On the Performance of Large Intelligent Surfaces with LDPC Codes

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Abstract—This study explores the integration of Low-Density Parity-Check (LDPC) coding with Large Intelligent Surface (LIS) systems in conjunction with Single Carrier with Frequency Domain Equalization (SC-FDE). LIS systems represent a revolutionary advancement in wireless communication, leveraging densely packed antenna arrays for enhanced signal processing and beamforming capabilities. The research evaluates the performance of four receiver configurations: Maximum Ratio Combining (MRC), Equal Gain Combining (EGC), Zero Forcing (ZF), and Minimum Mean Squared Error (MMSE). By incorporating LDPC codes, substantial improvements in error correction and system reliability are achieved. Specifically, simulation results indicate a performance gain of approximately 3 dB for a 4×25 LIS system and 2 dB for a 4×225 LIS system when compared to uncoded systems.

Keywords: Large Intelligent Surface, LDPC Codes, SC-FDE, Wireless Communications, Receivers, Beamforming, Error Correction.

1. INTRODUCTION

Future communications will be intelligent and interactive, making artificial surfaces electronically active to enhance wireless links. The rise of the Internet of Things (IoT) and billions of connected devices pose communication challenges [1]. Massive Multiple-Input Multiple-Output (m-MIMO), Ultra Massive MIMO (UM-MIMO), and Extremely Large Antenna Arrays (ELAA) have transformed the field, boosting data rates and network capacity. The Large Intelligent Surface (LIS) concept extends m-MIMO, further increasing the number of antennas.

Wireless communications typically occur in the far-field, beyond the Fraunhofer distance. LIS, composed of multiple panels with several antenna elements, operates in the near-field, focusing not just on direction and elevation but also on distance [2,3]. This reduces interference between aligned users at different ranges, improving beamforming efficiency. Antenna spacing is λ/2, and element correlation enables beam formation. A block transmission strategy, including Single Carrier with Frequency Domain Equalization (SC-FDE) [4,5], is applied to LIS. This paper explores integrating Low-Density Parity-Check (LDPC) codes into this system.

High-frequency transmission faces challenges like free-space path loss and power amplification issues. LIS mitigates these limitations with compact antenna aggregates and multiple panels [6], leveraging reflection effects to enhance coverage [7]. This could exponentially increase wireless network capacity [8]. As an extension of m-MIMO, LIS enables short-range communication, reducing energy consumption and interference [1,6]. This study compares four receivers: Zero Forcing (ZF), Maximum Ratio Combining (MRC), Equal Gain Combining (EGC), and Minimum Mean Squared Error (MMSE) [6,9]. Integrating LDPC codes with SC-FDE reduces the Bit Error Rate (BER) [10,11], the paper's key contribution.

LDPC codes are highly efficient, approaching Shannon capacity with low decoding complexity [12]. They outperform other error-correcting codes in handling errors and computational efficiency.

2. SYSTEM AND SIGNAL MODEL

As shown in Figure 1, the *n*th transmitted block of *N* symbols from the *t*th user equipment (UE) is denoted as $s_n^{(t)}$, while the *r*th antenna of the LIS system receives $y_n^{(r)}$. Communication occurs in the near-field rather than the far-field.

The frequency-domain representation of the transmitted block is obtained via the Discrete Fourier Transform (DFT):

$$DFT\left\{s_n^{(t)}; n = 0,1,\dots,N-1\right\} = \left\{S_k^{(t)}; k = 0,1,\dots,N-1\right\} \tag{1}$$

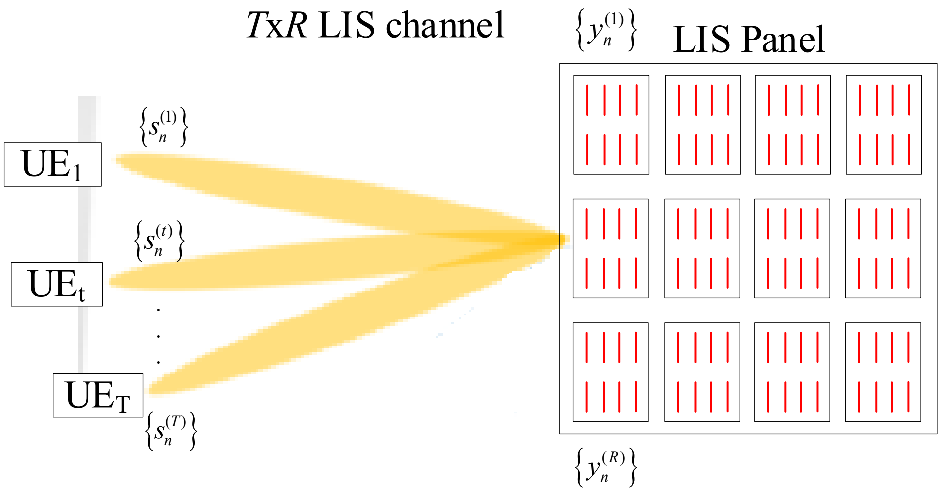

Figure 1. Block diagram of an LIS System.

The received block undergoes a similar transformation:

$$DFT\left\{y_n^{(r)}; k = 0,1, \dots, N-1\right\} = \left\{Y_k^{(r)}; k = 0,1, \dots, N-1\right\} \tag{2}$$

After cyclic prefix removal, assuming it exceeds the channel impulse response, the received frequency-domain signal is given by [13]:

$$Y_k = \left[Y_k^{(1)}, \dots, Y_k^{(R)}\right] = H_k S_k + N_k \tag{3}$$

where $S_k = \left[S_k^{(1)}, \dots, S_k^{(T)}\right]^T$ represents the transmitted symbols in the frequency domain, and H_k it the $T \times R$ channel matrix for the kth subcarrier, with its (r,t)th element denoted as $H_k^{(t,r)}$. The channel's frequency response is:

$$\{H_k;\ k = 0,1, \dots, N-1\} = DFT\{h_n; n = 0,1, \dots, N-1\} \tag{4}$$

Lastly, N_k represents the noise in the frequency-domain for the kth subcarrier [14].

ZF and MMSE receivers are computationally intensive, requiring channel inversion for each frequency component, leading to substantial battery consumption. The ZF receiver efficiently eliminates intersymbol interference but suffers from noise amplification, degrading performance in moderate to high noise scenarios. In contrast, MRC and EGC receivers are less complex, making them suitable for LIS deployments. However, they introduce some interference during decoding, which can be mitigated with iterative receivers.

For a non-iterative receiver, the estimated frequency-domain data symbols, denoted as $\tilde{\mathbf{S}}_k = \left[\tilde{S}_k^{(1)}, \dots, \tilde{S}_k^{(R)}\right]^T$, are calculated as described in [14]. Specifically:

$$\tilde{\mathbf{S}}_k = \mathbf{B}_k \mathbf{Y}_k \tag{5}$$

Depending on the algorithm, $\mathbf{B}_k$ can be computed differently [14]. Using the ZF receiver, $\mathbf{B}_k$ comes $\mathbf{B}_k = \mathbf{H}_k^H\left(\mathbf{H}_k \mathbf{H}_k^H\right)^{-1}$, while $\mathbf{B}_k$ comes $\mathbf{B}_k = (\mathbf{H}_k \mathbf{H}_k^H + \beta \mathbf{I})^{-1} \mathbf{H}_k^H$ for the MMSE, and where $\beta = \frac{\sigma_N^2}{\sigma_S^2} = \frac{\frac{E\left[|N_k|^2\right]}{2}}{\frac{E\left[|S_k|^2\right]}{2}}$ and where $\mathbf{I}$ is an $R \times R$ identity matrix. Using the MRC receiver, $\mathbf{B}_k$ comes $\mathbf{B}_k = \mathbf{H}_k^H$ and $\mathbf{B}_k$ comes $\mathbf{B}_k = exp\{j\ \ arg(\mathbf{H}_k^H)\}$ for the EGC.

Iterative block decision feedback equalization (IB-DFE) [13] is a highly efficient receiver for single-carrier frequency-domain equalization (SC-FDE), utilizing feedforward and feedback coefficients for enhanced performance. While MRC and EGC are computationally simple, they generate residual interference, especially with moderate signal-to-noise ratio (SNR) values. This can be countered by iterative receivers, similar to IB-DFE, implementing the function:

$$\tilde{\mathbf{S}}_k = \mathbf{B}_k^H \mathbf{Y}_k - \mathbf{C}_k \bar{\mathbf{S}}_k \tag{6}$$

where the interference cancellation matrix, $\mathbf{C}_k$, is computed as $\mathbf{C}_k = \mathbf{A}_k^H \mathbf{H}_k - \mathbf{I}$ [14], where $\mathbf{I}$ is an $R \times R$ identity matrix.

3. SIMULATION RESULTS AND ANALYSIS

Monte Carlo simulations assessed uplink BER performance in LIS systems with SC-FDE and LDPC codes, varying Eb/N0. QPSK modulation (N=256), rate ½ LDPC codes (32,400 length), and five-path Rayleigh fading were used. ZF, MMSE, MRC, and EGC receivers were compared. ZF and MMSE, requiring channel inversion, are computationally expensive. Matched Filter Bounds (MFB) served as performance lower bounds, indicating near-optimal receiver performance.

Figure 2 displays the results with 4X25 LIS System, with five users, with and without LDPC codes. Regarding these outcomes, we observe that the use of LDPC codes results in a performance improvement of the order of 3 dB, for all receiver types.

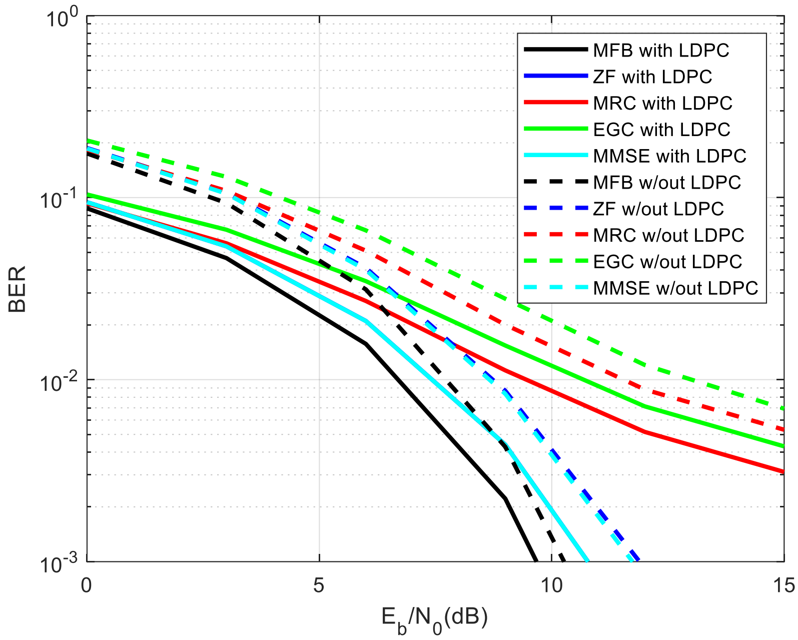

Figure 2. Results for 4X25 LIS System, with 5 users, with and without LDPC codes.

In Figure 3, the performance outcomes for a 4X225 LIS system, supporting five users, are presented, illustrating both coded and uncoded scenarios. Consistent with the trends observed in Figure 2, the implementation of LDPC codes yielded a performance improvement of approximately 2 dB compared to the uncoded configuration.

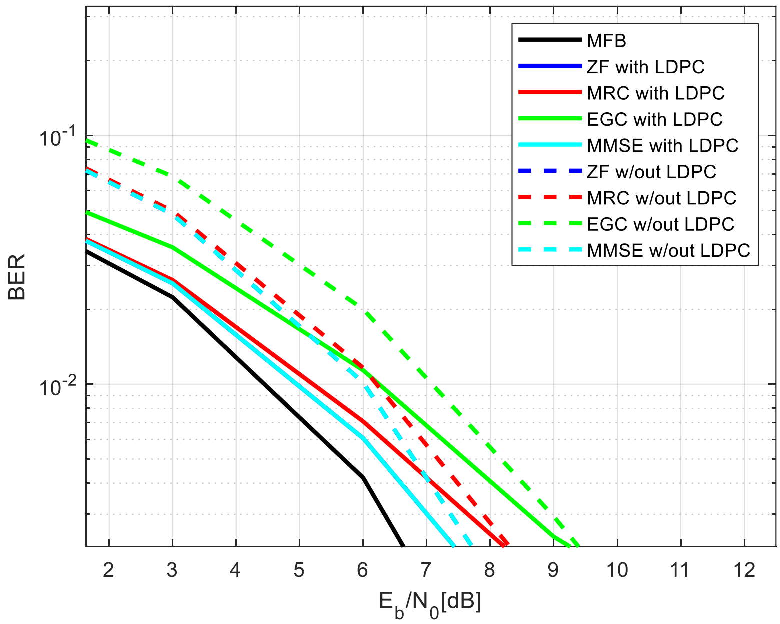

Figure 3. Results for 4X225 LIS System, with 5 users, with and without LDPC codes.

4. CONCLUSIONS

The findings underscore the efficiency of the MMSE receiver, which achieves the best overall performance due to its ability to mitigate interference. However, this comes at the cost of computational complexity. Alternatively, MRC offers a viable low-complexity solution while maintaining competitive results. The LIS system associated with the MRC receiver simplifies processing, further enhancing its feasibility for practical implementations. Additionally, the results demonstrate that the use of LDPC codes provides a significant performance gain compared to the uncoded system, improving BER by approximately 2-3 dB, depending on the LIS configuration. This highlights the effectiveness of LDPC codes in enhancing system reliability.

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REFERENCES

1. Decarli, N.; Dardari, D. Communication Modes with Large Intelligent Surfaces in the Near Field. IEEE Digit. Object Identifier 2021, 9, 165648–165666. https://doi.org/10.1109/ACCESS.2021.3133707.
2. Bjornson, E.; Özlem, T.; Sanguinetti, L. A primer on near-field beamforming for arrays and reconfigurable intelligent surfaces. In Proceedings of the 2021 55th Asilomar Conference on Signals, Systems, and Computers (ACSSC), Pacific Grove, CA, USA, 31 October–3 November 2021; pp. 105–112.
3. Dajer, M.; Ma, Z.; Piazzi, L.; Narayan, P.; Qi, X.; Sheen, B.; Yang, J.; Yue, G. Reconfigurable Intelligent Surface: Design the Channel—A New Opportunity for Future Wireless Networks. arXiv 2020, arXiv:2010.07408v1.
4. Borger, D.; Dinis, R.; Montezuma, P. An MRC-Based Receiver for SC_FDE Modulations with Massive MIMO Schemes. In Proceedings of the 2016 IEEE Global Conference on Signal and Information Processing (Global SIP), Washington, DC, USA, 7–9 December 2016.
5. Marques da Silva, M.; Dinis, R.; Guerriero, J. A Low Complexity Channel Estimation and Detection for Massive MIMO using SC-FDE. Telecom 2020, 1, 3–17.
6. Pereira, A.; Rusek, F.; Gomes, M.; Dinis, R. On the Complexity Requirements of a Panel-Based Large Intelligent Surface. In Proceedings of the 2020 IEEE Global Communications Conference, Taipei, Taiwan, 7–11 December 2020.
7. Hu, S.; Rusek, F.; Edfors, O. Beyond Massive-MIMO: The Potential of Data-Transmission with Large Intelligent Surfaces. arXiv 2017, arXiv:1707.02887v1.
8. Sanchez. J.R.; Rusek, F.; Edfors, O.; Liang Liu. Distributed and Scalable Uplink Processing for LIS: Algorithm, Architecture, and Design Trade-offs. arXiv 2020, arXiv:2012.05296v1.
9. Pereira, A.; Bento, P.; Gomes, M.; Dinis, R.; Silva, V. Complexity analysis of FDE receivers for massive MIMO block transmission systems. IET Commun. Inst. Eng. Technol. 2019, 13, 1762–1768.
10. Wenling, B.; Daqiao, B.; Yue, X. Performance evaluation of MIMO SC-FDMA system with FDE recoveries. In Proceedings of the 2009 IEEE International Conference on Wireless Communications & Signal Processing, Nanjing, China, 13–15 November 2009. https://doi.org/10.1109/WCSP.2009.5371554.
11. Hu, Y.; Wang, W.; Lin, Z.; Ding, M. Performance Analysis of Reconfigurable Intelligent Surface Assisted Wireless System with Low-Density Parity-Check Code. IEEE Commun. Lett. 2021, 25, 2879–2883.
12. Wanda, T. A Study on Performance of LDPC Codes on Power Line Communications. In Proceedings of the 2004 IEEE International Conference on Communications (IEEE Cat. No.04CH37577), Paris, France, 20–24 June 2004.
13. Johnson, S. Introducing Low-Density Parity-Check Codes. Univ. Newctle. Aust. 2006, 1, 2006. https://doi.org/10.13140/RG.2.1.1276.2324.
14. Yi, F.; Bi, G.; Yong Liang, G.; Lau, F. A Survey on Photograph LDPC Codes and Their Applications. IEEE Commun. Surv. Tutor. 2015, 17, 1989–2016.
15. Montezuma, P.; Borges, D.; Dinis, R. Low Complexity MRC and EGC Based Receivers for SC-FDE Modulations with Massive MIMO Schemes. In Proceedings of the IEEE Global Conference on Signal and Information Processing-Global SIP, Washington DC, USA, 7–9 December 2016.
16. Chen, J.; Liang, Y.C.; Cheng, H.V.; Yu, W. Channel Estimation for Reconfigurable Intelligent Surface Aided Multi-User MIMO Systems. arXiv 2019, arXiv:1912.03619v1.