Performance analysis of LDPC codes in MIMO-OFDM for next generation wireless systems

P. Aruna Kumari[1], Srinu Pyla[1], U. N. V. P. Rajendranath[1], Nirujogi Venkata Maheswara Rao[2]
[1]Department of Electronics and Communication Engineering, Gayatri Vidya Parishad College of Engineering (Autonomous), Visakhapatnam, India
[2]Department of Electronics and Communication Engineering, Gayatri Vidya Parishad College of Engineering for Women (Autonomous), Visakhapatnam, India

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ABSTRACT

Fifth Generation communication systems overcome the limitations of the fourth-generation systems and ensure improved data rates, lower latency, and higher connection density. 5G technology has the potential to unlock new internet of things (IoT) applications by utilizing the technologies such as multiple input multiple output orthogonal frequency division multiplexing (MIMO-OFDM), and Li-Fi. Low density parity check (LDPC) and polar codes are being preferred for data and control channels respectively in 5G systems as these coding techniques offer good error-detection and correction along with reduced latency. Morever, LDPC codes are power efficient. This paper aims to analyze the bit error rate (BER) performance of LDPC codes in MIMO-OFDM System for different modulation schemes. LDPC codes improve the BER performance of OFDM and MIMO-OFDM systems. MIMO-OFDM systems deliver better BER performance over OFDM system.

Corresponding Author:

Srinu Pyla
Department of Electronics and Communication Engineering
Gayatri Vidya Parishad College of Engineering (Autonomous)
Visakhapatnam, Andhra Pradesh 530048, India
Email: srinupyla@gvpce.ac.in

1. INTRODUCTION

Significance of digital communication has been increasing in the fields of cellular, satellite, wireless and network communication. Based on the noise level and interference, errors are occurred at the receiver and these errors can be controlled by using proper channel coding techniques. In 4G systems, turbo codes are used whereas in 5G systems, low density parity check (LDPC) and Polar codes are being preferred [1], [2].

The data rates of 2G general packet radio service (GPRS), and 2.5G enhanced data rate for GSM evolution (EDGE) systems are 40 kbps and 384 kbps respectively. The third generation (3G) systems were developed in 2000's with increased internet speeds and transmission rates. In addition, multitasking and video calling features are also provided in 3G systems.

The fourth generation (4G) technology offered greater efficiency and increased wireless internet access to the users. Orthogonal frequency division multiplexing (OFDM) [3] supports higher transmission rate and eliminates intersymbol interference (ISI). In addition, it mitigates the multipath fading. As a result, it becomes strong candidate for LTE and advanced LTE systems. The advancements in telecommunication offer machine to humans and machine to machine communication [4]. In addition, 4G systems use multi antenna systems for better reliability and enhanced transmission rates. 5G wireless networks focus on improving the quality of service, data rate, latency, and security in transmission [5]. The key parameters in

5G networks are low latency, large number of connections, and improved data transmission rates [6]. 5G uses spatial multiplexing, multiple-input-multiple-output (MIMO) techniques [7] to meet the requirements of contemporary communication systems by utilizing millimeter wave technology. Forward error correction (FEC) plays a vital role in networking to ensure fast and reliable communication. 5G communication systems use LDPC and polar codes for data and control channels respectively.

Channel coding is one of the techniques used to improve the Shannon channel capacity [8]. Several codes have been implemented for different applications [9]. The selection of the channel coding depends on the probability of the error correction during transmission. Channel coding offers: i) energy efficiency, which is a fundamental requirement for mobile application as they are powered by batteries and ii) less latency by avoiding retransmissions for reliable communication through an effective channel coding system. Turbo codes which are introduced in 1993 have good burst error detection and correction capabilities. Turbo codes nearly approach the Shannon channel capacity [10]. Because of iteration process in the turbo decoder, its latency is more, but the latency of 5G and beyond systems should be very small.

As LDPC codes have less latency and good correction capability, these codes are preferred in 5G and beyond communication systems. LDPC encoding is the essential data transmission technique that is suitable for correcting errors in large block sizes [11]-[14]. The parity-check matrix in LDPC encoding should have less number of 1s in comparison with the number of 0s. The functionality of LDPC encoding and decoding is discussed in detailed in the succeeding section. As the number of wireless applications as well as users is increasing continuously, the demand for high data rate transmission is also increasing. However, high data rate transmission in wireless systems leads to ISI along with multipath fading. Proper design of an OFDM system [15] mitigates both ISI and multipath fading.

In single antenna systems, the bandwidth is not sufficient to accommodate all the wireless applications and users. Hence, multi antenna systems such as MIMO systems [16] have been developed to improve reliability and transmission rate of the communication system. Hence, the combination of OFDM and MIMO that is MIMO-OFDM [17]-[19] meets the requirements of advanced wireless communication systems. Alamouti [20] introduced space-time code (STC) for multiple antennas at transmitter and single antenna receiver (1x2 MISO) system. Multiple antenna systems improve diversity gain and transmission rate. In [21]-[24] describe orthogonal space time block codes for more than two antennas to achieve maximum diversity. In this paper, section 1 covers the introduction. In section 2 describes the modelling of LDPC encoding and decoding. In section 3 deals with results and discussion of LDPC codes in OFDM and MIMO-OFDM systems. Finally, the paper is concluded in section 4.

2. SYSTEM MODEL AND IMPLEMENTATION

The LDPC encoded MIMO-OFDM system is shown in Figure 1. From Figure 1, binary data is encoded using LDPC encoder and the encoded data is modulated using PSK/QAM. The modulated data is given to the STBC encoder and each stream is applied to IFFT. Cyclic prefix (CP) is appended to the tail of the OFDM symbol. Here, the length of the CP should be slightly larger than the channel delay spread to make the system ISI free and bandwidth efficient. At the receiver, the CP is discarded and the data is applied to FFT and its output is given to the MIMO decoder as shown in Figure 1. Then the data is demodulated and decoded through the bit flipping process.

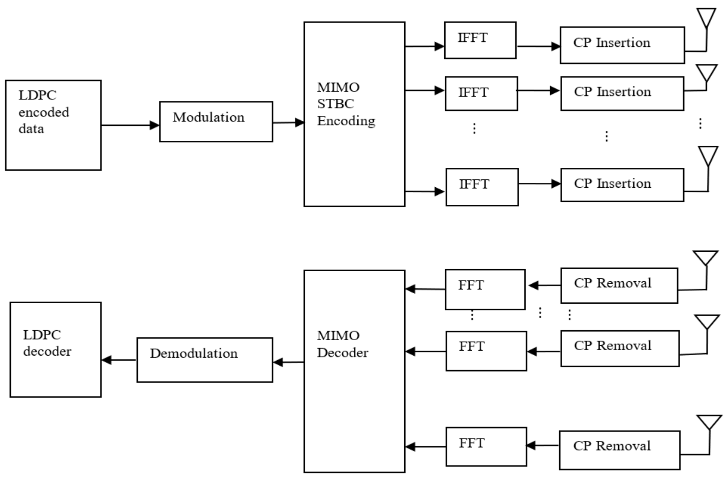

Figure 1. Block diagram of LDPC encoded MIMO OFDM system

2.1. LDPC codes

The size of H matrix in (n,k) LDPC code is $(n-k)$ x n. Here, k and n indicate the lengths of the message and codewords respectively. Tanner graph is used to represent parity check matrix. In tanner graph, check nodes (CN) and variable nodes (VN) indicates the rows and columns of parity check matrix. Number of '1's in the parity matrix gives the relation between CNs and VNs. Cyclic shifts, lifting size and base graph are the characteristics of parity check matrix. 46×68 (base graph1) and 42×52 (base graph2) base graphs are defined in new radio (NR) systems. A (4 × 7) sparse parity check matrix 'H' and its Tanner graph is shown in (1) and Figure 2. Based on the message length and code rate, base graphs are selected. Each base graph consists of eight parity check matrices and each lifting size set have one set of cyclic shifts [25].

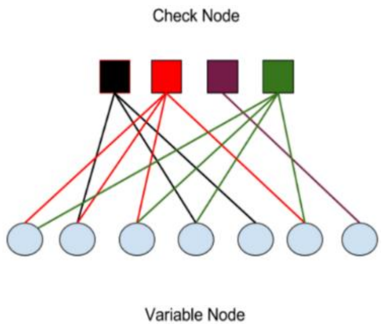

Figure 2. Tanner graph of 4×7 parity check matrix

2.2. LDPC encoder

In (n, k) LDPC code, the weights w_c and w_r indicates, 1's count in the columns and 1's count in the rows respectively. The classification of LDPC codes is based on w_c and w_r. Regular LDPC codes contains equal number of 1's in each column and row, otherwise the codes are called irregular LDPC codes [25]. Protograph is used in constructing LDPC codes. In LDPC encoding, the parity check matrix is obtained by expanding the base matrix which is obtained from the protograph construction. LDPC encoding process is illustrated in Figure 3.

$$H = \begin{bmatrix} 0 & 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 & 1 & 0 \end{bmatrix} \quad (1)$$

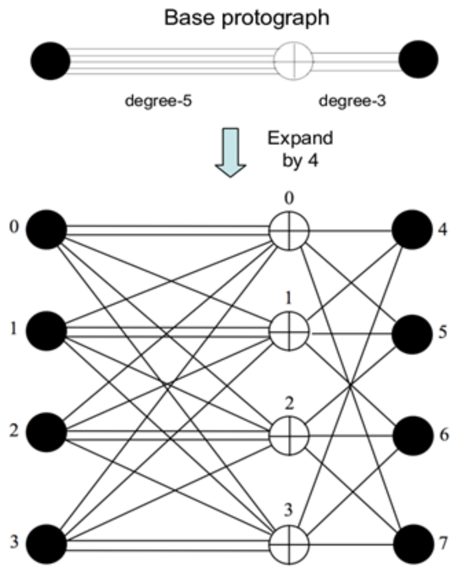

Figure 3. Expanding a base matrix using an expansion factor

$$H = \begin{bmatrix} x^2+x^3 & x & 1 & x^2 & 1 & x^3 & 0 & 1 \\ 1 & 1+x & 1 & 1 & 1 & 1 & 1 & 0 \\ x^3 & 1 & 1+x^2 & 1 & 0 & 1 & x & 1 \\ x^2 & 1 & 1 & 1+x^3 & 1 & 0 & 1 & 1 \end{bmatrix} \quad (2)$$

Parity Check Matrix

$$1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} x = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix} x^2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} x^3 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Circulants

$$H = \begin{bmatrix} I_1 & 0 & I_3 & I_1 & I_2 & I & 0 & 0 \\ I_1 & I & 0 & I_1 & 0 & I & I & 0 \\ 0 & I_4 & I_2 & I & I_1 & 0 & I & I \\ I_4 & I_1 & I & 0 & I_1 & 0 & 0 & I \end{bmatrix} \quad (3)$$

I_k: identity matrix in which column elements are shifted by k times

2.3. LDPC encoding mechanism

- Step 1: consider a parity check matrix with expansion factor 5, that includes expansion values: -1, 0, 1, 2, 3, and 4. Parity check matrix H is considered as per (2) along with the circulants 1, x, x^2, and x^3.
  On substituting the circulants, the parity-check matrix with expansion factor-5 modifies to (3).
- Step 2: consider the message [M_1 M_2 M_3 M_4] where each message is of 5 bits.
- Step 3: the codeword for the above message bits is [M_1 M_2 M_3 M_4 P_1 P_2 P_3 P_4] where P_1 P_2 P_3 P_4 are of 5-bit length.
- Step 4: codeword can be obtained by solving (4).

$$Hx[M_1 M_2 M_3 M_4 P_1 P_2 P_3 P_4]^t = 0 \quad (4)$$

- Step 5: extracting row elements in (4) and equating to zero, equations from (5) to (8) are obtained.

$$I_1 M_1 + I_3 M_3 + I_1 M_4 + I_2 P_1 + I P_2 = 0 \quad (5)$$

$$I_2 M_1 + I M_2 + I_3 M_4 + I P_2 + I P_3 = 0 \quad (6)$$

$$I_4 M_2 + I_2 M_3 + I M_4 + I_1 P_1 + I P_3 + I P_4 = 0 \quad (7)$$

$$I_4 M_1 + I_1 M_2 + I M_3 + I_2 P_1 + I P_4 = 0 \quad (8)$$

- Step 6: adding equations from (5) through (6), and upon solving (9), parity bit sequence P_1 is obtained.

$$I_1 P_1 = I_1 M_1 + I_3 M_4 + I_1 M_4 + I_2 M_1 + I M_2 + I_3 M_3 + I_4 M_2 + I_2 M_3 + I M_4 + I_4 M_1 + I_1 M_2 + I M_3 \quad (9)$$

- Step 7: by substituting P_1 in H matrix, the value of P_2 is calculated. Similarly using P_2, parity bit sequence P_3 and then P_4 are determined.

Case 1:

- Consider the message block sequence M = [1 0 1 0 0 0 0 0 0 1 1 1] and encode it by considering the above parity check matrix.

- Consider M_1 = [1 0 1]; M_2 = [0 0 0]; M_3 = [0 0 0]; M_4 = [1 1 1]

consider the parity check matrix as in (10) with expansion factor 3.

$$H = \begin{bmatrix} 1 & -1 & 1 & 2 & 2 & 0 & -1 & -1 \\ 2 & 1 & -1 & 0 & -1 & 0 & 0 & -1 \\ -1 & 2 & 2 & 1 & 1 & -1 & 0 & 0 \\ 2 & 1 & 0 & -1 & 2 & -1 & -1 & 0 \end{bmatrix} \quad (10)$$

Using LDPC encoding mechanism as mentioned in section 2.3, and upon solving, parity bit sequences P_1, P_2, P_3, and P_4 generated are P_1 = [0 1 0]; P_2 = [1 0 1]; P_3 = [1 0 0]; and P_4 = [1 1 1]. Then the encoded code word with expansion factor -3 is X= [1 0 1 0 0 0 0 0 0 1 1 1 0 1 0 1 0 1 1 0 0 1 1 1].

Case 2:

- Consider the message block sequence M = [1 0 1 0 1 0 0 0 0 0 1 1 1 1 1 0 1 0 1 0].
- Consider M_1 = [1 0 1 0 1]; M_2 = [0 0 0 0 0]; M_3 = [1 1 1 1 1]; M_4 = [0 1 0 1 0] and the parity check matrix as in (11) expansion factor 5.

$$H = \begin{bmatrix} 1 & 0 & 3 & 1 & 2 & -1 & 0 & 0 \\ 2 & -1 & 0 & 3 & 0 & -1 & -1 & 0 \\ 0 & 4 & 2 & -1 & 1 & 0 & -1 & -1 \\ 4 & 1 & -1 & 0 & 2 & 0 & 0 & -1 \end{bmatrix} \tag{11}$$

Using LDPC encoding mechanism as mentioned in section 2.3, and upon solving, parity bit sequences P_1, P_2, P_3, and P_4 generated are P_1 = [0 1 0 1 0]; P_2 = [0 1 0 0 1]; P_3 = [0 1 1 0 1]; and P_4 = [0 1 1 0 0]. Then the encoded code word with expansion factor -5 is X= [1 0 1 0 1 0 0 0 0 0 1 1 1 1 1 0 1 0 1 0 0 1 0 1 0 0 1 0 0 1 0 1 1 0 1 0 1 1 0 0].

2.4. LDPC decoding mechanism

For decoding of LDPC code, iterative algorithms are used to perform the sequential repair of error bits with the help of tanner graph [10]. In this work, hard decoding scheme is used. Error bits are detected in the received bit stream by CN based on the parity. If the parity is satisfied, data is sent to the message nodes else bits in the received data are adjusted to the required parity and then the corrected message is sent.

Bit flipping algorithm

Bit flipping algorithm is used for decoding a binary symmetric channel. Here, a specific bit is flipped from 0 to 1 or 1 to 0.

– Step 1: from the parity matrix, draw the Tanner graph.
– Step 2: perform even parity check for each check node.
– Step 3: flip those bits which are involved with the largest number of unsatisfied parity checks.
– Step 4: now, for the updated data, go back to step 2. Keep iterating until all checks are satisfied.

Decoding case:

Let the message bits be M = [0 0 0 0 0 0 0] and the received bits after transmission be y = [0 1 0 0 1 0 0]. The parity check matrix is considered as in (12).

$$H = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 \end{bmatrix} \tag{12}$$

The corresponding Tanner graph is as shown in Figure 4. The first bit flipping and the updated tanner graph is shown in Figure 5. After flipping the second bit, the obtained sequence is [0 0 0 0 0 0 0] which is equal to the transmitted sequence. Hence, the errors in the received sequence are corrected in this process.

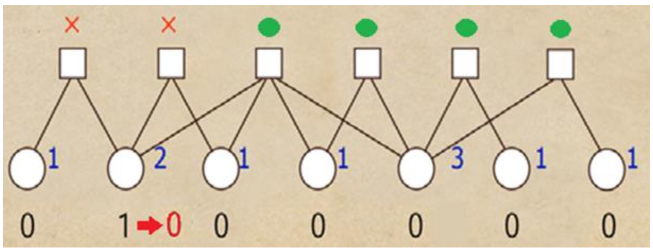

Figure 4. Tanner graph of parity check matrix

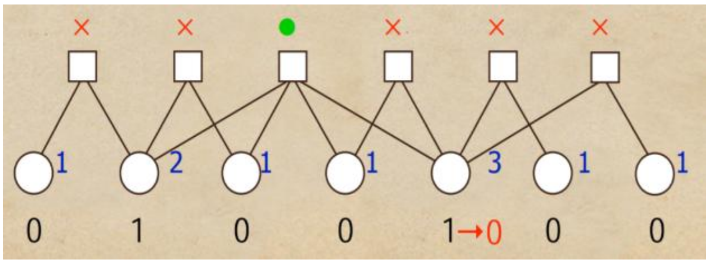

Figure 5. Bit flipping in Tanner graph of parity check matrix

3. RESULTS AND DISCUSSION

In this work, LDPC codes are implemented in OFDM and MIMO-OFDM systems and the error performance of the system is analyzed for different digital modulation schemes. Figure 6 describes the performance of LDPC code in terms of BER in QPSK modulated OFDM and 2×2 MIMO-OFDM communication system and it is observed that the BER of the system decreases with increase in SNR (in dB). The better BER performance of MIMO-OFDM over OFDM is also observed. Figure 7 illustrates the error performance of LDPC codes in 4 QAM modulated OFDM and 2×2 MIMO-OFDM systems. From Figure 6 and Figure 7, an improved error performance of 4 QAM MIMO-OFDM system over QPSK MIMO-OFDM system is observed. The BER of LDPC encoded QPSK 2×2 MIMO-OFDM system at 15 dB SNR is 10^{-3}whereas 4QAM 2×2 MIMO-OFDM system achieved same BER (10^{-3}) at 10 dB SNR only.

Figures 8 and 9 demonstrate the error performance of LDPC code in 8 PSK OFDM and 8 PSK 2×2 MIMO-OFDM and 8 QAM OFDM and 8 QAM 2×2 MIMO-OFDM systems respectively. By observing Figures 8 and 9, a better error performance of 8 QAM 2×2 MIMO-OFDM system is noticed in comparison with the 8 PSK MIMO-OFDM system. The SNR (in dB) required for 10^{-3} BER in 8 PSK 2×2 MIMO-OFDM system is more than 20. However, 8 QAM 2×2 MIMO-OFDM system achieves 10^{-3} BER with 15 dB SNR only. From Figures 10 and 11, the SNR (in dB) required in 16 PSK 2×2 MIMO-OFDM system and 16 QAM 2×2 MIMO-OFDM system is 23 and 17 respectively.

Hence, from the Figures 6 to 11, it is evident that the error performance of QAM system is always superior over PSK system for the same order of modulation. Moreover, it is also observed that the error performance of communication system is varied with the change in the order of modulation. The spectral efficiency (transmission rate) of the communication system improves with increase in order of modulation at the cost of error rate and vice versa. Hence, based on the requirement, the order of modulation is to be selected. For better reliability, lower order modulation and for higher data rate transmission, higher order modulation is to be selected.

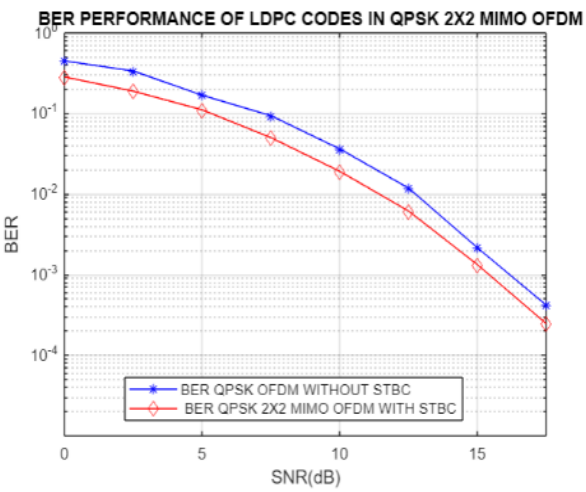

Figure 6. BER performance of OFDM and 2×2 MIMO-OFDM signal with QPSK modulation

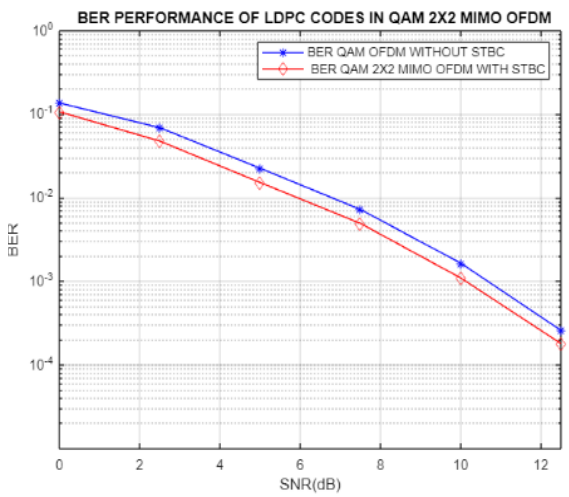

Figure 7. BER performance of OFDM and 2×2 MIMO-OFDM signal with 4QAM modulation

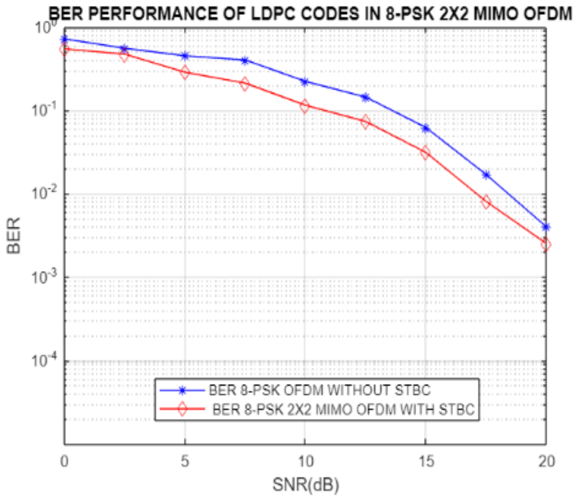

Figure 8. BER performance of 2×2 OFDM and MIMO-OFDM signal with 8 PSK modulation

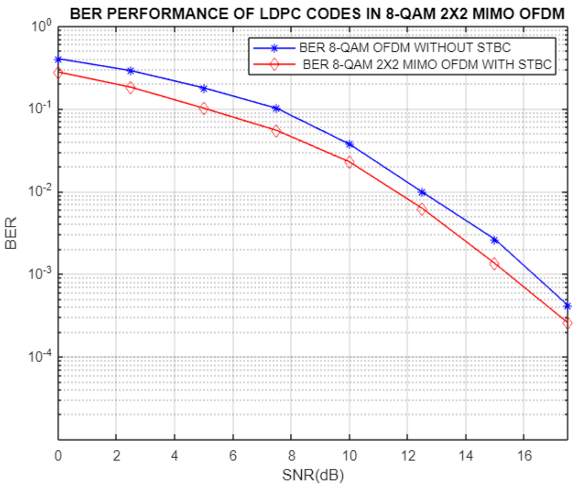

Figure 9. BER performance of OFDM and 2×2 MIMO-OFDM signal with 8 QAM modulation

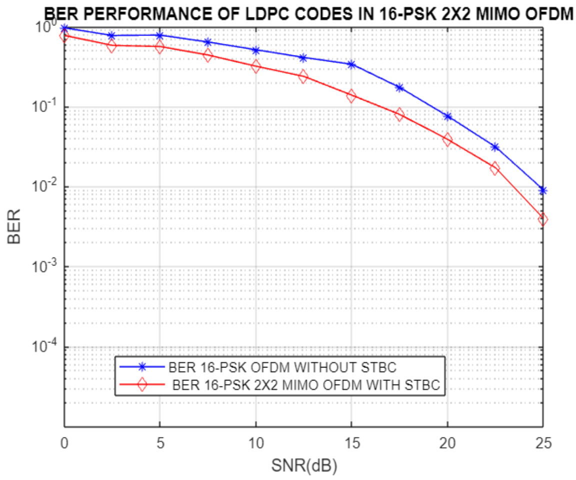

Figure 10. BER performance of OFDM and 2×2 MIMO-OFDM signal with 16 PSK modulation

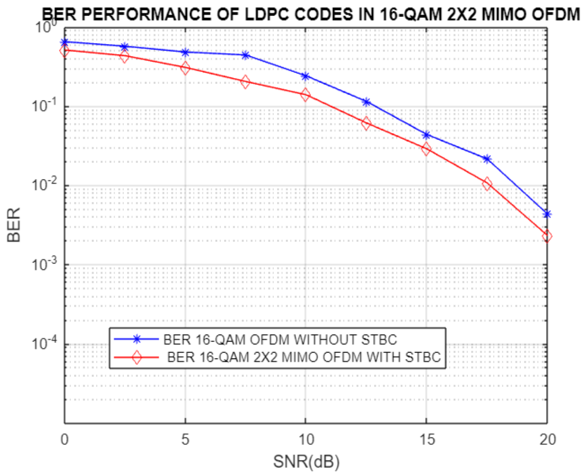

Figure 11. BER performance of OFDM and 2×2 MIMO-OFDM signal with 16 QAM modulation

4. CONCLUSIONS

In this work, basic OFDM and 2×2 MIMO-OFDM systems are implemented. For bit level protection, LDPC codes are used. The error performance of LDPC codes in OFDM and 2×2 MIMO-OFDM systems is analyzed for different digital modulation schemes. From the results, it is concluded that the error performance of MIMO-OFDM communication system in the presence of LDPC code is better than conventional communication system. Hence, LDPC code improves the reliability of communication system, along with the power efficiency. Because of better error performance, power efficiency and other numerous advantages, LDPC codes are being preferred in contemporary communication systems such as 5G and Beyong 5G systems. It is also observed that the performance of system depends on the order of modulation. The higher transmission rate is achieved through higher order modulation and better reliability is obtained by using lower order modulation or/and good channel codes such as LDPC codes.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
P. Aruna Kumari	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		
Srinu Pyla	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		
U.N.V.P. Rajendranath	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
Nirujogi Venkata Maheswara Rao	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] Z. Tu and S. Zhang, "Overview of LDPC Codes," in *proceedings of 7th IEEE international conference on computer and information technology (CIT-2007)*, pp. 469–474, 2007, doi: 10.1109/cit.2007.7.
[2] Thangaraj, Andrew, and N. Lecture, "LDPC and Polar Codes in 5G Standard - YouTube," 2019, [Online]. Available: https://www.youtube.com/playlist?list=PLyqSpQzTE6M81HJ26ZaNv0V3ROBrcv-Kc.
[3] A. K. Jagannatham, "Principles of modern wireless communication systems:theory and practice," *McGraw-Hill Education*, p. 312, 2016.
[4] M. Anju and U. Gawas, "An overview on evolution of mobile wireless communication networks : 1G-6G," *Ijritcc.Org*, vol. 3, no. 5, pp. 3130–3133, 2015.
[5] P. A. Kumari and I. S. Prabha, "Hierarchical and hybrid cell load balancing in 5G heterogeneous mobile networks," *International Journal of Communication Systems*, vol. 35, no. 1, Jan. 2022, doi: 10.1002/dac.5017.
[6] A. Laguidi, T. Hachad, and L. Hachad, "Mobile network connectivity analysis for device to device communication in 5G network," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 13, no. 1, p. 680, Feb. 2023, doi: 10.11591/ijece.v13i1.pp680-687.
[7] P. D. Arapoglou, K. Liolis, M. Bertinelli, A. Panagopoulos, P. Cottis, and R. De Gaudenzi, "MIMO over satellite: a review," *IEEE Communications Surveys and Tutorials*, vol. 13, no. 1, pp. 27–51, 2011, doi: 10.1109/SURV.2011.033110.00072.
[8] L. Wang, "Channel Coding Techniques for Network Communication," University of California, 2015.
[9] W. K. Abdulwahab and A. A. Kadhim, "Comparative study of channel coding schemes for 5G," *ICOASE 2018 - International Conference on Advanced Science and Engineering*, pp. 239–243, 2018, doi: 10.1109/ICOASE.2018.8548806.
[10] S. Pyla, K. P. Raju, and N. Balasubrahmanyam, "Performance analysis of OFDM system using pilots, coding bounds and MAP decoder for next generation applications," *International Journal on Communications Antenna and Propagation (IRECAP)*, vol. 7, no. 5, p. 364, Oct. 2017, doi: 10.15866/irecap.v7i5.10787.
[11] W. E. Ryan, "An introduction to LDPC codes," in *Coding and Signal Processing for Magnetic Recording Systems*, CRC Press, 2004, pp. 649–668.
[12] M. P. Singh and P. Kumar, "An efficient forward error correction scheme for wireless sensor network," *Procedia Technology*, vol. 4, pp. 737–742, 2012, doi: 10.1016/j.protcy.2012.05.120.
[13] H. D. Vu, T. V. Nguyen, D. N. Nguyen, and H. T. Nguyen, "On Design of Protograph LDPC Codes for Large-Scale MIMO Systems," *IEEE Access*, vol. 8, pp. 46017–46029, 2020, doi: 10.1109/ACCESS.2020.2979156.
[14] Y.-L. Ueng, C.-Y. Wang, and M.-R. Li, "An efficient combined bit-flipping and stochastic LDPC decoder using improved probability tracers," *IEEE Transactions on Signal Processing*, vol. 65, no. 20, pp. 5368–5380, Oct. 2017, doi: 10.1109/TSP.2017.2725221.
[15] C. Manikandan, P. Neelamegam, and E. Divya, "OFDM techniques for MIMO-OFDM system: a review," *Indian Journal of Science and Technology*, vol. 8, no. 22, Sep. 2015, doi: 10.17485/ijst/2015/v8i22/79103.
[16] J. K. Daksh, R. Mohan, and S. Sharma, "A survey of performance analysis in MIMO-OFDM systems," *International Journal of Advanced Computer Research*, no. 2, pp. 3–6, 2013.
[17] A. K. Jassim and R. H. Thaher, "Design of MIMO (4×4) broadband antenna array for mm-wave wireless communication applications," *International Journal on Engineering Applications (IREA)*, vol. 7, no. 2, p. 65, Mar. 2019, doi: 10.15866/irea.v7i2.16804.

[18] K. Mahender, T. A. Kumar, and K. S. Ramesh, "Simple transmit diversity techniques for wireless communications," in *Advances in Intelligent Systems and Computing*, vol. 669, 2019, pp. 329–342.
[19] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, Jul. 1999, doi: 10.1109/18.771146.
[20] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, 1998, doi: 10.1109/49.730453.
[21] S. Chaudhary and A. J. Patil, "Performance analysis of mimo-space time block coding with different modulation techniques," *ICTACT Journal on Communication Technology*, vol. 03, no. 01, pp. 510–514, Mar. 2012, doi: 10.21917/ijct.2012.0071.
[22] J. Xuehua and C. Peijiang, "Study and implementation of MIMO-OFDM system based on Matlab," in *2009 International Conference on Information Technology and Computer Science*, Jul. 2009, vol. 1, pp. 554–557, doi: 10.1109/ITCS.2009.120.
[23] Y. S. Cho, J. Kim, W. Y. Yang, and C. G. Kang, *MIMO-OFDM Wireless Communications with MATLAB®*. Wiley, 2010.
[24] F. El Bouanani and A. Bessate, "A comparative study on the performance of MIMO-STBC subject to Weibull fading channels," *International Journal of Communication Systems*, vol. 31, no. 13, Sep. 2018, doi: 10.1002/dac.3731.
[25] C. Prasartkaew and S. Choomchuay, "A design of parity check matrix for irregular LDPC codes," in *2009 9th International Symposium on Communications and Information Technology*, Sep. 2009, pp. 239–242, doi: 10.1109/ISCIT.2009.5341252.

BIOGRAPHIES OF AUTHORS

Dr. P. Aruna Kumari is working as an Assistant Professor in the department of Electronics and Communication Engineering, Gayatri Vidya Parishad College of Engineering (Autonomous). She received B.Tech. degree in ECE from J.N.T. University, and M.Tech. degree in Radar and Microwave Engineering from Andhra University College of Engineering. She was awarded with Ph.D. in Wireless Communications by Jawaharlal Nehru Technological University, Kakinada. She has 18 years of teaching experience and guided UG and PG projects. Her research interests include wireless mobile communications, mmWave communications, digital communications, coding theory and signal processing. She published technical papers in National and International Journals and Conferences. She can be contacted at email: hiaruna4u@gvpce.ac.in.

Dr. Srinu Pyla is working as an Assistant Professor from 2006 in the department of Electronics and Communication Engineering in Gayatri Vidya Parishad College of Engineering (Autonomous) Visakhapatnam, India. He received B E and, M. Tech from Andhra University and Kakatiya University in the year 2004 and 2006 respectively. He completed his Ph.D. from Jawaharlal Nehru Technological University Kakinada, India. He has published 16 technical papers in National/International Conferences and Journals. His fields of interest are communications and signal processing. He can be contacted at email: srinupyla@gvpce.ac.in.

Dr. U. N. V. P. Rajendranath is working as an Assistant Professor from 2018 in the department of Electronics and Communication Engineering in Gayatri Vidya Parishad College of Engineering (Autonomous) Visakhapatnam, India. He received B.Tech. from Acharya Nagarjuna University and, M.Tech. from Vellore Institute of Technology in the year 2013 and 2015 respectively. He completed his Ph.D. from SRU University Alwar, India. He has published 6 technical papers in National/International Conferences and Journals. His fields of interest are networking, internet of things, and embedded systems. He can be contacted at email: rajendranath@gvpce.ac.in.

Mr. Nirujogi Venkata Maheswara Rao is working as an Assistant Professor in the department of Electronics and Communication Engineering, Gayatri Vidya Parishad College of Engineering for Women (Autonomous). He received B.Tech. degree in ECE from J.N.T. University, and M.Tech. degree in Radar and Microwave Engineering from Andhra University College of Engineering. He was persuing Ph.D. in Communications and Signal Processing area in Jawaharlal Nehru Technological University, Kakinada. He has 15 years of teaching experience and guided UG and PG projects. He published technical papers in various National and International Journals and Conferences. His research interests include communications, signal processing, and high frequency antenna design. He can be contacted at email: himahesh4u@gvpcew.ac.in.