Low Complexity and High Performance in Selective LIS Systems

Ali Gashtasbi, Mario Marques da Silva and Rui Dinis

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Ali Gashtasbi[1] , Mario Marques da Silva[2], Rui Dinis[3],

[1] Faculty of Sciences and Technology, Universidade Nova, 2829-516 Caparica, Portugal
a.gashtasbi@campus.fct.unl.pt
[2] Autonoma TechLab, 1169-023 Lisboa, Portugal
mmsilva@autonoma.pt
[3] Faculty of Sciences and Technology, Universidade Nova, 2829-516 Caparica, Portugal
rdinis@fct.pt

Abstract. Large Intelligent Surfaces (LIS) play a crucial role in enhancing wireless communications, but due to their inherent complexity, they also face significant challenges. This study introduces selective LIS technology, which reduces complexity by activating only a portion of the antennas, thus preventing performance degradation. Simulation results indicate that increasing the number of active antennas reduces performance loss and strikes an optimal balance between efficiency and performance. Furthermore, combining selective LIS technology with LDPC codes improves this balance, offering a viable solution for next-generation wireless systems. These findings confirm the effectiveness of selective LIS as an efficient alternative to full LIS deployment in complex wireless communication environments.

Keywords: Selective LIS, Full LIS, Low complexity, LDPC.

1 Introduction

The introduction of Large Intelligent Surface (LIS) technology represents a significant advancement in wireless communication systems, offering substantial potential for improving spectral and energy efficiency [1]. LIS systems, which use large panels of active elements, provide precise control over the wireless propagation environment and the traffic generated. However, implementing a full-scale LIS system faces major challenges, such as high hardware complexity and substantial computational demands, making practical deployment difficult and costly [2]. This happens because the decoding complexity increases exponentially with the increase of the number of antenna elements [2].

The efficient solution to these challenges is selective LIS. Rather than activating all elements, selective LIS strategically activates only a subset of antennas that meet optimal conditions, thus reducing system complexity while maintaining acceptable performance levels [3]. The success of this approach relies on the careful selection of active elements, ensuring minimal degradation in communication performance.

Furthermore, integrating Low-Density Parity-Check (LDPC) codes with selective LIS technology enhances system reliability by providing stronger error correction. Selective antenna activation can cause signal degradation, but this integration can significantly improve data integrity and overall system performance, especially in environments with limited resources [4].

This paper is organized as follows: a background of Selective LIS and Full LIS systems is presented in Section 2; in Section 3, the system model of the LIS system is proposed, and four decoding techniques is derived in detail; section 4 introduces the Selective LIS Framework, while section 5 focuses on simulations results and analysis; finally, conclusions are drawn in Section 6.

2 Background

The LIS system enhances signal strength, reduces interference, and improves system performance by using panels and large arrays of antennas. This technology is particularly useful for applications such as ultra-reliable low-latency communication (URLLC), massive machine-type communication (mMTC), and enhanced mobile broadband (eMBB) [5]. However, implementing full LIS systems faces challenges such as high complexity, significant energy consumption, and high costs due to the need for extensive hardware and computational resources. To solve these challenges, selective LIS has been proposed, which activates only a subset of required and efficient antennas, thereby reducing system complexity while maintaining the necessary and acceptable performance levels. The use of intelligent selection algorithms in selective LIS helps optimize antenna usage and reduces overhead [6]. Additionally, integrating LDPC codes with selective LIS improves error correction and enhances system reliability, making it suitable for resource-constrained environments [7]. This paper explores the impact of active element selection on the trade-off between performance and complexity in selective LIS systems. Figure 1 provides a graphical representation of the selective LIS, illustrating how User 1 and User 2 connect to the nearest panel with the highest signal power to optimize performance.

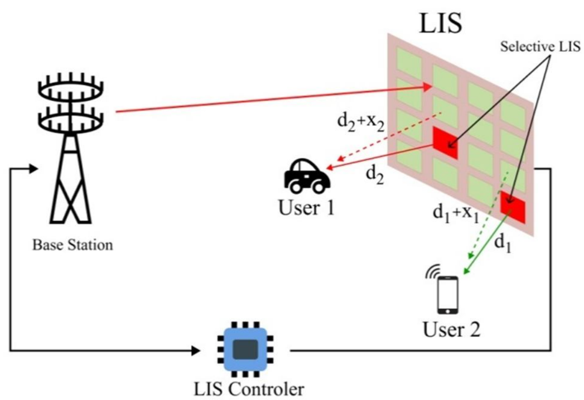

Figure 1. A graphical schematic of the Selective LIS.

3 System Model

The communication channels between the base station (BS) and users employ a Single-Carrier Frequency Domain Equalization (SC-FDE) transmission mechanism combined with Quadrature Phase Shift Keying (QPSK) modulation. The n-th transmitted block, consisting of N data symbols sent by the t-th user equipment (UE), is denoted as $\boldsymbol{s}_n^{(t)}$, while the corresponding block received by the r-th antenna of the LIS system is denoted as $\boldsymbol{y}_n^{(r)}$. The mapping between the time-domain signal and the frequency-domain signal for the k-th subcarrier (assumed that it remains invariant during the transmission of a given block) is represented by $DFT\left\{\boldsymbol{s}_n^{(t)} : n = 0,1,\dots,N-1\right\} = \left\{\boldsymbol{S}_k^{(t)} : k = 0,1,\dots,N-1\right\}$. This mapping applies similarly to the received signal block, the channel, and the noise, mutatis mutandis.
The received frequency-domain signal, represented in matrix-vector form, is given as follows [8]:

$$\boldsymbol{Y}_k = \left[\boldsymbol{Y}_k^{(1)},\dots,\boldsymbol{Y}_k^{(R)}\right] = \boldsymbol{S}_k\boldsymbol{H}_k + \boldsymbol{N}_k \tag{1}$$

Where $\boldsymbol{S}_k = \left[\boldsymbol{S}_k^{(1)},\dots,\boldsymbol{S}_k^{(T)}\right]^T$ represents the transmitted data symbols in the frequency domain, $\boldsymbol{H}_k$ denotes the $T \times R$ channel frequency-response for the k-th subcarrier, with (r,t)-th element $\boldsymbol{H}_k^{(r,t)}$. Moreover, $\boldsymbol{N}_k$ corresponds to the frequency-domain noise block for the subcarrier [8].

3.1 Receiver techniques

Assuming a non-iterative receiver, the estimated frequency domain data symbols $\tilde{\boldsymbol{S}}_k = \left[\tilde{\boldsymbol{S}}_k^{(1)}, \ldots, \tilde{\boldsymbol{S}}_k^{(R)}\right]^T$ are obtained as:

$$\tilde{\boldsymbol{S}}_k = \boldsymbol{B}_k \boldsymbol{Y}_k \tag{2}$$

Depending on the algorithm, can be computed [9] as:

Zero-Forcing (ZF) receiver attempts to eliminate interference by inverting the channel matrix, aiming to force the received signal to match the transmitted signal.

$$\boldsymbol{B}_k = (\boldsymbol{H}_k^H \boldsymbol{H}_k)^{-1} \boldsymbol{H}_k^H \tag{3}$$

Minimum Mean Squared Error (MMSE) receiver minimizes the mean squared error between the transmitted signal and the estimated signal by considering both the channel matrix and noise covariance.

$$\boldsymbol{B}_k = [\boldsymbol{H}_k^H \boldsymbol{H}_k + \beta \boldsymbol{I}]^{-1} \boldsymbol{H}_k^H \tag{4}$$

Where $\beta = \sigma_N^2 / \sigma_S^2 = \frac{E[|\boldsymbol{N}_k|^2]}{2} / \frac{E[|\boldsymbol{S}_k|^2]}{2}$ and where $\boldsymbol{I}$ is an $R \times R$ identity matrix.

Maximum Ratio Combining (MRC) combines signals from multiple antennas by weighting them according to their SNR to maximize overall SNR.

$$\boldsymbol{B}_k = \boldsymbol{H}_k^H \tag{5}$$

Equal Gain Combining (EGC) combines multiple received signals with equal gain to improve signal quality by summing the received signals coherently.

$$\boldsymbol{B}_k = \exp\{j \cdot \arg(\boldsymbol{H}_k^H)\} \tag{6}$$

4 Selective LIS Framework

The selective LIS framework aims to optimize the trade-off between system complexity and communication performance by selectively activating a subset of LIS elements [10]. To select a specific panel from the entire antennas panels in an LIS system, a certain criterion needs to be considered.

Antenna Selection Criteria:

- **Channel State Information (CSI):**
  Antennas with the highest channel gain or signal quality are prioritized. This ensures that only antennas contributing significantly to the received signal power are activated [11].
  For instance: If a system has 400 antennas, CSI analysis might select the 100 antennas with the strongest signal-to-noise ratio (SNR).
- **Proximity-Based Selection:**
  To enhance effective gain, antennas located closer to the direct line-of-sight path between the transmitter and receiver is selected [12].

For instance: In a rectangular LIS panel, antennas near the center may provide better performance for a user located straight ahead, as they lie on the shortest path.

- **Signal Strength:**
  The antennas with the highest received signal power are chosen, ensuring optimal performance.
  For instance: If two users are at different distances from the LIS panel, antennas aligned with the closer user may be prioritized. [13].
- **Thresholding:**
  Only antennas with a channel quality exceeding a predefined threshold are activated [14].
  For Example: A system may deactivate antennas with an SNR below 10 dB.
- **Improve Data Decoding:**
  Using techniques like LDPC codes, error correction is enhanced to ensure reliable communication even when fewer antennas are active.
  For instance: Selective LIS with LDPC codes can maintain a low BER (Bit Error Rate) while operating only 25% of antennas. [15].
- **Advanced Beamforming:**
  Techniques, such as ZF or MMSE, are used to enhance signal quality while reducing system complexity. These methods help mitigate interference and errors in signal transmission [16].
  For instance: A system uses MMSE beamforming to focus signals on users while reducing noise and interference.

These six methods balance performance, computational efficiency, and energy use, based on specific communication requirements.

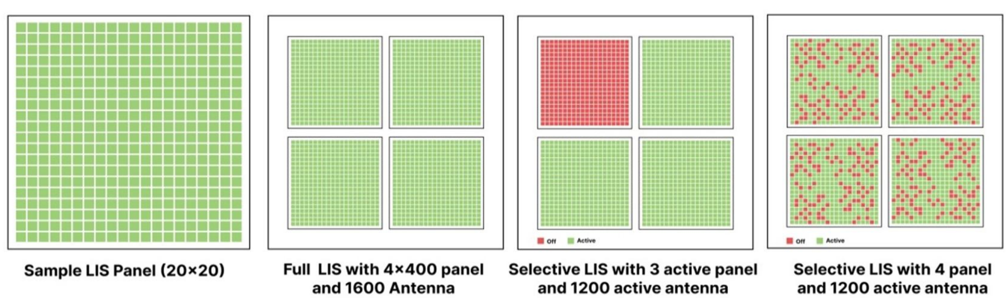

Figure 2. A graphical schematic of case study, Selective LIS vs. Full LIS.

5 Simulations and Results

This section analyzes the BER performance obtained through Monte Carlo simulations using LIS systems, combined with the SC-FDE block transmission technique and LDPC codes. Here, E_b represents the energy per transmitted bit, and N_0 is the one-sided noise power spectral density. The BER is evaluated as a function of E_b/N_0. A block size of N=256 symbols was used for QPSK modulation, with similar results observed for other values of N, as long as $N \gg 1$. LDPC codes of length 32,400 with a code rate of $1/2$ were applied. Regular LDPC codes were used, where all variable and check nodes have the same degree. In this work, a proximity-based antenna selection criterion is employed to enhance the performance of the LIS system. Antennas located closer to the line-of-sight path between the transmitter and receiver are prioritized, leveraging their superior channel conditions and effective gain. This approach reduces system complexity while maximizing signal quality. By activating only, the antennas in proximity to the user, power efficiency is improved. The proposed method demonstrates enhanced performance for users positioned within the main coverage zone of the LIS panel.

Figure 3 shows that the full LIS configuration (4 × 400), with 400 antennas across four panels, delivers exceptional performance by leveraging increased spatial diversity and array gain. This setup achieves remarkably low BER, particularly at higher E_b/N_0, making it ideal for applications requiring high reliability and robustness. However, this performance has drawbacks, including increased hardware complexity, higher costs, increased power consumption, and the computing demand of coordinating data from 400 antennas. On the other hand, the Selective LIS (1 × 400), with 400 antennas on a single panel, offers a more cost-effective and hardware-efficient alternative. This configuration significantly reduces system complexity, making it a viable choice for resource-constrained environments. However, the performance trade-off is evident, as the reduced antenna count results in lower spatial diversity and array gain, leading to slight BER degradation of performance. This performance gap becomes more noticeable at higher E_b/N_0, where the full LIS setup consistently outperforms the Selective LIS. Note that the degradation of performance achieved with the Selective LIS, compared to the full LIS, is of the order of 0.5 dB, while the computation requirements are much lower with the selective LIS.

Among the receiver types, ZF/MMSE demonstrates the best performance for both configurations, coming closest to the Matched Filter Bound (MFB), followed by MRC and EGC. While ZF/MMSE partially offsets the performance loss in the Selective LIS setup, it cannot fully bridge the gap caused by the reduced number of antennas. Moreover, it is worth noting that the MRC/EGC receivers are much simpler, in terms of computational requirements, than ZF/MMSE, as the former do not require the inversion of the channel matrix for each frequency component.

The MFB curve provides a benchmark for evaluating the performance of a channel, which is modeled as the sum of delayed and independently Rayleigh-fading rays.

These findings underscore the importance of carefully selecting an LIS configuration based on the desired balance between system complexity and performance requirements.

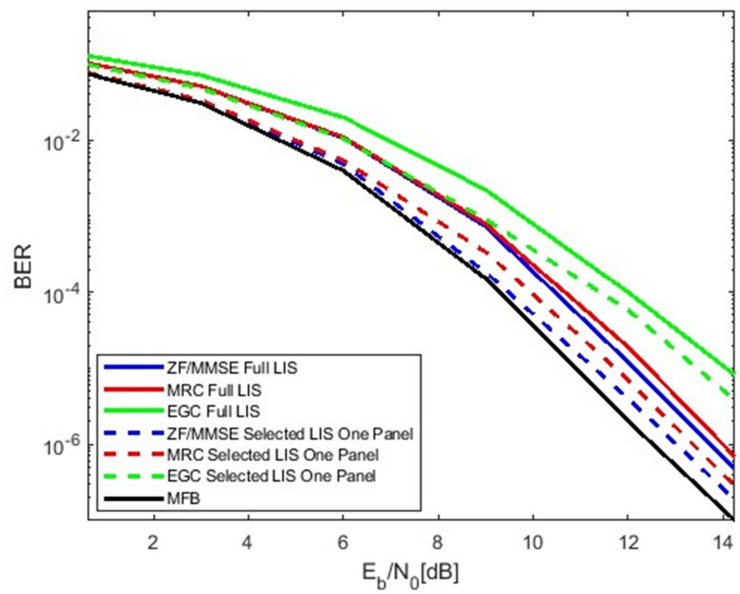

Figure 3. Performance results for 4X400 LIS System, with 4 users, without LDPC codes, with and without Selective LIS.

Figure 4 illustrates the BER performance of ZF, MMSE, MRC, and EGC detection techniques in LIS systems with 400 antennas distributed across 1, 2, 3, or 4 panels. ZF and MMSE outperform MRC and EGC due to their ability to effectively suppress interference, especially at higher E_b/N_0. Distributing antennas across multiple panels (e.g., 3 or 4) significantly improves BER performance for all methods by increasing spatial diversity and reducing signal correlation. A single-panel configuration, however, suffers from degraded performance due to limited spatial diversity and higher user interference. ZF and MMSE demonstrate the best results under multi-panel configurations, leveraging enhanced spatial separation for better user detection. Although MRC and EGC are simpler techniques, their performance is suboptimal and improves only slightly with multi-panel setups. Multi-panel configurations (3 or 4 panels) also enhance robustness to fading and interference, but they introduce additional system complexity and deployment challenges. Overall, distributing antennas across 3 or 4 panels achieves an optimal balance between BER performance and system complexity, making it a suitable design choice for multi-user LIS systems.

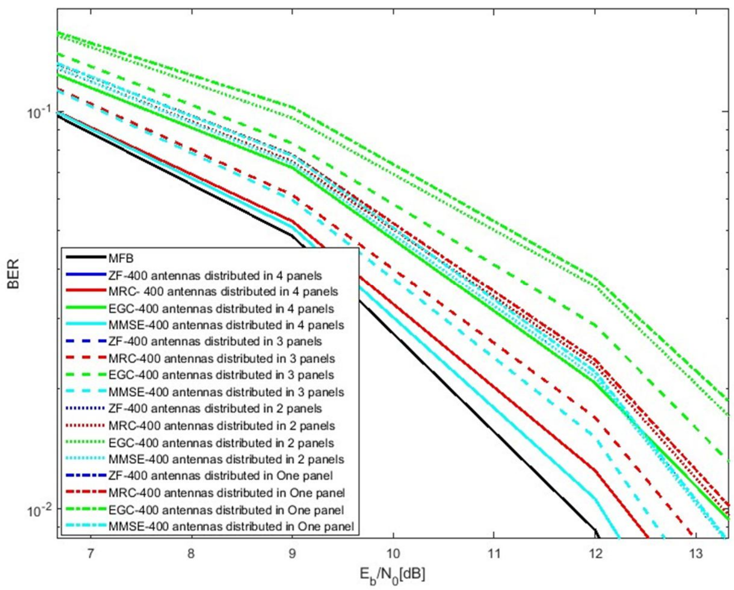

Figure 4. Performance results for LIS System, with 4 users, without LDPC codes, with 400 Antennas Distributed across 1, 2, 3, or 4 Panels in Selective LIS.

Figure 5 compares 4 panels with 300 antennas each and 3 panels with 400 antennas each (both totaling 1200 antennas). The 4-panel setup demonstrates superior performance due to its higher spatial diversity, which allows for better noise and interference rejection. With more panels, the 4-panel setup reduces antenna correlation, enhancing BER performance, especially for advanced methods like MMSE and ZF. In contrast, the 3-panel setup, with denser antennas per panel, increases antenna correlation and reduces diversity, making it less effective at interference mitigation. Although the 3-panel setup is slightly simpler and more energy-efficient, it compromises performance in challenging communication environments. The 4-panel setup achieves a better balance between complexity and BER performance, making it the preferred choice for scenarios demanding high reliability and diversity.

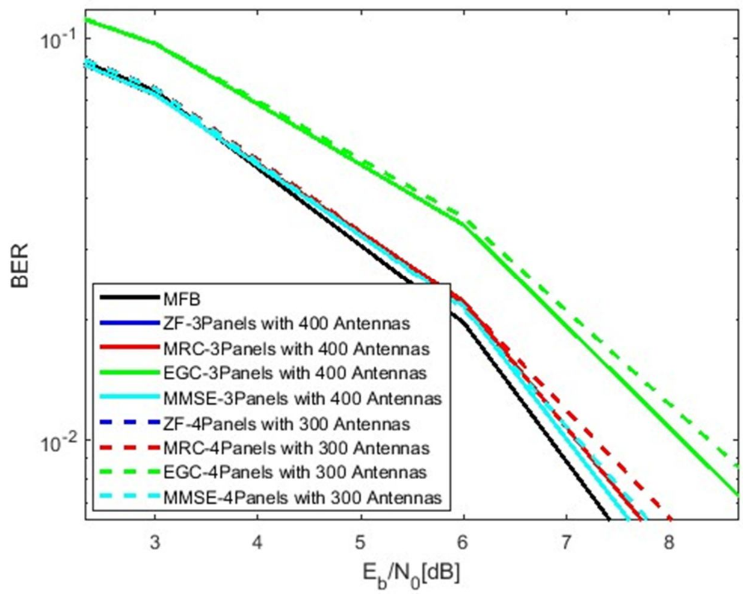

Figure 5. Comparison of BER Performance: 3 Panels with 400 Antennas vs. 4 Panels with 300 Antennas (both totaling 1200 antennas).

Figure 6 illustrates the performances obtained with the Selective LIS, with and without LDPC codes. LDPC codes provide powerful forward error correction, correcting residual errors caused by noise or interference. Together, they achieve reliable communication with reduced hardware and computational requirements. While Selective LIS may sacrifice diversity gain compared to Full LIS, the improved SNR ensures that LDPC codes can effectively correct remaining errors. This synergy enables robust BER performance even under resource constraints. Selective LIS reduces complexity, while LDPC codes ensure reliability, balancing efficiency and performance. Their integration is particularly beneficial for energy-efficient and low-complexity systems where full antenna usage is impractical. The simulation results show that LDPC codes significantly enhance the BER performance for all receiver techniques, particularly at lower E_b/N_0values. Full LIS achieves the best performance due to higher spatial diversity, but it comes with increased complexity. In contrast, Selective LIS reduces complexity by using fewer antennas, though it sacrifices some performance. LDPC codes mitigate this trade-off by improving error correction, especially in low-SNR conditions.

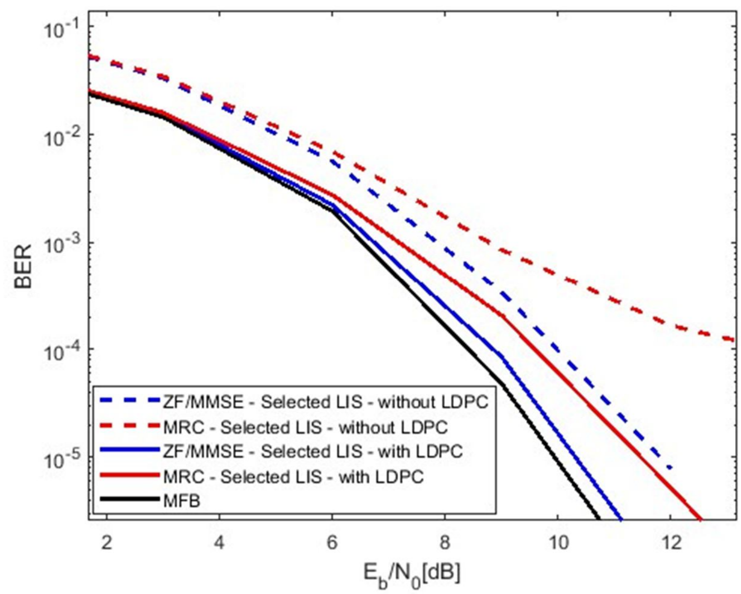

Figure 6. Performance results for 4X100 LIS System, with 4 users, with and without LDPC codes, with Selective LIS.

The trade-offs between Selective antenna and full antenna configurations involve critical criteria such as performance, complexity, energy efficiency, and scalability. Table 1 summarizes these comparisons:

Table 1. Comparison some criteria in Selective antenna vs. full antenna.

Criteria	Full LIS	Selective LIS
Number of Antennas	Full set of antennas (all panels)	A subset of all antennas
BER Performance	Best (lowest BER)	Moderate (close to full LIS)
Energy Efficiency	Lowest (high power usage)	Moderate
Hardware Requirements	High-performance systems required	Moderate
Scalability	Better (with multiple panels for large-scale applications).	Limited scalability with a single panel.

6 Conclusions

Selective LIS systems offer an effective solution in terms of complexity reduction, as compared to the full LIS deployments. This is done by using advanced antenna selection and optimization algorithms. This balance of low complexity and high performance makes Selective LIS an ideal choice for next-generation wireless networks, ensuring scalability and energy efficiency. Combining Selective LIS with LDPC codes improves error correction, providing reliable communication with minimal performance loss. This approach is highly suitable for resource-constrained systems in modern wireless networks.

Future work

Future work may make a comparison, in terms of performance results, between different antenna selection criteria. Moreover, future work may also develop an intelligent hybrid framework that includes Selective LIS with advanced machine learning algorithms to optimize antenna selection based on real-time channel state information (channel estimation), user distribution, and energy constraints. This framework aims to enhance system performance while minimizing complexity and power consumption, making it ideal for applications in 6G networks and Internet of Things environments.

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