Preliminary Studies on the Large Intelligent Surfaces Efficiencies Under Different Channels

Michelle S. P. Facina and Gustavo Fraidenraich

***Abstract*— This work investigates the impact of the channel model, and power allocation on the performance of a system employing Large Intelligent Surfaces (LIS). Most of the previous studies have considered the energy efficiency of such systems under the influence of Rayleigh channels and Zero-Forcing (ZF) precoding. We present results for Rice channels and Matched Filter (MF) receiver showing a surprising reduction in energy efficiency. We also derive an accurate approximation for spectral efficiency when the equal power allocation strategy is employed. According to our simulations, a loss of 6 dB is observed when the symbols are transmitted with the same power.**

***Keywords*— Large Intelligent Surfaces, Line-of-Sight, Matched Filter, Rayleigh, Rice, Zero Forcing.**

I. Introduction

Due to the growth in the number of applications and users requiring high-speed wireless communication, the Radio Frequency (RF) spectrum is becoming overly crowded [1]. For indoor environments, the situation is even worse. The density of users and bandwidth demands are enormous, mainly thanks to the coexistence of wireless services such as cellular networks, WiFi networks, Bluetooth systems, and the Internet of Things (IoT). Therefore, to accommodate this tremendous demand for wireless, high-efficiency spectrum approaches are highly desired [2], [3].

Recently proposed, Large Intelligent Surfaces (LIS) are a wireless communication system that can be considered as an extension of massive Multiple-Input Multiple-Output (MIMO) systems. But the idea transcends the traditional concept of antenna arrays on the base stations [4]. Its main advantage is to enable the focus of energy in the three-dimensional space through remote sensing with extreme precision. Because it constitutes the distributed intelligent wireless communications, sensing, and computing platform, capable of interconnecting the physical and digital worlds seamlessly and sustainably, LIS is considered the basis of future networks [5], [6].

The first studies on this subject began in 2014. From a range of experimental implementations, Hum et al. [7] showed that reconfigurable reflective arrangements and matrix lenses were capable of dynamically controlling the antenna beam. The concept similar to what we now call LIS was only mentioned for the first time in 2015 in the University of California Berkeley project [8]. The general idea consisted of electromagnetically active wallpapers with the built-in processing power. A chain of Field Programmable Gate Array (FPGA) automatically controls a compact integration of a large number of tiny antennas.

Nowadays, there is much research on this topic. However, challenges related to performance, user location estimation, user assignment, and power allocation need to be addressed more. Many of these works have focused on the LIS capacity for wireless communication, addressing some parameters previously developed for other systems.

For example, Björnson et al. [9] evaluate the performance of massive MIMO under adverse conditions, bringing insights on how to maximize the Energy Efficiency (EE) setting the number of Base Stations (BS) antennas and active users and the amount of transmit power. Defined as the number of bits transferred per Joule of energy, the EE is affected by many factors such as network architecture, transmission protocol, spectral efficiency, radiated transmit power, and circuit power consumption.

Following this same reasoning, a relevant point of the system with LIS is that it is aligned with the concepts of green communication [10]. In this topic, the critical task is to select energy-efficient communications, networking technologies, and products to minimize resource use whenever possible.

The works [11], [12] consider a LIS composed of passive antenna elements. Performing as a scatterer with reconfigurable characteristics, it does not require any dedicated energy source for either decoding, channel estimation, or transmission. To optimize the energy and spectral efficiencies, the authors come across a non-convex problem based on Majorization-Maximization (MM) alternated by fractional programming, since the objective function involves ratio terms. MM is an iterative optimization method that exploits a surrogate function's convexity to find their maxima or minima [13].

Although the optimization problem solution has already been given in [12], this work only considered LIS systems modeled from Rayleigh channels with Zero Forcing (ZF) precoding. Besides this, most previous research assumes that the channel fading is Rayleigh distributed. Of course, the Rayleigh-fading model is a reasonable assumption for the fading encountered in many wireless communications systems.

However, BS and LIS are part of the same infrastructure, and LISs are usually positioned to explore the Line of Sight (LoS) path concerning fixed BS in 6G networks. To be fairer, Hou et al. [14] use Rician fading channels for modeling the channel gains in a LIS-aided non-orthogonal multiple access (NOMA) network.

In this paper, we intend to compare the result already published in the literature to what we obtained from an LoS propagation modeled from Rician channels and Matched Filter (MF). Besides, due to the high computa-

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tional cost, optimization is not always possible. In this case, we derive an accurate approximation for spectral efficiency and evaluate the performance loss when BS transmits the symbols with equal powers to all users.

The remaining of this paper is organized as follows: Section II refers to the system model, while Section III presents the problem formulation under the optimal view. Section IV shows numerical simulations that confirm the superiority of Rayleigh channels in MIMO systems. An sub-optimal analysis is made in Section V. Finally, we close our discussion in the Section VI summarizing our conclusions.

II. System Model

Among a few works, there is a consensus on the adoption of a system model depicted as in Figure 1. As can be seen, the transmission occurs considering K autonomous terminals with only one antenna located in a three-dimensional environment and a two-dimensional LIS implanted in one plane. The M BS antennas transmit signals to N LIS units. Due to an obstacle, there is no direct way between BS and users.

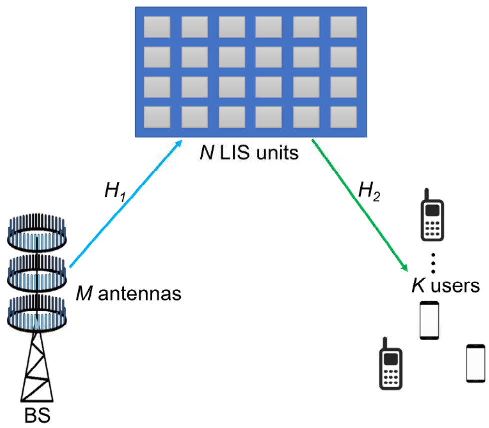

Fig. 1. Radiation model of a signal transmitted from BS to LIS [11].

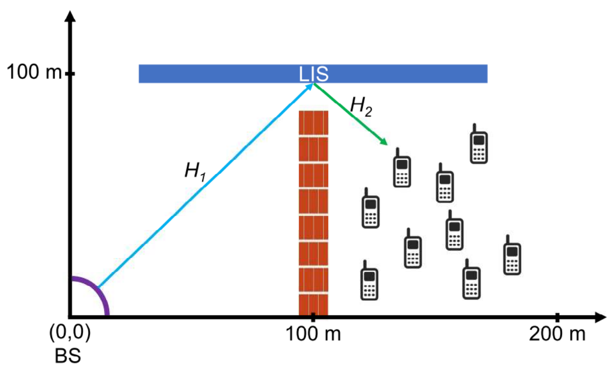

Fig. 2. Scenario adopted with K uniformly distributed users [11].

For analytic tractability, some simplifications are made primarily concerning propagation. An ideal situation is considered with Time Division Duplex (TDD) protocol and perfect timing. Also, the BS has complete knowledge of Channel State Information (CSI).

III. Problem Formulation

Considering the system model represented in Figure 1, the signal received at k-th mobile user can be written as

$$y_k = \beta_2 h_{2,k} \Phi \beta_1 H_1 x + w_k, \tag{1}$$

in which β_t denotes the large scale fading. In both of them, the index t refers to link 1 (BS→LIS) or to link 2 (LIS→k-user). $h_{2,k} \in \mathbb{C}^{1\times N}$ is the channel gain matrix between the LIS and user k, and $H_1 \in \mathbb{C}^{N\times M}$ represents the channel between the BS and LIS. Also, Φ is a diagonal matrix whose elements are the effective phase shifts applied by all LIS reflecting elements, and $\mathbf{\Phi} = e^{j\boldsymbol{\theta}}$ with $\theta_n \in [0, 2\pi]$, $w_k \sim \mathcal{CN}(0, \sigma^2)$ is the thermal noise modeled as a realization of a zero-mean complex circularly symmetric Gaussian variable with variance σ^2. Finally, $x = \sum_{k=1}^{K} \sqrt{p_k} g_k s_k$. In this expression p_k, g_k and s_k denote the transmit power, unit power complex valued information symbol chosen from a discrete constellation set, and precoding vector, respectively.

Then, the Signal-to-Interference-plus-Noise Ratio (SINR) is given by

$$\gamma_k = \frac{\beta_k p_k |h_{2,k} \Phi H_1 g_k|^2}{\sum_{i=1, i\neq k}^{K} \beta_i p_i |h_{2,k} \Phi H_1 g_i|^2 + \sigma^2}, \tag{2}$$

in which β_k is the k-user path-loss obtained by the product of β_1 and β_2.

The optimization problem appears since it is necessary to define the transmit powers for all users and the values for the LIS elements that jointly maximize the bit-per-Joule energy efficiency performance. Since the EE is defined as the ratio between the system achievable sum rate in bps and the total power consumption in Joule, the problem is to solve the following non-convex optimization.

$$\begin{aligned} \underset{\mathbf{\Phi}, \mathbf{P}}{\text{maximize}} \quad & \frac{\sum_{k=1}^{K} \log_2(1+\gamma_k)}{\xi \sum_{k=1}^{K} p_k + P_{BS} + K P_{UE} + N P_n(b)} \\ \text{subject to} \quad & \log_2(1+\gamma_k) > R_{min,k}, \ \forall k = 1, \ldots, K, \\ & \beta^2 \, \mathrm{Tr}[G P G^H] \leq P_{max}, \\ & |\Phi| = 1 \ \forall n = 1, \ldots, N, \end{aligned} \tag{3}$$

where ^{H}, ${}^+$ and Tr indicate Hermitian (conjugate transpose), pseudo-inverse, and trace of a matrix.

If we consider only the numerator of (3), it is possible to optimize the spectral efficiency (SE). This parameter measures information rate transmitted over a given bandwidth in a specific communication system, that is, how efficiently a limited frequency spectrum is utilized. Its optimization problem consists of (3) considering $\xi = 0$.

As our goal here is to analyze the LIS channel under different scenarios. In relation to g_k:

- It can be Zero Forcing (ZF) precoding whose matrix is given by $\boldsymbol{G} = (\beta_2 \boldsymbol{H}_2 \mathbf{\Phi} \beta_1 \boldsymbol{H}_1)^+$ or
- It can be Matched Filter (MF) precoding whose matrix is given by $\boldsymbol{G} = (\beta_2 \boldsymbol{H}_2 \mathbf{\Phi} \beta_1 \boldsymbol{H}_1)^H$.

It is worth mentioning that in both cases, $\boldsymbol{H}_2 = [h_{2,1}^T, h_{2,2}^T, ..., h_{2,K}^T]^T \in \mathbb{C}^{K\times N}$. Regarding the channel, both $\boldsymbol{H}_1$ and $\boldsymbol{H}_2$ can be modeled according to:

- Rayleigh fading: characterized by multipaths and modeled as $[H_1]_{i,j} \sim \mathcal{CN}(0, \sigma^2)]$ and $[h_{2,k}]_i \sim \mathcal{CN}(0, \sigma^2)]$

- Rician fading; when typically a dominant line of sight signal is much stronger than the others. In this paper $[H_1]_{i,j} \sim \mathcal{CN}(K_F, \sigma^2)]$ and $[h_{2,k}]_i \sim \mathcal{CN}(K_F, \sigma^2)]$ and the Shape Parameter, K_F is deterministic and is defined as the ratio of the power contributions by LoS path to the remaining multipaths.

On the other hand, in some cases where there is no high processing resource, the best thing to do is assume equal power for all users. Therefore, a sub-optimal analysis is also presented in Section V.

IV. Numerical Results

In this section, numerical results are presented to validate the simulations obtained from 10^3 realizations, considering the practical values shown in Table I. The efficient MM approach detailed in [12] is adopted. Beyond the variables defined in the table, it is considered that both, $h_{2,k}$ and H_1, follow Rayleigh or Rician distribution and $K_F \in \{1, 2, 4\}$. The multiple single-antenna mobile users are assumed randomly and uniformly placed in the 100m×100m half right-hand side rectangular, according to Figure 2.

TABLE I

Parameters adopted for the Monte Carlo simulations.

Description	Value
Noise variance, σ^2	1
Circuit dissipated power coefficients at BS, ξ	1.2
Large scale fading, β_t	$10^{-3.53}/d_t^{3.76}$
Circuit dissipated power, P_{BS}	40 dBm
Dissipated power at each user, P_{UE}	10 dBm
Dissipated power at n-th LIS element, $P_n(b)$	10 dBm
Individual QoS requirements, $R_{min,k}$	0
Maximum transmit power at BS, P_{max}	20 dBW
Transmission bandwidth	180 KHz

Figure 3 compares, from the EE point of view, the optimization technique performance under different propagation conditions. Two curves refer to the MM-based method considering the Rayleigh model, while the others are related to LoS with $K_F = 1$. Note that the channel's energy efficiency under the Rayleigh fading has a higher energy efficiency than the Rician case. The reason for this is the well studied rank degradation in MIMO environments and its reduction on the spectral efficiency [15].

Figure 4 presents this same parameter but considering the fading modeled as Rician distribution with different K_F deterministic factors. It is possible to notice that the higher K_F, the higher the power of the dominant component and the worse is the Rician channel performance, consequently.

In its turn, Figure 5 compares the MF and ZF performances considering the SE of Rayleigh and Rician channels. Just as in conventional MIMO systems, ZF stands for Rayleigh channels. However, when we consider the LoS scenario, MF precoding presents better performance.

Finally, Figure 6 compares the EE obtained from MF and ZF techniques for two different schemes with the Rayleigh channel. As expected, MF behaves better for low SNRs while the performance of ZF stands out for high SNRs. It is also possible to highlight that the average EE of the MF method decreases from a specific point thanks to the saturation of the spectral efficiency that occurs for high P_{max} values and is shown in Figure 5.

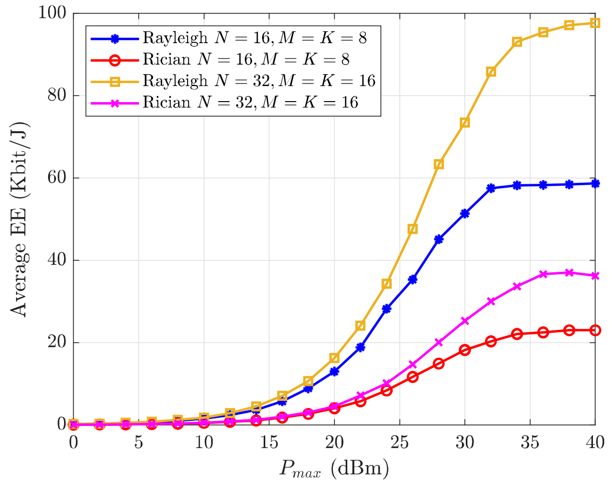

Fig. 3. Average EE of Rician and Rayleigh channels under different setups.

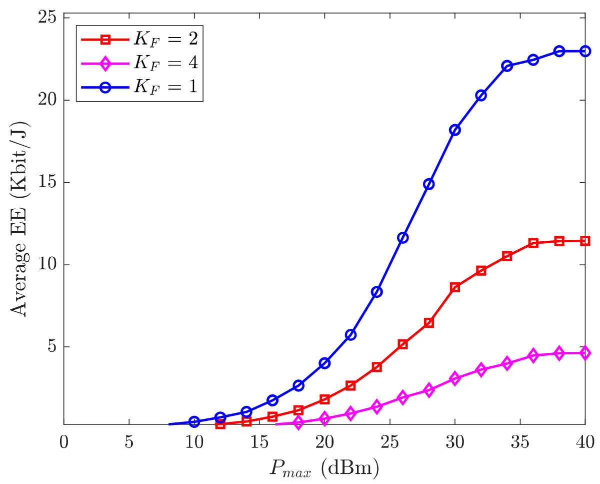

Fig. 4. Average EE of Rician channels with different K_F factors and $K = 8, M = 8, N = 16$.

V. Equal Power ZF

Another interesting aspect that deserves to be verified is to measure the loss in the system performance when the total power is not optimized. That is because it is not always possible to have the channel state information in real-time of a given effective system. In these cases, the best we can do is assume the uniform transmit power for all K users. So, the condition in (3) becomes an equality and we can write $\text{Tr}(GPG^H) = P_{max}$. Then

$$p_k = \frac{P_{max}}{K\,\text{Tr}(\alpha)}, \tag{4}$$

in which $\alpha = (\beta_2 H_2 \phi \beta_1 H_1)(\beta_2 H_2 \phi \beta_1 H_1)^H$.

Considering ZF precoding, let the sum-capacity be given by the sum of the spectral efficiency of all users

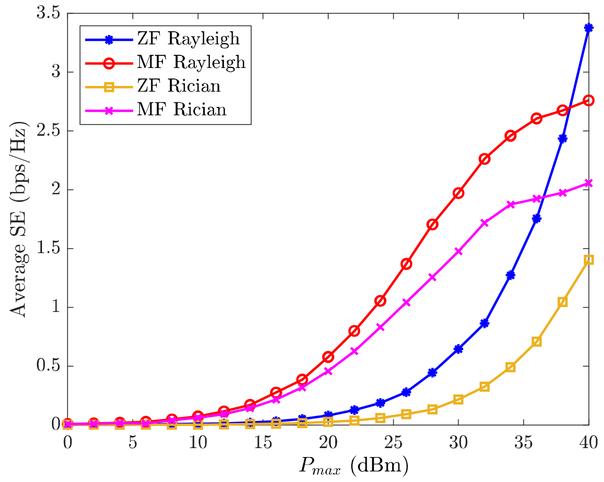

Fig. 5. Comparison between ZF and MF applied to Rayleigh and Rician channels with $N = 16$, $K = 8$ and $M = 8$.

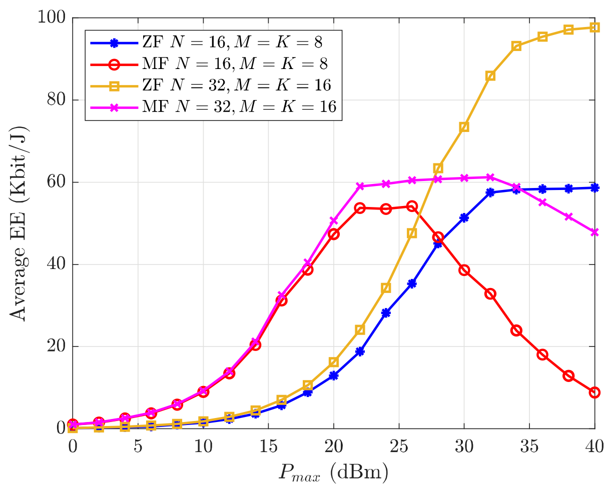

Fig. 6. EE considering ZF and MF techniques and $N = 16$, $K = 8$ and $M = 8$ for Rayleigh channels.

as

$$\begin{aligned} C &= \sum^{K} \log_2(1 + p_k\sigma^{-2}) \\ &= K \log_2\left(1 + \frac{P_{max}}{KTr[\alpha]}\right). \end{aligned} \tag{5}$$

Then, it is possible to obtain an analytical expression from the following steps.

Since α is a random variable that depends on path loss represented by β, the probability function is $p(\alpha, \beta) = p(\alpha|\beta)p(\beta)$ and so the expected value for the sum-capacity can be expressed by

$$\bar{C} = K \int_0^\infty \int_0^\infty \log_2\left(1 + \frac{P_{max}}{KTr[\alpha]}\right) p(\alpha|\beta)p(\beta)d\alpha d\beta. \tag{6}$$

A possible simplification is to replace β for its expected value. Then

$$\mathbb{E}[\mathrm{Tr}(\alpha)] = \mathbb{E}[\beta]^2\mathbb{E}[\mathrm{Tr}(\alpha_1)], \tag{7}$$

and

$$\mathrm{var}[\mathrm{Tr}(\alpha)] = \mathbb{E}[\beta]^2\sqrt{\mathrm{var}[\mathrm{Tr}(\alpha_1)]} \tag{8}$$

in which $\alpha_1 = (H_2\phi H_1)(H_2\phi H_1)^H$ and var(.) means variance operator. In this case, (6) can be rewritten by

$$\bar{C} = K \int_0^\infty \log_2\left(1 + \frac{P_{max}}{KTr[\alpha]}\right) p(\alpha)d\alpha. \tag{9}$$

From the central limit theorem, we can assume that $p(\alpha_1)$ follows a normal distribution. In this case, the mean value can be obtained as

$$\begin{aligned} \mathbb{E}[\mathrm{Tr}(\alpha_1)] &= \sum_{i=1}^{K}\sum_{i=1}^{M} \mathbb{E}[|g_{i,j}|^2] \\ &= KMN\sigma_{H_2}^2\sigma_\phi^2\sigma_{H_1}^2 \\ &= KMN, \end{aligned} \tag{10}$$

in which $g_{i,j}$ is the element of $\mathbf{G}$ located in the i-th row and in the j-th column. $\sigma_{H_2}^2$, σ_ϕ^2 and $\sigma_{H_1}^2$ are the variance of H_2, ϕ and H_1, respectively. On the other hand, the second moment $\mathbb{E}[\mathrm{Tr}^2(\alpha\alpha^H)]$ can be simplified by the following expression thanks to Mathematica software:

$$\begin{aligned} \mathbb{E}[\mathrm{Tr}^2(\alpha_1)] &= \sum_{b=1}^{N}\sum_{r=1}^{M}\sum_{p=1}^{K}\sum_{t=1}^{K}\sum_{b_1=1}^{N}\sum_{r_1=1}^{M}\sum_{p_1=1}^{K}\sum_{t_1=1}^{K} \Phi \\ &= KMN(K + M + N + KMN) \end{aligned} \tag{11}$$

in which Φ is expressed in (12) on the next top page.

Then,

$$\mathrm{var}[\mathrm{Tr}(\alpha_1)] = KMN(K + M + N) \tag{13}$$

Comparatively, Fig. 7 shows three versions of sum-capacity: one optimum simulated obtained by optimizing the transmit power and effective phase shifts of each user, a mean obtained through (6), and finally one suboptimal simulated. It is worth emphasizing that these last two consider the same transmit power for all users. The logarithmic scale is adopted to make clear the tendency of the curves. It is evident the MM optimization technique robustness since it offers a gain of 6 dB when used. However, considering situations in which CSI is not available, the approximation derived here is very accurate concerning the simulated sub-optimal results.

VI. Conclusions

In this paper, we have reproduced some LIS systems modeled from Rayleigh fading and ZF precoding. In the sequel, they are compared to systems that consider Rician channels and MF precoding. As already mentioned in the literature [16], [17], we have confirmed that Rayleigh channels perform better than Rician ones even in not conventional MIMO environments, like LIS.

This result can be explained from the spread, the higher the scattering, the better the system performance. What increases the spread, in this case, is the number of LIS reflecting units and the fact that the channel is Rayleigh composed of various multipath.

Besides, ZF is better when the system power is high. However, in adverse environments, when it is low, it is clear the MF superiority.

A suboptimal analysis has also been made assuming the same power for all users. An average gain of 6 dB in sum-capacity can be observed when the optimization is applied.

$$\Phi = \begin{cases} 1, \text{ if } (b = b_1) \cap (r = r_1) \cap (p_1 = t) \cap (p = t_1) \cap (p \neq t) \cup (p_1 \neq t_1) \cup (p = t \cap (p_1 = t_1) \cap (b \neq b_1) \cap (r \neq r_1) \cup (p \neq p_1) \\ 2, \text{ if } (b \neq b_1) \cup (r \neq r_1) \cap (b = b_1) \cup (r = r_1) \cap (p = p_1) \cap (p = t) \cap (p_1 = t_1) \\ 4, \text{ if } (b = b_1) \cap (p = p_1) \cap (r = r_1) \cap (p = t) \cap (p_1 = t_1) \end{cases} \tag{12}$$

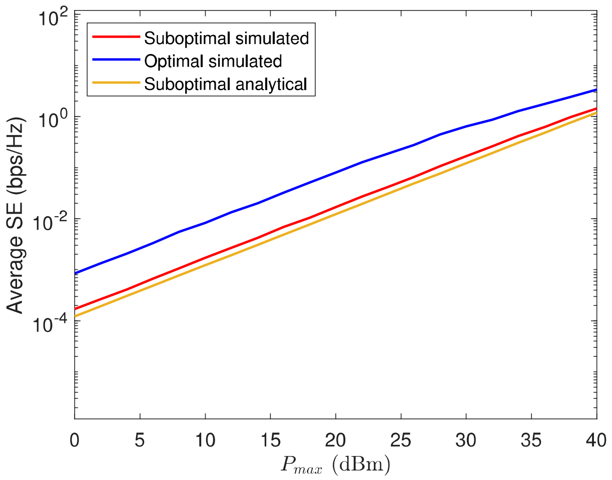

Fig. 7. Comparison between optimal, and suboptimal sum-capacity for $K = 8$, $M = 8$, $N = 16$.

It is worth mentioning that the analyzes presented here are preliminary. As future work, we intend to conduct more in-depth studies on LIS systems in different environments.

ACKNOWLEDGMENT

The authors would like to thank the grant #2018/19538-4, São Paulo Research Foundation (FAPESP), for the support in this research.

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