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Quality Image Transmission through AWGN Channel using Polar Codes

Anurag Mishra, Kanchan Sharma and Asok De

***Abstract*— Polar coded grayscale image communication over additive white Gaussian noise (AWGN) channels using orthogonal frequency division multiplexing (OFDM) system is demonstrated in this paper. The OFDM technique is effective multicarrier technique used in the high-speed transmission system. Polar codes are recently applied to the binary memoryless channel and binary erasure channels for achieving near to Shannon channel capacity. However, besides these two channels, the analysis of polar codes over other channels is still open to scrutiny. The additive white Gaussian noise (AWGN) channel is evaluated by transmitting still images through M-ary QAM modulated OFDM system using polar codes. By comparing with the Bose – Chaudhuri – Hocquenghem (BCH) codes in the same scenario, our results suggest that polar codes have better performance than that of BCH codes. We introduce the polar coded adaptive modulation OFDM system in which the modulation order of QAM is selected in accordance with the channel conditions and channel BER upper threshold value. The result shows that better spectral bandwidth utilization can be achieved by adapting the order of modulation in the polar coded OFDM system. We also concatenate the BCH code with polar code in same scenario using fixed 64-QAM modulation scheme. The obtained results confirm improvement in the behavior of channel BER and visual quality of transmitted images for the entire range of channel Eb/No in comparison to use of polar codes. Overall, it is concluded that polar codes are a good selection for wireless image communication.**

***Index Terms*— Polar Codes, Image Communication, OFDM, Peak Signal to Noise Ratio (PSNR), Structural Similarity (SSIM) and Adaptive Modulation**

I. INTRODUCTION

THE requirement of internet services in daily life leads to increase in the demand of high speed communications, high capacity channel and high quality transmission of visual data such as images over the media. Typically, this data requires large storage space and wide bandwidth for transmission. In order to reduce the bandwidth requirement, image compression is performed. However, compressed images are more sensitive to errors in both wired and wireless transmission media. Moreover, imperfect transmission over wireless channel may increase the chance of error due to the signal attenuation, co-channel interferences [1], [2]. As a result the quality of transmitted image gets degraded. Forward error correction (FEC) techniques could be employed to reduce the effects of errors on the quality of the reconstructed image. However, these error correction schemes increase the redundant bits on the transmitted data resulting in loss in the bandwidth efficiency and low data transmission rate. The requirement of visual data protection to ensure reliable transmission against hostile channel conditions by using error correcting codes has become an important objective of research and several methods are proposed for this in literature. When the channel condition is good, data can be transmitted at a high rate with comparatively less amount of forward error correction which ensures a good visual quality of the received image. The orthogonal frequency division multiplexing (OFDM) is a popular multi-carrier transmission scheme which optimizes overall channel capacity and improves throughput. Various studies for the selection of code rate for image transmission depending upon the channel conditions have been performed and reported in the literature.

Hyung Suk Chu et. al. [3] proposed an image transmission system that consists of wavelet based compression and adaptive OFDM system. The compression algorithm searches for appropriate positions while the adaptive OFDM system allocates the modulation bit of each subcarrier according to the channel condition by using the channel estimation algorithm. They argue that the proposed image transmission system progressively transmits the input image and improves upon the PSNR performance as compared to a fixed modulation scheme. B. Barmada and E. V. Jones [4] have proposed an adaptive modulation method for a multicarrier system such as OFDM. In their work, the modulation mode is adapted in each sub-channel according to current channel conditions. They compute the performance of their system for the Gaussian channel which was extended to fading channels as well. Their results clearly show that the visual quality of transmitted image is maintained over a wide range of channel Eb/No by making use of adaptive system as compared to fixed modulation schemes. The transmission of copyright content in

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the form of watermarked images over AWGN wireless channel using OFDM technique has been successfully demonstrated by Sharma et. al. [5]. They have initially reported the use of a 256-PSK fixed modulation scheme for watermarked image transmission over AWGN channels using OFDM system. In the second part of their simulation, they compare the performance of the OFDM system for 16-PSK with 16-QAM modulation schemes for transmission of the same image. They further report the use of (7, 4) Hamming Error correcting codes for this transmission and conclude that 16-QAM is better placed as compared to 16-PSK and that the transmission is further improved upon by the use of error correcting code. Vinay Chande et. al. [6] discussed the optimal design of a joint source channel coding of compressed images using embedded source codes over memoryless bit error channels and packet erasure channels with no feedback. For this purpose, they consider three performance measures such as average distortion, average PSNR and average useful source coding rate. They show that unequal error / erasure protection policies that allow the useful source coding rate allow for progressive transmission of images with optimal unequal protection at a number of intermediate rates. V. S. Sanchez et. al. [7] analyzed the effect of bit errors on the JPEG2000 compressed code stream. Their work exploits the concept of the hierarchical structure of the code stream for the purpose of bit stream protection. The channel protection is achieved by means of a rate compatible punctured convolutional (RCPC) code. They argue that the performance of correct decoding and received image quality is improved by applying this technique. In another publication, V. Sanchez et. al. [8] discussed the channel protection method of concatenating a cyclic redundancy check (CRC) outer coder and an inner rate-compatible punctured convolutional (RCPC) coder for a JPEG2000 bit stream. They verify the robustness of this technique for different channel conditions in Rayleigh faded channel. They claim that it improves the quality of the received images. Hyun Cheol Kim et. al. [9] discussed the improvement in the performance of turbo code by concatenating the BCH outer code with turbo code. They argue that their concatenated BCH –Turbo code is superior to the original turbo code at moderate to high E_b / N_o.

Arikan [10] introduced a new code that achieves the capacity of a large class of channels by using the concept of channel polarization, hence named as polar codes. These codes have the advantage of reducing the complexity involved in the encoding and the decoding operation of binary data i.e., O(Nlog2N), where N is the blocklength of code. Polar code polarizes the transmission channel into two sub-channels viz., the noisy channel (or bad channel) and the noiseless channel (or good channel). The information is transmitted over the noiseless channel while the bad channel is frozen simultaneously. These codes are very effective for source coding and channel coding [11]-[13], relay channels [14] and wiretap channels [15]. Recently, S. Zhao et. al. [16] effectively enhanced quality of speech communication application using polar codes. Hessam Madasavifar et. al. [17] presented the fact that Arikan polar code frame error probability gets reduced when it is used in concatenation of Reed Solomon (RS) code.

In this paper, we focus on investigating the performance of polar codes for the grayscale image transmission using the 64-QAM OFDM system over a continuous AWGN communication channel. To the best of our information, the performance of polar codes over this channel has not been investigated so far for image transmission. By comparing the transmission of images using BCH codes with that using polar code, we observe that more channel capacity is achieved in the case of the latter. We further choose polar codes as a channel code in OFDM system and investigate the benefits of adapting the modulation order of QAM by keeping a fixed upper threshold of channel BER and fixing the bounds of channel E_b/N_o. In this case, we observe that by making use of the adaptive modulation scheme, the performance in terms of smaller error and better spectral efficiency is improved.

The paper is organized as follows. In Section II, we briefly review Polar codes, BCH codes and OFDM system. Section III describes the system parameters used for image transmission in the present work. Section IV presents experimental results and their discussion. Section V gives a conclusion followed by the list of references.

II. BACKGROUND

A. Polar Codes and their construction

The basic idea of polar coding is to transmit the information bits over a capacity approaching channel and at the same instant of time, the predetermined bits are transmitted over the channel whose capacity approaches to zero. These predetermined bits are essentially needed at the decoding stage.

Let us define a binary discrete memoryless channel (B-DMC) as W and its mutual information as I (W) which gives its symmetric capacity by assuming equiprobable binary input symbols. Let m denote the input message or bit vector $(m_1, m_2, ..., m_N)$ and C denote the codeword vector $(C_1, C_2, ..., C_N)$. For any subset $T \subseteq \{1,2,3,..N\}$ let $m_T = \left(m_{i_1}, m_{i_2}, ..., m_{i_{|T|}}\right)$, where $i_u \in T$ and $i_u \le i_{u+1}$. The polar encoded output of length N can be obtained by multiplying the input message vector m of length N with the generator matrix G_N in the binary Galois field GF(2)[10]. The generator matrix is given in Eqn. 1:

$$G_N = \begin{bmatrix} G_{N/2} & 0 \\ G_{N/2} & G_{N/2} \end{bmatrix}, N \ge 2 \ \& \ G_1 = [1] \qquad (1)$$

The obtained coded output C= (m).(G_N) is transmitted over the B-DMC (W). Each source symbol (mi) can be transmitted independently over own channel $W_N^{(i)}$. Each channel output depends on the set of messages m_0, m_1, m_2… m_{i-1}, where i represent the bit reverse order coefficient of message vector (m). The bit channel having highest capacity is used for message transmission and rest bit channels are used for fixed value data transmission. The determination that the channel is good or bad is done by computing the Bhattacharyya parameter Z(W) of channel W and is given by Eqn. 2:

$$Z(W)=\sum_{y}\sqrt{W(y|0)W(y|1)} \quad (2)$$

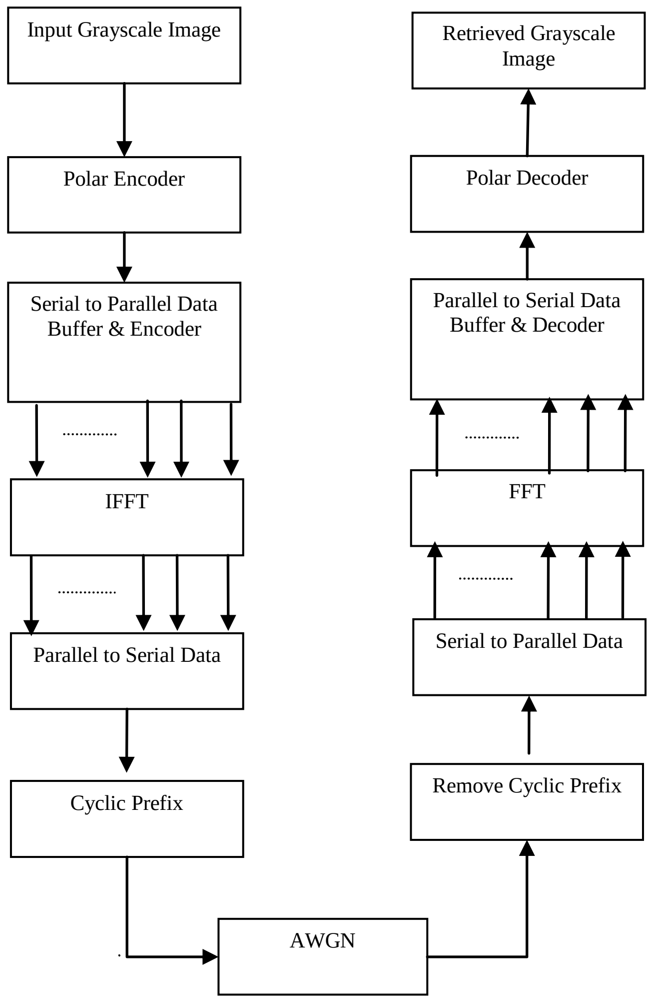

Fig. 1: Block diagram of grayscale image communication using a polar coded OFDM system

The recursive formula used for determining the Bhattacharyya parameter Z(W) is given by Eqn. 3:

$$\begin{aligned} Z(W_{2N}^{(2i-1)}) &= 2Z(W_{2N}^{(i)}) - [Z(W_{2N}^{(i)})]^2 \\ Z(W_{2N}^{(2i)}) &= [Z(W_{2N}^{(i)})]^2 \end{aligned} ,i=1,2,3,\ldots,N \quad (3)$$

With large block length N, the capacity of each channel $W_N^{(i)}$ becomes almost equal to one or zero. Thus, in designing the polar code of rate $R = K/N$, where K is the information size and N is the code length, we fix (1-R) indices of m to 0. The codeword is obtained as C=(m).(G_N), where $m_{T^c} = 0$ and $m_T \in \{0,1\}^{|T|}$. We use the successive cancellation algorithm for decoding the polar code. The probability of error for polar code in any arbitrary B-DMC is proved to be $P_e \le \sum_{I\in T} Z(W_N^{(I)})$.

B. BCH Codes and their construction

Bose – Chaudhuri – Hocquenghem (BCH) codes were first developed by A. Hocquenghem [18] in 1959 and independently by R. C. Bose and D. K. Ray-Chaudhuri [19] in 1960. BCH coding is an error correcting coding technique which belongs to the class of linear block cyclic codes. These codes are multiple errors correcting code. These are widely used in technologies such as satellite communication, mobile phones, digital TV and devices such as CD-ROM, DVD-ROM etc. For any integer $m \ge 3$ and $t_{BCH} < 2^m - 1$, a primitive BCH code can have the following parameters:

Table 1: OFDM System Parameters

FFT/IFFT SIZE	64
No of Data sub-carriers	52
Number of symbols	4000
Cyclic prefix	16
Modulation	64-QAM
Channel codes	1 BCH error correcting codes 2. Polar code(1/2) code rate 3. BCH as inner code and Polar code(1/2) as outer code
Input data	1. Grayscale Lena of size 512*512 2. Grayscale Cameraman of size 512*512 3. Grayscale Baboon of size 512*512

$$n_{BCH}=2^m-1, \quad n_{BCH}-k_{BCH} \le m t_{BCH}, \text{ and } d_{min} \ge 2t_{BCH}+1 \quad (4)$$

These parameters imply that a BCH code can have the random error correction capability equal to t_{BCH} or less than t_{BCH} over a span of $2^m - 1$ bit positions. The BCH coding involves five steps: (1) construction of generator polynomial, (2) encoding, (3) error detection, (4) syndrome computation and (5) error correction using error location polynomial.

C. Orthogonal Frequency Division Multiplexing

The OFDM is a recent technology used in the broadband communication like IEEE 802.11 wireless local area networks (WLANs) and IEEE 802.16 broadband fixed wireless access networks in a wireless multipath environment. The basic principle of OFDM is to split a higher rate data stream into a number of lower rate data streams which are transmitted simultaneously over a number of sub- carriers. The dispersion in time caused by the multipath delay spread is decreased relatively due to the increase of the symbol duration for lower rate parallel sub-carriers. Intersymbol interference (ISI) is completely eliminated by the addition of the guard time in every OFDM symbol [20]. Fig. 1 depicts the block diagram of the OFDM system used to transmit a polar coded gray scale image over AWGN channel. The OFDM system parameters used in this simulation are mentioned in Table 1.

III. System Description

Fig. 2 depicts the sequence of events used in the present work to transmit three different gray scale images of size 512*512 over AWGN channel. These images are Lena, Baboon and Cameraman and are depicted in Figs. 3-5 respectively. The OFDM system parameters used in this simulation are tabulated in Table 1. These images are firstly encoded using two different error correcting coding schemes viz., polar codes and BCH codes independently, pass through an OFDM modulator block and then transmitted over the said AWGN channel. Table 2 comprises of the error correcting code parameters used in the present work to encode the said images.

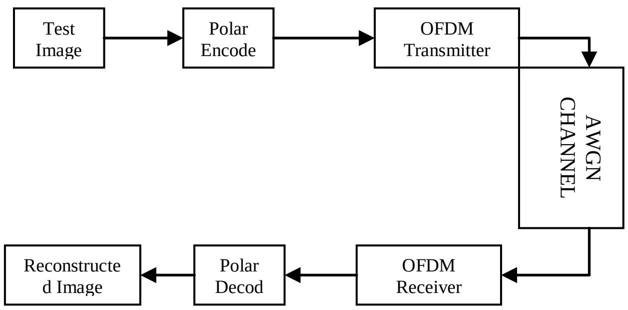

Fig. 2: Block diagram of system description

Table 2: Error correcting codes parameters

BCH code	POLAR code
(255, 247)	(512, 1024)
(255, 207)	(256, 512)

These images are then received and pass through an OFDM demodulator block before being decoded by using respective decoder. The decoded images are shown in Figs. 6-8 respectively. The transmitted images are examined for their visual quality by using two different image quality assessment metrics-peak signal to noise ratio (PSNR) and structural similarity (SSIM). PSNR is a metric which compares the luminance value of respective pixel coefficients of test and reference images and amplifies the difference between the two. The difference is computed and used as an assessment of image quality. The PSNR is not perceived as a metric which behaves according to human visual system [21]. Therefore, another metric commonly known as SSIM and is based on structural vector components of the image is also used. In this manner, the visual quality of the received image is also taken into account. This is done to investigate the image transmission in a more meaningful manner. The PSNR and SSIM are given by Eqn. 5 and Eqn. 6 respectively.

$$\mathrm{PSNR}(I,\bar{I}) = 10\times\log_{10}\frac{255^2}{\mathrm{MSE}(I,\bar{I})}(\mathrm{dB}), \quad (5)$$

$$\mathrm{SSIM}(I,\bar{I}) = \frac{(2\mu_I\mu_{\bar{I}}+c_1)(2\sigma_{I\bar{I}}+c_2)}{(\mu_I^2+\mu_{\bar{I}}^2+c_1)(\sigma_I^2+\sigma_{\bar{I}}^2+c_2)} \quad (6)$$

Where I is the grayscale value of the original image, $\bar{I}$ is the reconstructed grayscale image at the receiver, μ_I is the average of I, $\mu_{\bar{I}}$ is the average of $\bar{I}$, σ_I^2 is the variance of I, $\sigma_{\bar{I}}^2$ is the variance of $\bar{I}$, $\sigma_{I\bar{I}}$ is the covariance of I and $\bar{I}$, $c_1 = (k_1L)^2$, $c_2 = (k_2L)^2$, L is the dynamic range of pixel values, $k_1=0.01$ and $k_2=0.03$. These parameters are optimized by Zhou Wang & Alan Conrad Bovik [22].

IV. Experimental Results and Discussion

Fig. 3 – Fig. 5 depict original images Lena, Baboon and Cameraman each of size 512*512. However in order to adjust these within the manuscript, the size is reduced to half. Figs. 6-8 depict the respective reconstructed images at an E_b/N_o = 13 dB.

Fig. 3: Original grayscale image Lena

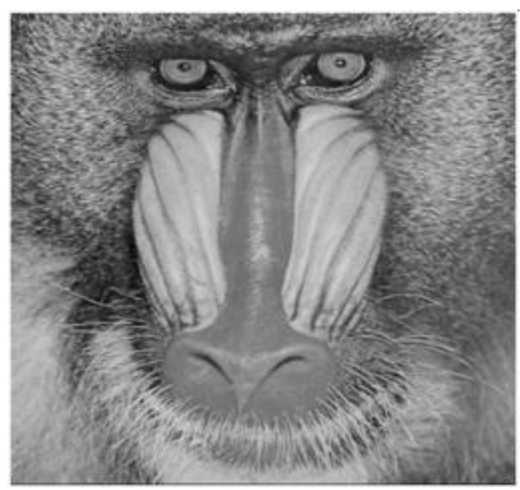

Fig. 4: Original grayscale image Baboon

The channel BER, PSNR and SSIM values of reconstructed images are tabulated in Table 3 and Table 4 respectively. We observe that for all these images, the low channel BER is achieved at lower E_b/N_o. Moreover, both PSNR and SSIM are the best for Baboon image. Another significant observation is that at channel E_b/N_o = 13 dB, (512, 1024) polar code produces the best results among all four combinations selected in this work. This is due to the fact that as we increase the block size, the probability of error between transmitted and reconstructed image data decreases, thereby giving better quality of reconstructed images.

Although, we have carried out our simulation for three different grayscale images, the plots of PSNR vs E_b/N_o, SSIM vs E_b/N_o, and channel BER vs E_b/N_o are shown in the case of Baboon image in this paper. This is because the results obtained in the case of Baboon are the best. We observe that the behavior of the respective plots for all three images is identical. Note that the performance of polar codes improves more greatly than that of BCH codes with the increase in code length. Fig. 9 shows the plot of channel BER vs E_b/N_o for the ascending size of blocklength of polar codes. In this case, higher the size of the polar cold, the lower is the channel BER achieved at low E_b/N_o compared to the smaller size of the polar code. In case of BCH codes, the number of parity bits is more in (255, 207) as compared to (255, 247) which means that as the error correcting capability is more for (255, 207) code combination, a lower channel BER is achieved at a lower E_b/N_o. Fig. 10-11 respectively show plots of PSNR vs E_b/N_o and SSIM vs E_b/N_o computed under the same scenario. These figures depict that as we increase the blocklength of polar code, we achieve higher PSNR and SSIM at relatively lower E_b/N_o which agrees with the result achieved for channel BER.

Channel E_b/N_o = 13 dB PSNR = 56.6816 dB

Fig. 5: Original grayscale image Cameraman

Channel E_b/N_o = 13 dB PSNR = 56.6816 dB

Fig. 6: Reconstructed grayscale image Lena

Channel E_b/N_o = 13 dB PSNR = 60.4727 dB

Fig. 7: Reconstructed grayscale image Baboon

Channel E_b/N_o = 13 dB PSNR = 44.7075 dB

Fig. 8: Reconstructed grayscale image Cameraman

Table 3: Channel BER, PSNR, SSIM for Lena, Baboon, and Cameraman w. r. t Channel E_b/N_o in Polar coded OFDM system
(256, 512) Polar code

E_b/N_o (dB)	LENA			BABOON			CAMERAMAN		
	Channel BER	**PSNR**	**SSIM**	**Channel BER**	**PSNR**	**SSIM**	**Channel BER**	**PSNR**	**SSIM**
5	0.47623	9.4938	0.0137	0.475296	9.6715	0.0191	0.47554	8.6462	0.0134
6	0.468222	9.5651	0.0143	0.466714	9.7363	0.0247	0.466934	8.7092	0.0137
7	0.453562	9.7184	0.0164	0.448919	9.8821	0.033	0.45189	8.8827	0.0157
8	0.423192	10.0316	0.0218	0.406601	10.3002	0.0575	0.422732	9.2505	0.0209
9	0.356036	10.8319	0.0364	0.316073	11.5474	0.1245	0.360064	10.0457	0.0352
10	0.241045	12.5879	0.0735	0.189558	14.3739	0.2907	0.247341	12.0194	0.0782
11	0.105222	16.6659	0.2278	0.075108	20.2497	0.6657	0.115345	15.3578	0.1987
12	0.026006	22.7663	0.6327	0.019398	28.2095	0.9387	0.030129	21.7232	0.5923
13	0.003442	32.266	0.9439	0.002629	37.6612	0.9922	0.004335	29.4748	0.9188
14	0.000381	49.1617	0.9986	0.000156	58.2099	0.9998	0.000399	41.4058	0.9927
15	2.53E-05	72.5298	1	7.1526E-06	90.5553	1	0	Inf	1
16	0	Inf	1	0	Inf	1	0	Inf	1
17	0	Inf	1	0	Inf	1	0	Inf	1
18	0	Inf	1	0	Inf	1	0	Inf	1
19	0	Inf	1	0	Inf	1	0	Inf	1
20	0	Inf	1	0	Inf	1	0	Inf	1

(512, 1024) Polar code

E_b/N_o (dB)	LENA			BABOON			CAMERAMAN		
	Channel BER	PSNR	SSIM	Channel BER	PSNR	SSIM	Channel BER	PSNR	SSIM
5	0.4814	9.432	0.0124	0.4813	9.63	0.0156	0.4817	8.559	0.0114
6	0.4778	9.449	0.0130	0.4770	9.66	0.0184	0.4772	8.593	0.0131
7	0.4714	9.497	0.0130	0.4706	9.70	0.0192	0.4717	8.627	0.0127
8	0.4609	9.599	0.0149	0.4579	9.78	0.0257	0.4593	8.744	0.0152
9	0.4292	10.13	0.0244	0.3952	10.42	0.0611	0.4228	9.240	0.0214
10	0.3191	11.78	0.0578	0.2501	13.30	0.2177	0.3238	10.87	0.054
11	0.1263	17.19	0.26	0.0933	22.26	0.76	0.1369	15.83	0.22
12	0.0176	31.74	0.90	0.0133	36.26	0.99	0.0196	26.61	0.82
13	5E-4	56.68	0.99	0.0005	60.47	0.99	0.0007	44.70	0.99
14	0	Inf	1	0	Inf	1	0	Inf	1
15	0	Inf	1	0	Inf	1	0	Inf	1
16	0	Inf	1	0	Inf	1	0	Inf	1
17	0	Inf	1	0	Inf	1	0	Inf	1
18	0	Inf	1	0	Inf	1	0	Inf	1
19	0	Inf	1	0	Inf	1	0	Inf	1
20	0	Inf	1	0	Inf	1	0	Inf	1

Table 4: Channel BER, PSNR, SSIM of Lena, Baboon, and Cameraman w. r. t Channel E_b/N_o in BCH coded OFDM system

(255, 207) BCH code

E_b/N_o (dB)	LENA			BABOON			CAMERAMAN		
	Channel BER	PSNR	SSIM	Channel BER	PSNR	SSIM	Channel BER	PSNR	SSIM
5	0.107718	14.6374	0.114	0.104621	14.9138	0.2902	0.10778	14.4128	0.1272
6	0.091261	15.3049	0.1307	0.087698	15.6166	0.3286	0.091792	15.0271	0.1411
7	0.074899	16.0988	0.155	0.071632	16.4505	0.3739	0.076118	15.7727	0.1607
8	0.06011	16.9509	0.1845	0.056321	17.4125	0.4255	0.060872	16.5279	0.1852
9	0.045096	18.0411	0.2267	0.040479	18.7674	0.5028	0.046364	17.6331	0.2251
10	0.028646	19.6243	0.3061	0.023175	20.9698	0.6268	0.030453	18.9732	0.2881
11	0.012895	22.5055	0.4828	0.008072	25.8152	0.8377	0.01501	21.3569	0.428
12	0.003946	27.8827	0.7828	0.001966	33.5407	0.9686	0.004954	25.773	0.6986
13	0.000898	37.812	0.9732	0.000619	46.8132	0.9982	0.001057	32.956	0.933
14	0.000119	52.3244	0.9987	0.000141	78.5687	1	0.000153	50.3238	0.9981
15	1.19E-05	87.6922	1	1.05E-05	90.5553	1	1.29E-05	87.6922	1
16	0	Inf	1	0	Inf	1	0	Inf	1
17	0	Inf	1	0	Inf	1	0	Inf	1
18	0	Inf	1	0	Inf	1	0	Inf	1
19	0	Inf	1	0	Inf	1	0	Inf	1
20	0	Inf	1	0	Inf	1	0	Inf	1

(255, 247) BCH code

E_b/N_o (dB)	LENA			BABOON			CAMERAMAN		
	Channel BER	PSNR	SSIM	Channel BER	PSNR	SSIM	Channel BER	PSNR	SSIM
5	0.117663	14.5194	0.1124	0.114343	14.7733	0.2846	0.117357	14.1746	0.1232
6	0.100765	15.1969	0.1288	0.097666	15.4308	0.3179	0.100786	14.8157	0.1371
7	0.084847	15.8680	0.1479	0.081133	16.2683	0.3650	0.085052	15.5139	0.1557
8	0.069838	16.6684	0.1741	0.065419	17.1423	0.4130	0.070475	16.3454	0.1804
9	0.055277	17.6498	0.2100	0.051124	18.2701	0.4751	0.056457	17.2860	0.2110
10	0.042223	18.8353	0.2634	0.03814	19.4592	0.5417	0.043124	18.3840	0.2539
11	0.030703	20.1431	0.3303	0.026989	21.1816	0.6358	0.031951	19.7080	0.3158
12	0.020893	21.7811	0.4323	0.017732	23.1187	0.7297	0.021883	21.3544	0.4074
13	0.012492	24.1043	0.5784	0.009508	26.063	0.8415	0.013402	23.3404	0.5286
14	0.005417	27.7687	0.7704	0.003775	30.6564	0.9377	0.006454	26.4511	0.7078
15	0.00162	32.6612	0.9152	0.000854	36.9281	0.9870	0.002063	30.9302	0.8836
16	0.000275	40.4969	0.9855	0.000113	47.7993	0.9984	0.000381	38.3086	0.9782
17	2.19E-05	48.7427	0.9985	1.1E-05	66.7315	1	4.82E-05	47.1876	0.9979
18	2.38E-06	55.4008	0.9996	1.43E-06	97.545	1	2.86E-06	61.1581	0.9997
19	0	Inf	1	0	Inf	1	0	Inf	1
20	0	Inf	1	0	Inf	1	0	Inf	1

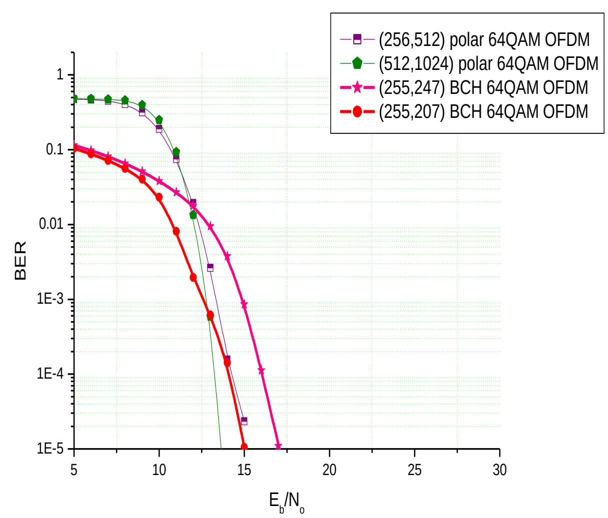

Fig. 9. Plot of computed channel BER vs. channel E_b/N_o for Baboon

We use (255, 247) and (255, 207) BCH codes as channel codes and compute channel BER, SSIM and PSNR of reconstructed image w.r.t channel E_b/N_o. These plots are also shown in Figs. 9 -11 respectively. These comprehensive plots clearly indicate that the performance metrics in 1024 blocklength polar coded OFDM system are better placed than their respective BCH counterparts in terms of achieving similar result at a lower channel E_b/N_o. S. Zhao et. al. [16] discussed the application of polar codes for speech communication and they compare its performance with LDPC codes. Their simulation results show that the polar codes have better performance with lower code rate and longer code length in case of AWGN and Rayleigh fading channels. It is clear from the aforementioned discussion that polar codes are superior to BCH codes for image transmission. We, therefore, next perform the M-ary QAM modulation using (512, 1024) polar coded OFDM system in the second part of this simulation.

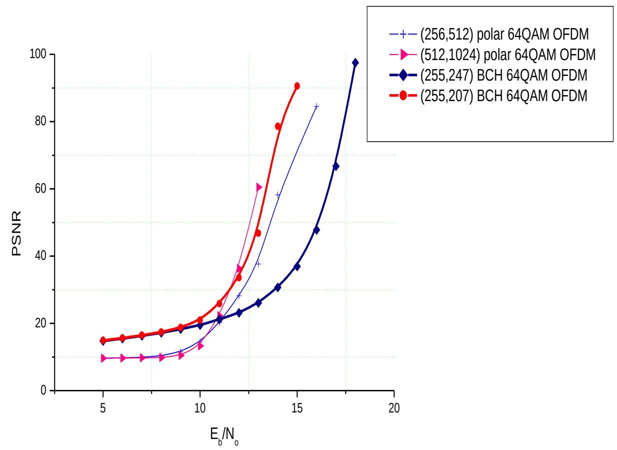

Fig. 10: Plot of computed PSNR vs. channel E_b/N_o for Baboon

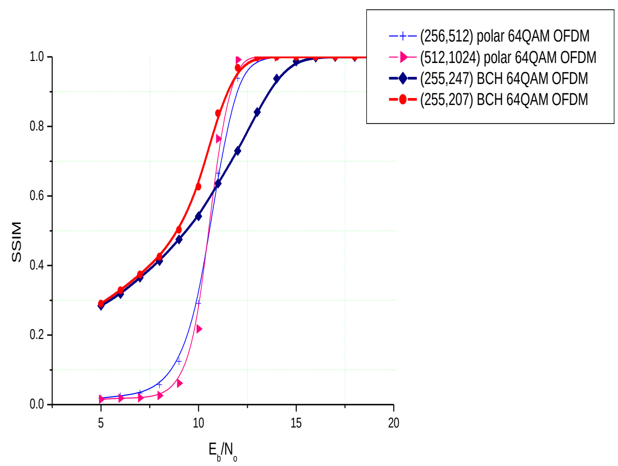

Fig. 11: Plot of computed SSIM vs. channel E_b/N_o for Baboon

In this case, the modulation order of QAM is made adaptive according to the bounds of the estimated channel E_b/N_o and channel BER upper threshold value. We assume that the modulation order is switched so as to obtain a maximum threshold of channel BER=10^{-3}. Reddy et. al. [23] implemented an adaptive modulation scheme so that the transmitter continuously monitors the dynamic channel and adjusts the transmitter parameters namely - modulation order, coding rate etc. Accordingly, they propose a blind modulation detection scheme based on this adaptive switching. They claim that their blind modulation detection scheme based on adaptive switching outperforms similar previously proposed algorithms. Rimas A Zrae [24] implemented an adaptive modulation scheme for grayscale Lena image transmission over Rayleigh wireless fading channels. They choose an upper threshold for channel BER=10^{-3} which is based on E_b/N_o level as seen by the receiver and sensitivity of the transmitted bit stream. Their channel E_b/N_o cutoff values lie in the range of 24 – 30 dB. In this paper, the authors report that in the case of adaptive scheme the visual quality of the JPEG 2000 image transmitted over Rayleigh faded channel is observed to be

Table 5: E_b/N_o and QAM modulation order for Baboon in adaptive Polar coded OFDM system

Channel E_b/N_o BOUNDS (dB)	MODULATION ORDER
5 dB ≤ E_b/N_o <9 dB	3(8-QAM)
9 dB ≤ E_b/N_o <10 dB	4(16-QAM)
10 dB ≤ E_b/N_o <13 dB	5(32-QAM)
13 dB ≤ E_b/N_o <15 dB	6(64-QAM)
15 dB ≤ E_b/N_o <18 dB	7(128-QAM)
E_b/N_o >19dB	8(256-QAM)

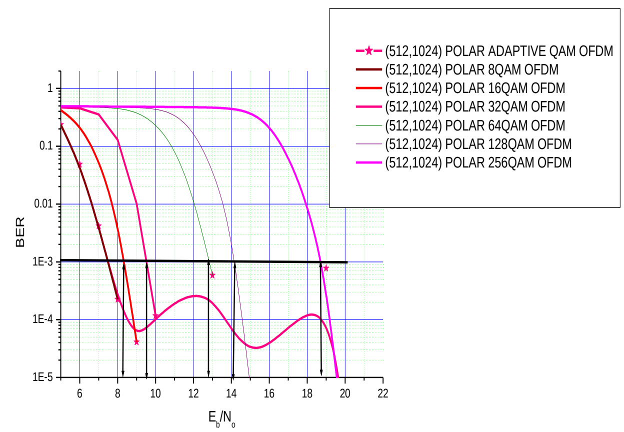

Fig. 12: Plot of computed channel BER vs. channel E_b/N_o in adaptive modulation for Baboon

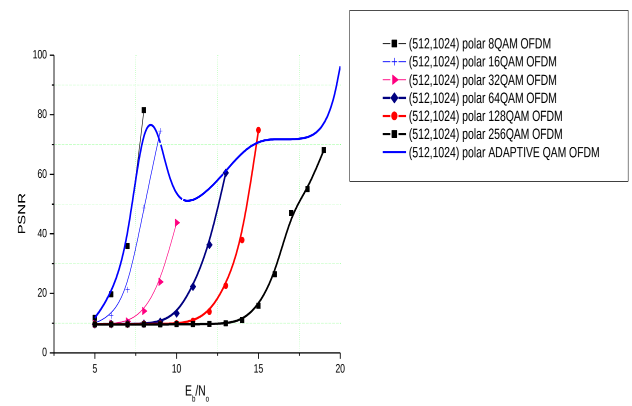

Fig. 13: Plot of computed PSNR vs. channel E_b/N_o in adaptive modulation for Baboon

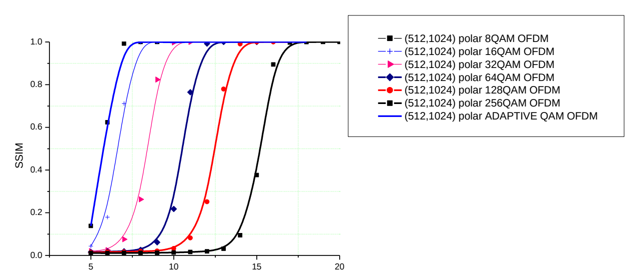

Fig. 14. Plot of computed SSIM vs. channel E_b/N_o in adaptive modulation for Baboon

slightly inferior than that they obtain for BPSK modulation scheme. They argue that the marginal decrease in PSNR (~2.6 dB) does not degrade the visual quality of transmitted image much, yet they achieve a considerable increase in spectral efficiency for their adaptive modulation scheme. Fig. 12 shows estimated channel E_b/N_o thresholds to adaptively carry out the transmission of the grayscale Baboon image. In this case, different modulation orders (ranging from 3 to 8) are chosen based on estimated channel E_b/N_o at the transmitter to obtain a maximum threshold of channel BER = 10^{-3}. The lower and upper bounds of estimated channel E_b/N_o are tabulated in Table 5 and different modulation schemes are selected for different E_b/N_o bounds. This ensures adaptive switching on the basis of E_b/N_o values. Fig. 12 also depicts the best fit curve for adaptively switched transmission of Baboon image. Note that in the entire range of channel E_b/N_o (8 – 20 dB), the channel BER is always less than the upper threshold value. This makes the transmission of Baboon image spectrally efficient. Combining this result with the ones shown in Figs. 13-14, it is quite clear that this spectral efficiency is achieved without compromising the perceptible quality of the transmitted image. The average PSNR obtained is always greater than 50 dB (Fig. 13) while Fig. 14 shows that the SSIM index is maintained at 1.0 within the given E_b/N_o range (8–20 dB). Fig. 15 depicts a plot of channel BER vs channel E_b/N_o only for two modulation orders viz., 8-QAM and 64-QAM. This is specifically shown to differentiate between image transmissions for these modulation orders. As in both these cases the channel BER is less than the upper threshold value, the switching is quite permissible depending upon our selection of low channel E_b/N_o along with a lower modulation order or vice versa. In view of this, adaptive transmission of an image is always advisable provided it maintains the visual quality of the transmitted / received image.

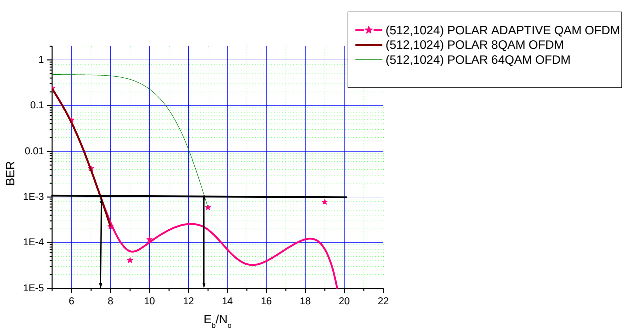

Fig. 15: Plot of computed channel BER vs. channel E_b/N_o in adaptive modulation for Baboon

It is clear from Fig. 13 – Fig. 14 that at channel E_b/N_o = 8 dB and 13 dB, the PSNR and SSIM are well above the minimum required (PSNR = 40 dB and SSIM = 0.9). We also achieve similar results for adaptive transmission of two other images-Lena and Cameraman.

Thus, it is concluded that the adaptive transmission of Baboon image gives more flexibility in terms of selection of QAM order and visual quality of the transmitted image by using polar codes. Therefore, this scheme is a better choice over fixed modulation scheme as both the transmission rate and visual quality of transmitted image are optimized. In this case, it is possible to have good visual quality at a lower transmission rate. On the other hand, the transmission rate can be increased at the cost of visual quality but not allowing it to fall below a certain threshold (PSNR = 40 dB). This result is similar to the one reported by Rimas A. Zrae et. al. [24]. We, in our simulation, achieve a better spectral efficiency (128-QAM and 256-QAM) without compromising the visual quality of the transmitted image (>40 dB in all cases). This is due to the threshold value of channel BER =10^{-3} which ensures that if BER goes below this threshold value for a specific QAM order, the adaptive modulation scheme switches to the next QAM order thereby improving the visual quality of transmitted image as well.

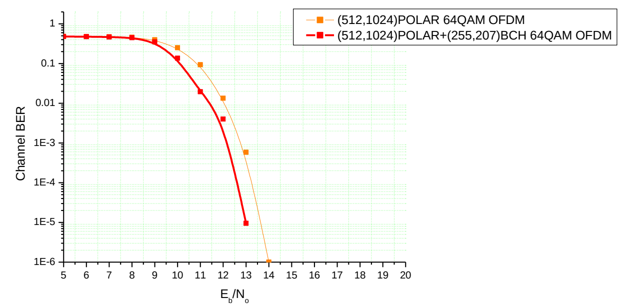

Fig. 16: Plot of channel BER vs. channel E_b/N_o for concatenated BCH - Polar codes

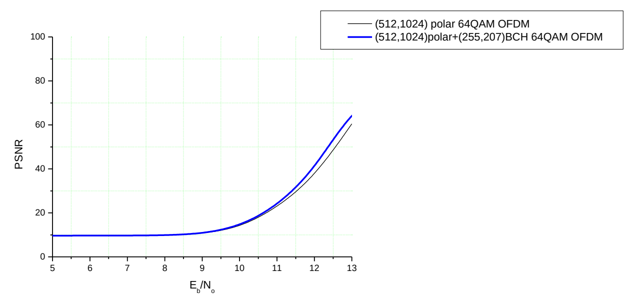

Fig. 17. Plot of PSNR vs. channel E_b/N_o for concatenated BCH - Polar codes

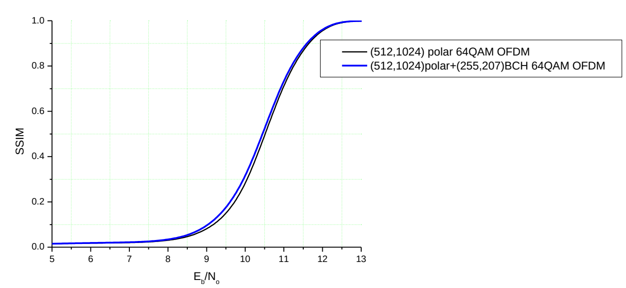

Fig. 18: Plot of SSIM vs. channel E_b/N_o for concatenated BCH - Polar codes

In the third and the last part of this simulation work, we use a hybrid code scheme by concatenating polar and BCH codes. For this purpose, the (255, 207) BCH code is used as an outer code and (512, 1024) polar code is used as an inner code in the same scenario described above in section III. At channel E_b/N_o = 13 dB, the fixed 64-QAM polar coded OFDM transmission yields a channel BER =5.83649x10^{-4} (Table 3) with PSNR and SSIM being 60.4727 dB and 0.9988 respectively. For the concatenated scheme, we obtain channel BER = 9.53674x10^{-6}, PSNR = 67.2579 dB and SSIM = 1.0 @ channel E_b/N_o = 13 dB. These values are plotted in Figs. 16 - 18 respectively.

Note that the concatenated scheme slightly improves upon the channel BER, PSNR and SSIM as compared to the fixed modulation scheme. Hessam Mahdavifar et. al. [17] has used polar codes in conjunction with Reed Solomon (RS) codes to transmit binary data over the binary memoryless channel. They present the asymptotic analysis of the error correction performance and stated that the concatenation scheme improves upon the error decay rate as compared to polar code of the same length. Hyun Cheol Kim et. al. [9] have shown that their concatenation scheme made by single error correcting BCH outer code and turbo inner codes reduces the errors dramatically at moderate to high E_b/N_o where E_b and N_o are energy per bit and noise power spectral density respectively. They argue that their concatenated BCH –Turbo code is superior to the original turbo code at moderate to high E_b/N_o. Their proposed scheme shows a performance improvement of 0.75 dB at BER = 10^{-6}. They also report that their frame error rate (FER) performance is improved by 1.00 dB as a result of concatenation. We are yet to find a paper which implements polar codes concatenated with BCH code as an outer code to transmit data of any kind. However, we observe that in our experiment, the channel BER, PSNR and SSIM are all improved after concatenation as compared to polar codes used in the same scenario.

V. Conclusion

In this paper we successfully demonstrated the transmission of polar coded grayscale images over AWGN channels using OFDM modulation scheme. The AWGN channel is evaluated by transmitting still images through the 64-QAM modulated OFDM system using polar codes. The comparison of polar codes with BCH codes is performed in the same scenario. The investigated results shows that the performance of the polar codes is superior to the performance of BCH codes in terms of visual quality of received images and the bit error probability. The framework clearly demonstrates the polar coded adaptive modulation OFDM system for which the modulation order of QAM is switched in accordance with the channel conditions and channel BER upper threshold, we observed the better spectral bandwidth utilization over the entire range of channel E_b/N_o unlike an OFDM system using fixed modulation order. The concatenation of BCH code with polar codes is further improved the quality and BER performance for the transmission carried out for fixed 64 QAM modulation scheme. It is concluded that comparatively the polar codes are a good selection for wireless image communication.

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