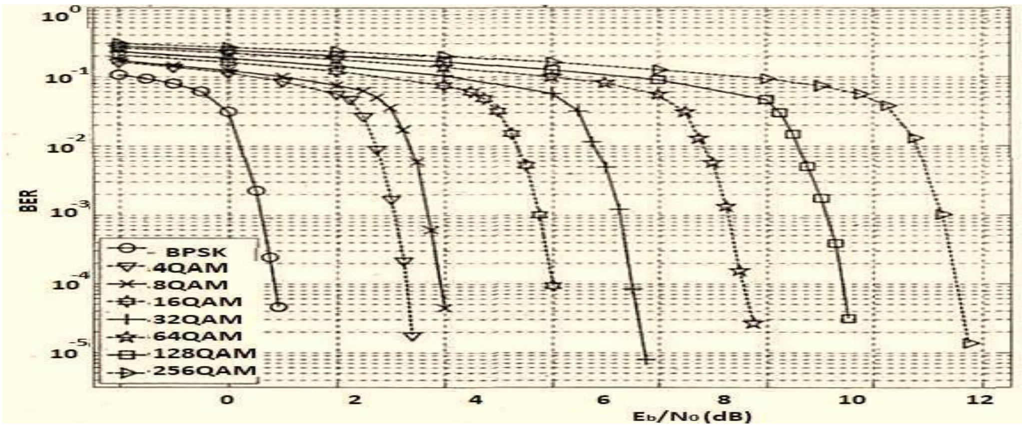

Figure 7: BER performances of LDPC-coded M-QAM with coding rate 3/4 transmitted over an AWGN channel

In addition, the LDPC coding scheme uses code rates of 1/2, 2/3, 3/4 and 5/6. The corresponding coded spectral efficiencies are given in Table 2. The spectral efficiency (bits/s/Hz) is computed using η = R log2M, where R is the coding rate and M is the constellation size. The BER performance of these eight LDPC-coded QAM schemes with coding rate of 1/2, 2/3, 3/4 and 5/6, respectively.

5. COMPARISONS BETWEEN THE CODED AND UNCODED QAM SCHEMES

For comparison purposes, four uncoded modulations with spectral efficiencies of 1, 2, 3 and 4 bits/s/Hz, respectively. The corresponding coded QAM schemes with the same spectral efficiencies are thus coded QPSK, 16-QAM, 64-QAM, and 256-QAM, with coding rate ½.

We can observe that the SNR gap between different uncoded modulation schemes increases gradually and the corresponding coded QAM schemes have SNR gaps of 2 to 3 dB between each other; thus the coding gain decreases as the spectral efficiency increases.

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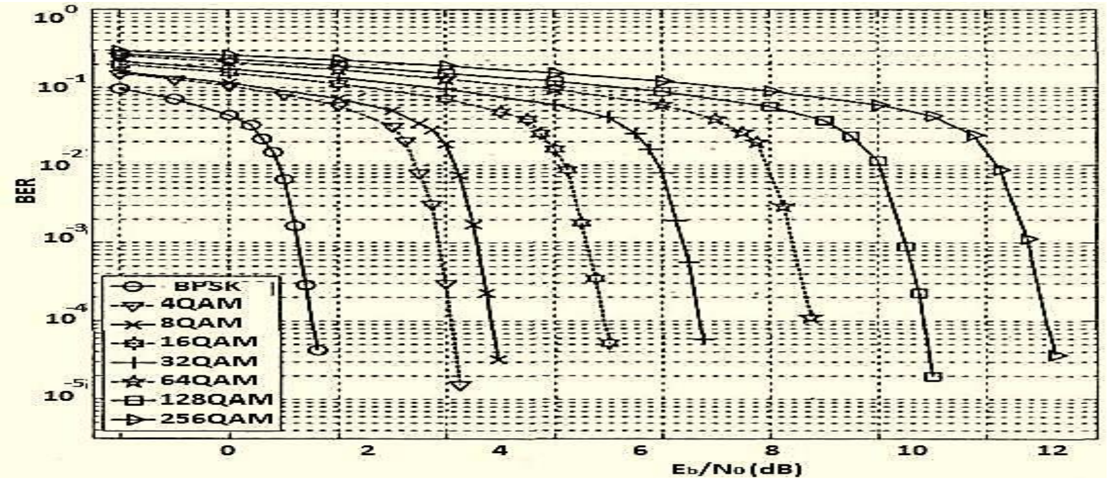

Figure 8: BER performances of LDPC-coded M-QAM with coding rate 5/6 transmitted over an AWGN channel

Coded QPSK has the maximum coding gain and the coding gains of coded 16-QAM and 64-QAM is greater than that of 256-QAM. It can be inferred from this observation that the lower and moderate-order QAM schemes are more efficient at improving performance as compared to high-order QAM for our LDPC-coded QAM scheme transmitted over an AWGN channel.

Various spectral efficiencies observed and we find that they have something in common: for coded cross 16-QAM, the BER curves are quite far from that of coded 8-QAM, and relatively close to that of coded 32-QAM. Thus, for a BER of 10^{-4}, coded 16-QAM with coding rate 1/2 has a gain of just 0.3 dB over coded 32-QAM, but with a loss of spectral efficiency of 0.6 bits/s/Hz compared to coded 32-QAM. Therefore, in practical applications, the coded cross 16-QAM scheme could be replaced by coded square 32-QAM with a little sacrifice in SNR when pursuing higher spectral efficiency. It can be explained that 16-QAM has a much larger average bit energy than QPSK while having slightly smaller average bit energy than that of 32-QAM, for a constant minimum distance between signal points in the constellations. For coded cross 64-QAM and 256-QAM, the SNR gaps to the square coded QAM schemes on both sides are almost the same. Therefore, the trade-off described above does not apply for these two cross constellations.

Among the various spectral efficiencies of the coded M-QAM system which are shown in Table 2, there are different pairs of coded modulation schemes with the same spectral efficiencies. We should choose one combination with better power efficiency for each code-modulation pair.

The comparisons of their SNRs at a BER of 10^{-4} are given in Table 2, where lower order QAM schemes are placed on the left column (Scheme-I); accordingly, the lower coding rate schemes are on the right (Scheme-II).

Table 2: Power efficiency (SNR) comparisons between the coded modulation schemes with the same spectral efficiencies

Spectrum Efficiency	Scheme-I			Scheme-II		
	Modulation	R	SNR	Modulation	R	SNR
1.6	QPSK	¾	2.9	QPSK	½	3.0
2.0	8QAM	2/3	4.8	8QAM	½	3.9
2.6	8QAM	5/6	6.1	16QAM	½	4.2

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3.1	16QAM	¾	6.0	32QAM	½	6.2
3.4	16QAM	5/6	6.3	32QAM	2/3	7.7
4.0	64QAM	2/3	8.7	64QAM	½	7.0
4.4	64QAM	¾	9.6	128QAM	½	8.2
5.2	128QAM	¾	11.8	256QAM	½	9.9
6.1	256QAM	¾	13.5	256QAM	2/3	14.5

For instance, the spectral efficiency of coded 8-QAM with a rate of 1/2 can be achieved by employing the combination of QPSK and rate 3/4. Note that coded QPSK has a lower complexity of implementation. The performance comparison is demonstrated in Figure 6. It shows that coded QPSK with rate 3/4 scheme has a gain of approximately 1.1 dB at a BER of 10-4 over coded 8-QAM with rate ½.

CONCLUSION

A coded modulation scheme using the MQAM LDPC codes is presented for wireless communication systems. This approach is pragmatic but quite effective for bandwidth efficient transmission, because only one encoder and one decoder are employed and it does not require an interleaver. This is an advantage over other coded modulation schemes such as Turbo coded modulation for reducing the associated complexity. It is difficult to analytically evaluate LDPC-coded modulation schemes, so we investigated and discussed their performances via computer simulations. The results show that the performance of LDPC- coded M-QAM scheme with Gray mapping on the AWGN channel is close to the Shannon limit, when using the LDPC codes with a length of 2304 bits and a maximum of 30 decoding iterations. Furthermore, this coded system can also achieve excellent performance over the flat uncorrelated Rayleigh fading channel. The performance can also be improved using a larger maximum number of decoding iterations and longer LDPC codes.

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